DIPLOMARBEIT

Visual Conditions in Contemporary Swimming Pool Halls in the City of Vienna

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KURZFASSUNG

Beleuchtungsplanung in Innenräumen von Schwimmbadhallen muss kritische Faktoren berücksichtigen, die für diese Gebäudekategorie einzigartig sind. Allgemein gesagt hat Beleuchtung einen großen Einfluss auf die Wahrnehmung der Umgebung. Sie weckt Emotionen und trägt direkt zum Gefühl des subjektiven Komforts innerhalb eines Raumes bei. In Schwimmbädern muss sie zusätzlich das Sicherheitsrisiko für die Badegäste minimieren. Herausforderungen der Tageslichtsteuerung, der Positionierung von Leuchten und der Orientierung in Bezug auf reflektierende Wasseroberflächen erhöhen die Wahrscheinlichkeit von Blendung und visuellem Unbehagen.

Ziel dieser Arbeit ist es, Daten über den aktuellen Stand der Kunstlichtanlagen und Tageslichtverfügbarkeit in Wiener Schwimmbadanlagen zu sammeln und zu analysieren. Der zweite Teil beschäftigt sich mit der Frage, welche Ähnlichkeiten teilweise kalibrierte Simulationsmodelle zu den Messungen erreichen können. Verlässliche, langlebige Simulationsmodelle sollen erstellt werden, die für zukünftige Planungen, wie z.B. die energetische Sanierung der jeweiligen Kunstlichtanlage verwendet werden können.

Im Rahmen des *"Bezirkshallenbäderprogramms"* wurden in Wien in den 1970er und 80er Jahren sechs nahezu identische Schwimmbadanlagen errichtet. Zwei Vertreter dieser Bauten wurden als Fallstudien für eine detaillierte Bewertung ausgewählt. Aufgrund der großen Ähnlichkeiten könn(t)en die Erkenntnisse auf andere Wiener Bezirksbäder übertragen werden.

Darüber hinaus wurden lichttechnische Messdaten in jedem der Bäder vor Ort unter Verwendung eines entsprechenden Mess-Setups erhoben. Der Vorgang wurde für jedes Gebäude zweimal unter verschiedenen Beleuchtungssituationen durchgeführt. Die Messung unter Tags berücksichtigt nur natürliches Licht, die Nachtmessung ausschließlich Kunstlicht. Die gesammelten Daten wurden ausgewertet und mit den Anforderungen relevanter Normen verglichen. Dabei wurden Defizite betreffend die Beleuchtungsstärke und Potenziale für Effizienzsteigerungen dokumentiert. Zusätzlich wurden die Ergebnisse der Fallstudiengebäude miteinander verglichen.

Ergänzend zu den Feldmessungen wurden Simulationsmodelle erstellt und mit den Messdaten kalibriert. Die Modelle erzielen dadurch hohe Übereinstimmungen mit den gemessenen Beleuchtungsniveaus. Abschließend wurden Optimierungsszenarien anhand von Simulationen aufgezeigt.

ABSTRACT

Appropriate lighting design in indoor swimming pool halls has to consider critical factors unique to this building category. Generally speaking, lighting conditions have an enormous impact on the perception of surroundings. They evoke emotions and directly contribute to the subjective comfort of occupants within a space. In swimming pool buildings, illumination additionally is required to minimize accident risks for the visitors and bath guests. There are challenges pertaining to daylight availability and control, luminaire positioning and orientation. The special setting with reflective water surfaces may increase the likelihood of glare and visual discomfort if not properly considered.

The major objective of this thesis is to acquire and analyse data about the current state of illumination in indoor swimming pool halls. Thereby, artificial lighting systems and daylight availability in Viennese swimming pool facilities are evaluated. Moreover, a part of the thesis focuses on the question which level of correspondence is achieved by partly calibrated simulation models by utilizing the measured data. As such, measurements and simulation results are compared, and discrepancies and potential systematic deviations are identified. The goal is to provide reliable long-lasting simulation models that can be used for future planning purposes, such as energy-saving motivated retrofit of the artificial lighting system.

As part of the “district indoor pool program”, six almost identical swimming pool facilities were constructed in Vienna in the 1970s and 80s. Two representatives of these buildings have been chosen as case study buildings for a detailed assessment including both in-situ measurements and modelling in a state-of-the-art lighting simulation tool. Due to the good fit of results, findings can be reasonably extended to other Viennese district baths.

Measurement data was acquired via in-situ measurements using illumination and luminance measurement devices. This process was performed twice for each building considering different lighting situations. Daytime measurement considered natural light only, while night-time measurement focused on the performance of the corresponding artificial lighting system. Further information was gathered by on-site inspections and face to face interviews with technical staff of the facilities. The collected data was evaluated and compared to requirements of relevant standards. Thereby, shortcomings in illumination levels and potential for efficiency improvements could be identified. In a subsequent effort, results of the case study buildings were compared against each other.

Supplementary to the field measurements, simulation models were generated in a lighting software and calibrated with obtained data. The efforts resulted in a rather high degree of correspondence of the results. Based on these efforts and analysis of the status quo, optimization scenarios were outlined aiming to improve visual performance.

Keywords

Indoor swimming pool, visual building performance, visual comfort, illumination measurement, lighting simulation

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I must express gratitude to Dipl.-Ing. Jochen Jandak as my first contact person of MA 44 for his cooperation and support. When I already saw the feasibility of my diploma thesis on the brink (because all pool buildings had to be closed due to the pandemic), he made it possible for me to have access to the pools under an exceptional permit. Furthermore, he provided me with plans of the district swimming pool buildings, which greatly accelerated the progress of the work. I would also like to thank the swimming pool managers of *Hietzing* and *Donaustadt* and their colleagues, who had to work extra shifts at night to allow me access to the buildings.

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CONTENTS

1 INTRODUCTION

1.1 Overview

The city of Vienna is one of the biggest public pool operators in Europe. Communal swimming pools as sports and recreational facilities are intricately connected to the city's culture (MA 44 - Bäder 2020). The numerous public baths of today are vital to the high standard of life and health, qualities for which Vienna is regularly internationally awarded for (Mercer 2019).

The Austrian architect Friedrich F. Grünberger and his role in the implementation of the 1968 *Bäderkonzept* can be considered as vital for the development of today's Viennese contemporary swimming halls. Within the concept, the authorities initiated numerous actions to refurbish existing and construct new indoor and outdoor communal bath facilities. The so called *"Viennese district pool program"* was part of the Bäderkonzept. During this program two main construction phases for indoor swimming pool halls in various districts of Vienna were realized within relatively short time. In 1976-'78 (first phase) three swimming pool halls were constructed. Between 1980-'84 (second phase) another three facilities were built. The experiences derived from the first stage were beneficial for the second phase in terms of technical improvement and economic efficiency. The main goal was to provide all citizens with easily accessible pool facilities for recreation, sports and communication (Feichtenberger 1994). The six bath facilities of this program are reasonably comparable due to all being based on the famous "Europe-bath" prototype suggested by Grünberger and sharing his role as chief architect. As such, they follow an almost identical geometry as well as floor plan and originate from a similar construction period. Today, the buildings are about 40 years old. Since 2000 all six Viennese district indoor pool facilities have been retrofitted resulting in increased energy efficiency (Walal 2018). The guidelines from Grünberger's bath-prototype are partly still applied standard of modern swimming pool halls, which highly illustrates the innovativeness of his design.

The purpose of this thesis is to document performance data pertaining to indoor lighting levels of two exemplary district pool case studies and compare them against prevailing standards. The evaluation provides information about identified performance issues and locates optimization potential. Additionally, a comparison between the structurally almost identical case studies reveals the impact of geometry, orientation and surroundings on the visual performance of the pool halls. The thesis assesses daylight availability and artificial lighting systems of the corresponding indoor environment. Exterior illumination of the case study buildings is no focal point of this thesis. However, this might be of interest in future research efforts.

The second part of this thesis includes modelling the existing situation in a profound, state-of-the-art lighting simulation software. Thereby, the focus is laid on the question if similarities to the measurement results can be found in the simulation results, and if the simulation can be calibrated by the measured data. Such virtual models that show a good correspondence to the measurements can be used for later planning purposes and offer an inexpensive and fast exploration of the impact of different improvement scenarios.

Two of the swimming pool halls, *Hallenbad Hietzing* (1978) and *Hallenbad Donaustadt* (1982) were selected as representative buildings for this work. Moreover, these two buildings were the swimming pool halls that were the first planned and constructed of each of the abovementioned construction periods. The findings and results of this thesis may serve as an adequate reference for the lighting performance of the other buildings of the same realization periods.

1.2 Motivation

Public swimming pool providers face the challenge of significant changes in demand. Swimming as form of exercise and thermal baths have always been but still are becoming increasingly more popular. Furthermore, more and more people can afford private pools or spend their time in fitness clubs. As such, private pools and fitness centres may be understood as competitors to public swimming pool halls. To maintain the tradition of Viennese communal swimming pool halls alive in future, it seems essential that the buildings are operated and maintained as efficiently as possible. The artificial illumination of large indoor areas contributes considerably to electricity demand. Lighting plays a vital role in the human’s perception of surroundings and directly contributes to the feeling of comfort. Additionally, a well-balanced lighting system in indoor swimming pool facilities ensures a safe environment.

Daylight availability, turbulent and reflective pool water surfaces resulting in glare potential are some of the challenging aspects in providing adequate visual performance.

Since 1984, the six district pool halls designed by Grünberger are an integral part of the offered recreational and sport activities in Vienna. In the last two decades, the communal baths have successfully undergone innovative technical refurbishments by Energy-Contracting models. According to the municipal authorities for baths in Vienna (MA 44), the implementations led to an overall decrease of 66% in energy and natural resource consumption. These efforts have also been awarded by the European Energy Service Initiative and by the European Commission with the *Green Building Partner Award* (APA OTS 2008). However, MA 44 needs to continue evaluating current strengths and deficiencies for composing efficient future strategies. As part of the retrofit actions lighting installations were optimized and partly upgraded to efficient LED technology. Despite implemented energy efficiency measures, there is no data of resulting visual quality and performance of artificial lighting systems within the pool facilities. Therefore, in-depth investigation and documentation of quantitative lighting levels will add to the knowledge about this specific building type. Since the bath type of district indoor pool hall includes six structurally almost identical buildings, the findings from the case study buildings can be reasonably mapped to all other district bath facilities. The derived results provide the opportunity for an objective assessment of the current visual performance regarding deficiencies as well as saving potential. Additionally, partly calibrated simulation models will allow access to long-lasting information and can serve as powerful tools for future refurbishments of these buildings.

1.3 Background

The *Illuminating Engineering Society*'s (IES) comprehensive lighting handbook (DiLaura et al. 2011) served as fundamental source for the theoretical background of this contribution. Relevant standards for sports facilities are defined in DIN EN 12193, the European standard for sports lighting (DIN EN 12193). Requirements are dependent on the type of sport and subdivided conditional to the class of play. A number of guidebooks on sports lighting (Sport England 2013; Philips Lighting 2003) is available online. They present design principles on artificial and natural lighting, specifically considering aspects of sports venues and swimming pool halls.

Historical background information of Vienna's contemporary swimming pool buildings is documented in an exhibition booklet about the architectural work of Grünberger (Künstlerhaus Wien 1974) and published literature (Feichtenberger 1994; Seemann and Lunzer 2004; Seledec et al. 1987). A thesis conducted at *University of Technology Vienna* (Walal 2018) studies thermal performance of one specific Viennese swimming pool building and includes an in-depth documentation about the importance of the work of the Austrian architect. Additionally, the work provides information about recently implemented Energy-Performance-Contracting projects and conducted refurbishment actions in Viennese swimming pool facilities. Both case study objects within present thesis have been part of mentioned Contracting projects.

According to published literature that examine energy performance of existing sports venues, swimming pool facilities categorize as high-level energy consumers compared to other building categories (Trianti-Stourna et al. 1998). Thereby, next to heating of air and water, lighting is determined to be one of the major energy loads of the typology. The literature contribution proposes energy conservation strategies based on reference data derived from case study buildings. The main share of existing studies targets indoor climate and reduction of heating demand.

Thermal performance will not be topic of this thesis. The field of visual performance seems not as extensively documented compared to thermal aspects of swimming pool buildings. A publication from Portugal (Coelho et al. 2016) addresses retrofit potential by upgrading artificial lighting systems to LED technology. The evaluation expands over four existing indoor swimming pool complexes that vary in size and level of competition. Next to significant reduction of energy use one finding was that LED-investment in the investigated smaller swimming pool complexes was not always economically viable.

A similar approach to lighting evaluation as within present contribution was conducted in other studies in Austria and India (Ansari 2015; Suresh et al. 2019). In both papers, the topic of illumination of existing sports facilities was assessed via measurements and simulation modeling. The documented status-quo enabled proposals for optimization scenarios targeting improvement of visual performance and energy efficiency.

This thesis should help fill the information gap that exists about visual building performance of contemporary Viennese swimming pool typology.

1.3.1 Historical context of Viennese bathing culture

The city of Vienna has a rich history in bathing culture and still is one of the biggest public pool operators in Europe. In 1804, the construction of the *Dianabad* marked the early beginning of a new age in European bathing culture. During summertime the magnificent interior pool hall was used for swimming, during winter the pool was covered and the same space served as a pompous ballroom. It was the first indoor swimming pool hall in Vienna and the biggest in Europe. In 1838, *Sophienbad* followed as the second Viennese swimming palace. At that time both bathing buildings were unparalleled in Europe and contributed significantly to the development of bathing industry (Seemann and Lunzer 2004).

The first so-called *"Tröpferlbad"* was opened in 1887. Expenses in the public bath sector were understood as investments in public health. The idea of providing the middle-class population with communal shower and bathing facilities in each district was driven by catastrophic health conditions. The demand for such facilities was excessive as basic hygiene was poor. The communal shower and bathing facilities enabled the broad public to proper basic sanitation. The reception of the mass douches and communication centres proved to be an enormous success (Seemann and Lunzer 2004).

A key factor for Vienna's leading role in bath development was the favourable position at the Danube river. The first Danube regulation in 1870 led to new possibilities. Multiple open-air baths directly provided by natural river water were founded. Since the inner-city districts became denser due to demographic growth, living conditions worsened in form of limited living space. As a result, people longed for a sense of nature. New baths were enthusiastically accepted within the population. *Gänsehäufel* (1907) became the biggest public summer bath in Europe.

The interwar period was characterized by immense extension and construction of public swimming facilities. Although residential buildings of that time were already equipped with showers and running water, the luxury of baths (to be understood as body care facilities) remained reserved for public facilities. According to Sedlecek and Kretschmer, the lively construction activity of the interwar period of indoor and summer baths laid the foundation of the wide range and standard of today's public baths. Vienna's reputation as "city of beautiful communal baths" can be led back to that time (Seledec et al. 1987).

The main consideration was that swimming must be accessible for all social classes and must not be seen as a privilege of the rich. Therefore, in the year 1926

Amalienbad, the second municipal indoor swimming pool hall (after *Jörgerbad* 1914), was constructed.

The primary interests and bathing behaviour developed from covering basic hygiene to recreational pastime. Numerous summer baths were systematically positioned in the suburban areas. The extension included *Krapfenwaldbad* (1923), *Ottakringer Bad* (1926), *Hohe Warte Bad* (1927), *Kongressbad* (1928) and *Stadionbad* (1931).

Additionally, the new type of "*Kinderfreibad*" or children's summer bath came up in 1917. Access for children between 6 and 14 years was free. Because of their positive public reception 23 children baths have been constructed in the interwar period, which in major parts still exist (Seledec et al. 1987).

1.3.2 The concept of the "Inexpensive Europe bath"

As in all of Europe, World War II also left its mark on the bathing facilities of Vienna. The flourishing expansion of the sector abruptly stopped. Reconstruction of the city infrastructure as well as residential housing became the primary focus. The construction of new recreational infrastructure was put on hold until 1957. Out of 72 operating swimming facilities in Vienna, only 17 survived the war without major damage. Most of the facilities were damaged severely, seven were destroyed due to bombings and ground attacks. The City of Vienna focused on quick reconstruction. 30 of the existing swimming pool facilities were able to reopen until the end of 1945 (Seledec et al. 1987).

In the early 1950s, Professor Florian Friedrich Grünberger realized the upcoming need for recreational public bathing facilities. They became focal point of his architectural work. In detail, his economical and cost-efficient approach established his role as an experienced and well-recognized international expert in the field of recreational swimming facilities. The press addressed him with the nickname "bath pope" (Bednarik and Bruckbauer 1995).

With rise of the economy and the slow re-establishment of economic power within the population, topics of hygiene, exercise and health gained interest. Political efforts strived towards development of inexpensive concepts for construction of sports facilities. This is since financial resources for revitalisation of infrastructure and bath buildings were low compared to the growing public demand.

In the year 1967, the European Council for bathing culture hosted a seminar in Cologne with the purpose of addressing cost-efficient construction and operation of sports facilities. Grünberger was invited as an expert representative for the Austrian state. His convincing approach to affordable swimming pool buildings was received exceedingly positive. His considerations and cost analysis presented in the lecture during the seminar led to the prototype of "*Europabad*" and to him being suggested to become an advisor of the European Council for bathing culture. Grünberger's intent was to reduce time and expenses in construction and operation whilst still guaranteeing excellent workmanship and use of quality materials as well as technical equipment.

One of the main pillars of the Europe-bath-concept was the idea of constructing the buildings in stages. The plan considered the economic situation of that time. Extensions of the building, for example restaurants, milk bars, saunas, changing rooms, bowling alleys and various other leisure rooms, could be added in later years regarding their relevance to the building. The construction stages were clear, functionally self-contained, and were ranked hierarchically (Bednarik and Bruckbauer 1995):

- Wind- and weatherproof indoor swimming pool hall with a standard swimming Pool of 25 x 10m, including space for technical equipment.
- Extension including 200 group locker rooms and changing booths.
- Extension including a teaching pool (shallow water, 10 x 8 m size) and non-swimmer hall.
- Extension including further locker cabins for schools or clubs. Possibility for sauna and/or buffet rooms.
- Extension including a multifunctional hall with a diving pool of 10.50x7.65m, including waterslides, springboards, etc.
- Extension including a spectator's gallery.
- Realization of further individual assets following the interest of the communities.
- Definition of a package price and a construction completion date.

This modular structure allowed low financial effort for a construction that meets public basic demand while maintaining extension potential optional.

The inexpensive Europe bath concept was designed to be adaptable to the context of the surrounding environment, landscape and size of the communities as well as their individual interests. The main aim of the concept was reduction of building volume and corresponding investment costs. Further assets were the possible integration of prefabricated construction and the optimizing the ratio of traffic to water area.

Until Grünberger's "inexpensive Europe bath", it was considered standard for an indoor pool hall to feature one combination pool that fulfilled the needs for all activities. In contrast, the revolutionary Europe bath introduced individual pools of different sizes and depths with respect to their function. The replacement of the combination pool led to improved efficiency in use of the individual pools. While the overall water surface increased, the pool volume decreased. This further resulted in the possibility to reduce ceiling height in the swimmer- and non-swimmer areas. Only pools with springboards or diving-pools still required a higher minimum ceiling height. The benefits were overall reduction of building volume, external walls, window surfaces and water demand. Consequently, technical equipment, operational and maintenance costs such as heating and cooling of air and water, water filtration and circulation, required luminaires, and maintenance/cleaning were significantly decreased.

Further volume reduction resulted from the space-efficient revolution of changing areas and locker rooms. Grünberger introduced gender-separated group locker rooms with few individual changing booths instead of single cabins. The implementation led to savings of two thirds of space, dedicated to locker rooms.

In addition, hallways were redesigned in a more space-effective way. Hallways used barefoot and with street shoes were no longer separated. Alternatively, boot scrapers, shoe brush devices and disinfection basins were integrated at strategic points of the floor plan design (Künstlerhaus Wien 1974).

Figure 1 illustrates the principal Europe bath floor plan layout.

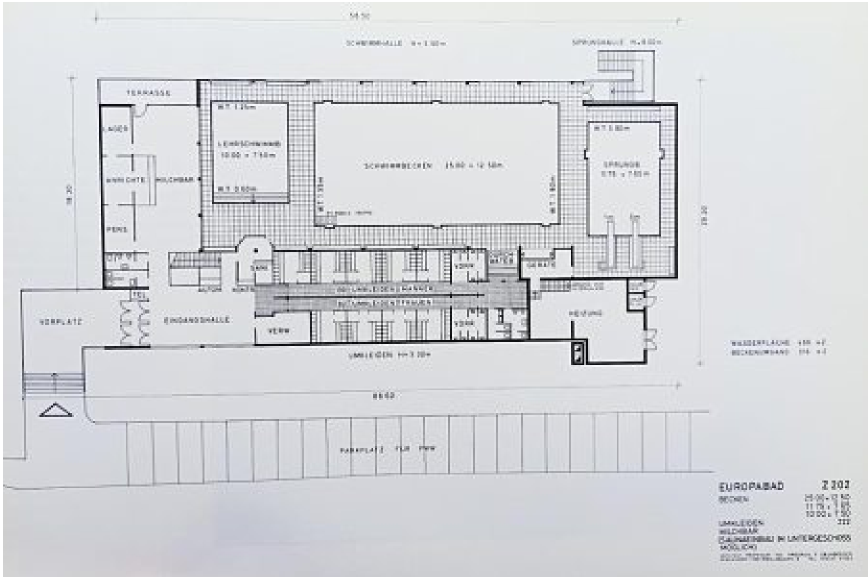


Figure 1: Europabad layout by F.F. Grünberger (Künstlerhaus Wien 1974)

1.3.3 Viennese bath concept and district indoor pool program

The 1960s marked an important chapter in the history of Vienna's modern bathing culture. Most people could not afford to go on vacation but urged for relaxation. Public baths were perceived as a "vacation close to home" (Feichtenberger 1994). In a time after the population has recovered from direct impact of World War II, the responsible city council member Hubert Pfoch decided to invest into the expansion of its swimming pool program. The future oriented "*Bäderkonzept*" was enacted in December 1968 and was unique in Europe. The concept emerged in cooperation of the urban structure planning committee and the administration of baths in Vienna. A network of summer baths and indoor pool facilities should be constructed within less than a decade. The space dedicated to communal recreation should be integrated into the context of the dense and growing city of Vienna and meet the needs of the broad public. The main goal was to provide the population with several modern, well-equipped public buildings that should both fulfil requirements for leisure time as well as necessities for training and sportive environment. A direct translation out of the strategy of the *Bäderkonzept* states:

"*At a time when people's pace of life is more strained than ever before, the creation of sufficient opportunities for recreation for the metropolitan population is of the utmost importance. It is necessary more than ever to strive for the best possible supply of the urban area with recreational areas and facilities." (Seledec et al. 1987)*

To offer sufficient quantities of swimming pool area in the foreseeable future, the concept was based on demand calculations. The amount of swimming pool facilities was estimated according to international guidelines that suggested that for every citizen there should be 1m² outside pool / water surface, for every 333 citizens there should be 1m² indoor pool surface. The resulting layout of 1968 bath concept would cover the demand of the city of up to two million people (MA 44 - Bäder 2020; Feichtenberger 1994).

The *Bäderkonzept* encompassed the following projects (Feichtenberger 1994):

- Construction of the new *Dianabad* as a general refurbishment of the existing facility was not feasible due to severe war damages to the structure.
- General refurbishment of the severely war damaged *Amalienbad*.
- General refurbishment of the bath *Hadersdorf-Weidlingau*.
- Construction of the *Stadthallenbad*, which is equipped for competitive sports events with capacity of up to 800 spectators.

- Extension of the (at that time open-air only) *Ottakringer bath* in form of the erection of indoor hall with sauna facility (Note the *Ottakringer bath* was also planned by F.F. Grünberger and is in some extent similar to the indoor district pool halls of the *Bezirkshallenbäder-Programm*).
- General refurbishment of the facilties *Kongressbad* and *Jörgerbad*.
- Construction of child-friendly summer baths *Schafbergbad*, *Höpflerbad*.
- Construction of six indoor district pool halls.

One of the main objects of the concept was the realization of the Viennese district indoor pool halls. The program foresaw the construction of six municipal indoor swimming pool facilities in the suburban districts of Vienna. Except for one facility, all indoor district baths were planned to be extended by open air facilities in later, upcoming years. This so-called combination baths provided the possibility for swimming activities all year round, widely independent from weather conditions. Each citizen should have close access from home to one of the public recreational facilities. (Seledec et al. 1987)

Architect Grünberger was assigned the task of planning the district pool halls. The city council was convinced of Grünberger's expertise and international experience in the bathing sector. The expectation was significant reduction of construction cost and time, which was an important component of the program. The typology of "*Bezirkshallenbad*" is based on the fundamental principles of his *Europabad* prototype (Feichtenberger 1994).

All six district pool halls follow the same typology, dimensions, share an almost identical floor plan, are equipped with similar surface materials, and therefore closely resemble each other. The room program includes the following amenities (Künstlerhaus Wien 1974):

- 25.00m x 12.50m main pool
- 12.50m x 8.00m teaching pool
- A small paddling pool
- Water temperature of 28°C – 30 °C (Until 1965 the water temperature of indoor pools was at a maximum of 22°C. The cooler indoor pools were mainly aimed for training and exercise instead of broad public recreational use.)
- Sauna gender-separated facilities
- Restaurants accessible for bath guests and pedestrians from outside

Differences between the Europe bath concept and the realized district pool buildings can be found in the designation of the pool basins. As the district pools' primary purpose is relaxation and leisure, Grünberger decided on waiving the diving pool and including a smaller paddling pool for family-friendly utilization. The dimensions of the main and teaching basin were increased slightly (increased width of the main pool). The Europabad layout in Figure 1 is following a rectangular, longitudinal shape, while the district indoor buildings feature an almost squared building shape. The room height was furtherly economized. Moreover, the extensive 8m of free room height was reduced to a maximum of 4.75m by waiving the necessity of a diving tower. Therefore, the generation of district baths were even more cost-efficient than the revolutionary *Europabad*.

The building planning and delivery processes were realized within ten years in two construction stages from 1974 to 1984. Three buildings were planned and realized in the first construction stage. The construction time of each of these buildings was less than 14 months:

- *Hallenbad Hietzing* in the 13th municipal district of Vienna was the first building to be opened to the public in August 1978. The facility was extended with a summer bath within the following year.
- District indoor pool building *Simmering* is located in the 11th municipal district of Vienna. It opened in September 1978.
- Hallenbad *Döbling* in the 19th municipal district of Vienna was opened in December 1978.

The experiences that could be made with the buildings of the first construction phase, such as required technical adjustments derived from the first buildings of the program, supported and optimized the planning process of the second construction stage. The room program for the buildings of this phase was extended with a fourth basin as a hot-tub, quiet areas and additional rooms for solarium and massages.

The following buildings were realized in the second phase (Feichtenberger 1994; Seledec et al. 1987):

- *Hallenbad Donaustadt* in the 22nd municipal district of Vienna was the first building to be opened of the second construction stage in October 1982.
- *Hallenbad Brigittenau* in the 20th municipal district of Vienna was opened in April 1983.
- *Hallenbad Großfeldsiedlung* in the 21st municipal district of Vienna was opened in April 1984.

According to plan material derived from MA37 and MA44 the geometry of the first and second construction stage deviates slightly. The elevated ceiling above the main pool was lowered from 4.80m free room height of the first construction stage to 3.75m free room height in the second construction stage. This adaptation reduces the net volume of the overall geometry. It can be reasonably assumed that the alteration allowed to further spare construction costs. While baths in *Hietzing*, *Simmering* and *Döbling* have windows as vertical skylights to naturally illuminate the interior, *Donaustadt*, *Brigittenau* and *Großfeldsiedlung* feature individual horizontal skylights. The positioning of the skylights above the main pool was the key difference in architectural design between both phases of the program. The similarities of interior swimming pool halls and overall geometry of the district bath typology can be seen in Figure 2.

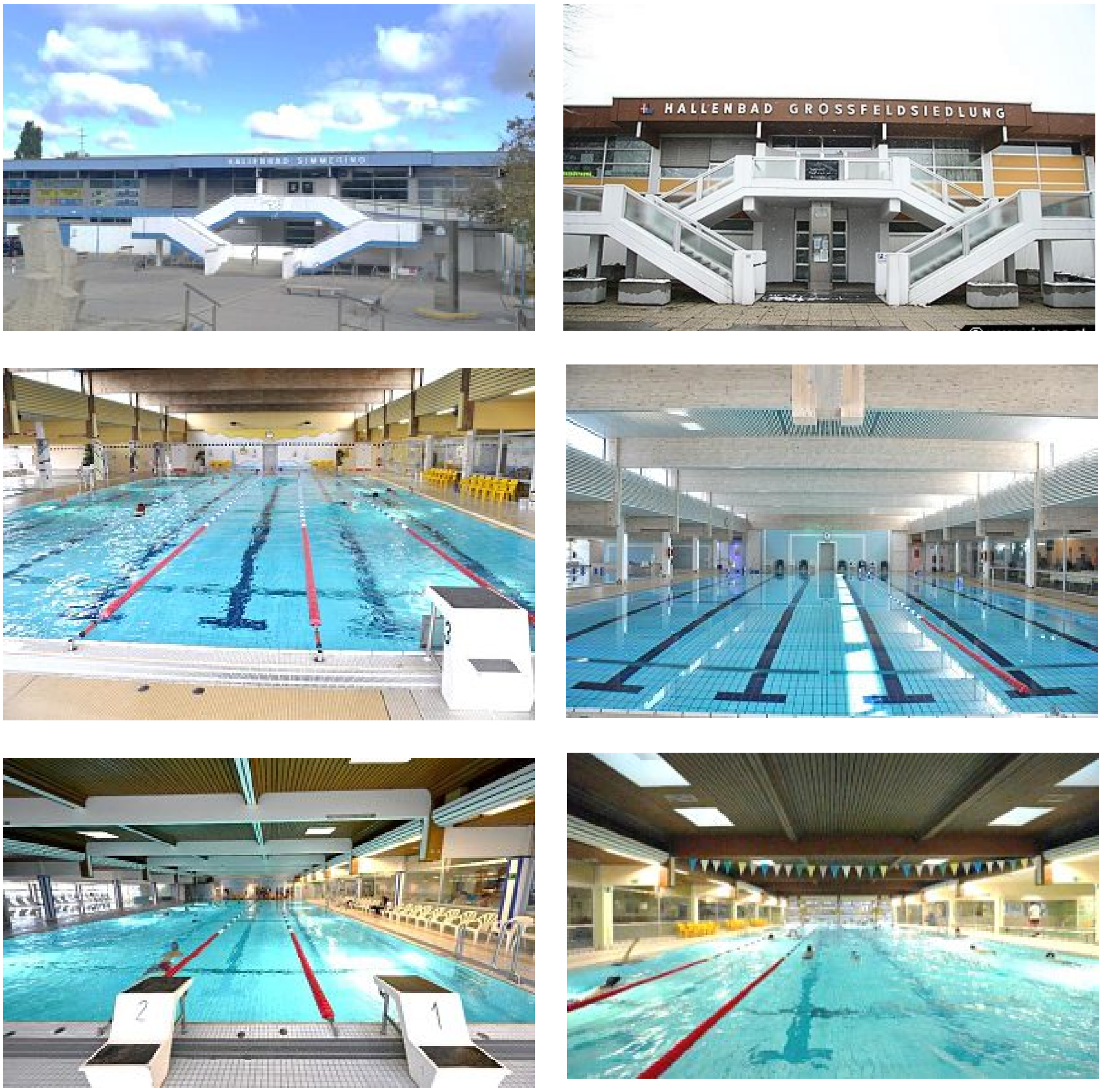


Figure 2: Photographs of the district pool buildings, from top left to bottom right: Simmering, Großfeldsiedlung, Hietzing, Simmering Donaustadt, Brigittenau (wien.gv.at)

1.3.4 Energetic retrofit and future strategies

As previously stated, the municipal authorities for public baths in Vienna (MA44) are one of the biggest pool operators in Europe. In total, there are 38 public facilities under city administration. The operational costs of communal sports buildings are rather high in comparison to many other building usages. Therefore, long-lasting optimization of the buildings regarding energy efficiency and natural resource consumption contains vast cost- and energy saving potential (MA 44 - Bäder 2020).

In the last two decades, the MA44 has undertaken major efforts in modernization of building technology and technical equipment. The model of Energy Saving Contracting proved to be successful. Each contracting project involves analysis of saving potentials and implementation of individually adapted measures. The projects are pre-financed by the contractor. The payback of the contract-taker, the MA44 in this case, is conditional to the actual amount of energy savings. Therefore, the payment is solely success oriented, providing a very good business model for public operators of facilities.

Since the year 2000, 14 public pool buildings in Vienna have been refurbished via energy contracting projects. From 2003 to 2018, more than two thirds of annual consumption of water, natural gas and district heating could be reduced, which equals savings of about six Million € in operational expenses. The ecological footprint decreased accordingly. CO_2 emissions were reduced by 6 900 tonnes per year. For its ecological achievements due to innovative technology and promoting environmental awareness, the MA44 has been internationally awarded (Österreichischer Städtebund; MA 44 - Bäder 2020).

The measures that have been implemented were tailored to the conditions of the individual baths. The retrofit efforts prioritised updating technological equipment (HVAC and swimming pool related technology) over retrofit of the building envelope. The refurbishment mainly encompassed the implementation of central building control technologies, the construction of solar energy panels partly in combination with heat pumps and optimization of district heating stations. The water consumption significantly decreased after the implementation of modern filtering systems, heat recovery of pool water and the reuse of filter water for lawn irrigation. Aging luminaire systems were replaced by modern and efficient LED technologies in many of the swimming pool halls (Österreichischer Städtebund).

Optimizations within the contracting project of the pool hall *Hietzing* have been implemented in the years of 2003, 2009-10 and 2016-17. In 2017, all luminaires, including the underwater spotlights were exchanged with LED-technology (Walal 2018; Obermaier unpublished interview from 2/3/2021).

Refurbishments as part of the contracting project of the pool hall *Donaustadt* were conducted in 2008-09, 2011 and 2015. A refurbishment of the artificial lighting system was not addressed in the course of the contracting project until today (Walal 2018; Toth unpublished interview from 5/15/2020) .

The dynamic demographic growth of Vienna, especially in urban development areas, are current challenges that must be addressed in near future. In this context, the MA 44 has published its strategy for the bath sector development until 2030. The 1968 *Bäderkonzept* considered the quantity of indoor pool water surfaces sufficient for a city of up to two million people. Vienna's population is on the threshold of passing this number. Social and recreational infrastructure must grow in corresponding speed to the population numbers. Figure 3 illustrates the change of demand of Viennese bath structures since the 1950s until today. The interest in municipal swimming pool buildings and summer baths has been continuously increasing ever since. Therefore, extension possibilities of the capacity within existing bath facilities and building sites for new facilities are topic of ongoing evaluation and planning efforts. Further main aspects that require consideration by the swimming pool hall operators are a reaction on the effects of climate change, a certain flexibility due to changes of leisure behaviour of different interest groups, and aspects of digitalization (Statistik Austria 2020; MA 44 - Bäder 2020).

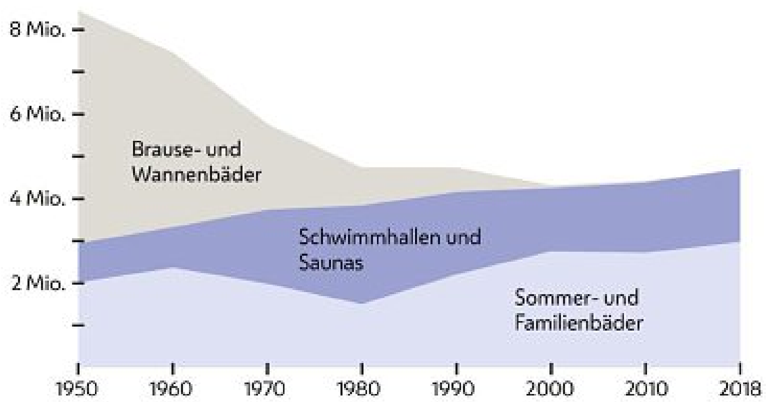


Figure 3: Number of visitors of public baths in Vienna from 1950 - 2018 (MA 44 - Bäder 2020)

During the *Covid19-Pandemic* in 2020 and 2021, many of the swimming pool halls in Central Europe were closed due to the characteristics of swimming pool halls as potential infection drivers. However, during Summer 2020, the MA 44 lanced a traffic-light system for open-air facilities as a measure to reduce infection risk during operation in times of the pandemic.

The evaluation conducted as base for the 2030 strategy report of MA44 detects potential for extension of the existing summer baths in/of *Simmering*, *Laaerbergbad*, *Höpflerbad* and *Großfeldsiedlung* with additional indoor pool halls. The 22nd district, as one of the fastest growing districts in Vienna contains potential as location for a new indoor pool facility (MA 44 - Bäder 2020). Figure 4 is published in the strategy report. It gives an overview of current bathing facilities in Vienna and possible extension sites based on urban development areas.

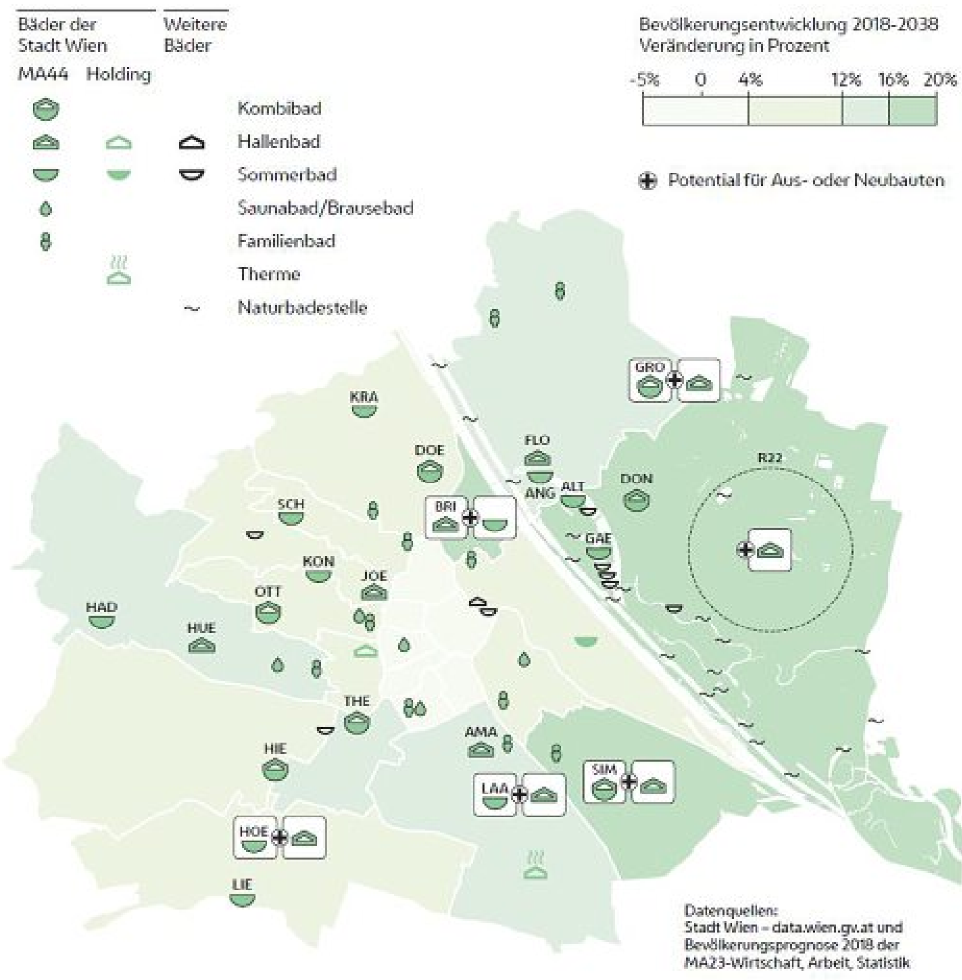


Figure 4: Overview of public baths in Vienna and extension possibilities (MA 44 - Bäder 2020)

1.4 Relevant Illumination criteria

During the sport of swimming, it is assumed that users hardly look upwards. Therefore, the focus of the lighting environment must lie on well-distributed horizontal illuminance (DiLaura et al. 2011).

The relevant standard for lighting in European sports facility buildings is *DIN EN 12193* (DIN EN 12193). Depending on the *Class of Play*, describing the level of professionalism, and the expected number of spectators, facilities are grouped to specified classes of competition. Generally speaking, the higher the skill level of the competitions and athletes, the higher the requirements to the lighting environment. Table 1 lists the definitions for the classes of play according to the standard.

Table 1: Classes of play (DIN EN 12193)

Classes of Play	I	II	III
Internation / national	x		
Regional	x	x	
Local	x	x	x
Training		x	x
Recreational / School			x

- Class I: National and international competitions with a high number of expected audiences. Large visual distances between spectators and athletes are assumed.
- Class II: Regional, local competitions and professional training. Fewer spectators and shorter visual distances than in class I.
- Class III: Competitions without spectators; general training purposes, school classes and recreational use is assumed.

Both case study buildings discussed in this work can be categorized into competition class III. They are not equipped for hosting spectators and their primary function is for training purposes, public leisure swimming and elementary school courses. The necessary minimum requirements for the individual areas can be derived from Table 2.

Table 2: Lighting standards for swimming pool halls (DIN EN 12464-1; DIN EN 12193)

Lighting standards for Swimming Pool Halls (Class III)			
Area	**E_{hor} [lx]**	**U_o**	**UGR_L**
Swimming pools	200	0.5	22
Pool decks	150	0.4	22
Entrance hall	100	0.4	22
Lockers	200	0.4	25

E_{hor} … Horizontal illuminance (average minimum value) [lx]
U_o … Uniformity (minimum-to-average-illuminance)
UGR_L … Unified Glare Rating

In this contribution, the term "*pool deck*" is understood as the immediate surrounding calculation points around the pool basins.

1.5 Quantitative parameters

The IES's (Illuminating Engineering Society) comprehensive lighting handbook (DiLaura et al. 2011) endeavours to be the most important reference document for lighting knowledge. It served as fundamental source for the theoretical background of this thesis. The relation between quantitative parameters is visualized in Figure 5.

Luminous flux

The luminous radiant power emitted from a light source is called luminous flux. The physical symbol for luminous flux is Phi (Φ). It is measured in the unit of lumen (lm).

In practice the term luminous flux is often substituted with the abbreviation "light" itself. *"Light can be considered the luminous equivalent of power and is properly called luminous flux."* (DiLaura et al. 2011).

Luminous intensity

The term luminous intensity describes the density of luminous flux emitted from a light source in a particular direction. Another term for luminous intensity is candlepower. As it is a spatial measure of radiant power it is invariant to distance to the light emitting source. The unit of luminous intensity is lumens per steradians ($lm*sr^{-1}$) or candela (cd).

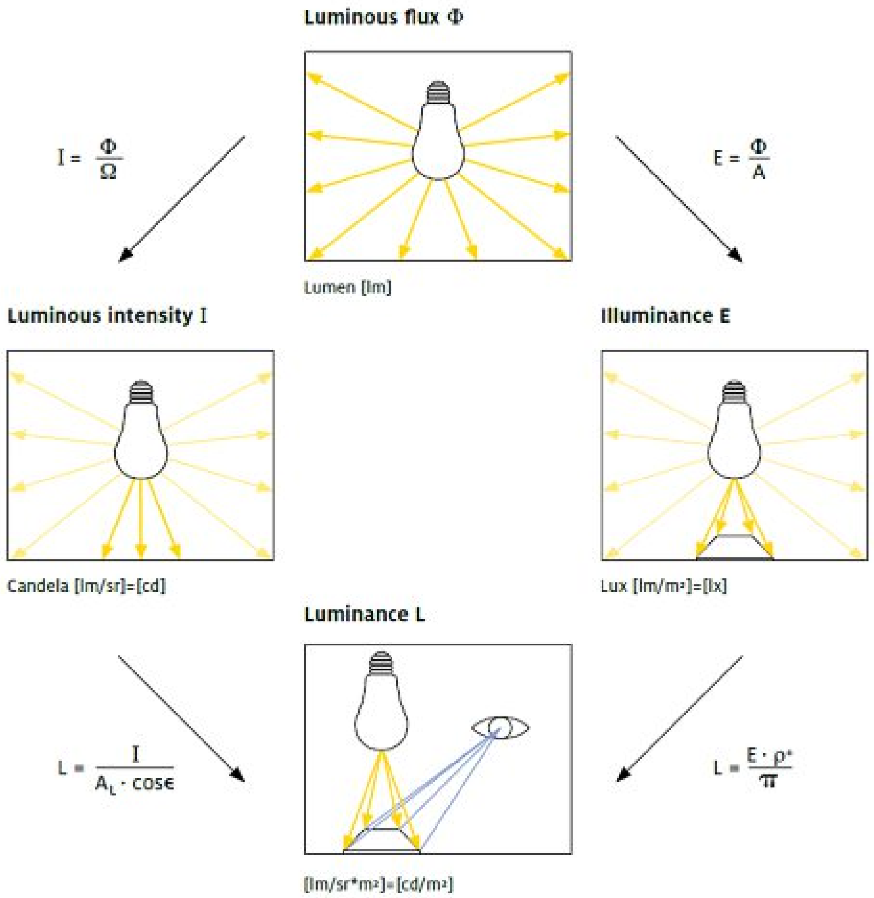


Figure 5: Relation between basic lighting parameters (Zumtobel Lighting GmbH 2018)

Illuminance

Illuminance (E) is the measure of the quantity of total light arriving on a surface. The unit lux describes the luminous flux per area.

Standards specify minimum illumination values for indoor and outdoor scenes of a task and the immediate surrounding area. Requirements are dependent on the type of sport and the class of play. Generally stated, the faster the sport activities / movements and the more spectators, the higher the illuminance requirements.

Dependent on the orientation of the illuminated surface, the term is further specified as horizontal, vertical, or inclined illuminance. The number of vertical illuminance planes is infinite. Therefore, it is common to specify meaningful directions for vertical illuminance. In practice, it is sufficient to define a maximum of the four main directions for analysis.

Luminance

Luminance (L) describes the light perceived by the human eye when looking at a surface. It is also a measure for the perception of brightness of a light source. Surface reflection and roughness have substantial impact on luminance. The unit is candela*m^{-2}.

According to IES, luminance is the only basic lighting parameter describing the perception of light by the human eye and therefore may be the most important one to be considered in lighting design.

1.6 Qualitative aspects of illumination

Qualitative sports lighting must fulfil three main criteria: First, it has to ensure good visibility for all participants (swimmers/athletes, spectators, life guards). Second, lighting should create interesting and pleasant surroundings. Third, artificial light as well as daylight should be integrated in the overall architectural design.

Moreover, for providing satisfactory levels of illumination, additional relevant criteria for ensuring high-quality lighting in swimming pool halls are:

Uniformity

The uniformity is an indicator describing how even illumination is distributed over the area of interest. A well-balanced scene avoids disturbing changes in lighting levels. There are different methods to determine uniformity. It is common for standards to specify acceptable gradients of illumination for sports activities. DIN EN 12193 (DIN EN 12193), the standard for European sports lighting expresses requirements for following illuminance ratio:

$$U_{hor} = E_{min} / E_{avg} \qquad (1)$$

Where: U = Uniformity

E = Illuminance [lx]

Glare

The experience of glare commonly occurs when there is too much light, for example direct sunlight, or when provoked by a bright light source within the visual field. It can be caused directly from luminaires without proper glare control, or indirectly from reflectance of surfaces. In all cases it leads to a feeling of discomfort and a reduction of visual performance. Especially in swimming pool halls the issue of discomfort and disability glare results in safety issues in form of sliding and slippery floors. Therefore, lighting design must be considered carefully and aim for glare limitation. Daylighting from rooflights above swimming pools is desirable, while natural light from vertical windows is likely to create glare and unpleasant reflection effects. Main factors that influence glare are viewing angles, luminaire light control and intensity of the light source in relation to its installation height (DiLaura et al. 2011).

Unified Glare Rating

Although discomfort glare can be a very subjective matter, the unified glare rate (UGR) is a mathematical method for glare prediction. For different activities and tasks the UGR index specifies maximum thresholds. The index is initially describing everyday tasks in interior spaces. Because of varying viewing directions that come with the nature of sport activities, the European standard for sports lighting states that the UGR calculation is not directly applicable. The standards recommend utilization of an equation that is usually only applied in outdoor sports environments (DIN EN 12193). However, this calculation refers only to viewing positions below the horizontal, which is only conditionally applicable for recreational swimming. In the scope of this thesis, the interior unified glare rating calculation has been conducted for a rough estimation of glare sensation. Brightness of enclosing surfaces and luminaires are considered in the formula (DiLaura et al. 2011; Zumtobel Lighting GmbH 2018):

$$UGR = 8\,log\,\left(\frac{0.25}{L_b}\,\Sigma\,\frac{L^2\Omega}{p^2}\right) \qquad (2)$$

Where:
- L_b = luminance of the task area [cd/m²]
- L = luminance of a luminaire in the direction of the observer
- Ω = solid angle of luminaire
- p = position index of luminaire

Surface reflections (veiling reflections)

Surface reflectance describes the ratio of reflected light to the total amount of incident light of a surface. Reflectance of enclosing surfaces of an indoor space has significant effect on illuminance levels. Surface reflectivity is a material property, which can be determined by the following formula (Zumtobel Lighting GmbH 2018):

$$\rho = L \times \pi \times E^{-1} \qquad (3)$$

Where:
- L = luminance at the point of interest [cd/m²]
- E = horizontal illuminance of the point of interest [lx]
- ρ = reflectance value of diffuse surfaces

One of the main challenges of swimming pool hall lighting design is minimizing reflections and glare to reduce visual discomfort and visual disability. The water body surface acts mirrorlike, thus can create specular reflections. Another aspect to consider are scattered reflections due to turbulent water, caused by swimming actions. A swimming pool's water surface is assumed to be disturbed by a maximum of +/- 20% from the horizontal, which increases the reflective surface (DiLaura 2011).

If incident light strikes the water surface at shallow angles, the amount of reflected light increases whilst the light component penetrating the pool surface reduces. This causes critical safety issues as it makes visibility beneath the water surface difficult for observation tasks of the lifeguard. Additionally, reflected light in the visual field of observers produces the sensation of glare and might cause difficulties in distinguishing the pool edge. Surface reflections that veil important information are called veiling reflections. They are common in indoor pool environments and depend on line of sight. Figure 6 illustrates the effect of reflective swimming pool surfaces.

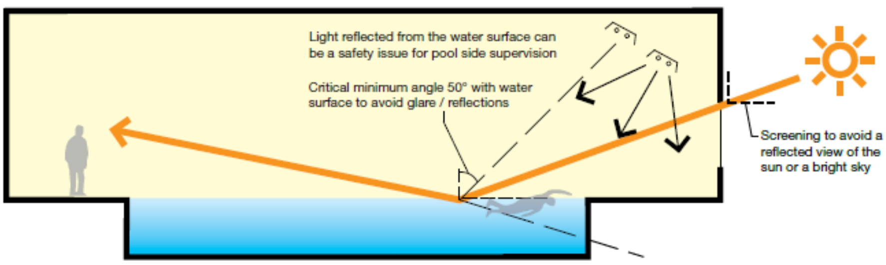


Figure 6: Swimming pool surface reflections and incident lighting angles (Sport England 2012)

A controlled approach onto integration of daylight as well as luminaire positioning, especially considering the incident angle to the water surface, can reduce the effect of glare and veiling reflections in swimming pool halls (DiLaura et al. 2011; Sport England 2012).

Modelling and shadows

Lighting has the ability to define three-dimensional shapes and texture. It describes how well an object, or a person can be separated from its background. Good modelling has impact on how attractive a scene looks. In sports environments, the lighting system should avoid harsh shadows (Philips Lighting 2003).

Colour appearance

Colour appearance of artificial light sources impacts the basic atmosphere of a scene considerably. It is indicated by the correlated colour temperature (CCT) of a lamp and measured in Kelvin. The lower the temperature, the “warmer” is the impression of the light. Warm light appears reddish. The higher the CCT, the “cooler” the apparent light colour. High CCT is perceived as blueish. Colour temperature of 4 000 K appears as neutral to the human eye. For sports lighting colour appearance of 4 000 K to 6 500 K is recommended (DiLaura et al. 2011; Philips Lighting 2003).

New quality criteria

According to the Zumtobel Lighting handbook (Zumtobel Lighting GmbH 2018) new quality criteria for lighting are under development and can be included for evaluation of lighting quality of an interior scene. As ecological factors become more relevant, lighting design should consider possibility of personal control, energy efficiency, changing lighting situations, daylight control and treating light as an architectural design element itself.

2 METHODOLOGY

2.1 Overview

This chapter describes the implemented workflow to determine the existing lighting distribution within the case study indoor pool facilities. Two representative swimming pool buildings were chosen as case study objects. Data about the lighting performance was collected following the suggestions of DIN EN 12193, the European norm for sports lighting.

Information of illumination levels was acquired via in-site measurements. This included multiple measurement processes considering different lighting conditions. Daytime measurements were performed in morning hours to assess daylight availability without additional support from electric lighting. Moreover, measurement days were chosen based on the general weather situation, widely considering an overcast sky. Artificial lighting performance was measured during night-time. During the night-time measurements artificial lights were switched on in order to simulate regular evening-operation.

After the collection of measurement and building geometry data, the buildings were modelled in *DIALux*, a state-of-the-art lighting design software and calibrated with measured data. The simulation process started from a base case model, which was modelled separately from any measurement findings and based solely on geometry and default settings of the software. Subsequently, measurement data was used to optimize the simulation model. The aim of the calibration steps was to achieve similarities to the measurement results to a point at which the simulation behaves closely to reality. This process is regularly called calibration. Acceptable deviation of simulation results relative to the measurement, including tolerance factors, are assumed with maximum 10%. The calibration efforts can be described as successful. As such, the simulation models provide realistic results and can be used as tools to determine possible optimization scenarios of lighting installations and electricity consumption. A set of optimization scenarios were envisioned and corresponding simulations conducted.

The following list describes the methodological procedure which was applied in this thesis step by step:

- Conducting comprehensive background research.

- Selection of representative case study buildings.
- Establishing personal contact to the responsible municipal authority for bath management MA44, "Wiener Bäder" and owner of the case study facilities.
- Organization of plan material from relevant municipal authorities (MA37 and MA44).
- On-site visits and face-to-face interviews with technical staff, including photo documentation of the building interior and the artificial lighting system.
- Calculation of measurement grids following the guidelines of DIN EN 12193.
- Preparation of measurement equipment and plan material for documentation.
- Interior and exterior illuminance measurement during day and night-time; Documentation of date and exact time of measurement at each point.
- Luminance measurements for calculation of surface reflectance.
- Analysis of measurements and comparison to prevailing lighting standards (DIN EN 12193); Definition of illuminance deficiencies and visual performance issues.
- Generation of simulation models in *DIALux* software (in part calibration efforts are based on the measured data).
- Simulation of the existing Status Quo lighting situation.
- Comparison of simulation results to measurement values to detect the validity of the simulation models and conducting of calibration efforts.
- Proposing lighting system optimizations and running corresponding simulation.
- Comparison of the existing visual performance between the case studies.

The installed fluorescent lamps in the swimming pool halls require preheating before reaching their ideal operating pressure and thus their full luminosity. Therefore, the measurement process for artificial lighting system was started after the lamps were switched on for a minimum of 15 minutes preheating time. Emergency lighting has not been taken into consideration as the impact on illumination levels is widely negligible. Consecutively, existing emergency lighting was not considered in the simplification of a simulation model.

While certain factors, such as position of the luminaires, and general working hours of the pool halls, could be easily determined, this is not necessarily true for other aspects. For instance, the exact types of some luminaires were not identifiable and thus required approximation.

2.2 Case study buildings

Both buildings, designed by F.F. Grünberger are combination bath buildings, which include a swimming pool hall as well as an attached summer bath outside facility. The buildings are part of the "*Viennese district indoor pool program*". Respectively, the buildings are named after their according district in Vienna. Figure 7 shows the location of the two facilities, which are topic of this work.

Figure 7: Map of Vienna, locations of case study buildings (Stadt Wien)

The measurement procedures in the buildings were conducted in May 2020, during a period where the Covid-19 pandemic intensely affected public life and respectively had impact on bath buildings as well. Due to government regulations, the bathing facilities had to be closed from March until October. The summer baths could reopen during a shortened summer season with respect to strict hygienic safety measures. As a result of this regulations the water from all interior pools was drained. This impacted the status quo assessment. Therefore, the measurements correspond to a swimming pool hall with empty swimming basins. The effects are stated as follows: (i) There were no reflections caused by water surfaces. Usually, the bathers provoke an irregular motion of the water surface which leads to scattered reflections to the surrounding. The unpredictability is taken away under the given circumstances. (ii) Further, the swimming pools are usually lit with underwater spotlights. The water body refracts light emitted from the luminaires and acts as a light source itself. It can be assumed that under regular conditions the main hall would achieve slightly higher values in terms of illuminance data, especially under artificial lighting conditions in the evening.

Both case study bath facilities are mainly used for recreational purposes, swim classes performed by elementary schools and training sessions of general sport clubs. As described in chapter 1.3.3., all six bath buildings of the district pool program share an almost identical layout. The compact, almost square-shaped buildings consist of two floor levels. The ground floor is the operational technical centre, whereas the first floor, incorporating the swimming pools, is the heart of the building and dedicated to public use.

The ground level accommodates the sauna facilities with an outside cooling basin and locker rooms. Most of the ground floor`s area is assigned to storage spaces, staff rooms and spaces for building and water processing technology, such as swimming pool maintenance corridors, electrical installations, HVAC installations and filter systems.

A staircase leads the visitors from the on-site parking lot on ground floor level in front of the building to the main entrance on the first floor. This storey can be divided into three tracts or functional blocks. The first entrance block is formed by the foyer with the cash desk, the main office and the adjacent restaurant. From this area the bathers access the locker and changing rooms, including the shower area, which span over the full length of one facade of the building. The third block is the swimming pool hall.

The buildings have been constructed as a reinforced concrete skeleton construction. The load bearing elements, the pillars and beams are integrated into the architectural design and can be seen in the swimming pool hall. The construction type allows natural light to enter through the glass facades which cover all the building's fronts and by additional skylights.

Further information about the individual case study buildings is provided in specific sections hereafter.

2.2.1 Object 1: Donaustadt district pool building

The first case study object is the *Donaustädter Hallenbad*. It is located in *Portnergasse 38*, 22nd district of Vienna. The building was the first of the second construction stage of the Viennese *Bezirkshallenbäderprogramm* to be inaugurated. It was officially opened to the public on 6th October 1982. Figures 8 to 11 illustrate the urban context, cross sections and floor plans of the *Donaustädter Hallenbad*.

Figure 8: Site map, Hallenbad Donaustadt (Stadt Wien)

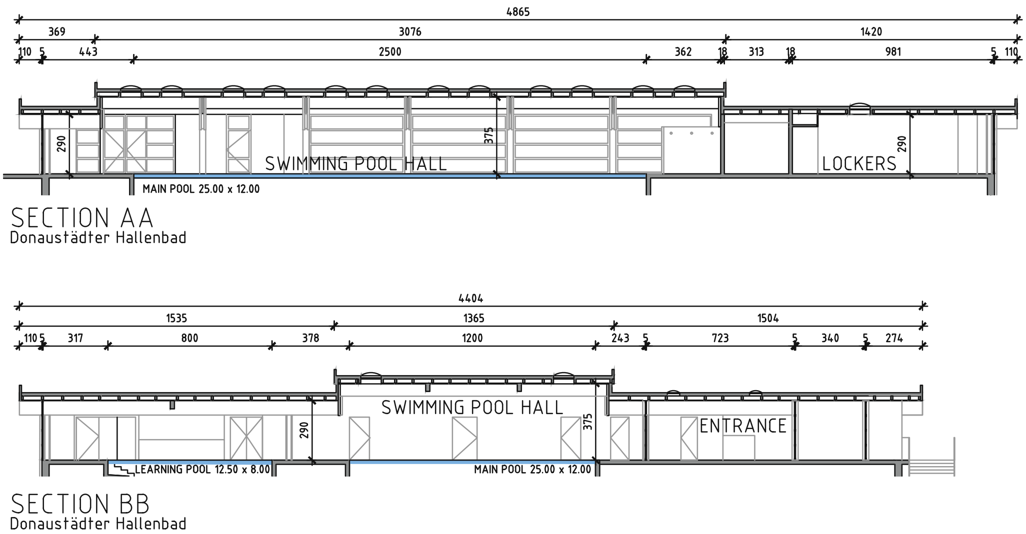


Figure 9: Cross sections, Hallenbad Donaustadt (CAD drawing by the author)

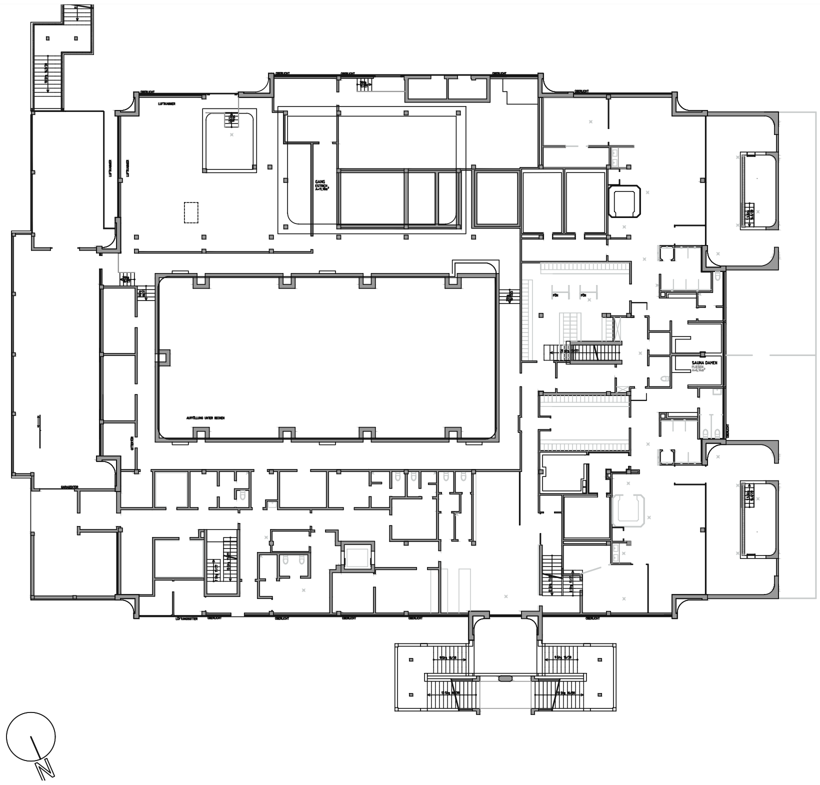


Figure 10: Ground floor, Donaustadt (based on MA44, edited by the author)

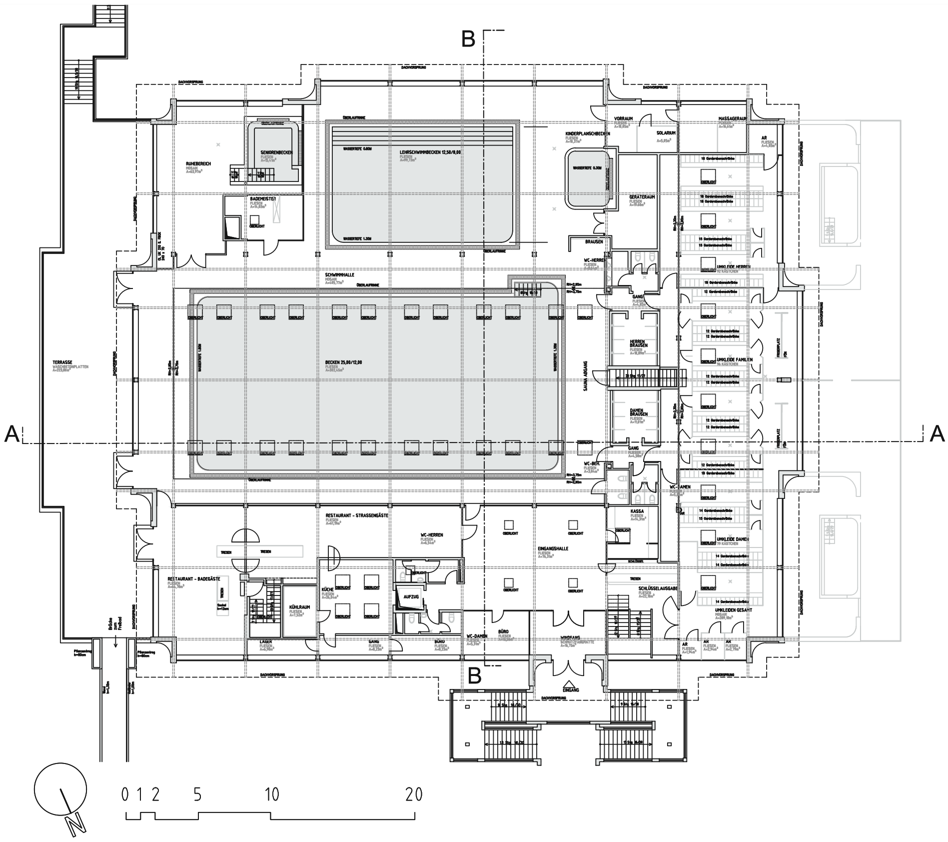


Figure 11: First floor, Donaustadt (based on MA44, edited by the author)

2.2.1.1. Swimming hall

The swimming hall is almost square-shaped and measures approximately 31.50m x 29.00m in length and width, totalling about 913.00m² of usable (net) floor area. Within the hall there are four different swimming pools. The main pool features a dimension of 25.00m x 12.00m, the teaching pool 12.50m x 8.00m, the small paddling pool 2.80m x 3.80m and the hot tub for elderly citizens 4.15m x 3.50m. The water surface areas add up to a total of 428m² and account for 46.90%, almost half of the swimming hall net area. As already discussed in previous sections, Grünberger's concept for the district bath program was targeting low construction and operation cost while keeping up a high indoor quality of the pool area. By keeping the ceiling height at a minimum the building volume was economized. The free room height measures 2.90m. As an architectural design aspect, the flat roof above the main pool is elevated. The room height in this area measures 3.75m. There are 24 horizontal skylights of 1.00m x 1.00m located in the elevated roof construction, providing longitudinal natural illumination along the main pool in the centre of the building. Therefore, natural light illuminates the pool hall without increasing the risk of glare. Additionally, as a design feature the skylights intensifies the perception of the main pool as the core of the overall building. The swimming pool hall floor plan can be seen in Figure 12.

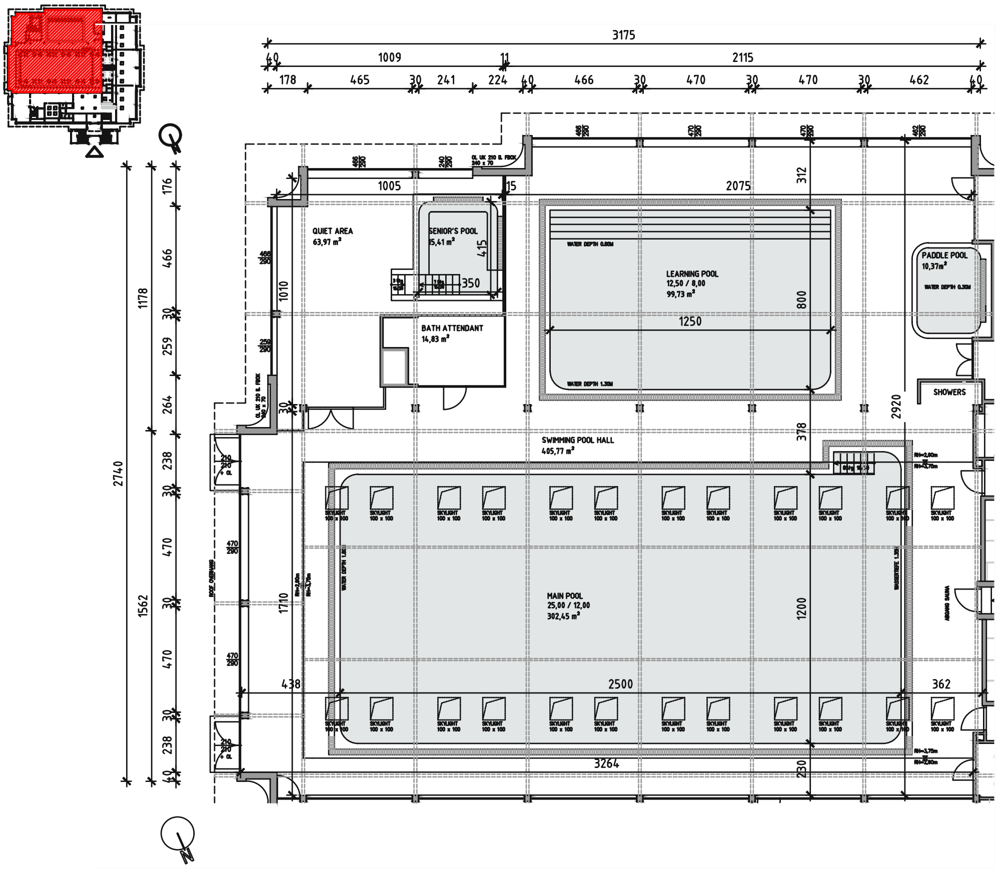


Figure 12: Pool hall floor plan, Donaustadt (based on MA44, edited by the author)

The swimming pool hall is south-east oriented. It can be entered from two sides, either from the foyer / restaurant area or from the changing rooms. Further natural light enters through two room-high glass facades, stretching a length of approximately 27.00m to the south and 22.50m to the east. The transparent parts of the façade are constituted by highly insulating triple glazing. Another 0.60m x 0.60m sized skylight is positioned above the lifeguard’s room. A 1.10m external overhang of the roof structure in front of the glass façade limits daylight input. There are no additional internal or external shading or glare control devices.

The surface of the floor is covered with mosaic ceramic tiles. Various shades of grey colour of the tiles differentiate areas of sub purposes within the main hall. The white tiles inside the two main pools, both on the floor and the walls are of higher reflectivity compared to the surrounding areas. The ceiling finish consists of wooden battens. The surfaces of pillars and beams are covered with white plaster. An interior glass wall separates the swimming hall from the restaurant and the entrance area. The wall to the east, separating locker and shower rooms, is opaque and covered with light-blue ceramic tiles. The interior walls to the lifeguard’s cabin and the quiet area, including the pool for the elderly, are equipped with green ceramic tiles.

The colour blue is the recurring common theme in the interior design of *Donaustadt* swimming pool hall. Accents of blue are found in different materials and surfaces, e.g. pool deck tiles, paddling pool area and blue plaster on the corners of the pillars. For better readability, the colour blue is used in this work to represent values and results in chart-graphs of the pool building *Donaustadt*.

Figure 13 to 15 show interior shots and a simulation model rendering of the *Donaustädter Hallenbad.*

Figure 13: Interior shots pool hall Donaustadt (photographs by the author)

Figure 15: Interior shots teaching pool Donaustadt (photographs by the author)

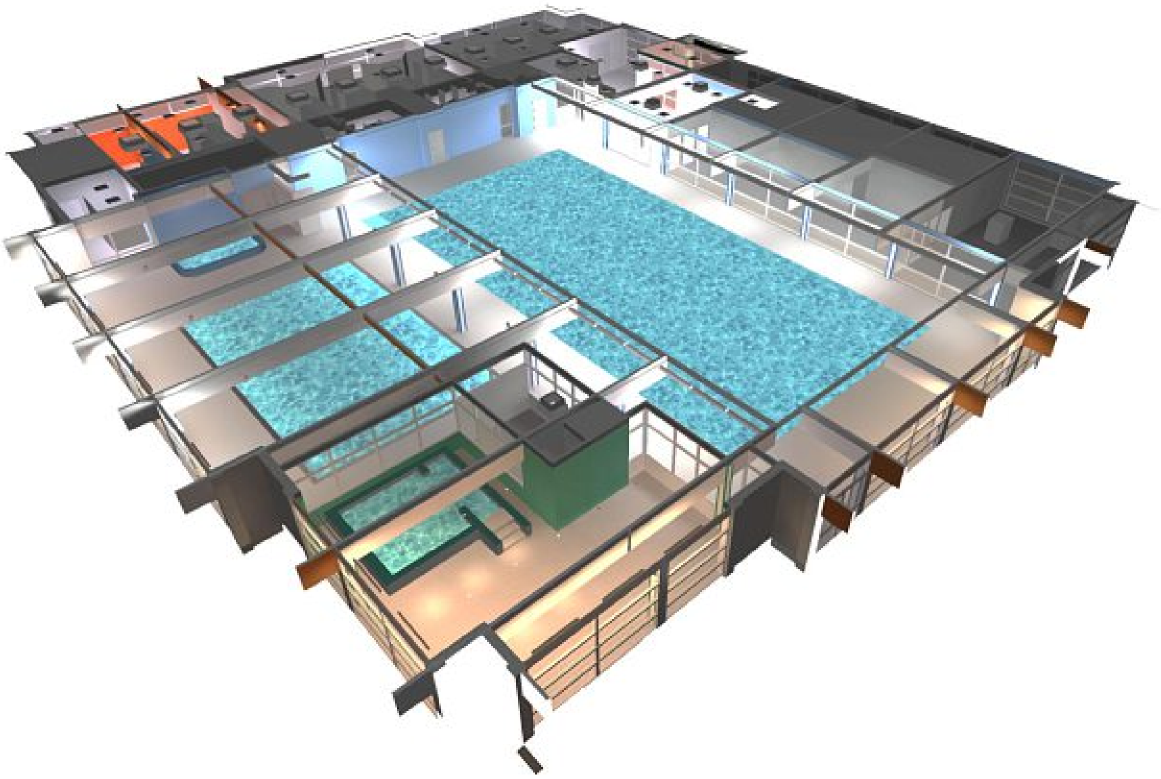


Figure 14: Swimming pool hall Donaustadt simulation model (figure by the author)

2.2.1.2. Entrance

The foyer can be accessed via the exterior main staircase in the north of the building. The rectangular foyer area of approximately 72.00m² measures 9.95m in length, 7.23m in width and 2.90m in height. A vestibule of about 5.20m x 3.00m acts as buffer area between the exterior staircase and the foyer.

The floor of the foyer and the vestibule are covered with brown ceramic tiles, the vestibule is partly covered with dark carpet. The walls to the restaurant, the swimming hall and to the exterior staircase are post and beam facades. The columns and beams are coated with thin white plaster layer. The surface of the suspended ceiling consists of grey acoustic ceiling panels.

Natural light enters the foyer through the 2.10m x 2.10m glass door portal of the vestibule. The foyer itself has no direct access the exterior façade of the building. Four symmetrically arranged 0.60m x 0.60m skylights illuminate the interior of the room with direct sunlight. Figures 16 and 17 illustrates the entrance situation of the swimming pool hall *Donaustadt*.

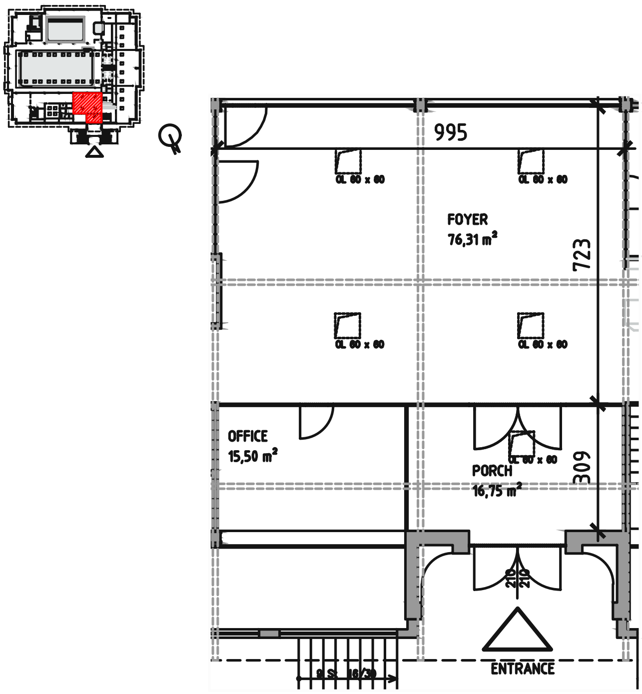


Figure 17: Entrance floor plan, Donaustadt (based on MA44, edited by the author)

Figure 16: Entrance Donaustadt (photograph by the author)

2.2.1.3. Locker and changing cabins

The locker and changing rooms are positioned along a corridor on first floor in the west of the building. This long, rectangular area is divided into separate changing room areas dedicated for women, families, and men, connected through a common hallway. The measurements of about 6.70m to 9.50m in width and 33.30m in length add up to a total net area of approximately 289m². According to floor plans provided by the municipal authority for bath management there is a maximum capacity of 289 lockers (and thus a comparable number of attendees).

The floor's surface consists of pale-yellow ceramic tiles. The metal lockers are light blue or white, depending on the gender-specific colour scheme. The separating walls are made of plastic panels with a white finish. The suspended ceiling uses acoustic panels similar to those in the foyer. In the centre of each locker row corridor area, there is a 0.60m x 0.60m skylight positioned, providing daylight to the interior. The exterior west façade is covered up with orange façade panels up to a height of 2.20m. The last quarter of the 2.90m high room is formed by a skylight. The interior wall adjacent to the swimming hall and sanitary groups is covered with bright lime-coloured and brown tiles. Figure 18 and 19 illustrate the corridor and locker room situation.

Figure 18: Lockers and Changing Booths, Donaustadt, from left to right: men's lockers, family lockers, hallway (photographs by the author)

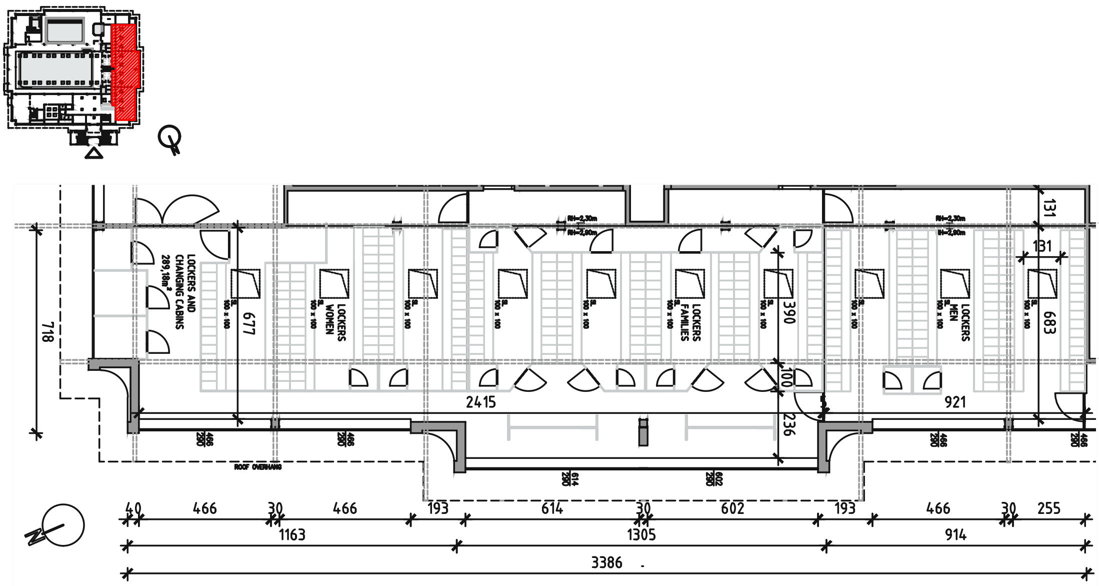


Figure 19: Locker rooms floor plan, Donaustadt (based on MA44, edited by the author)

2.2.2 Object 2: Hietzing district pool building

Indoor pool building *Hietzing* was the first to be inaugurated pool facility of the Viennese district indoor pool program. It was opened to the public on 26th of August 1978. The recreational building is located at *Atzgersdorfer Straße 14*, 13th district of Vienna. Figures 20 to 23 illustrate the urban context, cross sections and floor plans of the *Donaustädter Hallenbad*.

Figure 20: Site map, Hallenbad Hietzing (Stadt Wien)

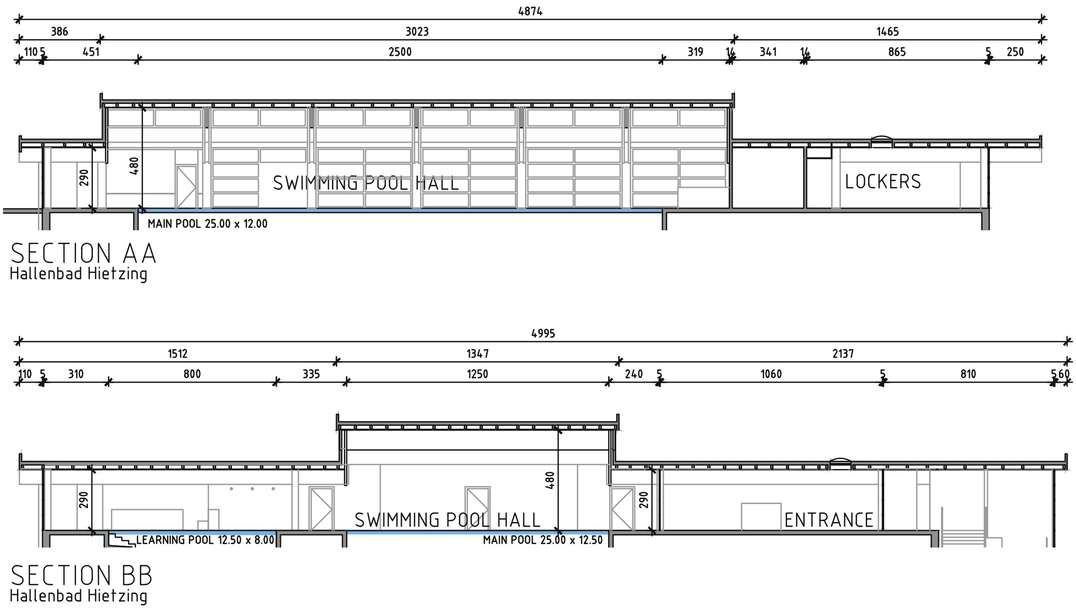


Figure 21: Cross sections, Hallenbad Hietzing (CAD drawing by the author)

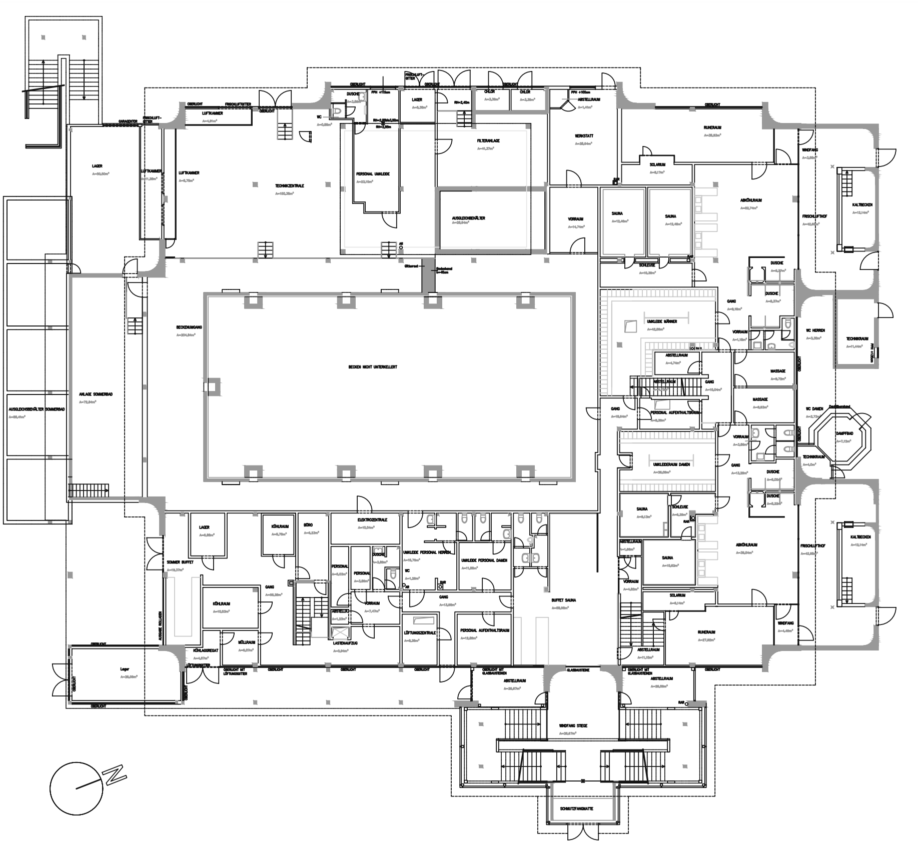


Figure 22: Ground floor, Hietzing (based on MA44, edited by the author)

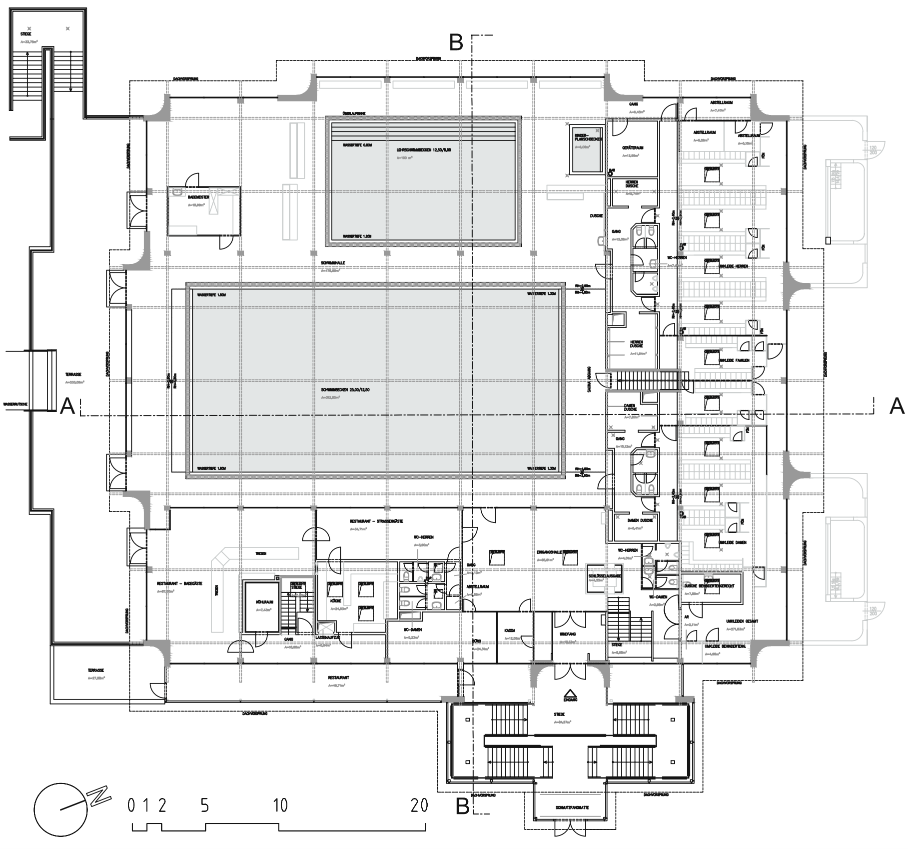


Figure 23: First floor, Hietzing (based on MA44, edited by the author)

2.2.2.1. Swimming hall

The rectangular swimming hall on the first floor has dimensions of approximately 31.10m x 29.30m in width and length, resulting in 912.93m² of useable (net) floor area. 418.58m², respectively 45.85% of the overall swimming hall area is water surface of the swimming pools. The main pool measures 25.00m x 12.50m, the teaching pool 12.50m x 8.00m and the small paddling pool about 2.00m x 3.00m. The free room height measures 2.90m, whereas the area of the flat roof above the main pool is elevated to a clear room height of 4.80m.

Identical to the other two buildings of the first construction stage of district indoor pool halls, *Simmering* and *Döbling*, the exterior wall facades of the elevated roof cubicle above the main pool feature window skylight strips running along both lengths.

The swimming pool hall is south-west oriented. Post and beam constructions with double-glazed insulating glass cover both exterior facades. In south direction, the wall spans a length of 22.60m and to the west 26.90m. The view through the south glass wall is partly covered by three plants (pot-trees) stretching until the ceiling.

The floor surface consists of ceramic tiles. Various beige-colours designate different subareas within the hall. The three pool basins are equipped with white rectangular, glossy tiles of presumably higher reflectance. Calculated reflection values of the material surfaces can be found in the results chapter. The floor plan of the pool hall can be seen in Figure 24.

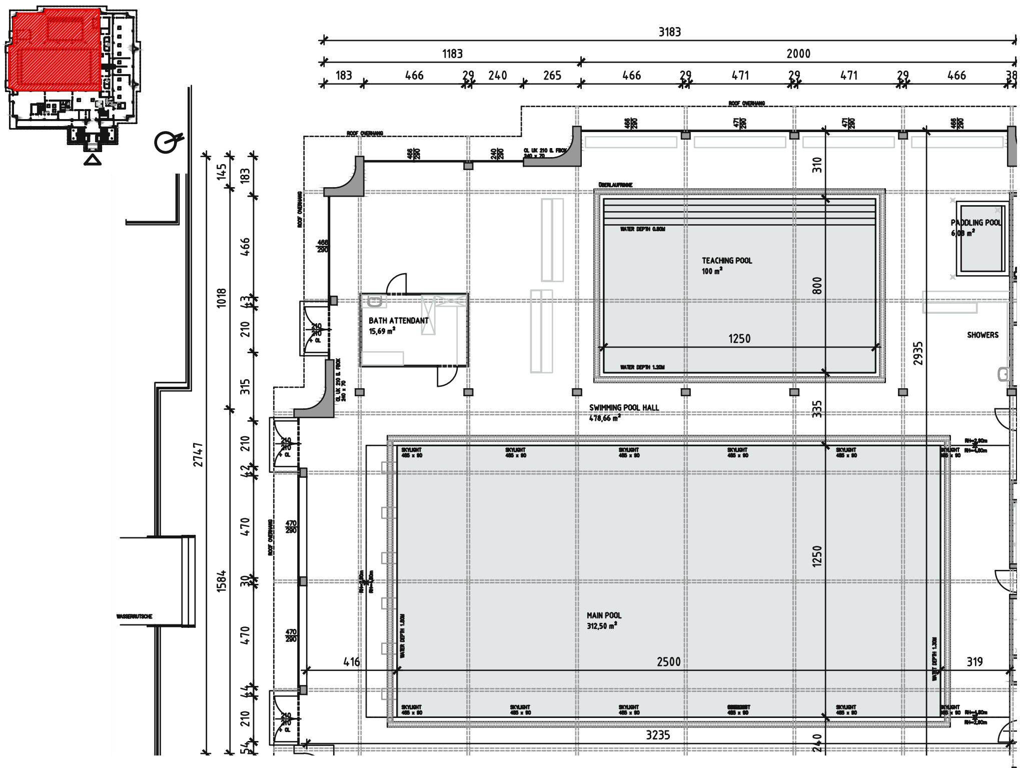


Figure 24: Pool hall, Hietzing (based on MA44, edited by the author)

The beams and ceiling as well as the walls of the elevated roof cubicle above the main pool have a timber finish. Wooden elements are coloured in a pastel-yellow tone, except for the area of the elevated roof structure, which is coloured in a dark brown-tone. The pillars are decorative, a bottom layer of white spray plaster shines through colourful tiles until a height of 2.20m. At this height, the main beams are resting on the pillars. A glass wall separates the swimming pool hall from the lifeguard’s area, the restaurant and the foyer. The interior wall adjacent to the sanitary blocks and changing rooms is covered with cream-coloured ceramic tiles.

Brown earth-tones and light pastel-yellow as colour and playful ceramic tile decorations are the common theme in the interior design of the swimming pool hall. For better readability, the colour brown is used in this work to represent values and results in chart-graphs of pool building *Hietzing*.

Figure 25 and 26 show interior shots and simulation model renderings of the *Hietzinger Hallenbad.*

Figure 25: Interior shots pool hall Hietzing (photographs by the author)

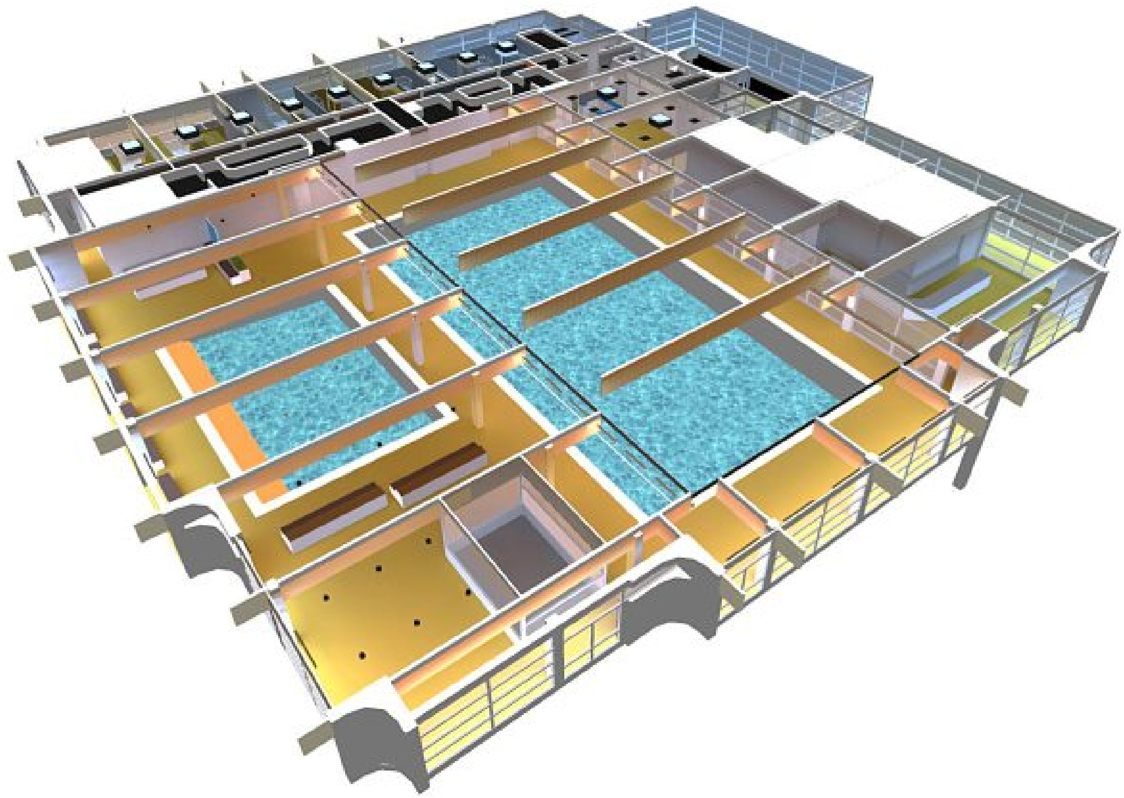


Figure 26: Swimming pool hall Hietzing simulation model (figure by the author)

2.2.2.2. Entrance area

The building is accessed through a two-storey high glass cubicle in the east of the building, which leads to a vestibule including the staircase. The staircase guides visitors up to the first floor to the foyer, where the cash desk and the locker key issuance are located. The foyer has dimensions of 9.80m x 7.05m in length and width and 2.90m in height. The usable (net) floor area is about 85.80m ².

The surface materials are of light grey colour. The floor is ceramically tiled and the suspended ceiling is covered with acoustic panels. The walls, columns and beams are plastered with white colour. The walls to the office and the neighbouring restaurant are transparent.

Natural light penetrates the foyer via two 0.60m x 0.60m sized skylights. Figures 27 and 28 illustrate the foyer situation.

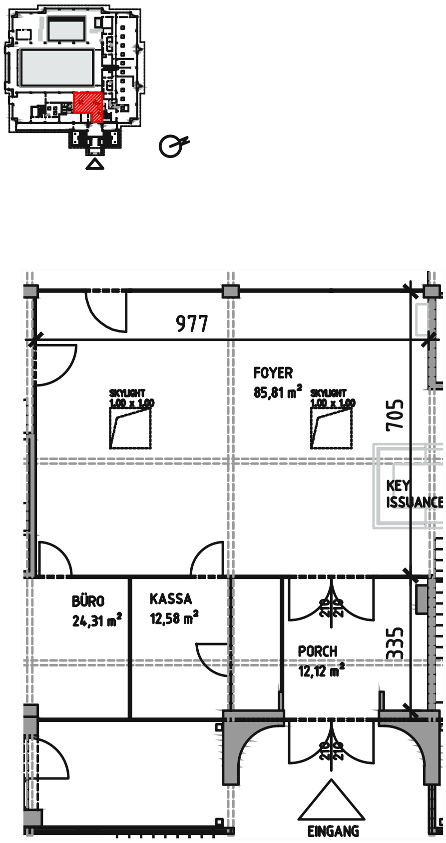


Figure 27: Entrance floor plan, Hietzing (based on MA44, edited by the author)

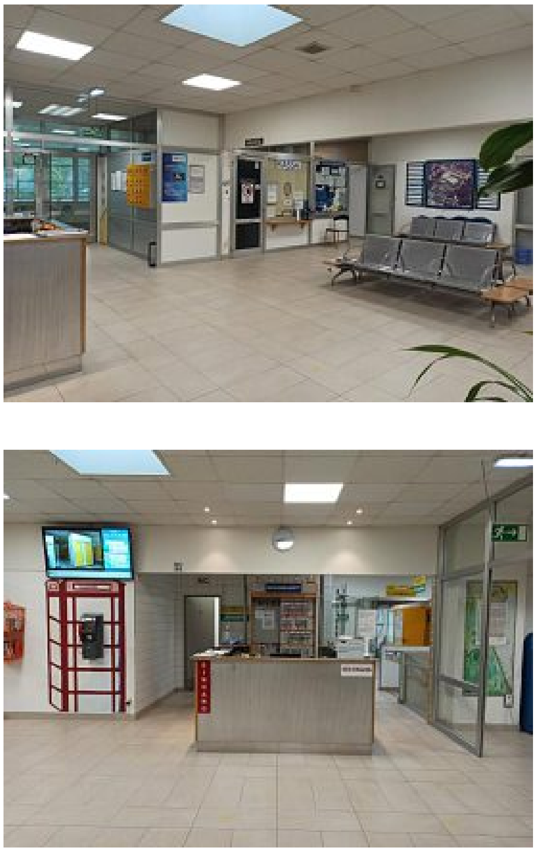


Figure 28: Entrance swimming pool building Hietzing (photograph by the author)

2.2.2.3. Locker and changing cabins

Relating to the concept of *Bezirkshallenbäder*, the gender-divided locker and changing rooms are aligned along a corridor in the north of the building. The area can be entered after passing the cash desk. It has multiple connective hallways leading into the swimming pool hall, passing shower and sanitary groups. The dimensions are approximately 35.00m in length, 6.80m in width and 2.90m in height, totalling to 276.50m² of net floor area.

The floor finish of the changing and locker rooms is made of ceramic tiles. The ceiling is covered with acoustic panels. Each locker row has a 0.60m x 0.60m skylight in the centre and therefore is this naturally illuminated. The metal lockers and separating wall panels are yellow. The load-bearing beams are made of timber. The wall between the swimming hall and the changing rooms is covered with tiles of different colours, bright orange in the men and women section and brown and lime-coloured in the family area. Figures 29 and 30 illustrate the locker room situation.

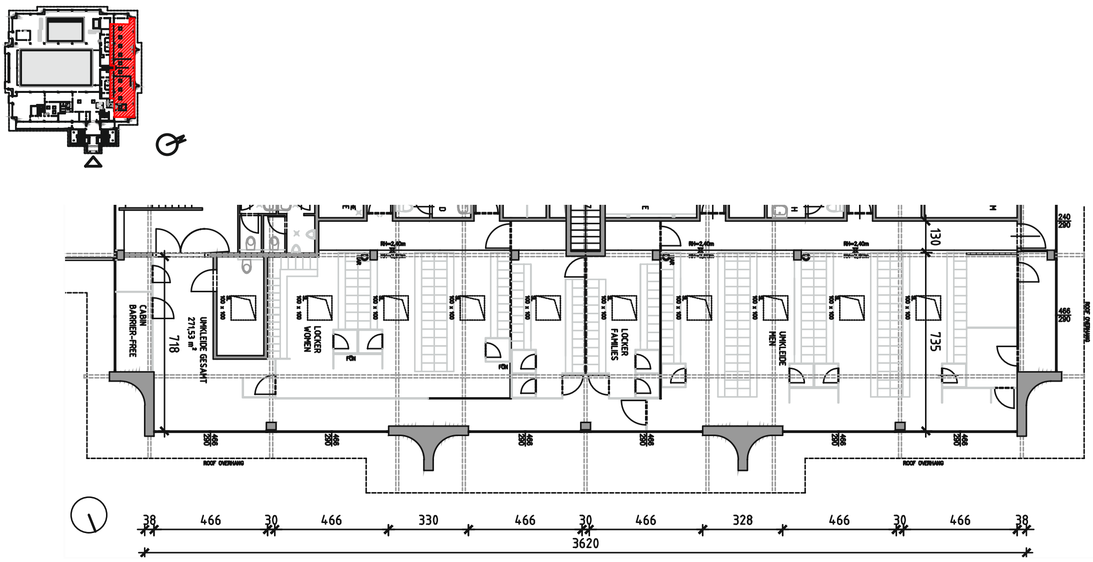


Figure 29: Locker rooms floor plan, Hietzing (based on MA44, edited by the author)

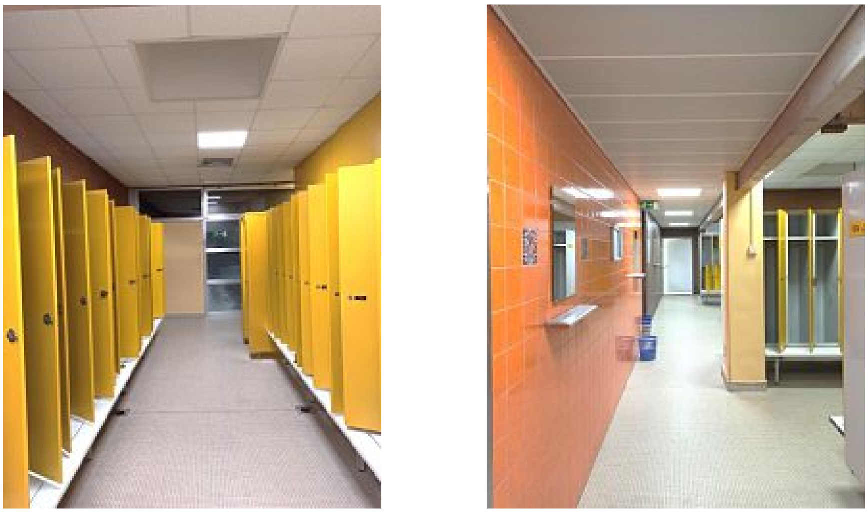


Figure 30: Lockers and changing booths, Hietzing, locker row family (left), hallway (right) (photographs by the author)

2.3 Measurement Setup

For the implementation of field measurements, it is necessary to define a uniform measurement grid. Number and distance of analysis points have been carefully determined based on recommendations of DIN EN 12193. The goal is comparability of various measurement processes and different buildings by defining a stringent measurement concept. The possibility to validate measured illuminance and luminance-derived indicators with standards is assured via this approach as well.

Reference grids for sport facilities must be set in accordance with the court area. Each sport discipline has different requirements regarding court size and shape. The standard distinguishes between principal area (PA) and total area (TA). The principal area is defined by the court boundary area, in which the sport is carried out. The total area is an extension of the PA, including a perimeter for relevant activities or a safety buffer zone. Minimum requirements are defined for the principal area. The TA must fulfil 75% fraction of the requirements of the PA (DIN EN 12193).

In case of swimming pool facilities, the PA is defined by the dimensions of the pool basins. For this thesis, the TA was assumed to include the pool deck as a circumferential buffer zone by an offset of one measurement point. This seems in line with the purpose of the standard, as it covers access areas and spaces where springboards are to be positioned, and people tend to spend time close to the basin's edge to chat and pause. The difference between principal and total area is visible in Figure 31.

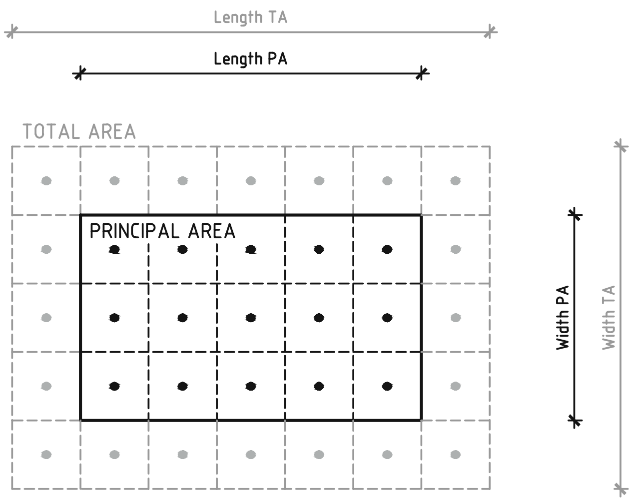


Figure 31: Principal area and total area (illustration by the author)

In common practice the spacing / intervals between the grid points is approached by the following formula (DIN EN 12193):

$$p = 0{,}2 \times 5^{\log(d)} \qquad (4)$$

Where: p = distance between grid points

d = length of reference surface (total area)

Multiple pools within the same space must be evaluated by separately calculated grids. Based on the results the reference grid is divided into congruent rectangles with one grid point in each rectangle centre, in which the measurement equipment should be placed. The rectangles should approximate a square shape. To sustain symmetry of the grid the standard recommends resulting in an uneven numbers of analysation points per grid side. This provides the possibility to reduce the number of total grid points whilst maintaining uniformity. Furthermore, the arrangement of the calculation points should not be identical with the positions of the luminaires. In such cases the grid should be extended (DIN EN 12193). It is further specified to exclude a perimeter of 0.5m adjacent to the room boarders from the measurement area (DIN EN 12464-1).

For this thesis, separate analysis grids have been calculated for most of the important areas in respect to the building's typology. The vertical position of the grid plane is assumed at floor level, which is more or less the eye level of the athletes and attendees swimming in the pool. The resulting grid dimensions, applicable to both swimming pool halls, are summarized in Table 3.

Table 3: Measuring grids (DIN EN 12193; DIN EN 12464-1)

MEASURING GRID	Room	Principal / Reference Area, Length x Width [m]	Grid dimensions, Length x Width [m]	Grid points	Reduced number of gird points
Donaustadt	Main pool	25.00 x 12.00	1.92 x 1.71	13 x 7	6 x 3
	Teaching pool	12.50 x 8.00	1.14 x 1.14	11 x 7	5 x 3
	Quiet area	8.95 x 5. 11	1.01 x 1.02	9 x 5	5 x 3
	Entrance	8.96 x 6.23	1.00 x 0.89	9 x 7	5 x 4
Hietzing	Main pool	25.00 x 12.50	1.92 x 1.79	13 x 7	6 x 3
	Teaching pool	12.50 x 8.00	1.14 x 1.14	11 x 7	5 x 3
	Entrance	8.77 x 6.05	0.97 x 0.86	9 x 7	5 x 4

Additional areas, such as two representative locker rooms, the space between the glass façade and the main pool basin, the small paddling pool and a seating area inside the swimming pool hall of *Hietzing* have been included in the measurement process. The grids applied to these spaces deviate from the recommended calculation procedure, although areas within the pool hall are covered by the extension of the measurement grids of the pool basins. These areas have merely been included to get an overview about the visual performance of such spaces, even though their size or function are not of main priority to the building (and thus of this thesis). The results will provide further information about the overall area performance and can support the evaluation of the accuracy of the simulation models.

2.4 Measurement Equipment

In this section the applied measurement gear is described.

2.4.1 Konica Minolta T-10A Illuminance Meter

The T-10A Illuminance Meter is a multi-functional illuminance-measuring instrument. The device automatically calibrates after turning on, which makes it rather user-friendly and fail safe against measurement errors due to lack of calibration. The measured values are displayed in digits on the backlit LCD screen.

The silicon photocell receptor head measures 25mm in diameter. It is detachable from the body. This function allows the device to be used as a multi-point inspection system, connecting to a maximum of up to 30 measurement points via a LAN (Local Area Network) cable.

The instrument can measure illuminance (lx), illuminance difference (lx) and ratio (%), integrated illuminance (lx) based on corresponding integration time (h), and average illuminance (lx). Users can choose the displayed unit between lux and foot candles (which is used in anglo-american context). According to the manufacturer, the illuminance measuring range spans between 0.01 to 299.900 lx or 0.01 to 29.90 fcd. The accuracy is given with ± 2% ± 1 digit of the displayed value. The measurement speed is continuous with 2 measurement cycles per second. The device enables the user to calibrate the Colour Correction Factor (Konica Minolta Sensing Inc. 2013).

The Konica Minolta T10A model has a tripod socket and a "hold" function, which freezes the display of a measured value. Both functions proved useful for the conducted measurement efforts of this work. In context of the present contribution the device was used for measuring interior horizontal illuminance of the previously defined measurement grids and spot illuminance of building component’s surfaces. The collected data was furtherly used for calculation of surface reflectance and daylight factors within the swimming pool buildings.

2.4.2 Konica Minolta LS 100 Luminance Meter

The Konica Minolta LS 100 is a compact, handheld spot luminance meter with a silicon photocell receptor. The device measures luminance, luminance ratio and peak luminance. The SLR (single reflex lens system) and the viewfinder display support precise focus and targeting. The exact measured area is displayed in the viewfinder regardless of the distance to the measured object. Measured surface brightness values are shown on both the LCD screen and on the viewfinder display. The user can switch between units of cd/m² and fL. A broad range of light sources can be measured. For a fast response time of maximum 1 second the manufacturer claims the range between 0.001 cd/m² to 299.900 cd/m². The accuracy is given with ± 2% ± 2 digits of displayed value. The device enables the user to calibrate the Colour Correction Factor (Konica Minolta Sensing Inc. 2013).

In the context of this work the luminance meter was used for spot luminance measurements of interior room surfaces. Based on the data and corresponding illuminance values surface reflectance of the interior building components were calculated.

2.4.3 Ahlborn Almemo 2590-4S Data logger with lux sensor

The concept of Almemo systems by Ahlborn is to offer one intelligent data aquisition instrument that is combinable with a multitude of different connectors and over 65 measuring ranges. Dependent on the type of the plugged-in sensor equipment the device enables sensor-specific functions and configurates automatically. The instrument has inputs for four external sensors.

Data is displayed on a screen numerically. Up to twelve measured values can be displayed in bar chart form directly on the device. All sensor data is saved in the measuring instrument. Measuring menus can be freely configurated by users preferences The device offers sensor programming for range, units and output models (Ahlborn 2015).

In the context of this thesis the connected sensor type was the Lux-measurement probe *FL A603-VL4*. The range of measured illuminance is specified with 1 to 250.000 lux. The sensor and connected data logger were used to acquire external horizontal illuminance data.

Figure 32 illustrates the utilized measurement instruments.

Figure 32: Measurement equipment, from left to right: Konica Minolta T-10A Illuminance Meter, Ahlborn Almemo 2590-4S, Konica Minolta LS 100 Luminance Meter (Konica Minolta Sensing Inc 2013, Ahlborn 2015)

2.5 Simulation software

The software used for this thesis was *DIALux* (*evo*). It is one of the most professional, yet easy-to-use tools for lighting design and simulation. It is both suitable for interior and exterior lighting scenes. Up-to-date minimum requirements of standards for individual areas of use are coded into the software and can be altered individually for an automatic comparison against required standards.

The software is freeware and provides several helpful features to support the efficiency of the workflow (A number of prominent luminaire producers has set up the tools development many years ago). CAD-files such as .dwg and .dxf as well as image files can be imported into a *Dialux* project. The CAD-layers stay intact and allow an quick and easy to use model derivation. Moreover, they act as basis for the well-organized structure of a building within the project.

A powerful feature provided in the program is the integration of product catalogues from leading brands in the industry. Besides the pre-installed luminaires, it is possible to download additional catalogues from the official website. For the selection of individual luminaires, the online database *LUMsearch* offers a wide selection from various manufacturers. Through a pre-installed plugin real-life product information such as photometric data and the 3D model of the desired luminaire are transferred directly into the *Dialux* project. Moreover, luminaires can be designed by the user in supportive tools and imported to the simulation environment. As such, the tool is literally enabling any kind of lighting simulation, even in cases where no pre-defined luminaires exist in the default database.

Furthermore, *Dialux Evo* is able to calculate lighting scenes with artificial light only, daylight only and any set of mixture between these light sources (DIALux 2016).

2.6 Simulation setup and workflow

The simulation models focus on artificial lighting performance to assess the implemented lighting system. The night-time measurements (artificial light only) were used as target values for calibration efforts of the virtual models.

The simulation workflow of this thesis basically follows three main steps:

- Initial model

The geometry of the buildings was modelled in the simulation software following the plan material provided by MA 44. Due to lack of data of existing structures such as exact lamp/luminaire type and performance data, luminaires of the integrated *DIALux* catalogues from ordinary manufacturers were chosen to approximate the measured lighting situation and prevailing lighting equipment. Default surface reflectance values of Dialux were assumed (floor: 0.20, walls: 0.50, ceiling: 0.70). The initial simulation model is generated separately from any measurement findings.

- Base Case / Status Quo, calibration effort including measurement data

Next, the model was calibrated using the measurement data. Surface reflectance values of enclosing surfaces and information of the status quo about functionality of luminaires were applied. Since luminaire models had to be assumed, dimming for luminaire types were implemented in areas that indicated systematically too much brightness. The model including the calibration efforts was chosen as base case to represent the status quo. Tolerances of maximum 10% for deviations between the simulated and measured illuminance were assumed as a good fit of the simulation results.

- Optimization scenarios

In the following, the well-corresponding base case models of the two case study facilities, with average deviations below 10% were used for optimization scenarios. The main objective was to react to detected deficiencies to the standards by achieving sufficient illuminance levels and adequate uniformity. Refurbishment actions that were relatively easy and inexpensive to implement were considered first. The optimization approaches are building on the results of the previous retrofit simulation run.

2.7 Measured and simulated key performance indicators

Relevant criteria for evaluating lighting quantity and quality are described in more detail in chapter 1.5 and 1.6. The assessment of this thesis is based on measurements, simulations and derived key performance indicators, such as:

- Illuminance

Illuminance values describe the available brightness within a space at individual measurement points. Brightness measurements are used as the primary source for evaluating the adequacy of lighting systems. In the scope of this work, horizontal Illuminance was measured at the centre of the reference grid cells. Grid calculations followed the European standard for sports lighting (DIN EN 12193). Additionally, exterior illuminance was measured at one constant position close to the building.

- Uniformity

The uniformity indicator provides information about how evenly light is distributed on the ground. Interior horizontal illuminance measurement and simulation result arrays served as calculation base for individual areas of the buildings. The approach conducted in this thesis considered minimum to average horizontal illuminance. A small difference between minimum to average illuminance results in a high ratio, therefore better light uniformity.

- Daylight Factor

The daylight factor describes the subjective daylight quality within a room. It expresses interior daylight availability as a ratio in regard to exterior daylight availability. Internal and external daytime illuminance measures were performed within a 5-second time interval. The values were used to determine the daylight factor at each individual grid point of the swimming pool hall. For comparison and concluding statements, the daylight factors were averaged. This one numerical performance indicator, the average daylight factor, representatively expresses daylight availability of the individual areas of the pool halls.

- Unified Glare Rating (UGR)

The UGR assesses glare potential at specific positions and viewing directions. The key performance indicator takes brightness of walls and ceilings, as well as luminaires into account. A UGR index describes limits for tasks and activities, that are the suggested as maximum for the sensation of glare. UGR calculation in this thesis was conducted via *DIALux* software. Relevant positions and heights, such as swimmers within the main pool lanes, visitors walking along the pool deck and the lifeguard in his designated room were assumed. The simulations were conducted for viewing directions of 360°, calculated in 15° steps.

3 RESULTS & DISCUSSION

In the following section, the measurement and simulation results of the two case study objects are described. The individual areas of the building as presented in methodology are discussed separately. The communication of the results happens via tables and diagrammatic illustrations, such as isolux graphs and false colour plan views.

At the beginning of each subsection the luminaire arrangement and the applied reference grid are illustrated (The process of grid generation has been extensively discussed in the previous section). Subsequently, the illuminance measurement results for day- and night-time and luminance measurement-derived surface reflectance values are shown, followed by an analysis and comparison to the standards. The measurement analysis describes the status quo of the visual performance.

In the following subchapter the results of the simulation efforts are presented. First the initial model was generated separately from any of the measurement findings. The initial model is based on plan material and default surface reflectance values of the utilized software. Afterwards few calibration runs of the model included implementation of measurement-derived information, like surface reflectance values and location of defected luminaires. To optimize the correspondence of the simulation model to the measurements, alteration of the luminaire dimming settings was chosen, since areas seemed systematically too bright and exact luminaire models were unknown. To make simulation runs comparable, an indicator for evaluation of approximation to the status-quo was defined. In the following it is called “averaged deviation of simulated values from measured values”. The indicator expresses how large the simulation results deviate from the measurements. The stray is given in percent and averaged over the total number of calculation points of the reference surface. This renders an easy possibility to identify the most accurate simulation run. The lower the average deviation of simulation to measurement is, the better the fit of the calibration, as the systematic deviation is reduced as far as possible. The focus of the calibration prioritizes the swimming hall, as this represents the main function of the building. Secondary rooms such as changing rooms and entrance play a subordinate role in the optimization of the simulation model, and thus have not been prioritized.

At the end of the results and discussion chapter, proposals for improving the performance of the artificial lighting system will be presented.

The exterior illuminance was recorded in a five second interval. The device was positioned at a height of 70cm above floor level besides the building. It was distanced from the façade to avoid interference of reflections or shade on the sensor. As a result, it was possible to measure interior and exterior horizontal illuminance simultaneously for each grid point, which is important for the accuracy of the daylight factor derivation.

3.1 Object 1

Hereinafter the results of indoor pool building in *Donaustadt* will be shown and analysed.

3.1.1 Main Pool

The luminaire arrangement and the calculated measurement grid of the main pool, including positions for the UGR calculation, are shown below in Figures 33 and 34.

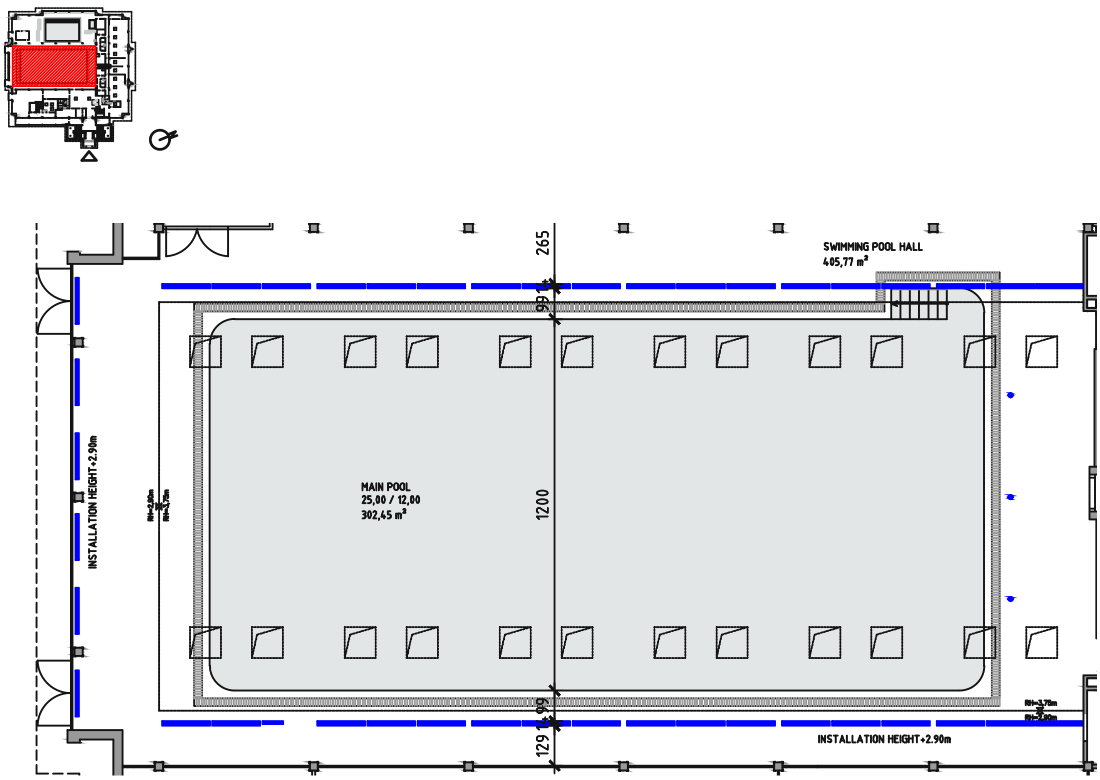


Figure 33: Luminaire arrangement, Donaustadt main pool (based on MA44, edited by the author)

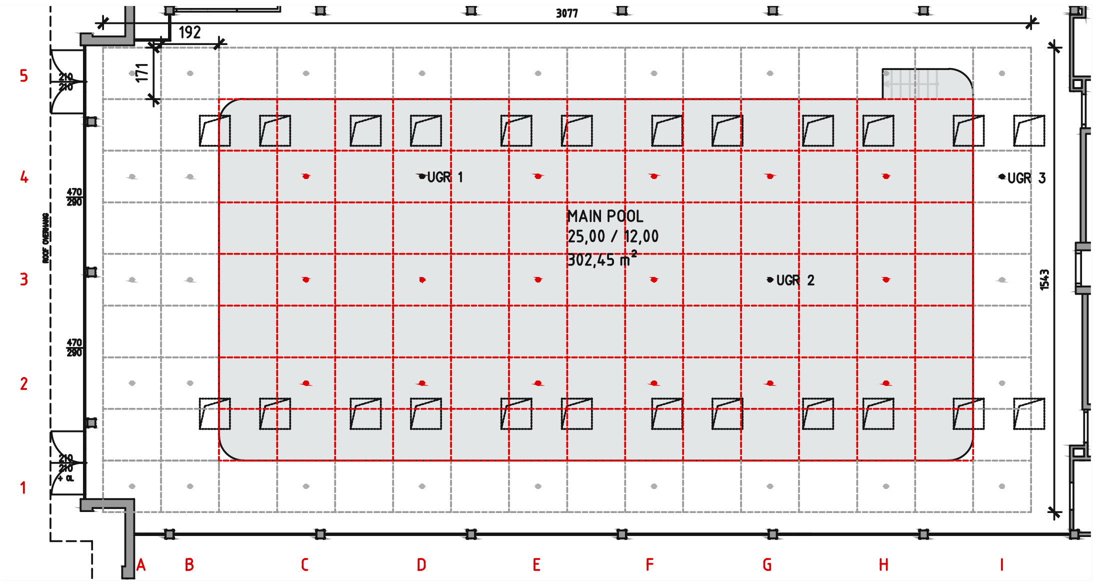


Figure 34: Measuring grid, Donaustadt main pool (based on MA44, edited by the author)

The artificial lighting concept of the main pool has a direct lighting system with splash water protection. The main provider of illumination of the overall swimming pool hall are 36 tubular fluorescent lamps with open light distribution. Each luminaire consists of a fixture holding two bulbs. The light sources are arranged in two linear constellations, running parallel along the length of the main pool. Six additional tubular fluorescent lamps are aligned perpendicular to the other described luminaire line arrangement along the glass façade. These luminaires consist of one fluorescent bulb only.

The luminaires are ceiling-mounted at a height of +2.90m above floor level. One luminaire in the northern row has smaller dimensions and different specifications due to an adjacent ventilation duct.

Furthermore, three small spotlights in the west of the hall are suspended from the elevated roof above the water area at a height of 3.75m above floor level. These are installed at different angles to each illuminate one of the three doors leading to the locker and shower facilities.

During the measurements, six lamps were identified as not running (defected. This was considered in the calibration process of the simulation of the artificial lighting. The lighting system can be switched on and off in form of different control groups. Dimming, that is reducing the output of the luminaires, is neither foreseen nor possible in the current state of the luminaires system.

The uniform reference grid was defined following the suggestions of DIN EN 12193. The generation of the grid was discussed in the previous chapter. Each grid cell follows the dimensions of 1.92m x 1.71m in horizontal and vertical axis.

3.1.1.1. Daytime Measurement

The measurement procedure was performed twice (daytime and night-time measurement). The daytime measurement was conducted with all artificial lights turned off (daylight only).

The measurements were performed on 29.05.2020 from 08:20am to 09:20am under partly cloudy to overcast sky (the day was chosen based on the weather forecast and organizational aspects regarding accessibility of the swimming pool hall). Weather circumstances included an outside temperature of in average 13°C and about 15km/h wind speed.

Table 4 displays the measurement results. Each grid point contains two illuminance values, external and internal illuminance. The measurement process is described in the methodology. The two values per grid point are measured at the same 5 second interval. The blue area marks the pool surface, which is considered the most relevant in this work. As already mentioned, measurements were conducted with empty pools (swimming pool halls had been closed during the COVID19 pandemic).

Table 4: Daytime Measurement, Donaustadt main pool

5	outside	36 610	36 690	40 460	43 640	44 640	45 910	45 370	46 830	47 770
	inside	13 090	3 280	850	578	466	424	401	394	401
4	out	35 710	33 970	47 630	50 780	50 200	49 210	49 250	47 930	48 300
	in	8 400	4 170	1 275	859	680	621	558	531	574
3	out	42 230	31 470	48 010	49 650	49 200	49 330	49 540	48 020	48 450
	in	12 580	2 880	913	483	312	267	216	196	192
2	out	41 830	31 150	48 110	48 500	50 410	49 660	49 730	48 390	36 130
	in	6 080	1 926	1 225	906	743	667	616	590	410
1	out	34 640	31 240	30 919	30 500	30 340	30 250	30 120	29 520	29 200
	in	1 005	870	436	307	239	206	188	180	188
main pool, daylight		A	B	C	D	E	F	G	H	I

Table 5 expresses the daylight factor at each grid point derived from the measured external and internal illuminance.

Table 5: Daylight factors, Donaustadt main pool

5	35.8%	0.9%	2.1%	1.3%	1.0%	0.9%	0.9%	0.8%	0.8%
4	23.5%	1.2%	2.7%	1.7%	1.4%	1.3%	1.1%	1.1%	1.2%
3	29.8%	0.9%	1.9%	1.0%	0.6%	0.5%	0.4%	0.4%	0.4%
2	14.5%	0.6%	2.5%	1.9%	1.5%	1.3%	1.2%	1.2%	1.1%
1	2.9%	2.8%	1.4%	1.0%	0.8%	0.7%	0.6%	0.6%	0.6%
main pool, DF	A	B	C	D	E	F	G	H	I

At a specific point of each material's surface illuminance and luminance were measured as described in methodology. Table 6 provides the assumed surface reflectance values of main pool hall *Donaustadt*.

Table 6: Surface reflectance, Donaustadt main pool

	Surface	Reflectance
Main pool	Floor (mosaic tiles in average)	0.46
	Main Pool basin (white, tiles)	0.64
	Wall (blue, tiles)	0.6
	Wall, showers (white, tiles)	0.75
	Wall (white, plaster)	0.88
	Columns (white, plaster)	0.88
	Ceiling (wood)	0.17
	Beams (white, plaster)	0.88

3.1.1.2. Night-time Measurement

The results were acquired on 15.05.2020 from 09:20pm to 10:30pm. The sun set at 8:28pm that day, resulting in the absence of sunlight during the measurement process (Note: impact from surrounding luminaires could not totally be neglected due to the large glazing areas of the building's envelope).

The artificial lighting system was turned on 30 minutes before the measurement process, as the fluorescent lamps require a preheating period to reach their full luminosity. Table 7 and 8 summarize the night-time measurement results.

Table 7: Night Measurement, Donaustadt main pool

5	56	123	320	336	333	207	300	285	305
4	110	99	115	147	138	105	123	126	122
3	129	88	72	81	80	77	80	81	81
2	133	110	108	124	116	116	123	140	144
1	128	176	188	360	252	245	294	336	331
main pool, artif.	A	B	C	D	E	F	G	H	I

Table 8: Night-measurement performance, Donaustadt main pool

	Main Pool	Main pool + deck	Minimum standards
E min [lx]	72	72	-
E max [lx]	147	360	-
E avg [lx]	108	175	200 | 150
Uniformity	0.66	0.41	0.5 | 0.4

3.1.1.3. Analysis

Tables 4 and 5 illustrate the daylight availability at the main pool area. As could be expected, the grid points close to the glass façade achieve the highest illuminance values. Due to the 24 skylights in the elevated roof, natural light is transmitted even to areas rather distant from the facade, e.g. corners of the space, which are about 33 meters away from the façade. As the daylight factor is lower than two percent at almost all grid points except for grid cells close to the façade, standards would recommend supplementary electric lighting to achieve satisfactory lighting levels. Despite the low daylight factors in the back of the hall, the measured illumination values significantly surpass the minimum requirements of horizontal illuminance. The minimum value of 196 lux is the only grid point slightly underachieving the required standard value of 200 lux mentioned in the methodology section.

The Table 7 containing the night-time measurements demonstrates the illumination generated by the artificial lighting system. The grid points adjacent to the lighting sources show the highest illuminance values. These are the only grid points achieving sufficient lighting levels. Towards the centre of the pool, the illuminance is gradually reducing. This creates a symmetrical illumination distribution in the room, with the centre length of the pool being the symmetry axis (table 7, row 3). The illuminance values along this axis are the lowest of all measured points. The measured minimum horizontal illuminance is 72 lux, which is rather far below the recommended standard value of 200 lux. Overall, the artificial lighting quality can be considered as low, especially in the middle of the pool. It can be concluded that the main pool area does not fulfil the recommended illumination criteria under the given circumstances.

It must be mentioned that six of the 36 main fluorescent luminaires were not running (defected) during the measurement cycles. Another aspect that needs to be taken into account is the absence of the water body as well as the eight round underwater lights being turned off as a result. The water surface would reflect incident light and overall brighten the surrounding. It could be expected that higher illuminance values could be measured under regular operational circumstances.

The relation between minimum and average illuminance of the pool surface results in a uniformity value of 0.66. The uniformity including the pool deck is 0.41. Both values meet the required minimum criteria.

3.1.1.4. Simulation Results

To optimize correspondence of the initial simulation model measured surface reflectance and information about luminaire defects were implemented. In areas that seemed systematically too bright dimming values of 85% have been implemented for luminaire types. Given the lack of the maintenance intervals of the luminaires regarding cleaning, this seems not totally far from reality. Results of the initial simulation run of night-time simulation can be found in the appendix of this work. Table 9 lists results and information of the calibration steps.

Table 9: Simulation workflow results, main pool Donaustadt

MAIN POOL GRID, DONAUSTADT					
Calibration steps (implemented in DIALux)	Avg. deviation from simulation model to measurement		Difference (improvement) to previous step of calibration		notes
	%	lx	Percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	32%	45	-	-	Initial model, separate from measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	9%	15	23	29	Results show small deviations in lighting distribution at the pool basin
Application of measured surface reflactances	12%	19	-3	-4	Results show big deviations in brightness close to the facade and entrance hall
Dimming adjustments (CALIBRATED MODEL)	7%	11	5	8	Facade lights (85%), entrance lumianire dimming (85%)
Total improvements from INITIAL model to CALIBRATED model			**25**	**34**	

Figure 35 illustrates the reference area (including calibration efforts) in greyscale picture and isolines during night-time conditions. It displays almost identical deficiencies of illuminance levels as in the measurement result array. The symmetrical illuminance distribution is clearly visible. It can also be seen that the pool area does not achieve the required illuminance threshold of 200 lux.

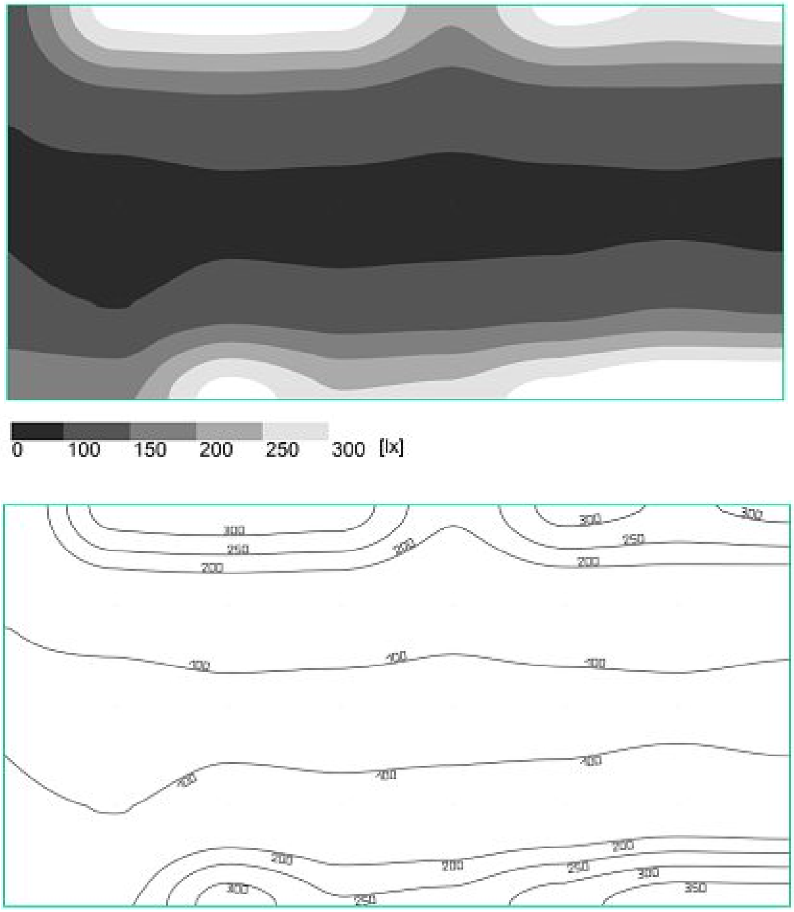


Figure 35: Calibrated simulation, greyscale and isoluxlines, Donaustadt main pool (figure by the author)

Unified Glare Rating (UGR)

Vertical illuminance was simulated at three points of interest. These are shown in Figure 34. UGR 1 and UGR 2 are positioned at eye height of the swimmers, 5cm above water surface. UGR 3 is located 1.50m above floor level at the main pool deck. For this simulation, the water body was considered in the simulation model. The UGR calculation was implemented via *DIALux* at different times and dates. The calculation included directions of view of 360° in steps of 15°. The simulations were conducted with overcast and subsequently with clear sky model.

- 21.06.2020, 12:00 and 16:00, which is the longest day of the year.

- 21.12.2020, 12:00 and 16:00, which is the shortest day of the year.

- 29.05.2020, 08:30, which was the date and time of measurement.

UGR at all points was below a value of 10. Values below or equal to 22 are considered as widely free of glare in rooms designated for sports activities (DIN EN 12464-1).

3.1.1.5. Comparison of Measurements and Simulation Results

Tables 10 and 11 put the night-time simulation results and measurement values for horizontal illuminance in relation.

Table 10: Measurement vs. Simulation [lx], Donaustadt main pool

5	Simulation	65	129	328	340	330	209	320	295	314
	Measurement	56	123	320	336	333	207	300	285	305
4	Simulation	124	101	127	138	132	113	127	130	121
	Measurement	110	99	115	147	138	105	123	126	122
3	Simulation	143	95	76	87	86	86	86	90	84
	Measurement	129	88	72	81	80	77	80	81	81
2	Simulation	157	113	99	122	114	120	127	147	137
	Measurement	133	110	108	124	116	116	123	140	144
1	Simulation	148	191	192	328	257	268	328	384	383
	Measurement	128	176	188	360	252	245	294	336	331
main pool, artificial light		A	B	C	D	E	F	G	H	I

Table 11: Measurement vs. Simulation [%], Donaustadt main pool

5	Sim. / Measurem.	16%	5%	2%	1%	-1%	1%	7%	4%	3%	4%
4	Sim. / Measurem.	13%	2%	10%	-6%	-4%	8%	3%	3%	-1%	6%
3	Sim. / Measurem.	11%	8%	6%	7%	8%	12%	8%	11%	4%	8%
2	Sim. / Measurem.	18%	3%	-8%	-2%	-2%	3%	3%	5%	-5%	5%
1	Sim. / Measurem.	16%	9%	2%	-9%	2%	9%	12%	14%	16%	10%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		15%	5%	6%	5%	3%	7%	6%	7%	6%	

Average deviation from Simulation to Measurement	
6.7%	**11lux**

A maximum tolerance of 10% for deviations between measured and calculated average illuminance was assumed. To simplify evaluation of the correspondence of the simulation in grid cells of Table 11 are colour coded. Cells that stray no further than 10% from the measured value are highlighted in green. Cells with a higher variation are marked orange. Because of rather precise modelling and calibration efforts, the average deviation from simulation to measurement results could be reduced to about 7%, more specifically 11 lux.

Daylight Factor

Simulation of the daylight situation with an overcast sky model results in considerable deviations from the measurement. Differences between assumptions of the simulation tool regarding exterior daylight availability and measured daylight illumination on the outside might play a role here. The exterior sky setting considers illuminance of 13.700 lux while the measured exterior illuminance was about 43.200 lux. This deviation leads to systematically too high daylight factors. To generate more meaningful results the ratio between measured and simulated exterior illuminance was applied proportionally at each reference point. Therefore, the resulting simulated daylight factors consider almost identical exterior illuminance conditions. As illustrated in Figure 36 and table 12, the adjustment improves correspondence of simulated daylight factors. The deviation of main pool area including the pool deck still indicates significant deviation from the measurement. Generally stated, areas that are directly influenced by daylight through glass facades and skylights stray further from the corresponding measurement. Initially simulated values indicate overall higher daylight availability, applied exterior-illuminance-ratio daylight factor results seem to be slightly lower compared to the measurement.

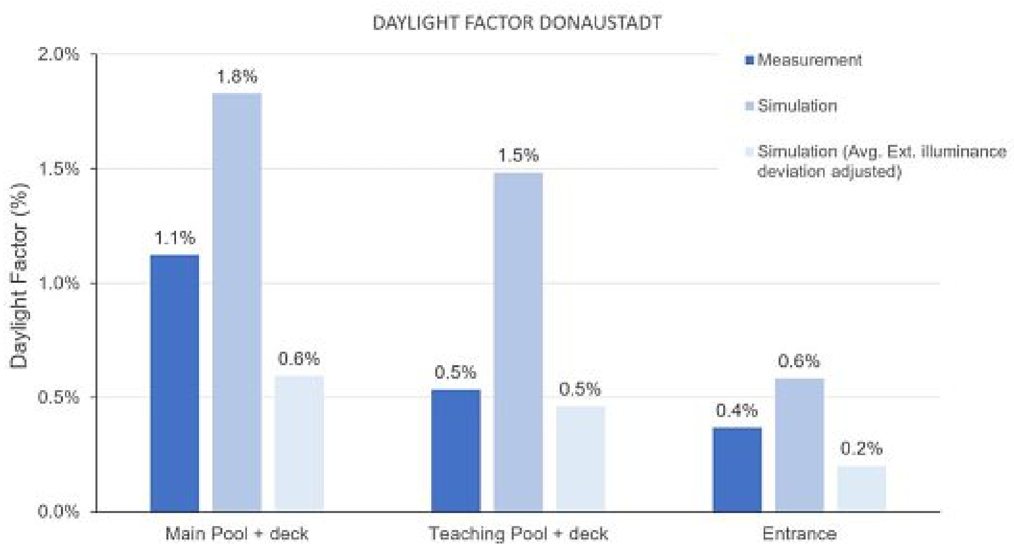


Figure 36: Daylight factors, Donaustadt (figure by the author)

Table 12: Daylight factors, Donaustadt

DF avg [%]	Measurement	Simulation	Simulation (Avg. Ext. illuminance deviation adjusted)
Main Pool + deck	1.1%	1.8%	0.6%
Teaching Pool + deck	0.5%	1.5%	0.5%
Entrance	0.4%	0.6%	0.2%

E exterior average (lx)	43 234	13 732	41 928
E exterior average ratio to measurement	-	32%	97%

3.1.2 Teaching Pool

The luminaire arrangement and the calculated measurement grid (including one UGR calculation point) of the teaching pool and the adjacent quiet room with the pool for senior citizens is shown below in Figures 37 and 38. The grid size follows the suggestions of DIN EN 12193, as described in the methodology chapter.

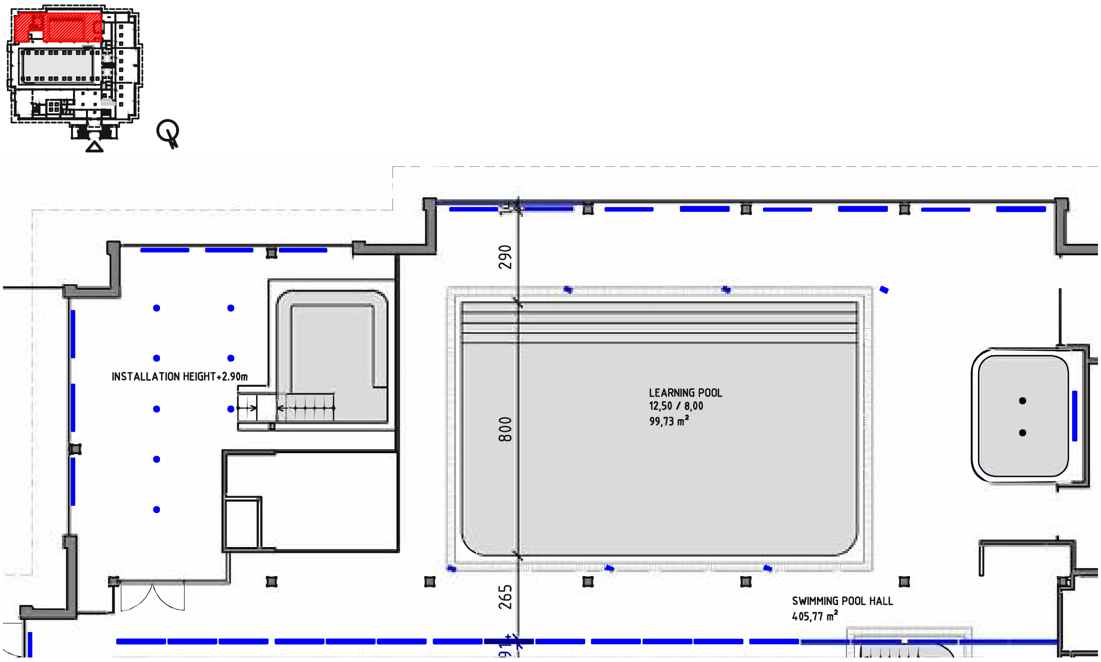


Figure 37: Luminaire arrangement, Donaustadt teaching pool and quiet area (based on MA44, edited by the author)

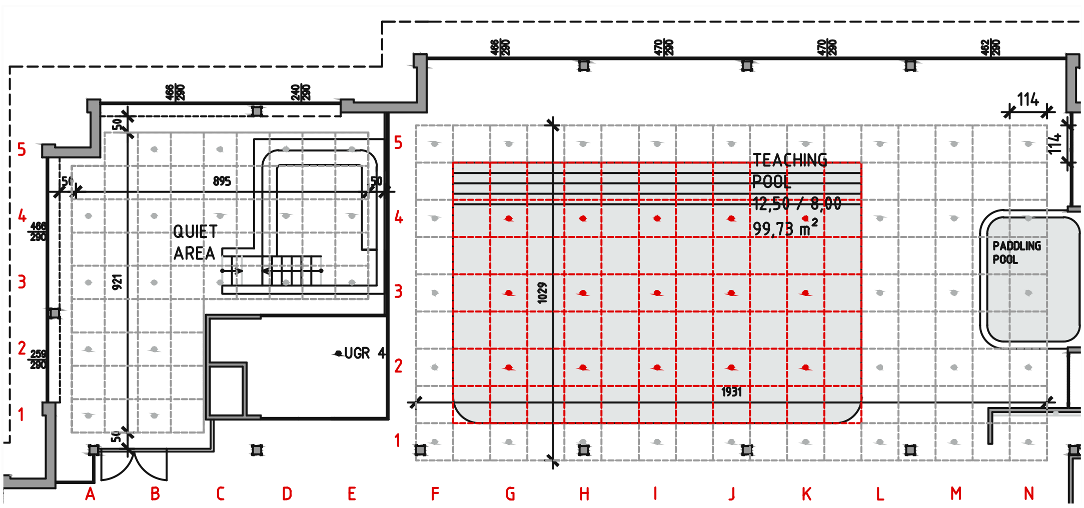


Figure 38: Measuring grid, Donaustadt teaching pool and quiet area (based on MA44, edited by the author)

The artificial lighting concept of the teaching pool has a direct lighting system with splash water protection. Eight tubular fluorescent lamps are aligned along the façade of this area. Four luminaires are of the same lamp type as the main pool fluorescents. Four lamps consist of a fixture with one fluorescent tube. They are installed in alternating order. The luminaires are ceiling-mounted at a height of +2.90m above floor level. The row of artificial lights at the bottom of Figure 37 is running along the centre of the overall swimming pool hall and therefore illuminates both swimming pools. Because of the open floor plan and the transparent glass walls of the swimming pool hall, dimming alterations in each of the individual areas have an impact on the overall hall as well as the entrance foyer.

Six fluorescent-based spotlights are suspended from the ceiling. Their positions are evenly distributed along the lengths of the teaching pool basin. They are mounted at different horizontal angles to face the pool's water surface. According to the technical staff of the building, they are in use for swim training of school classes. Otherwise, for the most part turned off. Therefore, they were not considered in the measurement as well as the simulation.

A group of three artificial lights is mounted above the paddling pool. Two round ceiling-recessed energy-saving downlights and one linear ceiling-mounted lamp.

The same downlight lamp type is installed eight times in two linear constellations in the quiet room. The main provider of illuminance in this room are six tubular fluorescent lamps mounted to the ceiling in front of the façade. They are the same lamp type as the façade lights in the main pool area.

Two round lights were defected during the measurement process. This was considered in the simulation of artificial lighting.

3.1.2.1. Daytime Measurement

Tables 13 to 16 present the measured horizontal illuminance values for the quiet area and the teaching pool. The daytime measurement was conducted with all artificial lights turned off (daylight only).

The measurements were performed on 29.05.2020 from 08:20am to 09:20am under partly cloudy to overcast sky (the day was chosen based on the weather forecast and organizational aspects regarding accessibility of the swimming pool hall). Weather circumstances included an outside temperature of in average 13°C and about 15km/h wind speed.

The grey coloured cells are outside the perimeters of the defined measurement grid.

Table 13: Daytime measurement, Donaustadt quiet area

5	out		31 090	30 160	29 470	29 360
	in		1 750	1 082	694	409
4	out	36 690	31 100	30 590	30 380	30 370
	in	5 960	2 167	820	552	313
3	out	36 570	31 200	30 140	30 190	30 290
	in	6 880	1 955	490	350	168
2	out	35 930	31 100			
	in	8 300	1 542			
1	out	34 740	31 470			
	in	1 073	818			
quiet area, daylight		A	B	C	D	E

Table 14: Daylight factors measurement- based, Donaustadt quiet area

5		5.6%	3.6%	2.4%	1.4%
4	16.2%	7.0%	2.7%	1.8%	1.0%
3	18.8%	6.3%	1.6%	1.2%	0.6%
2	23.1%	5.0%			
1	3.1%	2.6%			
quiet area, DF	A	B	C	D	E

Table 15: Daytime measurement, Donaustadt teaching pool

5	out	43 640	44 190	45 120	45 680	45 740	45 280	45 550	40 860	40 550
	in	433	531	522	609	616	713	643	805	410
4	out	45 020	42 860	42 860	43 360	43 690	44 040	46 830	43 420	44 360
	in	225	208	226	260	243	253	288	311	165
3	out	45 150	42 540	42 250	41 830	41 480	40 830	47 450	44 180	40 330
	in	134	138	129	151	145	148	133	106	71
2	out	44 770	48 950	48 650	47 970	46 390	45 020	47 770	44 430	44 210
	in	93	108	105	111	104	110	97	79	42
1	out	41 370	44 820	46 180	47 410	48 050	48 130	48 360	45 110	45 280
	in	141	163	126	141	125	111	125	112	92
teaching pool, daylight		F	G	H	I	J	K	L	M	N

Table 16: Daylight factors measurement based, Donaustadt teaching pool

5	1.0%	1.2%	1.2%	1.3%	1.3%	1.6%	1.4%	2.0%	1.0%
4	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%	0.6%	0.7%	0.4%
3	0.3%	0.3%	0.3%	0.4%	0.3%	0.4%	0.3%	0.2%	0.2%
2	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%
1	0.3%	0.4%	0.3%	0.3%	0.3%	0.2%	0.3%	0.2%	0.2%
teach. pool, DF	F	G	H	I	J	K	L	M	N

Table 17 contains the assumed surface reflectance of all enclosing surfaces in the quiet room and teaching pool area.

Table 17: Surface reflectance, Donaustadt teaching pool and quiet area

	Surface	Reflectance
Quiet area	Floor (white, tiles)	0.55
	Senior Pool basin floor (green, tiles)	0.22
	Senior Pool basin walls (grey, tiles)	0.55
	Wall (green, tiles)	0.38
	Wall (white, plaster)	0.88
	Columns (white, plaster)	0.88
	Ceiling (wood, light)	0.49
	Beams (white, plaster)	0.88

	Surface	Reflectance
Teaching pool	Floor (mosaic tiles in average)	0.46
	Learning Pool basin (white, tiles)	0.60
	Paddling Pool basin (blue, tiles)	0.32
	Wall (blue, tiles)	0.60
	Wall, showers (white, tiles)	0.75
	Wall (white, plaster)	0.88
	Columns (white, plaster)	0.88
	Ceiling (wood)	0.17
	Beams (wood)	0.17

3.1.2.2. Night-time Measurement

The results were acquired on 15.05.2020 from 09:20pm to 10:30pm under the same conditions as the main pool measurement of artificial lighting. Table 18 and 19 inform about night-time measurement results.

Table 18: Night measurement, Donaustadt teaching pool and quiet area

5		164	158	115	59
4	172	163	158	64	42
3	161	130	80	33	22
2	126	90			
1	82	91			
quiet area, artif.	A	B	C	D	E

5	72	103	105	115	118	115	116	113	115
4	47	58	61	63	62	61	58	63	83
3	49	57	56	54	56	55	54	45	139
2	85	89	81	73	82	80	75	65	30
1	167	182	63	144	134	172	155	180	187
teach. p., artif.	F	G	H	I	J	K	L	M	N

Table 19: Night-measurement performance, Donaustadt teaching pool

	Teaching Pool	Teaching pool + deck	Minimum standards
E min [lx]	54	47	-
E max [lx]	89	182	-
E avg [lx]	66	89	200 | 150
Uniformity	0.82	0.53	0.5 | 0.4

3.1.2.3. Analysis

Quiet room and the teaching pool are analysed individually.

The relatively small quiet room is bordered by two external glass walls. Therefore, natural light is sufficiently present. The support of electrical light during daylight conditions is rarely needed. In correlation to the daylight availability, the horizontal illuminance values in the quiet room are exceedingly high.

The night-time measurement describes an uneven lighting distribution between values of 22 lux to 172 lux. The lowest values are measured at the area where the small pool for senior citizens is positioned. Illumination data of 22lux to 64lux is failing the recommended minimum values by far. According to the IES lighting handbook (DiLaura et al. 2011) hot-tubs are presumed to be internally lighted. As mentioned before, underwater pool lights could not be included in the measurement process due to the absence of water bodies. It can be assumed that illuminance levels in the senior pool's area would be increased during regular operational conditions.

The teaching pool area does not appear daylit as strongly. Contrary to the main pool there are no skylights in this area. Therefore, the positive effect of daylight quality several meters off the facade is missing. Slight sunlight availability and sufficient horizontal illumination measurements are present only close to the façade. All grid points of row 3 to 1 of Table 15 are about 7 to 11 meters away from the façade and do not meet the minimum requirement of 200 lux for the pool area nor 150 lux for the pool deck. According to standard definitions of the daylight factor it is suggested to use electrical light most of the day in the teaching pool area to offer the users a safer and more pleasing visual experience.

The night-time measurements of the teaching pool's electrical lighting performance range between 47 lux and 182 lux. The grid cells between main pool and teaching pool seem to be the best-lit of the measurement grid. These are the only areas fulfilling the required minimum criteria. The pool basin itself is poorly illuminated. For the intended purpose, the electrical lighting does not offer acceptable conditions for the teaching pool including its pool deck. Nevertheless, the low illumination of the teaching pool basin itself is evenly distributed. The uniformity of 0.82 is well above the required standards.

It must be mentioned that the six spotlights aiming at the pool were turned off during the measurement process to simulate regular operational conditions. It can be expected that their luminous flux would increase the low lighting levels.

3.1.2.4. Simulation Results

To optimize correspondence of the initial simulation model measured surface reflectance and information about luminaire defects were implemented. In areas that seemed systematically too bright dimming values of 85% have been implemented for individual luminaire types. Given the lack of the maintenance intervals of the luminaires regarding cleaning, this seems not totally far from reality.

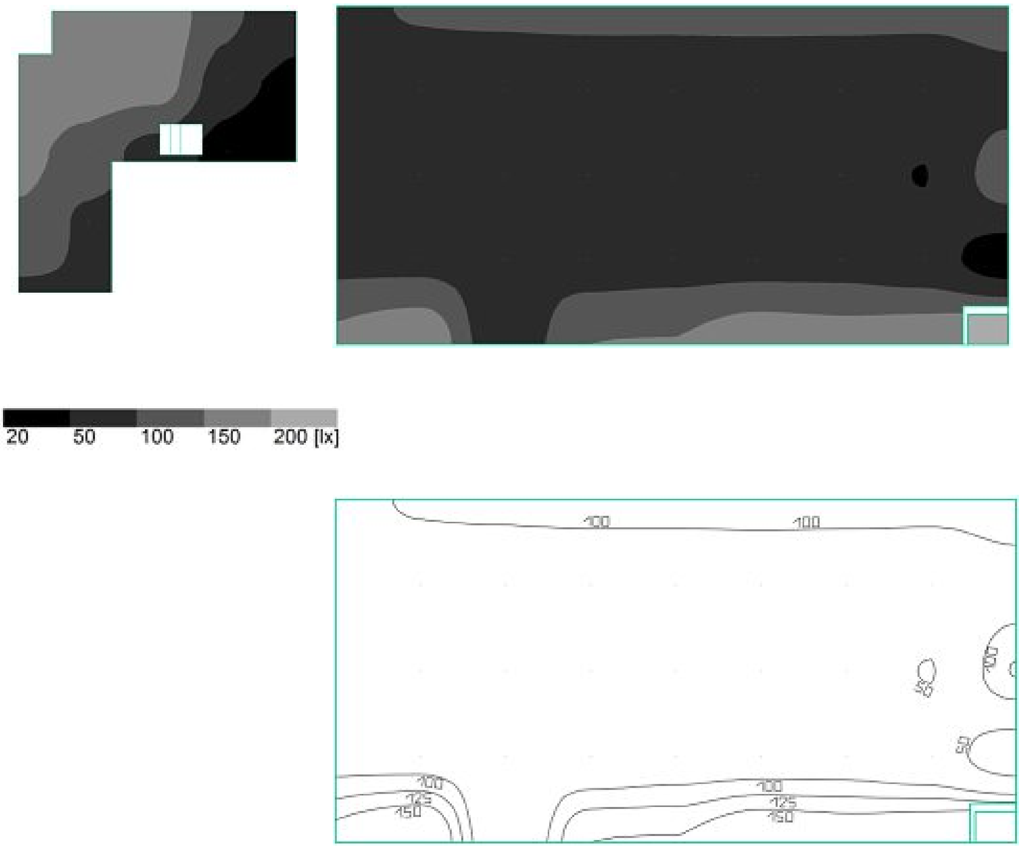


Figure 39: Calibrated simulation, greyscale and isoluxlines, Donaustadt teaching pool (figures by the author)

Figure 39 illustrates the reference area (including calibration efforts) in falsecolour picture and isolines during night-time conditions. It displays almost identical deficiencies of illuminance levels as in the measurement result array. The overall low illumination of the teaching pool area is clearly visible, as well as the gradient in the quiet room. Table 20 lists results and information of the individual calibration steps.

Table 20: Simulation workflow results, Teaching pool Donaustadt

TEACHING POOL GRID, DONAUSTADT					
Calibration steps (implemented in DIALux)	Avg. deviation from simulation model to measurement		Difference (improvement) to previous step of calibration		notes
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	69%	53	-	-	Initial model, separate from all measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	16%	13	53	40	Lighting distribition does not correspond very well to measurements
Application of measured surface reflactances	13%	12	3	2	Lighting distribution shows better correspondance, illuminance close to facade locations seems systematically too bright
Dimming adjustments (CALIBRATED MODEL)	5%	5	8	7	Facade lights (85%), entrance lumianire dimming (85%)
Total improvements from INITIAL model to CALIBRATED model			**64**	**48**	

Unified Glare Rating (UGR)

Vertical illuminance was simulated at one point of interest in this area. It is shown in Figure 38. UGR 4 is positioned 1.20m above floor level. It simulates the view of the lifeguard at sitting height. For this simulation, the water body was considered in the simulation model. The UGR calculation was implemented in Dialux at different times and dates. The calculation included directions of view of 360° in steps of 15°. The simulations were conducted with overcast and subsequently with clear sky model.

- 21.06.2020, 12:00 and 16:00, which is the longest day of the year.

- 21.12.2020, 12:00 and 16:00, which is the shortest day of the year.

- 29.05.2020, 08:30, which was the date and time of measurement.

UGR at all points was below a value of 10. Values below or equal to 22 are considered as widely free of glare in interior sports rooms (DIN EN 12464-1).

3.1.2.5. Comparison of Measurements and Simulation Results

Tables 21 and 22 put the night-time simulation results and measurement values for horizontal illuminance in relation.

Table 21: Measurement vs. simulation [lx], Donaustadt teaching pool

5	Simulation		189	184	116	62	77	106	110	112	112	113	113	111	124
	Measurement		164	158	115	59	72	103	105	115	118	115	116	113	115
4	Simulation	179	174	174	69	42	51	61	62	63	64	65	63	62	80
	Measurement	172	163	158	64	42	47	58	61	63	62	61	58	63	83
3	Simulation	166	126	85	35	26	53	58	57	54	59	59	58	49	127
	Measurement	161	130	80	33	22	49	57	56	54	56	55	54	45	139
2	Simulation	137	92				90	88	81	75	82	83	83	71	26
	Measurement	126	90				85	89	81	73	82	80	75	65	30
1	Simulation	94	97				166	193	55	150	152	183	175	184	205
	Measurement	82	91				167	182	63	144	134	172	155	180	187
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N

Table 22: Measurement vs. simulation [%], Donaustadt teaching pool

5	Sim./Measurem.		15%	16%	1%	5%	7%	3%	5%	-3%	-5%	-2%	-3%	-2%	8%	4%
4	Sim./Measurem.	4%	7%	10%	8%	0%	9%	5%	2%	0%	3%	7%	9%	-2%	-4%	4%
3	Sim./Measurem.	3%	-3%	6%	6%	18%	8%	2%	2%	0%	5%	7%	7%	9%	-9%	5%
2	Sim./Measurem.	9%	2%				6%	-1%	0%	3%	0%	4%	11%	9%	-13%	5%
1	Sim./Measurem.	15%	7%				-1%	6%	-13%	4%	13%	6%	13%	2%	10%	8%
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N	
							6%	3%	4%	2%	5%	5%	8%	5%	9%	

Average deviation from Simulation to Measurement	
5.3%	5lux

The simulation model results in a very low deviation from the measured status quo. In average each grid point varies 5.3%, more specifically about 5 lux from the measured values. The lowest spread between simulation and measurement data was achieved at the teaching pool basin itself. This high level of correspondence renders the simulation model a meaningful tool for future optimization efforts.

3.1.3 Entrance

The luminaire arrangement and the calculated measurement grid of the entrance hall and the porch is shown below in Figure 40.

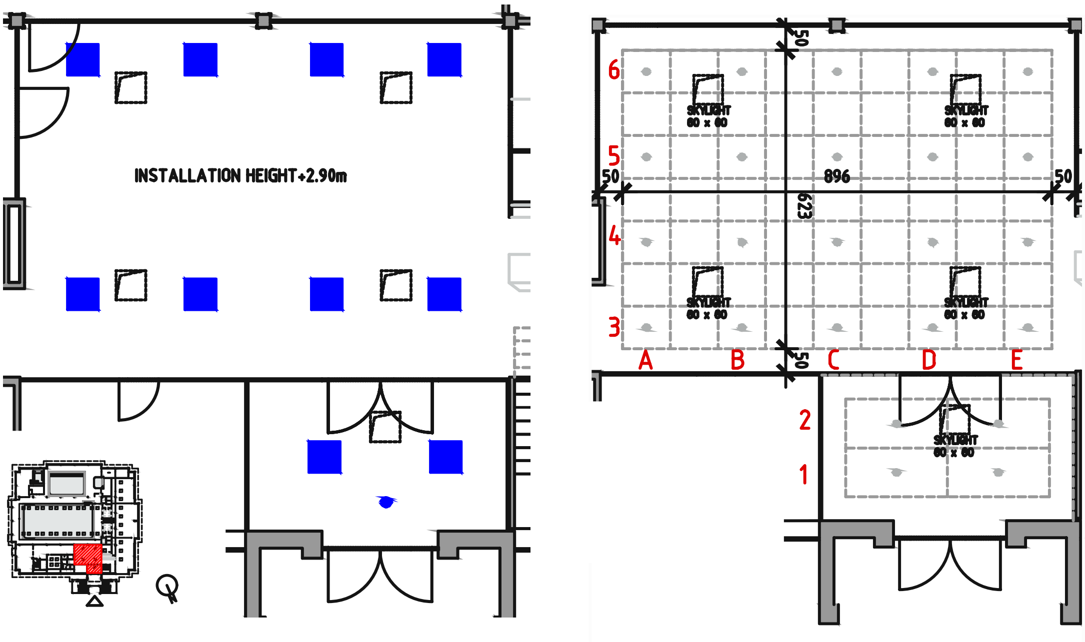


Figure 40: Luminaire arrangement and measuring grid, Donaustadt entrance (based on MA44, edited by the author)

The artificial lighting system of the entrance hall consists of eight symmetrically distributed luminaires. They are ceiling-recessed at a height of +2.90m above floor level. Their measurements correspond to the size of one ceiling-panel which is estimated to 0.60m x 0.60m.

Two luminaires of the same type are positioned in the porch area. Both have been turned off during the measurement process. One round downlight served as a light source during the measurement process. In the simulation the same lamp type as installed in the quiet room was assumed for this position.

3.1.3.1. Daytime Measurement

Tables 23 and 24 present the measured horizontal illuminance values for the entrance hall including the porch. Daytime measurement was conducted with all artificial lights turned off (daylight only). Table 25 contains measurement-derived surface reflectance values of the entrance hall.

The results were attained on 29.05.2020 from 08:20am to 09:20am under the same conditions as the swimming pool hall. The grey coloured cells were obstructed by permanent furnishing during the measurement process or are outside of the perimeter of the defined measurement grid for the entrance hall.

Table 23: Daytime measurement, Donaustadt entrance

6	out	40 590	38 520	38 500	38 460	38 370
	in	101	79	104	136	116
5	out	39 510				38 060
	in	123				161
4	out	42 200				40 460
	in	100				209
3	out	42 320	42 240	41 470	41 420	40 020
	in	76	164	112	328	270
2	out				38 180	38 510
	in				480	681
1	out				38 370	38 460
	in				627	942
entrance, daylight		A	B	C	D	E

Table 24: Daylight factors, Donaustadt entrance

6	0.2%	0.2%	0.3%	0.4%	0.3%
5	0.3%				0.4%
4	0.2%				0.5%
3	0.2%	0.4%	0.3%	0.8%	0.7%
2				1%	2%
1				2%	2%
entrance, DF	A	B	C	D	E

Table 25: Surface reflectance, Donaustadt entrance

	Surface	Reflectance
Entrance	Floor (brown, tiles)	0.4
	Wall (white, plaster)	0.88
	Columns (white, plaster)	0.88
	Ceiling (grey, drywall)	0.89
	Beams (white, plaster)	0.88

3.1.3.2. Night-time Measurement

The results were acquired on 15.05.2020 from 09:20pm to 10:30pm under the same conditions as the main pool measurement of artificial lighting. Table 26 and 27 inform about night-time measurement results.

Table 26: Night Measurement, Donaustadt entrance

6	275	313	318	309	274
5	235				272
4	200				279
3	295	294	269	262	250
2				58	61
1				66	70
entrance, artif.	A	B	C	D	E

Table 27: Night-measurement performance indicators, Donaustadt entrance

	Entrance hall	Minimum standards
E min [lx]	200	-
E max [lx]	318	-
E avg [lx]	275	100
Uniformity	0.73	0.4

3.1.3.3. Analysis

The entrance hall is not situated at an external façade. It is separated by the small porch area. The architectural design includes four skylights above the entrance hall and one skylight above the porch. Therefore, natural light flows into the room and provides a naturally illuminated entrance experience. The derived daylight factors of the foyer are below 0.8%. Nevertheless, except for two grid points the minimum illuminance of 100 lux is exceeded under the specified conditions. One of the underachieving measurement points was shadowed by a nearby plant. The closer the grid points are to the porch, which is accessed by natural light through the glass portal, the higher the registered illuminance. It can be summarized that the skylights and the glass portal alone provide sufficient openings for a well-lit environment during daylight under the specified conditions.

The artificial lighting system installed at the entrance area reveals satisfactory visual performance. The illumination is evenly distributed with a uniformity of 0.73. The measured data noticeably exceeds the minimum criteria at each grid point. The porch area is not lit sufficiently by the installed spotlight. The two luminaires which were not in operation during the night-time measurement should be turned on to assumably reach sufficient lighting levels.

3.1.3.4. Simulation Results

To optimize correspondence of the initial simulation model the measured surface reflectance and information about luminaire defects were implemented. In areas that seemed systematically too bright dimming values of 85% have been implemented for individual luminaire types.

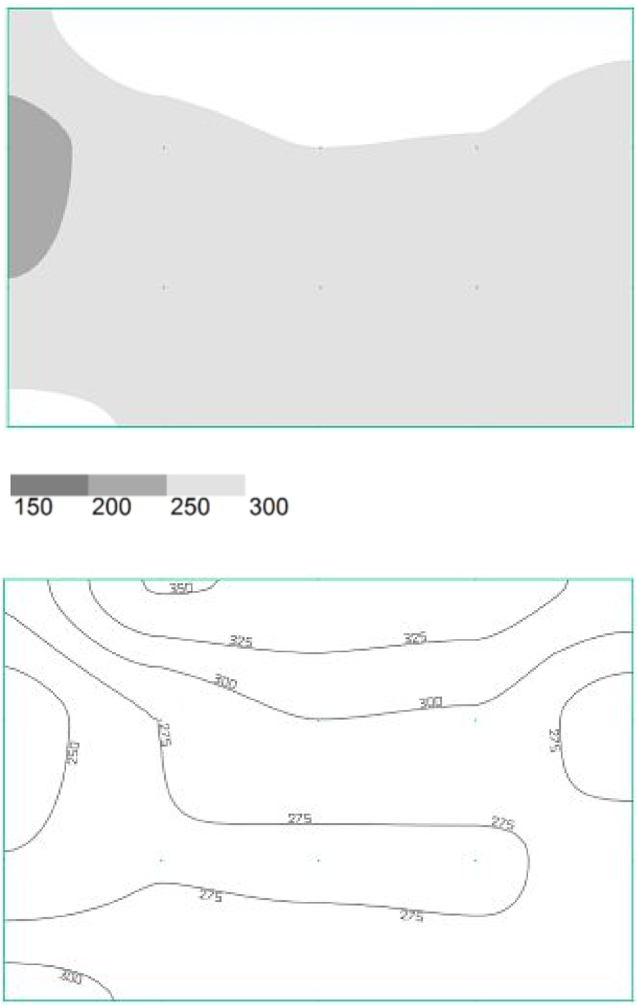


Figure 41: Calibrated simulation greyscale and isoluxlines, Donaustadt entrance (figure by the author)

Figure 41 displays similar distribution of illumination as the measurement. It provides information about the even illumination of the entrance hall (including calibration efforts). The brightest area is close to the glass wall which separates the swimming pool hall from the entrance area. Table 28 lists results and information of the individual calibration steps.

Table 28: Simulation workflow results, entrance hall Donaustadt

ENTRANCE HALL, DONAUSTADT					
Calibration steps (implemented in DIALux)	Avg. Deviation from simulation to measurement		Difference (improvement) to previous step of calibration		notes (table excludes porch area)
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	12%	35	-	-	Initial model, separate from all measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	12%	34	0	1	Uneven lighting distrubition compared to measurements
Application of measured surface reflactances	15%	41	-3	-7	Distribution corresponds better, overall illuminance seems systematically too bright
Dimming adjustments (CALIBRATED MODEL)	8%	21	7	20	Facade lights (85%), entrance lumianire dimming (85%)
Total improvements from INITIAL model to CALIBRATED model			**4**	**13**	

3.1.3.5. Comparison of Measurements and Simulation Results

Tables 29 and 30 put the night-time simulation and the measurement results in relation.

Table 29: Measurement vs. simulation [lx], Donaustadt entrance

6	Simulation	281	351	344	339	310
	Measurement	275	313	318	309	274
5	Simulation	235				259
	Measurement	235				272
4	Simulation	252				285
	Measurement	200				279
3	Simulation	311	297	293	284	278
	Measurement	295	294	269	262	250
2	Simulation				59	64
	Measurement				58	61
1	Simulation				72	75
	Measurement				66	70
entrance, artificial light		A	B	C	D	E

Table 30: Measurement vs. simulation [%], Donaustadt entrance

		A	B	C	D	E	
6	Sim. / Measurem.	2%	12%	8%	10%	13%	9%
5	Sim. / Measurem.	0%				-5%	2%
4	Sim. / Measurem.	26%				2%	14%
3	Sim. / Measurem.	5%	1%	9%	8%	11%	7%
2	Sim. / Measurem.				2%	5%	3%
1	Sim. / Measurem.				9%	7%	8%
entrance, artificial light		A	B	C	D	E	
		8%	7%	9%	7%	7%	

Average deviation from Simulation to Measurement	
8.1%	**21lux**

The simulation model of the entrance hall results in a low deviation from the measured status quo. In average each grid point varies 8.1% or about 21 lux from the measured values. One clear outlier is marked in Table 30 in orange colour (4A). The outlier can be explained since plants and furnishing were not modelled. Therefore, the simulation produces a higher illuminance value than the measured one at this specific position.

3.1.4 Lockers and changing cabins

The luminaire arrangement and the calculated measurement grid of the locker rooms and changing booths is shown below in Figures 42 and 43.

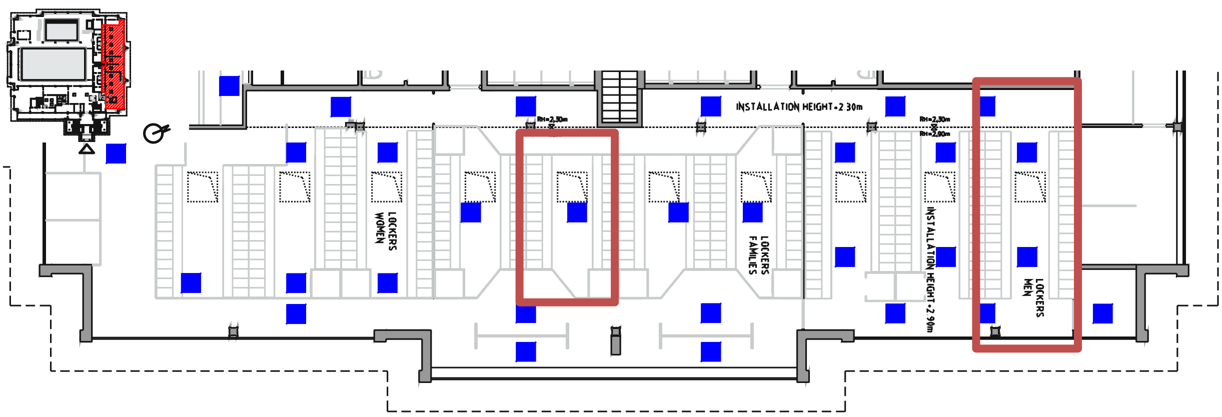


Figure 42: Luminaire arrangement, Donaustadt lockers (based on MA44, edited by the author)

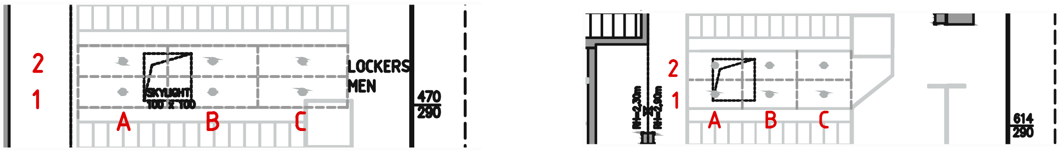


Figure 43: Measuring grid, Donaustadt lockers men (left) and women (right) (based on MA44, edited by the author)

All lamps in the locker rooms, connecting hallways and hair dryer stations are ceiling recessed. They are of the same lamp type as the installations in the entrance hall. The luminaires are arranged in a regular pattern. The male locker rows feature two lamps. The evaluated female locker row features one luminaire.

3.1.4.1. Daytime Measurement

Table 31 and 32 present the measured horizontal illuminance values for two the specified locker rooms. Daytime measurement was conducted with electrical lighting turned on (daylight and artificial light).

The results were attained on 29.05.2020 from 08:20am to 09:20am under the same conditions as the swimming pool hall.

Table 31: Daytime measurement, Donaustadt lockers men and women

2	out	40 360	40 610	40 870
	in	495	544	226
1	out	40 410	40 740	40 860
	in	450	522	227
locker M, daylight		A	B	C

2	out	40 660	42 430	43 870
	in	528	556	314
1	out	41 100	42 960	43 420
	in	548	562	308
locker W, daylight		A	B	C

Table 32: Daylight factors, Donaustadt lockers men and women

2	1.2%	1.3%	0.6%
1	1.1%	1.3%	0.6%
lockers M, DF	A	B	C

2	1.3%	1.3%	0.7%
1	1.3%	1.3%	0.7%
lockers W, DF	A	B	C

3.1.4.2. Night-time Measurement

The results were acquired on 15.05.2020 from 09:20pm to 10:30pm under the same conditions as the main pool measurement of artificial lighting. Table 33 and 34 inform about night-time measurement results.

Table 33: Night measurement, Donaustadt lockers men and women

2	251	183	197
1	286	188	217
locker M, artif.	A	B	C

2	143	181	170
1	122	157	153
locker W, artif.	A	B	C

Table 34: Night measurement performance indicators, Donaustadt locker

	Men	Women / Family	Minimum standards
E min [lx]	183	122	-
E max [lx]	286	181	-
E avg [lx]	220	154	200
Uniformity	0.83	0.79	0.4

3.1.4.3. Analysis

Due to the small number of measurement points and the overall small size of the reference grid the results of the measurement are of lower validity. Measurements of illumination were mainly documented to gain ability to compare simulation results.

Natural light is available through the glass façade and one skylight per locker row. The combination of daylight and artificial light results in high illumination levels in both areas of interest.

The average illuminance by electrical lighting alone of the men's area measures 220 lux, the women's area 154 lux. The men's locker room records higher illumination levels due to the second luminaire and fulfils the requirements. The lighting performance in the women's locker room should be increased to reach acceptable minimum values.

Under daylight conditions the women's area displays higher overall illumination values. This could be explained by the fact that the external wall in the men's locker area has an overhead light-band opening in the examined area instead of a completely transparent façade component.

According to the calculated uniformity of 0.83 in the male area and 0.79 in the female area both locker rooms show similar and even lighting distribution.

3.1.4.4. Simulation Results

To optimize correspondence of the initial simulation model the measured surface reflectance and information about luminaire defects were implemented. In areas that seemed systematically too bright dimming values of 85% have been implemented for individual luminaire types. Table 35 lists results and information of the individual calibration steps.

Table 35: Simulation workflow results, Lockers Donaustadt

LOCKERS Male and Female, DONAUSTADT					
Calibration steps (implemented in DIALux)	Avg. deviation from simulation to measurement		Difference (improvement) to previous step of calibration		notes
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	16%	27	-	-	Initial model, separate from measurement findings
Application of measured surface reflactances	14%	24	2	3	Areas overall too bright
Application of measured surface reflactances (CALIBRATED MODEL)	6%	11	8	13	Locker luminaire (identical to entrance) dimming to 85%
Total improvements from INITIAL model to CALIBRATED model			**10**	**16**	

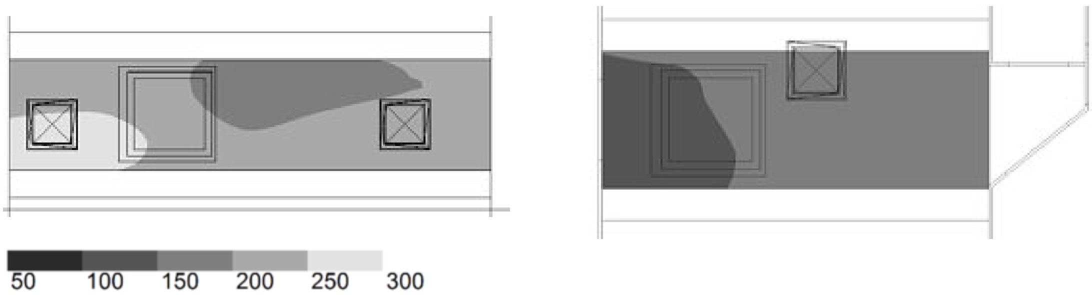


Figure 44: Calibrated simulation, Donaustadt lockers men (left) and women (right) (figure by the author)

Figure 44 illustrates the reference area in greyscale picture during night-time conditions. It displays similar deficiencies of illuminance levels as in the measurement result array. The overall higher illumination values in the men's locker room are visible.

3.1.4.5. Comparison of Measurements and Simulation Results

Table 36 and 37 put the night-time simulation and the measurement results in relation.

Table 36: Measurement vs. simulation, Donaustadt lockers men

2	Simulation	223	173	186
	Measurement	251	183	197
1	Simulation	255	195	226
	Measurement	286	188	217
Lockers Men, artificial l.		A	B	C

2	Sim./Meas.	-11%	-5%	-6%	7%
1	Sim./Meas.	-11%	4%	4%	6%
Lockers M, artif.		A	B	C	
		11%	5%	5%	

Table 37: Measurement vs. simulation, Donaustadt lockers women

2	Simulation	144	178	171
	Measurement	143	181	170
1	Simulation	133	165	168
	Measurement	122	157	153
Lockers Women, artif.		A	B	C

2	Sim./Meas.	1%	-2%	1%	1%
1	Sim./Meas.	9%	5%	10%	8%
Lockers W, artif.		A	B	C	
		5%	3%	5%	

Average deviation from Simulation to Measurement	
5.6%	**11lux**

The simulation of the locker rooms results in a low average deviation from the measured status quo. The simulated values show a higher correspondence of the women's locker room than the men's area. The average relative deviation from simulation to measurement results for both investigated locker rows could be reduced below 6% (11 lux). There are no obvious outliers.

3.1.5 Optimization proposals Object 1

In the course of this contribution a 3D model of *Donaustädter Hallenbad* was generated and calibrated with measured values. The comparison of simulated and measured artificial lighting performance results in an average relative deviation significantly below 10% at each individual area of the overall model. In the swimming pool hall, the simulated data indicates the highest correspondence. The low margin provides the opportunity to implement optimization steps and get conclusive and immediate feedback from the virtual model.

The following proposals aim to improve the visual performance of the artificial lighting system. They react to detected deficiencies in illuminance and uniformity. The suggestions are limited to the swimming pool area. Entrance and locker rooms are not included in this section. Any optimization measures in an existing building must be well planned. The cost-benefit-ratio must play a substantial role. An in-depth refurbishment of the electrical lighting system, technical feasibility and cost factors are beyond the scope of this thesis. Therefore, the propositions are focused on simple and cost-effective solutions for efficiency improvement. The effect on lighting levels is tested in the model and documented in the graphs and tables hereinafter.

Base case: Simulation model including calibration efforts (Base case)

As reference, the simulation of existing values is illustrated as base case in Figures 45 and 46.

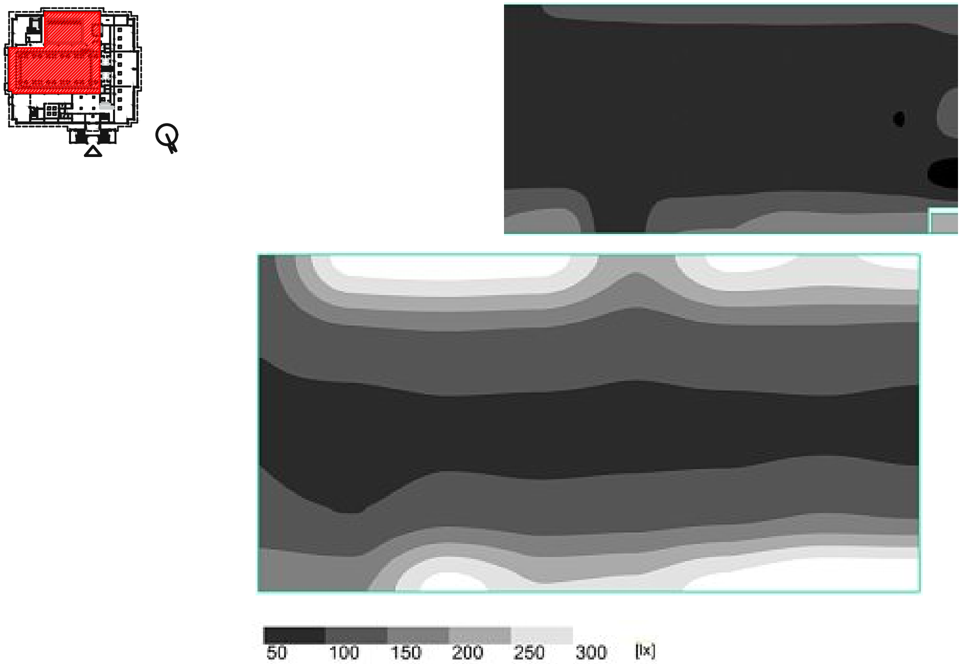


Figure 45: Greyscale Base case, swimming pool hall Donaustadt (figure by the author)

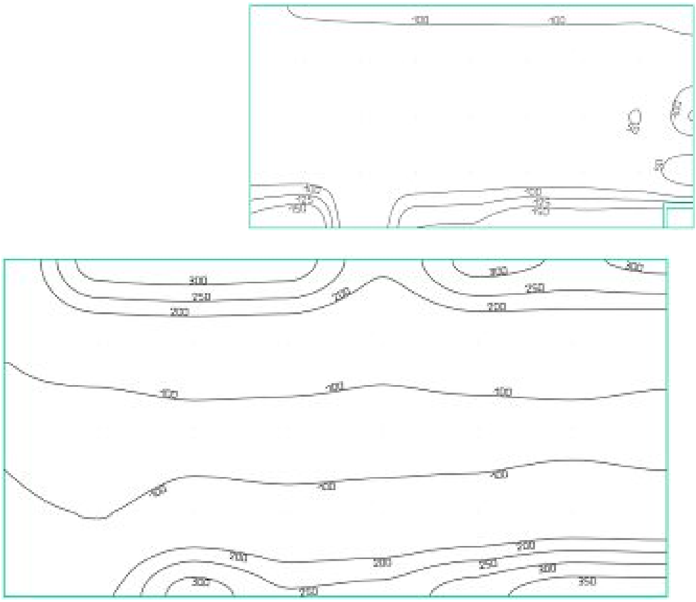


Figure 46: Isolux lines Base case, swimming pool hall Donaustadt (figure by the author)

Optimization suggestion number 1: Replacing misfunctioning luminaires.

Six of the tubular fluorescent lamps, the main lighting source of the swimming pool hall did not emit light. They are considered as functional in this optimization simulation. Additionally, all six spotlights surrounding the teaching pool are considered switched on. They were not considered in the measurement procedure since they are not regularly in operation during evening opening hours of the building according to staff.

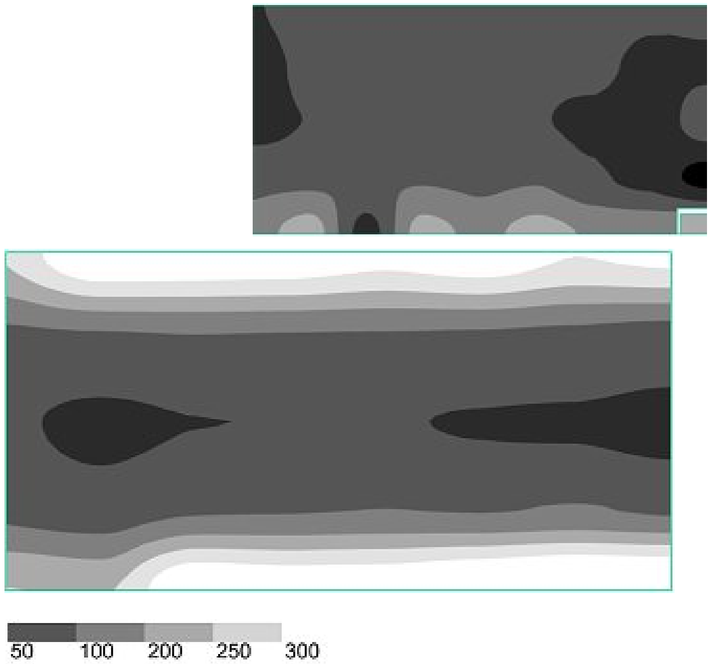


Figure 47: Greyscale Optimization #1, swimming pool hall Donaustadt (figure by the author)

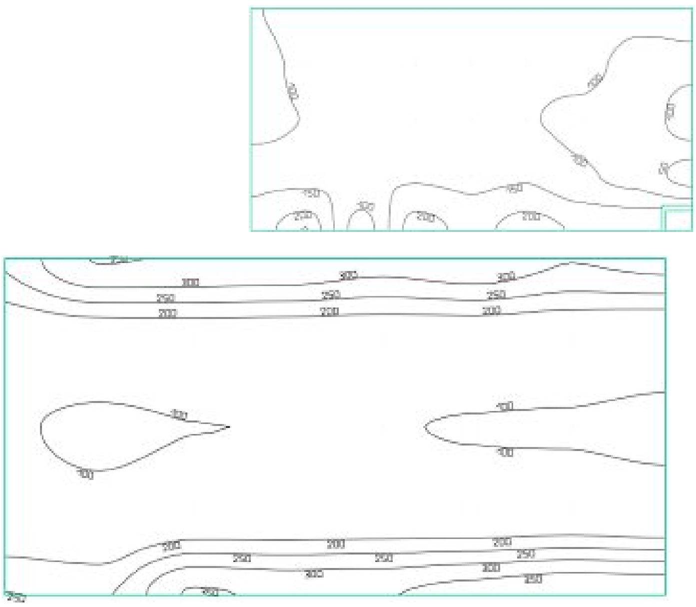


Figure 48: Isolux lines Optimization #1, swimming pool hall Donaustadt (figure by the author)

Figures 47 and 48 clearly illustrate the increased illumination in both pool areas. Illuminance levels of the main pool basin rise by 14%, those of the teaching pool by 79%. The distribution of light in the hall is more uniform. However, none of the calculation points meet required minimum values of 200 lux at the pool surfaces and only few meet the standards of 150 lux at the pool decks.

Optimization suggestion number 2: Increasing ceiling surface reflectance.

The surface reflection value, derived from luminance and illuminance measurement, is expected to be 17%. It can be assumed that a higher reflectivity would improve the overall illumination levels of the hall. Figures 49 and 50 illustrate the results of a ceiling painted with white colour and includes full functionality of all luminaires (thus building up on optimization scenario 1). Surface reflectance of 80%, similar to measurement derived values from white plaster of pillars of the pool hall is assumed in this scenario.

Compared to optimization proposal 1, the simple measure further improves illumination levels of the main pool by 6%, those of the teaching pool by 35%. The effect of enhanced ceiling surface reflectance is higher at the teaching pool area. This could be expected because of the lower free room height. A higher number of reflections is possible. The ceiling above the main pool on the other hand is elevated.

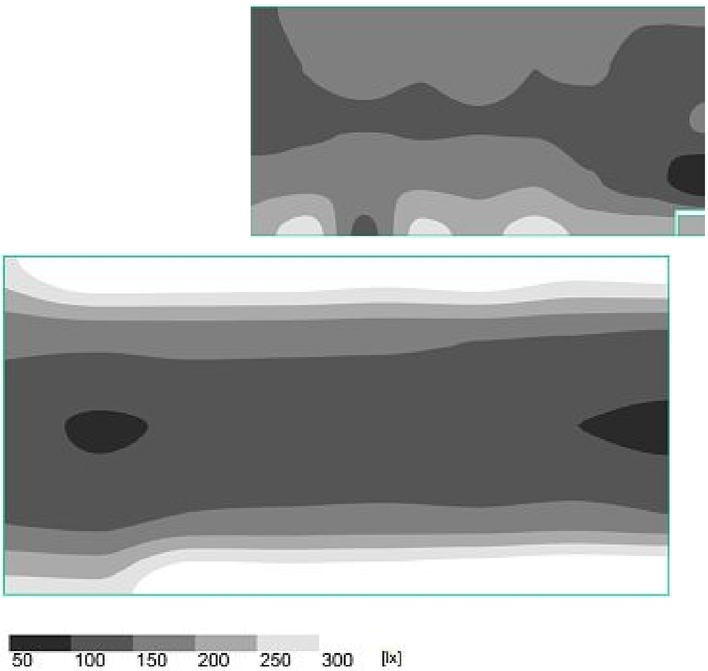


Figure 49: Greyscale Optimization #2, swimming pool hall Donaustadt (figure by the author)

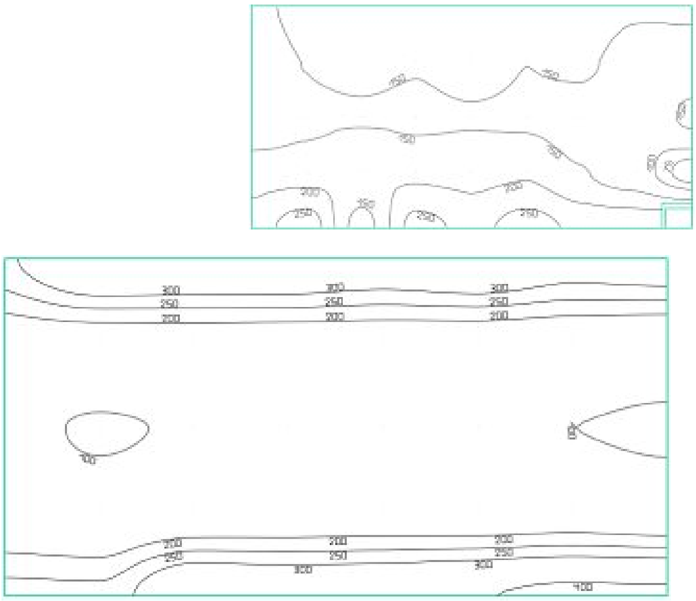


Figure 50: Isolux lines Optimization #2, swimming pool hall Donaustadt (figure by the author)

Minimum values of 200 lux at the pool's surfaces are still not met at any of the pool basin's calculation points.

Optimization suggestion number 3: Installation of additional luminaires.

The lumen method is a common calculation technique for estimating how much light is necessary within a space to reach a desired level of illumination (DiLaura et al. 2011). This calculation results in a required number of luminaires to be mounted in a regular pattern. For the existing situation of the pool hall, this empirical method is not adequately applicable. Due to different ceiling heights and existing structures including skylights and beams, the implementation of this method is barely possible. Therefore, the empirical assessment is not considered in this thesis.

The proposed layout of additional luminaires targets reaching minimum illuminance and uniformity requirements. The positioning was envisioned in line with the architectural design. Figures 51 and 52 display the positioning and the benefit in illuminance levels and distribution with one additional parallel row of twelve luminaires centrally above the main pool and two luminaires above the teaching pool. The approach is based on the built-in tool in Dialux for estimation of required number of luminaires to achieve desired illuminance levels. Optimization suggestion 1 and 2 are already considered in this simulation. The lamp type is identical to the base simulation in this scenario.

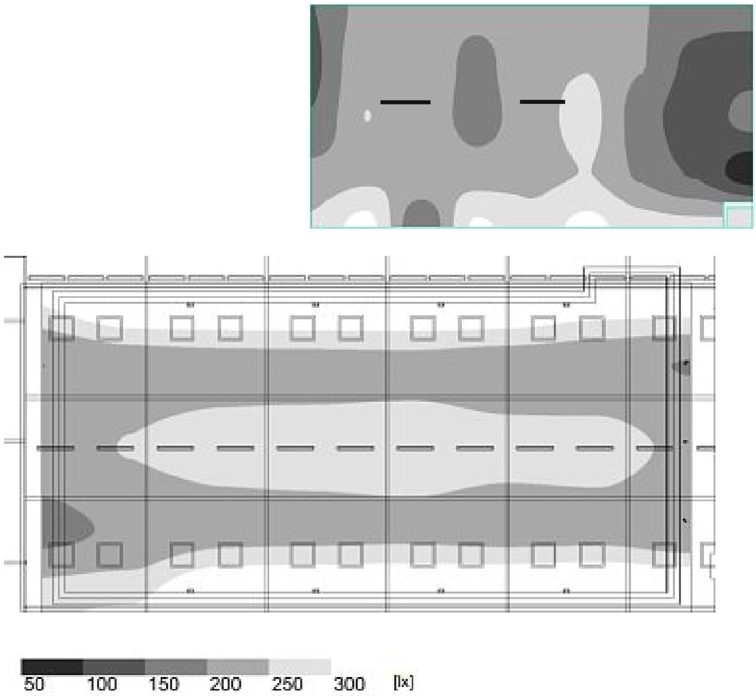


Figure 52: Greyscale Optimization #3, Swimming pool hall Donaustadt (figure by the author)

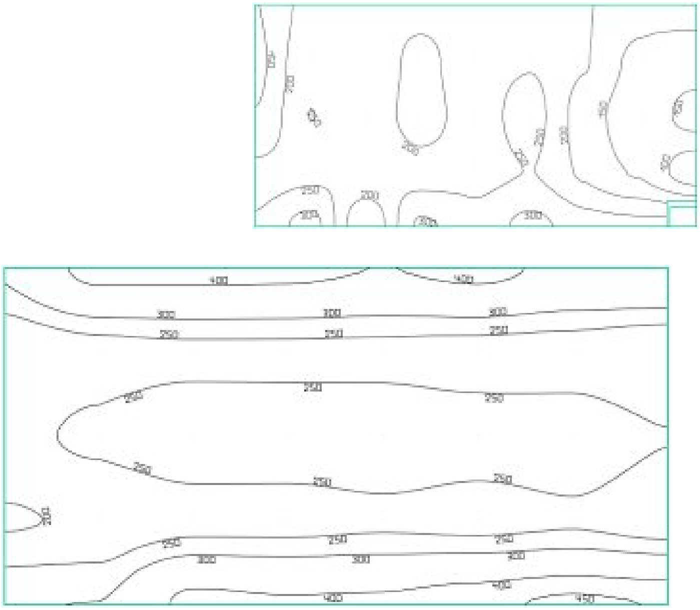


Figure 51: Isolux lines Optimization #3, swimming pool hall Donaustadt (figure by the author)

The resulting lux values and the uniformity meet the minimum standards. The optimization proposal further improves the average illumination of the main pool by 83%, the teaching pool by 42%. Illuminance levels of the main pool basin range between 208 lux and 280 lux. It must be mentioned that this measure is cost intensive in investment and maintenance and requires technical consultation.

Comparison of optimization proposals

Figure 53 and Table 38 and 39 compare simulation-based optimization results of *Donaustädter Hallenbad*. The optimisations build on the respective previous optimisation steps

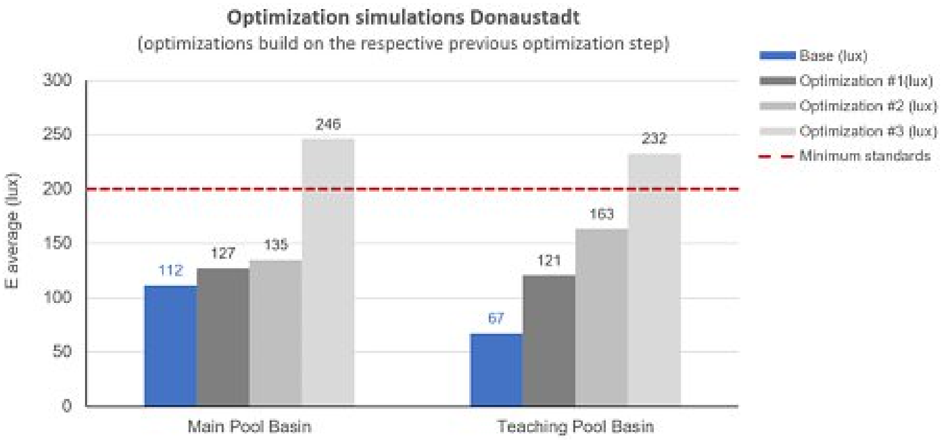


Figure 53: Optimization scenarios results, Donaustadt main pool (figure by the author)

Table 38 Optimization scenarios results, Donaustadt main pool

Main pool basin Donaustadt, optimzation steps					
Indicators	Base model	Optimization #1 (building on base)	Optimization #2 (building on #1)	Optimization #3 (building on #2)	Minimum standards
E min [lux]	76	89	95	208	-
E max [lux]	147	152	160	280	-
E avg [lux]	112	127	135	246	200
Uniformity	0.68	0.70	0.71	0.85	0.5
E avg improvement (to respective previous optimization step)	-	14%	6%	83%	-

Table 39 Optimization scenarios results, Donaustadt teaching pool

Teaching pool basin Donaustadt, optimzation steps					
Indicators	Base model	Optimization #1 (building on base)	Optimization #2 (building on #1)	Optimization #3 (building on #2)	Minimum standards
E min [lux]	54	101	137	180	-
E max [lux]	88	146	196	266	-
E avg [lux]	67	121	163	232	200
Uniformity	0.80	0.84	0.84	0.77	0.5
E avg improvement (to respective previous optimization step)	-	79%	35%	42%	-

General optimization suggestions

It can be assumed that necessary actions that aim to fulfil required lighting standards increase electricity consumption. However, the optimization proposals considered in this contribution strive for ensuring safety and enhancing overall visual comfort.

According to technical staff of pool hall *Donaustadt* the artificial lighting system consists of aged tubular fluorescent lamps and fluorescent based energy saving lamps.

A replacement of fluorescent luminaires to LED as light source should be considered in future retrofit actions. A paper from Portugal (Coelho et al. 2016) assesses refurbishments of light sources that are commonly used in indoor swimming pool complexes. Thereby, LED is considered state of the art. While initial investment costs are high, operational and maintenance costs decrease significantly due to longer life span and immediate lower energy consumption. According to the paper an upgrade from fluorescents to LED might not always be economically viable. The findings are not directly applicable to the discussed swimming pool buildings, but it can be assumed that LED have the lowest energy consumption and would reduce operational and maintenance costs. In long-term view, they could be the most cost-effective solution. Every refurbishment case should be preceded by detailed lighting evaluations.

Further energy savings of contemporary lighting design can result from installation of control schemes. Since the measurements suggest high daylight availability in some areas, implementation of daylight-based control system in the pool hall could reasonably improve energy efficiency. The technology detects areas where sufficient illumination is provided by natural light and dims luminaires in that specific area.

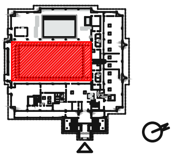
Viable savings should be calculated in detail in advance of any refurbishment project. The feasibility requires precise planning and consultation from a technician. The calculations are beyond the scope of this thesis.

3.2 Object 2

Hereinafter the results of indoor pool building *Hietzing* will be shown and analysed. The luminaire arrangement and the measurement grids for the individual areas are almost identical to Object 1.

3.2.1 Main pool

The luminaire arrangement and the calculated measurement grid of the main pool area is shown in Figures 54 and 55.



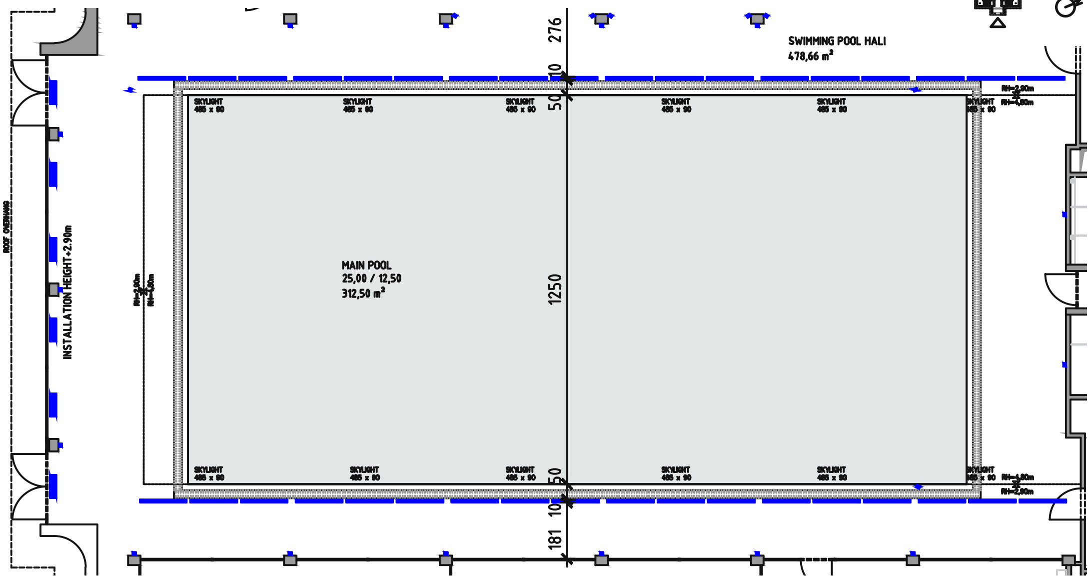


Figure 55: Luminaire arrangement, Hietzing main pool (based on MA44, edited by the author)

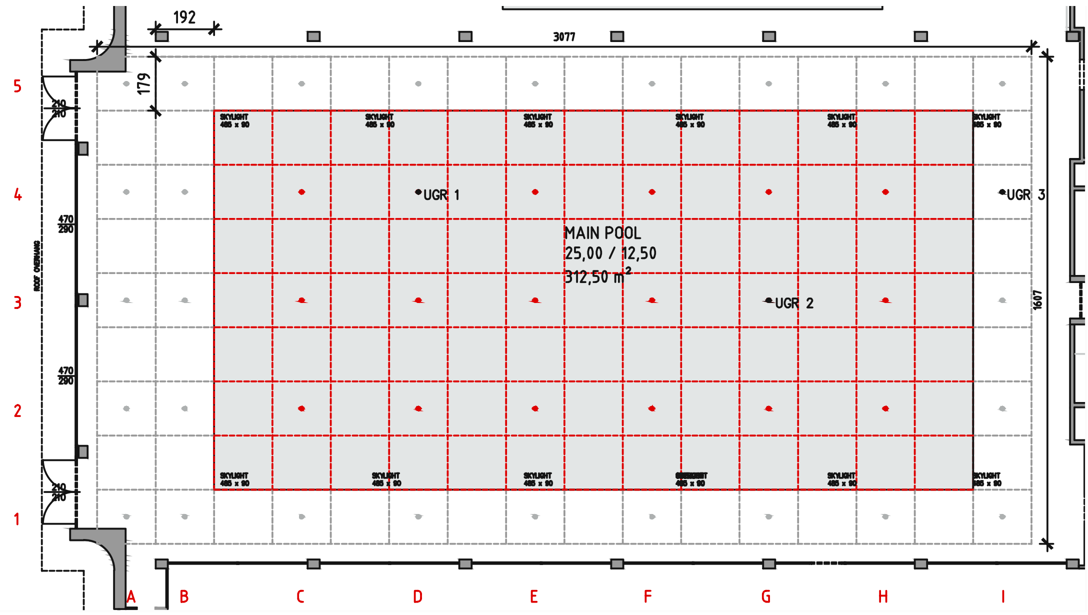


Figure 54: Measuring grid, Hietzing main pool (based on MA44, edited by the author)

The artificial lighting concept of the main pool has a direct lighting system with splash water protection. The main provider of illumination of the overall swimming pool hall are 36 tubular LED lamps with open light distribution. The light sources are arranged in two linear constellations, running parallel to the length of the main pool basin. Six additional LED lamps are mounted along the facade. All described luminaires are installed to the ceiling at a height of +2.90m above floor level.

15 of the load-bearing columns are illuminated by an individual, small LED spotlight. The tilting angle of the spotlights can be adjusted. They are mounted to the bottom of the beams at a height of +2.20m above floor level and are facing downwards. The main function of the spotlights is to highlight the decorative mosaic work of the columns.

Two spotlights of the same lamp type are installed to the wall separating the swimming hall from the locker and shower rooms. They are mounted at an angle to horizontally emit light. Another spotlight is installed close to the glass façade at an angle to illuminate the door to the terrace. In total there are 18 spotlights in the discussed area. All luminaires were turned on during the measurement process. Their light colour can be altered from a control panel. All luminaires of the pool hall are switchable in form of control groups. Dimming is not possible, nor foreseen in the swimming pool hall.

3.2.1.1. Daytime measurement

The measurement procedure was performed twice (daytime and night-time measurement). The daytime measurement was conducted with all artificial lights turned off (daylight only).

The measurements were performed on 29.05.2020 from 10:20am to 11:20am under partly cloudy to overcast sky (the day was chosen based on the weather forecast and organizational aspects regarding accessibility of the swimming pool hall). Weather circumstances included an outside temperature of in average 15°C and about 1km/h wind speed.

Table 40 and 41 display the daylight-measurement results. Each grid point contains two illuminance values, external and internal illuminance. The two values per grid point are measured at the same 5 second interval. The blue area marks the pool surface, which is considered the most relevant in this work. As already mentioned, measurements were conducted with empty pools (swimming pool halls had been closed during the COVID19 pandemic). The grey coloured cell is obstructed and inaccessible because of plant pots.

Table 40: Daytime measurement, Hietzing main pool

5	out	55 370	49 160	41 000	39 520	33 010	32 090	32 030	32 070	33 020
	in	2 135	655	304	286	302	299	287	261	234
4	out	39 710	46 290	31 290	30 320	29 928	28 571	28 019	26 630	32 160
	in	2 348	990	546	505	523	503	476	431	462
3	out		46 480	31 420	30 420	29 752	28 776	27 934	26 816	32 020
	in		980	648	665	699	701	663	623	649
2	out	39 140	54 090	31 515	30 520	29 601	28 904	27 738	27 002	32 320
	in	1 508	837	436	430	429	395	373	361	434
1	out	39 560	44 950	43 360	46 290	44 330	52 250	50 770	36 010	33 800
	in	786	294	163	121	109	111	116	102	103
main pool, daylight		A	B	C	D	E	F	G	H	I

Table 41: Daylight Factors, Hietzing main pool

5	3.9%	1.3%	0.7%	0.7%	0.9%	0.9%	0.9%	0.8%	0.7%
4	5.9%	2.1%	1.7%	1.7%	1.7%	1.8%	1.7%	1.6%	1.4%
3		2.1%	2.1%	2.2%	2.3%	2.4%	2.4%	2.3%	2.0%
2	3.9%	1.5%	1.4%	1.4%	1.4%	1.4%	1.3%	1.3%	1.3%
1	2.0%	0.7%	0.4%	0.3%	0.2%	0.2%	0.2%	0.3%	0.3%
main pool, DF	A	B	C	D	E	F	G	H	I

Table 42 contains reflection values of enclosing diffuse room surfaces. They have been calculated including the measurements of luminance and illuminance at one specific point at each surface. Following reflectance values have been considered in the calibration process of the simulation model.

Table 42: Surface reflectance, Hietzing main pool

	Surface	Reflectance
Main Pool	Floor (mosaic tiles in average)	0.39
	Main Pool basin (white, tiles)	0.62
	Wall, showers (creme, tiles)	0.73
	Wall, showers (creme, tiles)	0.73
	Wall (white, plaster)	0.83
	Columns (white, plaster)	0.81
	Columns (yellow, mosaic)	0.77
	Ceiling (yellow, wood)	0.71
	Ceiling (dark wood)	0.17
	beams (yellow, wood)	0.68
	beams (wood)	0.23

3.2.1.2. Night-time Measurement

The results were acquired on 13.05.2020 from 09:20pm to 10:20pm. The sun set at 8:25pm that day, resulting in the absence of sunlight during the measurement process (Note: impact from surrounding luminaires could not totally be neglected due to the large glazing areas of the building's envelope). Table 43 and 44 inform about night-time measurement results.

Table 43: Night measurement, Hietzing main pool

5	211	350	478	478	491	469	490	492	484
4	88	120	157	173	158	160	153	164	171
3		69	73	79	81	80	83	82	79
2	105	129	162	159	166	158	179	195	194
1	185	388	512	508	514	527	554	548	545
main pool, artificial	A	B	C	D	E	F	G	H	I

Table 44: Night-measurement performance indicators, Hietzing main pool

	Main Pool	Main pool + deck	Minimum standards
E min [lx]	73	69	-
E max [lx]	195	554	-
E avg [lx]	137	276	200 | 150
Uniformity	0.53	0.25	0.5 | 0.4

3.2.1.3. Analysis

The daytime measurement data and the daylight factors reveal daylight availability throughout the swimming pool hall. Due to the skylight strips of the elevated roof, natural light is transmitted even to areas rather distant from the facade, e.g. corners of the space, which are rather far away from the façade. As the daylight factor is lower than two percent at almost all grid points except for the façade, standards would recommend supplementary electric lighting to achieve satisfactory lighting levels.

The highest amount of daylight illumination is perceived close to the glass façade (column A in table 40 and 41) and along the centre axis of the main pool (row 3). The two light bands of the of the elevated roof structure contribute to illumination values of up to 700 lux without the supplementation of additional electrical light. Grid cells 1D to 1I (Table 40) in the main pool deck's area the only ones to record data of insufficient illumination levels. The measurement points are up to 33 meters away from the façade. During daytime the use of the artificial lights in this area is suggested to achieve the minimum value of 150 lux for the pool deck. Otherwise, under the specified conditions no additional artificial night is needed to meet the requirements.

The night-time measurement with all electrical lights turned on reveals poor brightness levels. Except for grid rows 5 and 1 of Table 43, which are paralleling the length of the pool basin, the measured data results in illuminance deficiencies. In direct contrast to the daylight situation the lowest values are documented along the centre axis of the pool. The minimum illuminance value is registered at about 70 lux, whereas DIN EN 12193 requires 200 lux as the acceptable minimum. The distribution of light flow is satisfactory concerning the standards. The uniformity of the measurement points of the main pool is 0.53, just above the standardized minimum. The derived uniformity including the pool deck of 0.25 is causing a high illumination difference. This leads to an unpleasant effect on the visual experience in the hall and possible safety issues.

It must be mentioned that the absence of the water body is partly to be accused of the low illumination of the pool basin. It can be assumed that reflections on the water surface would enhance the lighting availability in the overall area. Additionally, the uneven light distribution of light would be improved. It is unclear to which extent the deficiencies could be eliminated in this scenario.

3.2.1.4. Simulation Results

In order to optimize the correspondence of the initial simulation, measured surface reflectance values were applied. In areas that seemed systematically too bright (since exact lamp models were unknown) dimming values of 85% for the different lamp types were implemented. The value seems plausible due to maintenance standard of the luminaires. Table 45 lists results and information of the individual calibration steps.

Table 45: Simulation workflow results, main pool Hietzing

MAIN POOL GRID, HIETZING					
Calibration steps (implemented in DIALux)	Avg. Deviation from simulation to measurement		Difference (improvement) to previous step of calibration		Notes (All results of this table without outliers of Row A and B)
	%	lx	Percentage point	lx	
Default Dialux surface reflactances (INITIAL MODE	14%	39	-	-	First initial model, separate from measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	14%	39	0	0	
Application of measured surface reflactances	16%	47	-2	-8	Brightness levels overall too high
Dimming adjustments (CALIBRATED MODEL)	6%	17	10	30	Main pool, facade and locker luminaires to 85%
Total improvements from INITIAL model to CALIBRATED model			**8**	**22**	

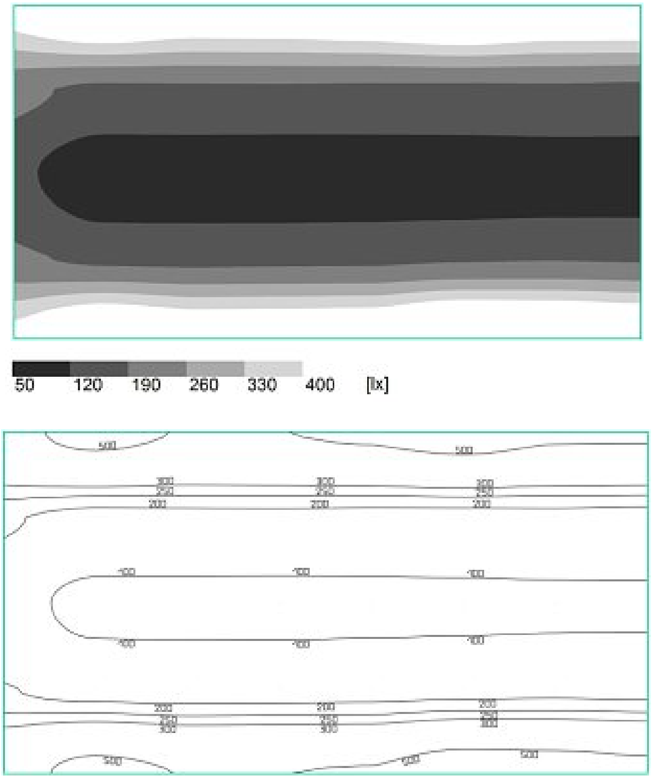


Figure 56: Calibrated simulation greyscale and isoluxlines, Hietzing main pool (figures by the author)

Figure 56 illustrates the reference area (including calibration efforts) in falsecolour picture and isoluxlines during night-time conditions. It displays almost identical deficiencies of illuminance levels as in the measurement result array. The symmetrical illuminance distribution is clearly visible. It can also be seen that the pool area does not achieve the required illuminance threshold of 200 lux. The poor illumination quality towards the centre of the pool stands out.

Unified Glare Rating (UGR)

Vertical illuminance was simulated at three points of interest. These are shown in Figure 55. UGR 1 and UGR 2 are positioned at eye height of the swimmers, 5cm above water surface. UGR 3 is located 1.50m above floor level at the main pool deck. For this simulation, the water body was considered in the simulation model. The UGR calculation was implemented in *DIALux* at different times and dates. The calculation included directions of view of 360° in steps of 15°. The simulations were conducted with overcast and subsequently with clear sky model.

- 21.06.2020, 12:00 and 16:00, which is the longest day of the year.

- 21.12.2020, 12:00 and 16:00, which is the shortest day of the year.

- 29.05.2020, 10:55, which was date and time of the measurement.

UGR at all points was below a value of 10. Values below or equal to 22 are considered as widely free of glare in rooms designated for sports activities (DIN EN 12464-1).

3.2.1.5. Comparison of Measurements and Simulation Results

Tables 46 and 47 show the night-time results in reference to the simulated values.

Table 46: Measurement vs. simulation [lx], Hietzing main pool

5	Simulation	412	444	540	495	499	519	560	518	516
	Measurement	211	350	478	478	491	469	490	492	484
4	Simulation	387	211	174	177	178	175	174	177	173
	Measurement	88	120	157	173	158	160	153	164	171
3	Simulation		140	79	78	76	78	80	83	85
	Measurement		69	73	79	81	80	83	82	79
2	Simulation	383	207	174	172	174	176	181	185	182
	Measurement	105	129	162	159	166	158	179	195	194
1	Simulation	370	437	544	497	499	511	581	572	547
	Measurement	185	388	512	508	514	527	554	548	545
main pool, artificial light		A	B	C	D	E	F	G	H	I

Table 47: Measurement vs. simulation [%], Hietzing main pool

5	Sim. / Measurem.	95%	27%	13%	4%	2%	11%	14%	5%	7%	19.68%
4	Sim. / Measurem.	340%	76%	11%	2%	13%	9%	14%	8%	1%	52.62%
3	Sim. / Measurem.		103%	8%	-1%	-6%	-3%	-4%	1%	8%	16.69%
2	Sim. / Measurem.	265%	60%	7%	8%	5%	11%	1%	-5%	-6%	41.05%
1	Sim. / Measurem.	100%	13%	6%	-2%	-3%	-3%	5%	4%	0%	15.18%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		199.9%	55.7%	9.1%	3.5%	5.6%	7.4%	7.5%	4.8%	4.4%	

Avergae Deviation from Simulation to Measurement	
29%	24lux

Average Deviation without outliers row A and B	
6%	17lux

The data comparison of the main pool (including calibration effort) reveals several obvious discrepancies between simulation and measurement. Most of the simulation points are within a relative deviation below 11% and attest to a well calibrated simulation model. Generated values in column A and B (Table 47) must be labelled statistical outliers. The maximum spread between simulation and measurement in this area is 340%. A value of this scale has little to no informative value. The enormous variation might be explained by the plants between calculation points and the façade. During the measurement process the plants blocked a considerable amount of the emitted light of the façade-luminaires (Figure 57). In the simulation only the plain building geometry was modelled. As a simplification interior plants and furnishing were not included. Therefore, the simulation generates significantly higher illumination values than the measured ones at the specified grid positions. The simulated values provide information about the illuminance levels that would be achieved if the plants were removed. It might be assumed that they are positioned in front of the glass façade to reduce incident daylight and act as glare limitation. If the described outliers are not considered, the averaged deviation from simulation to measurement would be reduced to 6% (17 lux).

Figure 57: Plants as glare control, Hietzing main pool (photograph by the author)

Daylight Factor

Simulation of the daylight situation with an overcast sky model results in considerable deviations from the measurement. Differences between assumptions of the simulation tool regarding exterior daylight availability and measured daylight illumination on the outside might play a role here. The software considers exterior sky setting that reach only a 50% fraction compared to the external daylight measurement. While the measured exterior illuminance was about 34 600 lux, the simulation generates only 16 600 lux. This deviation leads to systematically too high daylight factors. Therefore, the ratio between measured and simulated exterior illuminance was applied proportionally at each reference point so that resulting simulated daylight factors consider almost identical exterior illuminance conditions. As illustrated in Figure 58, the adjustment improves correspondence of simulated daylight factors significantly at all individual areas.

Figure 58 and Table 48 compare average daylight factors of measurement and simulation values of individual areas of the building. Tables with daylight simulation results for each grid point of the pool hall are to be found in the appendix.

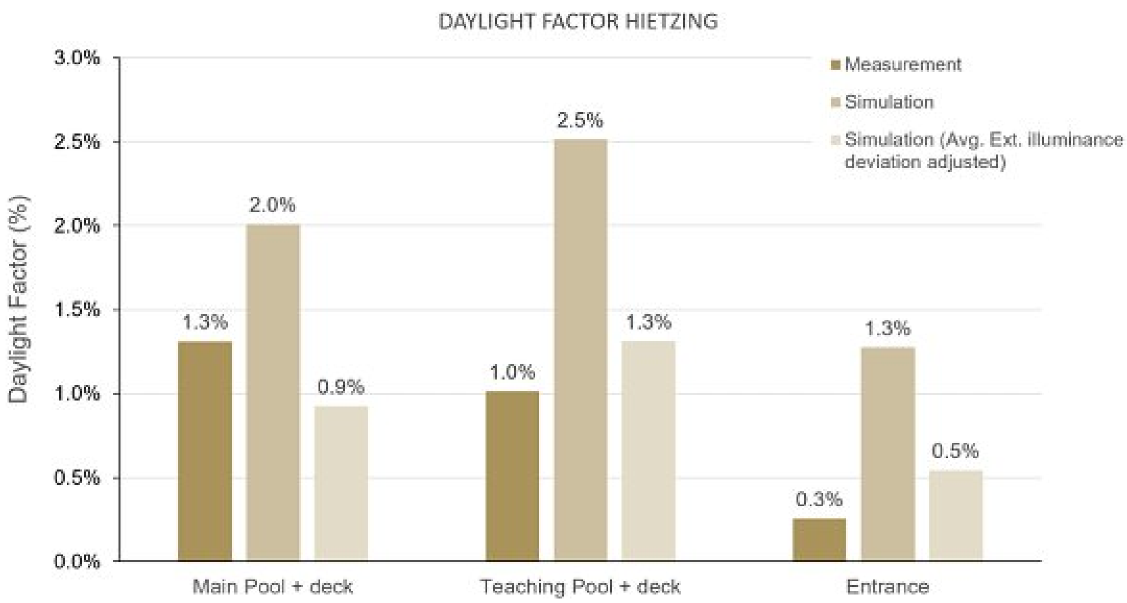


Figure 58: Daylight factors, Hietzing (figure by the author)

Table 48: Daylight factors, Hietzing

DF $_{avg}$ [%]	Measurement	Simulation	Simulation (Avg. Ext. illuminance deviation adjusted)
Main Pool + deck	1.3%	2.0%	0.9%
Teaching Pool + deck	1.0%	2.5%	1.3%
Entrance	0.3%	1.3%	0.5%

E exterior average (lx)	34 600	16 560	33 600
E exterior average ratio to measurement	-	48%	97%

3.2.2 Teaching pool

The luminaire arrangement and the measurement grid of the teaching pool with the adjacent sitting / relaxing area (4a to 5b) is shown below in Figures 59 and 60. The grid size follows DIN EN 12193 described in the methodology chapter.

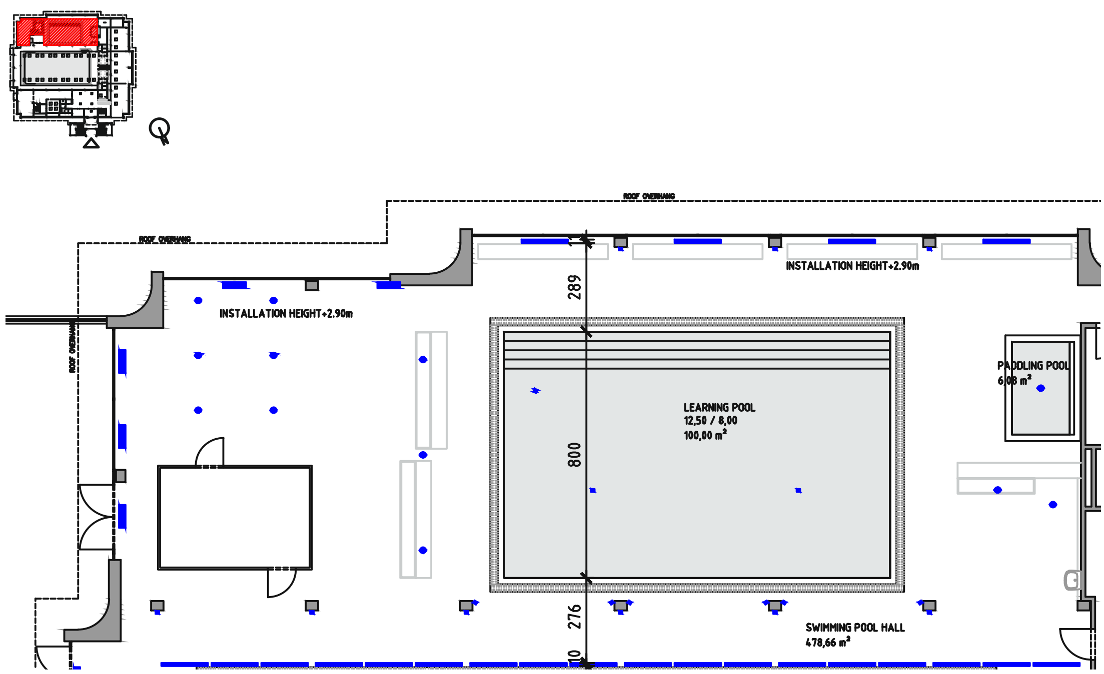


Figure 59: Luminaire arrangement, Hietzing teaching pool (MA44 based, edited by the author)

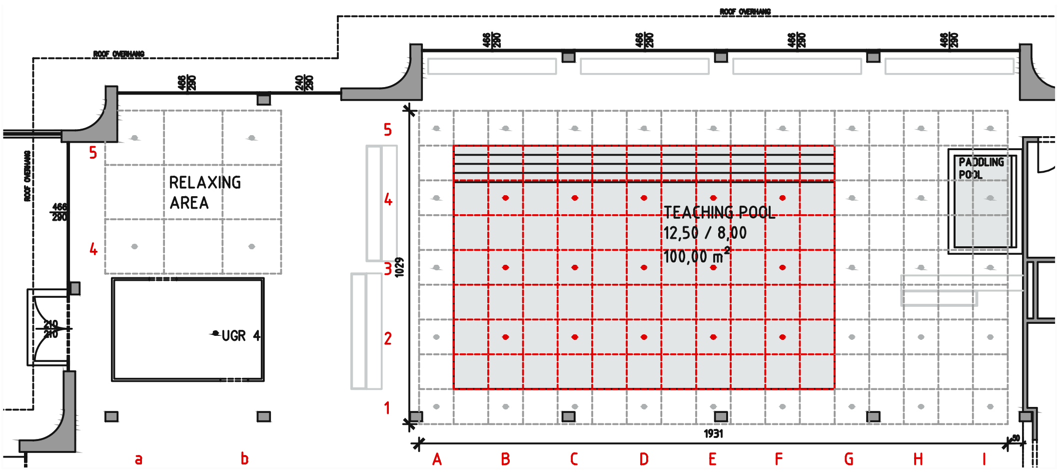


Figure 60: Measuring grid, Hietzing teaching pool (based on MA44, edited by the author)

The artificial lighting concept of the teaching pool has a direct lighting system with splash water protection. Nine tubular LED lamps are aligned along the façades. The pool area benefits from the 18 light sources of the main pool which can be seen at the bottom of the light arrangement plan in Figure 59. The luminaires are ceiling-mounted at a height of +2.90m above floor level.

Six spotlights are mounted to the four central columns at a height of +2.20m above floor level. Their light is horizontally emitted parallel to the ceiling. Three additional spotlights are installed above the water area of the teaching pool. They are facing downwards to directly increase the lighting levels of the pool. Another downwards facing spotlight is positioned centrally above the paddling pool. Next to the spotlight there is a round ceiling-recessed downlight, which was defected during the measurement process. A group of six round downlights of the same type is mounted above the relaxing area. Three lamps of this type can be found in a linear constellation along the plant boxes and bench groups which separate the pool area from the relaxation zone. Two additional LED downlights are installed at the shower area.

All installed light sources of *Hallenbad Hietzing* are LED based. Collectively, the total amount of luminaires in this area sums up to nine tubular lamps, ten spotlights and twelve downlights supplementary to the tubular LEDs of the main pool. The light spectrum of all spotlights is controllable and can be adjusted to various light colours.

3.2.2.1. Daytime measurement

Table 49 and 50 presents the daylight measurement results for the extended area of the teaching pool. The daytime measurement was conducted with all artificial lights turned off (daylight only). The results were attained on 29.05.2020 from 10:20am to 11:20am. The measured data was collected under the same conditions as described for the main pool. The grey coloured cells are outside the perimeters of the defined measurement grid.

Table 49: Daytime measurement, Hietzing teaching pool

5	out	34 550	34 520	47 010	42 590	42 360	44 920	47 630	48 130	32 950	46 740	42 740
	in	660	830	500	610	571	591	585	586	541	579	503
4	out	46 820	44 660	40 280	22 900	22 880	22 840	22 840	22 830	35 370	48 920	40 280
	in	558	235	225	360	376	368	387	355	300	287	213
3	out			38 150	23 140	23 160	23 200	23 250	23 330	33 960	37 750	35 890
	in			194	246	258	265	265	260	209	154	83
2	out			35 930	24 240	24 030	23 830	23 780	23 630	33 620	35 200	33 970
	in			186	230	230	253	237	236	190	148	122
1	out			36 800	36 340	34 640	33 970	33 710	33 510	33 780	33 510	34 340
	in			208	211	179	215	196	209	197	184	136
teaching p., daylight		a	b	A	B	C	D	E	F	G	H	I

Table 50: Daylight factors, Hietzing teaching pool

5	1.9%	2.4%	1.1%	1.4%	1.3%	1.3%	1.2%	1.2%	1.6%	1.2%	1.2%
4	1.2%	0.5%	0.6%	1.6%	1.6%	1.6%	1.7%	1.6%	0.8%	0.6%	0.5%
3			0.5%	1.1%	1.1%	1.1%	1.1%	1.1%	0.6%	0.4%	0.2%
2			0.5%	0.9%	1.0%	1.1%	1.0%	1.0%	0.6%	0.4%	0.4%
1			0.6%	0.6%	0.5%	0.6%	0.6%	0.6%	0.6%	0.5%	0.4%
teaching p., DF	a	b	A	B	C	D	E	F	G	H	I

Table 51 lists measurement-derived surface reflectance values of the teaching pool area.

Table 51: Surface reflectance, Hietzing Teaching Pool

	Surface	Reflectance
Teaching Pool	Floor (mosaic tiles in average)	0.39
	Learning Pool basin (white, tiles)	0.64
	Learning pool basin (orange, tiles)	0.27
	Paddling pool basin (white, tiles)	0.66
	Wall (blue, plastic)	0.50
	Wall, showers (creme, tiles)	0.73
	Wall (grey, tiles)	0.47
	Wall (white, mosaic tiles)	0.81
	Columns (white, tiles)	0.81
	Columns (yellow, mosaic)	0.77
	Ceiling (yellow, painted wood)	0.71
	Ceiling (dark wood)	0.17
	beams (yellow, painted wood)	0.68
	bench (black, stone)	0.10

3.2.2.2. Night-time Measurement

The results were acquired on 13.05.2020 from 09:20pm to 10:20pm. The sun set at 8:25pm that day, resulting in the absence of sunlight during the measurement process. Table 52 and 53 inform about night-time measurement results.

Table 52: Night measurement, Hietzing teaching pool

5	351	256	154	154	136	161	142	155	142	136	137
4	284	181	112	100	87	88	88	93	71	71	68
3			110	161	128	100	128	141	80	66	44
2			153	171	158	129	157	164	131	169	192
1			275	287	192	262	185	284	264	301	276
teach. p., artif.	a	b	A	B	C	D	E	F	G	H	I

Table 53: Night measurement performance, Hietzing teaching pool

	Teaching Pool	Teaching pool + deck	Minimum standards
E min [lx]	87	71	-
E max [lx]	171	153	-
E avg [lx]	126	287	200 | 150
Uniformity	0.69	0.25	0.5 | 0.4

3.2.2.3. Analysis

Natural light is available at most of the measurement points. Daylight factors vary between 0.2% and 2.4%. The values suggest utilization of supplementary artificial lighting most of the day. Nevertheless, with the exception of four grid points, the measured illumination under daylight conditions surpass the standard values significantly. The areas with insufficient lighting levels are the ones furthest away from the glass facade and partly separated by the wall for the shower areas. The highest illumination levels were measured in the relaxation area. This could be expected, since it benefits from direct impact of two external glass walls. The pool area itself reveals excellent and uniform natural lighting conditions. Under the specified circumstances, there is no need for additional electrical light.

On the other hand, the artificial lighting performance falls short of the minimum specifications of DIN EN 12193. The teaching pool basin's night-time measurements span from a minimum of 87 lux to a maximum of 171 lux. Even the maximum value does not meet the required levels. The LED bulbs along the main pool generally seem to be more powerful light sources than the façade lamps. Therefore, the lowest measurements are to be found along row 4 (Table 52) of the measurement grid. They are 10 meters away from the bright main pool luminaires and not as close to the façade lamps as the higher illuminated points in row 5. The paddling pool area measures the poorest electrical lighting quality of the overall hall.

Whereas uniformity of 0.69 of the teaching pool meets the standard, the immediate surrounding of the basin reveals a very uneven distribution of electrical lighting on floor level. To ensure a safer environment for the users and to reduce the presumably unpleasant effect of illumination difference the uniformity should be raised to the minimum of 0.4. This can be achieved by increasing illumination of the teaching pool basin.

3.2.2.4. Simulation Results

In order to optimize the correspondence of the initial simulation, measured surface reflectance values were applied. In areas that seemed systematically too bright dimming values of 85% for the different lamp types were implemented. Table 54 lists results and information of the individual calibration steps.

Table 54: Simulation workflow results, teaching pool Hietzing

TEACHING POOL GRID, HIETZING					
Calibration steps (implemented in DIALux)	Avg. Deviation of simulation to measurement		Difference (improvement) to previous step of calibration		notes
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	29%	32	-	-	Initial model, separate from all measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	23%	28	6	4	Lighting distrubition is very off (from the measurements)
Application of measured surface reflactances	20%	27	3	1	Overall illuminance seems too bright in some locations
Dimming adjustments (CALIBRATED MODEL)	10%	10	10	16	Main pool, facade and locker luminaires to 85%
Total improvements from INITIAL model to CALIBRATED model			**19**	**21**	

Figure 61 illustrates the reference area (including calibration efforts) in falsecolour picture and isoluxlines during night-time conditions. It displays almost identical deficiencies of illuminance levels as in the measurement result array. The lowest illumination is registered between teaching and paddling pool basin and along the measurement row closest to the four stairs leading into the teaching pool (row 4). The figure displays the uniformity of the teaching pool reference grid as acceptably even but in general too low.

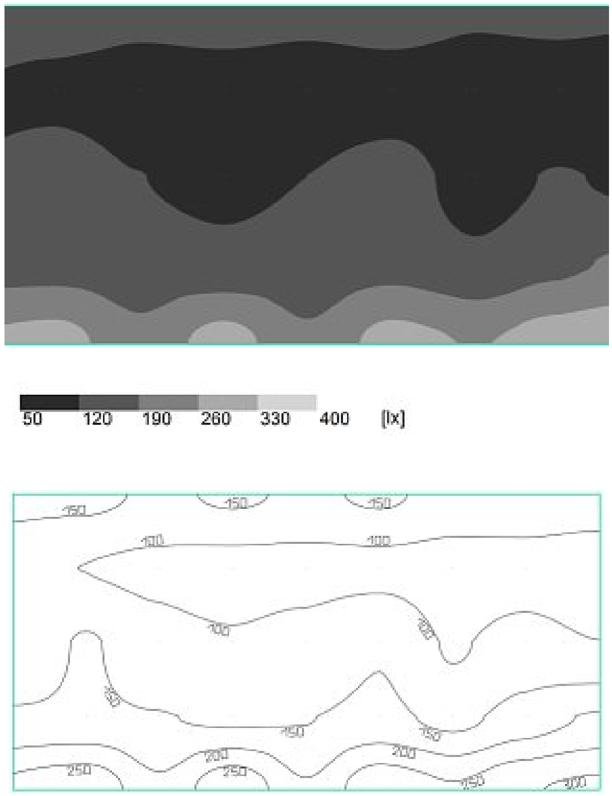


Figure 61: Calibrated simulation, greyscale and isoluxlines, Hietzing teaching pool (figure by the author)

Unified Glare Rating (UGR)

Vertical illuminance was simulated at one point of interest. It is shown in Figure 60. UGR 4 is positioned 1.20m above floor level. It simulates the view of the lifeguard at sitting height. For this simulation, the water body was considered in the simulation model. The UGR calculation was implemented in *DIALux* at different times and dates. The calculation included directions of view of 360° in steps of 15°. The simulations were conducted with overcast and subsequently with clear sky model.

- 21.06.2020, 12:00 and 16:00, which is the longest day of the year.

- 21.12.2020, 12:00 and 16:00, which is the shortest day of the year.

- 29.05.2020, 10:55, which was the date and time of measurement.

UGR at all points was below a value of 10. Values below or equal to 22 are considered as widely free of glare in rooms designated for sports activities (DIN EN 12464-1).

3.2.2.5. Comparison of Measurements and Simulation Results

Tables 55 and 56 put the night-time simulation results and measurement values for horizontal illuminance in relation.

Table 55: Measurement vs. simulation [lx], Hietzing teaching pool

5	Simulation	372	258	164	163	141	158	141	158	133	144	135
	Measurement	351	256	154	154	136	161	142	155	142	136	137
4	Simulation	338	142	121	99	89	84	84	85	80	75	65
	Measurement	284	181	112	100	87	88	88	93	71	71	68
3	Simulation			120	154	122	107	120	147	95	125	102
	Measurement			110	161	128	100	128	141	80	66	44
2	Simulation			158	160	153	140	148	163	136	171	206
	Measurement			153	171	158	129	157	164	131	169	192
1	Simulation			265	285	217	287	210	284	257	294	311
	Measurement			275	287	192	262	185	284	264	301	276
teaching pool, artificial l.		a	b	A	B	C	D	E	F	G	H	I

Table 56: Measurement vs. simulation [%], Hietzing teaching pool

5	Sim. / Measu.	6%	1%	6%	6%	3%	-2%	-1%	2%	-6%	6%	-1%	4%
4	Sim. / Measu.	19%	-22%	8%	-1%	2%	-5%	-5%	-9%	13%	6%	-4%	6%
3	Sim. / Measu.			9%	-4%	-5%	7%	-6%	4%	19%	89%	132%	31%
2	Sim. / Measu.			3%	-6%	-3%	9%	-6%	-1%	4%	1%	7%	4%
1	Sim. / Measu.			-4%	-1%	13%	10%	14%	0%	-3%	-2%	13%	6%
teaching pool, artif. l.		a	b	A	B	C	D	E	F	G	H	I	
				6.1%	3.7%	5.2%	6.4%	6.3%	3.1%	8.8%	20.9%	31.5%	

Average Deviation from Simulation to Measurement	
10.2%	**10lux**

Average Deviation without outliers 3G, 3H, 3I	
5.3%	**10lux**

The simulation model results in a 10% deviation from the measured values in the teaching pool and paddling pool zone (excluding the relaxing area). This statistic includes two outliers higher than 89%. The differing simulation values are most likely the result of the simplification of the simulation model. The orange cells 3G to 3I in Table 56 represent measurement points next to plants. They block the direct rays of the light source. The situation is visualised in Figure 62. The average relative deviation of simulation to measurement results (which is not considering mentioned outliers) could be reduced to 5.3%, or 10 lux.

Figure 62: Interior plant obstructions, Hietzing pool hall (photograph by the author)

3.2.3 Entrance

The luminaire arrangement and the calculated measurement grid of the entrance hall and vestibule is shown below in Figure 63.

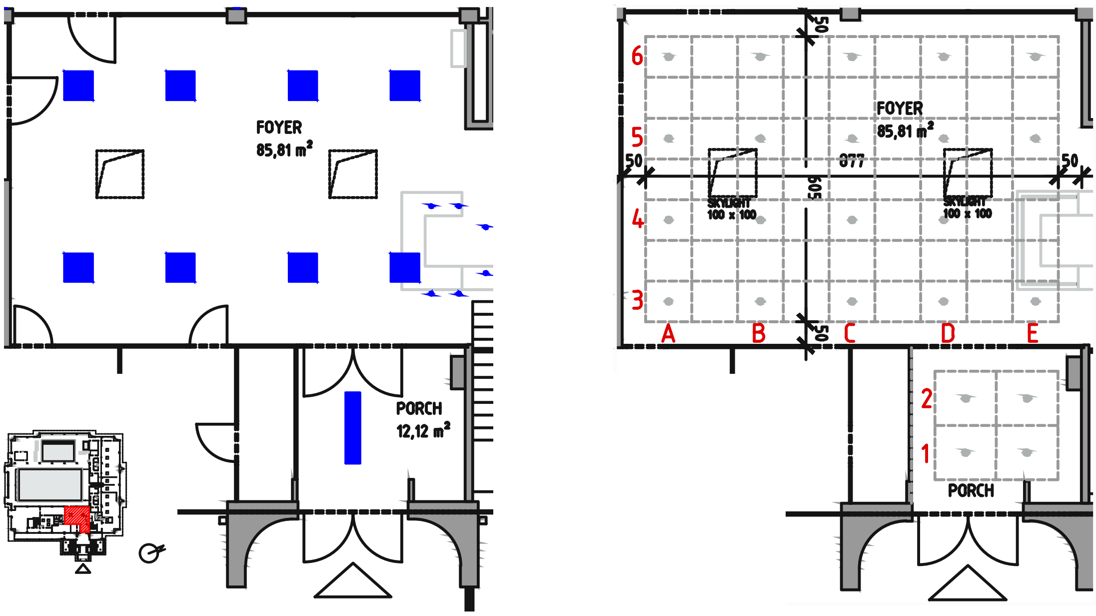


Figure 63: Luminaire arrangement and measuring grid, Hietzing entrance (based on MA44, edited by the author)

The artificial lighting system of the entrance hall consists of eight symmetrically distributed, ceiling-recessed LED panels and six downlights around the reception table. Their measurements correspond to the size of one ceiling panel, which is estimated to 0.60m x 0.60m. One ceiling mounted linear luminaire is installed in the porch area.

3.2.3.1. Daytime Measurement

Table 57 and 58 present daylight measurement results for the entrance hall including the porch. The daytime measurement was conducted with all artificial lights turned off (daylight only).

The results were attained on 29.05.2020 from 10:20am to 11:20am. The measured data was collected under the same conditions as described for the main pool. The grey coloured cells are outside the perimeters of the defined measurement grid.

Table 57: Daytime measurement, Hietzing entrance

6	out	37 160	37 470	36 250	32 820	33 140
	in	124	93	82	94	103
5	out	40 560	39 830	30 460	30 850	32 230
	in	87	101	65	109	106
4	out	43 190	42 540	40 160	29 830	27 550
	in	58	72	88	40	178
3	out	44 010	44 710	44 980	45 190	46 380
	in	37	38	42	104	253
2	out				4 619	4 648
	in				208	173
1	out				4 583	4 587
	in				230	187
entrance, daylight		A	B	C	D	E

Table 58: Daylight Factors, Hietzing entrance

6	0.3%	0.2%	0.2%	0.3%	0.3%
5	0.2%	0.3%	0.2%	0.4%	0.3%
4	0.1%	0.2%	0.2%	0.1%	0.6%
3	0.1%	0.1%	0.1%	0.2%	0.5%
2				5%	4%
1				5%	4%
entrance, DF	A	B	C	D	E

Table 59 lists measurement-derived surface reflectance values of the entrance hall.

Table 59: Surface reflectance, Hietzing entrance

	Surface	Reflectance
Entrance	Floor (beige, tiles)	0.37
	Wall (white, plastic)	0.85
	Wall (white, plaster)	0.88
	Columns (white, plaster)	0.81
	Ceiling (grey, drywall)	0.89
	beams (plaster)	0.88
	Desk (blue, plastic)	0.10

3.2.3.2. Night-time Measurement

The results were attained on 13.05.2020 from 09:20pm to 10:20pm under the same conditions as the swimming pool hall. Table 60 and 61 inform about night-time measurement results.

Table 60: Night Measurement, Hietzing entrance

6	291	374	327	304	305
5	256	301	208	355	280
4	256	314	194	350	
3	226	280	270	323	264
2				279	213
1				312	208
entrance, artificial l.	A	B	C	D	E

Table 61: Night measurement performance, Hietzing entrance

	Entrance hall	Minimum standards
E min [lx]	194	
E max [lx]	374	-
E avg [lx]	288	100
Uniformity	0.67	0.4

3.2.3.3. Analysis

Despite two skylights the daylight availability is minimal. Daylight Factors are below 0.6% at the specified grid points of the entrance hall (excluding the porch area). The porch is illuminated brightly through the glass portal. Minimum requirements of 100 lux are met at grid points directly underneath the skylight and close to the porch. The minimum value of 37 lux expresses a low presence of sunlight. Artificial luminaires should be operated during all opening hours of the pool building to ensure the quality of visual conditions.

Regarding the uniformity and illumination levels of the electrical lighting system the performance is convincing. The distribution of light is even, though a slight gradient between the brightest spots is noticeable in the results. All measured values surpass the minimum criteria to a highly satisfactory degree.

3.2.3.4. Simulation Results

In order to optimize the correspondence of the initial simulation, measured surface reflectance values were applied. In areas in the pool hall that seemed systematically too bright dimming values of 85% for the different lamp types were implemented.

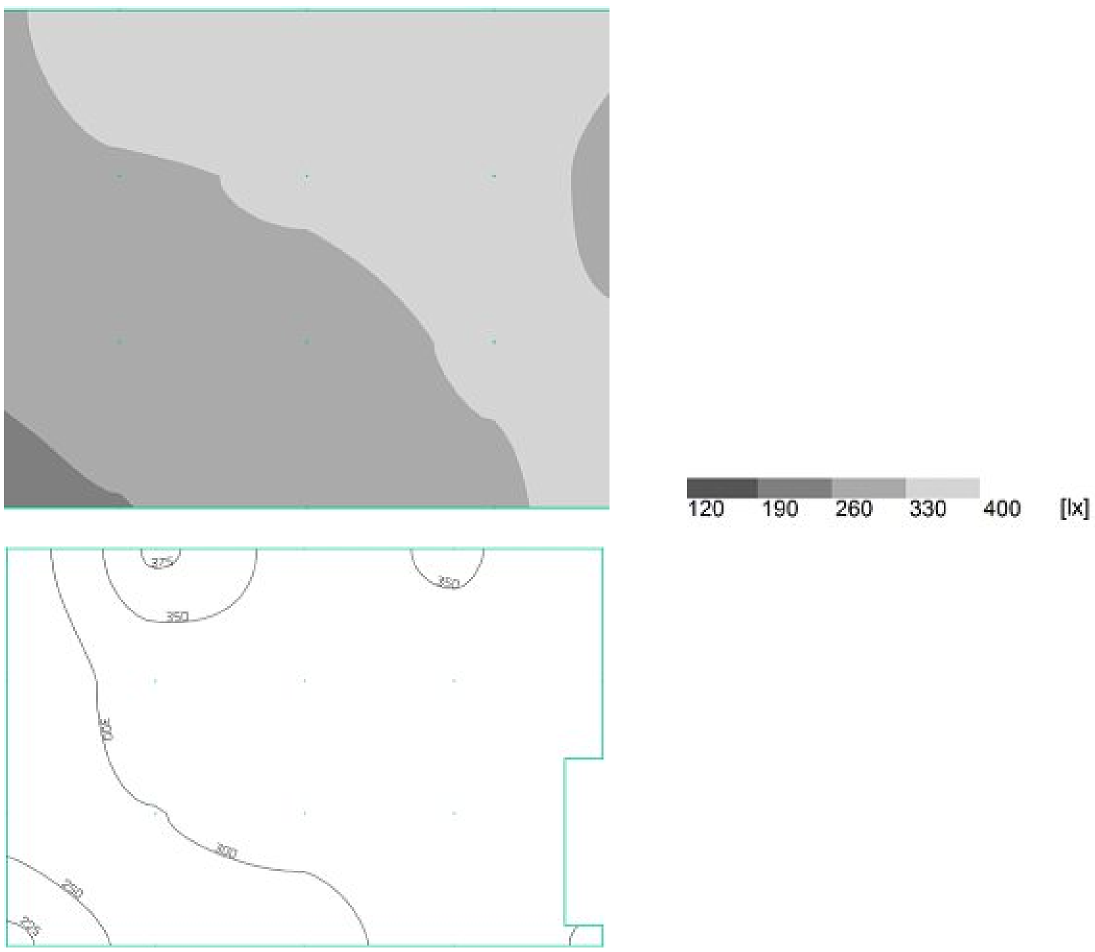


Figure 64: Calibrated simulation greyscale and isoluxlines, Hietzing entrance (figure by the author)

Figure 64 illustrates the reference area (including calibration efforts) in greyscale picture and isolines during night-time conditions. It displays similar deficiencies of illuminance levels as in the measurement result array. It provides information about the even illumination of the entrance hall. The brightest areas are close to the glass wall which separates the swimming pool hall from the entrance area. Table 62 lists results and information of the individual calibration steps.

Table 62: Simulation workflow results, Entrance hall Hietzing

ENTRANCE HALL, HIETZING					
Calibration steps (implemented in DIALux)	Avg. Deviation from simulation to measurement		Difference (improvement) to previous step of calibration		notes (table excludes porch area)
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL	20%	53	-	-	Initial model, separate from all measurement findings
Defected luminaires (finding from measurement) assumed as off in Dialux	14%	34	6	19	
Application of measured surface reflactances	13%	29	1	5	No dimming asjustments in entrance hall, main pool luminaires to 85%
Dimming adjustments (CALIBRATED MODEL)	7%	19	6	10	Exclusion of explainable outliers
Total improvements from INITIAL model to CALIBRATED model			**13**	**34**	

3.2.3.5. Comparison of Measurements and Simulation Results

Tables 63 and 64 put the calibrated night-time simulation and the measurement results in relation.

Table 63: Measurement vs. simulation [lx], Hietzing entrance

6	Simulation	277	378	340	353	329
	Measurement	291	374	327	304	305
5	Simulation	260	323	333	339	316
	Measurement	256	301	208	355	280
4	Simulation	260	297	315	342	
	Measurement	256	314	194	350	
3	Simulation	220	259	279	323	354
	Measurement	226	280	270	323	264
2	Simulation				279	237
	Measurement				279	213
1	Simulation				292	232
	Measurement				312	208
entrance, artificial light		A	B	C	D	E

Table 64: Measurement vs. simulation [%], Hietzing entrance

		A	B	C	D	E	
6	Sim. / Measurem.	-5%	1%	4%	16%	8%	7%
5	Sim. / Measurem.	2%	7%	60%	-5%	13%	17%
4	Sim. / Measurem.	2%	-5%	62%	-2%		18%
3	Sim. / Measurem.	-3%	-8%	3%	0%	34%	10%
2	Sim. / Measurem.				0%	11%	6%
1	Sim. / Measurem.				-6%	12%	9%
entrance, artificial light		A	B	C	D	E	
		3%	5%	32%	5%	16%	

Average Deviation from Simulation to Measurement	
12.6%	**29lux**

Avg. Deviation without outliers 4C, 5C	
6.9%	**19lux**

The simulation model could be reduced to a 12.6% deviation from the measured values of the entrance hall. Two grid points indicate a 60% and 62% deviation (highlighted in orange colour). This suggests that the simulation model generates significantly higher illumination in these spots than were measured. Similar to the swimming pool hall the variance must be put context with the furnishing of the entrance hall. Illumination values were measured close to the centrally positioned benches. The deviations of cells 6D and 3E result from another nearby bench, a plant pot or the entrance desk as visible in Figure 65. Other than that, the simulation of the entrance hall describes a high level of accuracy with a 6.9% deviation approximating the measurements.

Figure 65: Measurement obstructions, Hietzing entrance (photograph by the author)

3.2.4 Lockers and changing cabins

The luminaire arrangement and measurement grid of the locker rooms and changing booths is shown below in Figures 66 and 67.

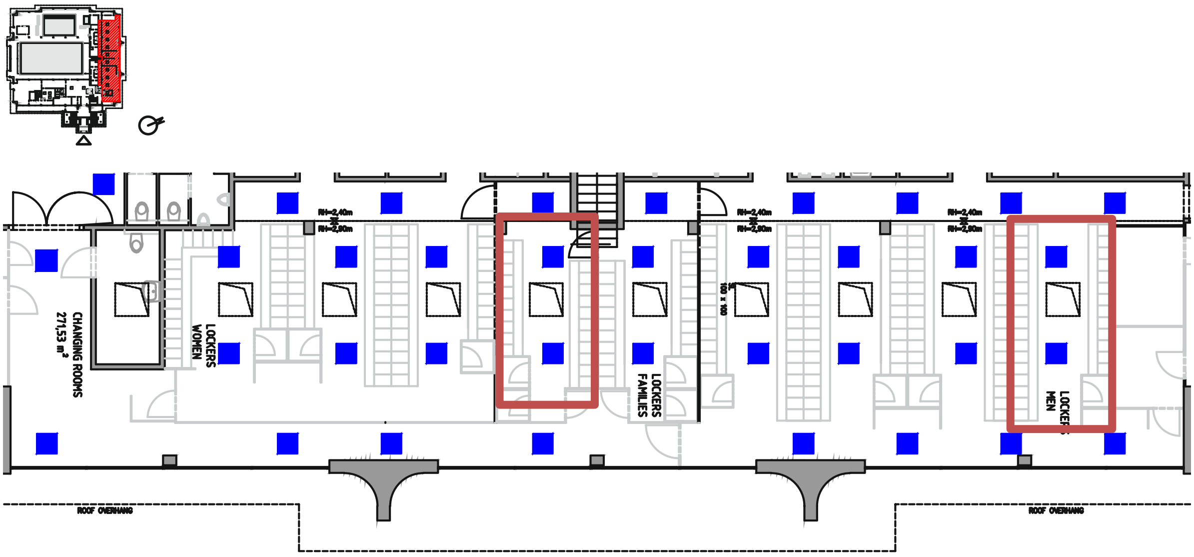


Figure 66: Luminaire arrangement, Hietzing lockers (based on MA44, edited by the author)

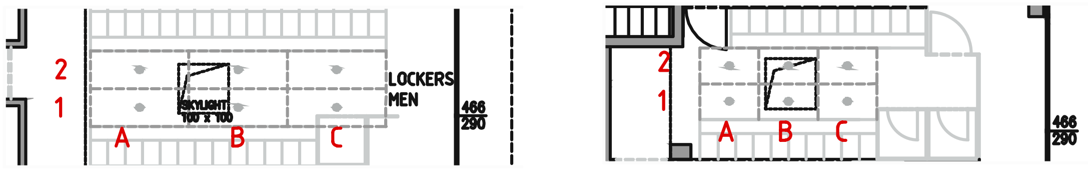


Figure 67: Measuring grid, Hietzing lockers men (left) and women (right) (based on MA44, edited by the author)

All lamps in the locker rooms, connecting hallways and hair dryer stations are ceiling-recessed LED panels. The luminaires are arranged in a regular pattern. Each locker row features two artificial luminaires.

3.2.4.1. Daytime Measurement

Table 65 and 66 present measurement results for the specified locker rows. Daylight factors are illustrated in Table 67. The daytime measurement was conducted with all artificial lights turned off (daylight only). The results were attained on 29.05.2020 from 10:20am to 11:20am. The measured data was collected under the same conditions as described for the main pool.

Table 66: Daytime measurement, Hietzing lockers men (left), women (right)

2	out	49 380	48 480	47 880
	in	183	160	155
1	out	48 930	47 950	47 650
	in	198	151	156
lockers M, daylight		A	B	C

2	out	59 300	58 050	55 160
	in	168	160	129
1	out	58 860	57 380	50 070
	in	178	169	129
lockers W, daylight		A	B	C

Table 65: Surface reflectance, Hietzing lockers

	Surface	Reflectance
Locker / changing rooms	Floor (creme, tiles)	0.42
	Wall (white, plaster)	0.81
	Wall Women L (orange, tiles)	0.31
	Wall Men (brown, tiles)	0.15
	Separating wall (yellow, plastic)	0.48
	Columns (yellow, plaster)	0.68
	Ceiling (grey, drywall)	0.89
	beams (wood)	0.18

Table 67: Daylight factors, Hietzing lockers men (left), women (right)

2	0.4%	0.3%	0.3%
1	0.4%	0.3%	0.3%
lockers M, DF	A	B	C

2	0.3%	0.3%	0.2%
1	0.3%	0.3%	0.3%
lockers W, DF	A	B	C

3.2.4.2. Night-time Measurement

The results were acquired on 13.05.2020 from 09:20pm to 10:20pm under the same conditions as the swimming pool hall. Table 68 and 69 inform about night-time measurement results.

Table 68: Night measurement, Hietzing lockers, men (left), women (right)

2	162	133	128
1	178	125	128
Lockers M, artif.	A	B	C

2	143	136	115
1	150	147	118
Lockers W, artif.	A	B	C

Table 69: Night measurement performance indicators, Hietzing lockers

	Men	Women / Family	Minimum standards
E min [lx]	125	115	200
E max [lx]	178	150	-
E avg [lx]	142	135	-
Uniformity	0.88	0.85	0.4

3.2.4.3. Analysis

Due to the small number of measurement points and the overall small size of the reference grid the results of the measurement are of lower validity and significance for this work. Measurements were mainly conducted to gain ability to compare simulation results.

Natural light is available through the glass façade and one skylight per locker row. The uniformity generated by the installed luminaires during the night-time measurement results in 0.88 in the men's and 0.85 in the women's locker room. Therefore, illumination distribution is spread evenly in both areas of interest.

The men's locker room displays slightly higher illumination values in each measurement run (day- and night-time). However, in all lighting scenarios the required minimum values of 200 lux are not met. To improve the conditions during daylight situation it is recommended to use the supplementary artificial lighting system at all operational hours.

3.2.4.4. Simulation Results

In order to optimize the correspondence of the initial simulation, measured surface reflectance values were applied. Since the overall brightness of the simulation model was too high dimming values of 85% for the LED panels were implemented. Table 70 lists results and information of the individual calibration steps.

Table 70: Simulation workflow results, Lockers Hietzing

LOCKERS Male and Female, HIETZING					
Calibration steps (implemented in DIALux)	Avg. deviation from simulation to measurement		Difference (improvement) to previous step of calibration		notes
	%	lx	percentage point	lx	
Default Dialux surface reflactances (INITIAL MODEL)	43%	59	-	-	Initial model, separate from measurement findings
Application of measured surface reflactances	24%	33	19	26	Overall brightness too high
Application of measured surface reflactances (CALIBRATED MODEL)	8%	10	6	23	Locker luminaire (identical to entrance) dimming to 85%
Total improvements from INITIAL model to CALIBRATED model			**25**	**49**	

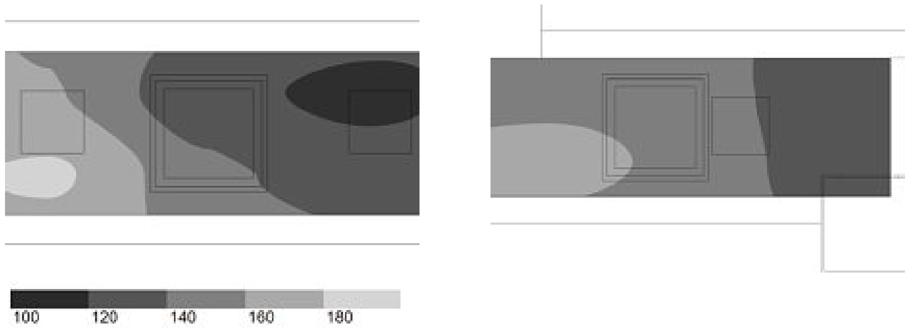


Figure 68: Simulation Greyscale, Hietzing Lockers Men and Women (figure by the author)

Figure 68 illustrates the reference area (including calibration efforts) in greyscale picture during night-time conditions. It displays similar deficiencies of illuminance levels as in the measurement result array. In both locker rooms the highest illuminance values are simulated close to the hallway. The figure displays a similar illumination flow in both locker rooms. It can also be seen that the pool area does not achieve the required illuminance threshold of 200 lux.

3.2.4.5. Comparison of Measurements and Simulation Results

Table 71 and 72 compare final simulation results to night-time measurements for the men's and women's locker areas.

Table 71: Measurement vs. simulation, Donaustadt lockers men

2	Sim.	162	127	116
	Measur.	162	133	128
1	Sim.	183	146	130
	Measur.	178	125	128
Lockers M, artificial l.		A	B	C

2	Sim./Meas.	0%	-5%	-9%	5%
1	Sim./Meas.	3%	17%	2%	7%
Lockers Men, artif.		A	B	C	
		1%	11%	5%	

Table 72: Measurement vs. simulation, Hietzing lockers women

2	Sim.	156	149	131
	Measur.	143	136	115
1	Sim.	166	153	132
	Measur.	150	147	118
Lockers W, artificial l.		A	B	C

2	Sim./Meas.	9%	10%	14%	11%
1	Sim./Meas.	11%	4%	12%	9%
Lockers women, artif.		A	B	C	
		10%	7%	13%	

Average Deviation from Simulation to Measurement	
7.9%	**10lux**

The simulation results of the locker rooms indicate slight deviations from the measured status quo. The simulated values in the men's locker room seem to be more accurate to the measurements than in the women's locker rooms. The average deviation of both areas could be reduced below 8%, more specifically 10 lux.

3.2.5 Optimization proposals Object 2

In the course of this contribution a 3D model of *Hallenbad Hietzing* was generated and calibrated with measured values. The comparison of simulated and measured values of artificial lighting system could be reduced to an average deviation of significantly below 10 lux at all individual areas of the overall model (excluding the mentioned statistical outliers).The small margin provides the opportunity to implement optimization steps and get conclusive and immediate feedback from the virtual model.

The following proposal are suggestions to improve the visual performance of the artificial lighting system. They react to the detected deficiencies of the night-time measurement. The suggestions are limited to the swimming pool areas. Entrance and locker rooms are not included in this section. The effect on lighting levels is tested in the model and documented in Figures 69 and 70.

Base case: Simulation model (including calibration efforts)

As reference, the simulation of existing values is illustrated in Figures 69 and 70.

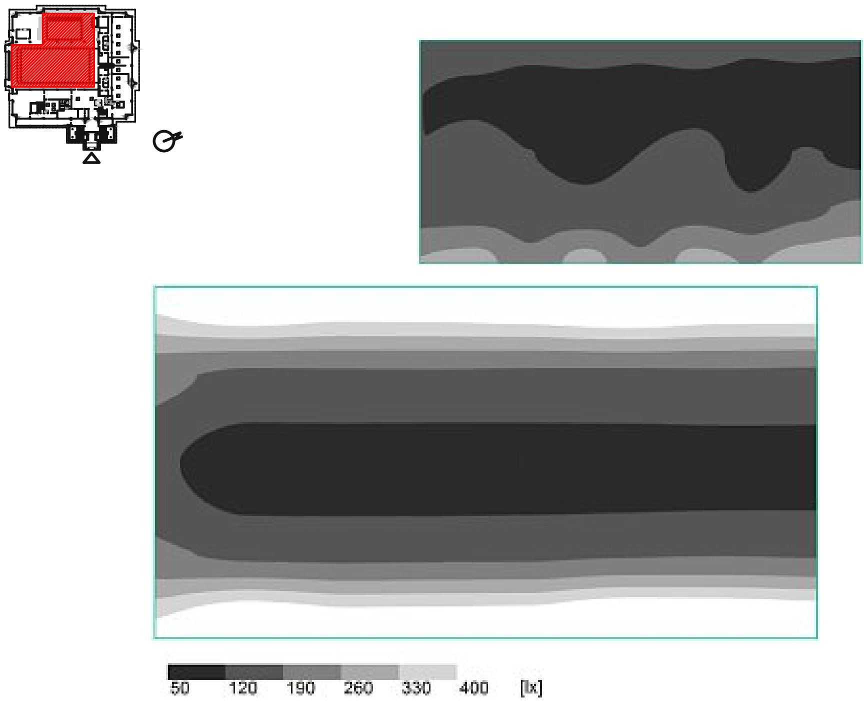


Figure 69: Greyscale Base case, swimming pool hall Hietzing (figure by the author)

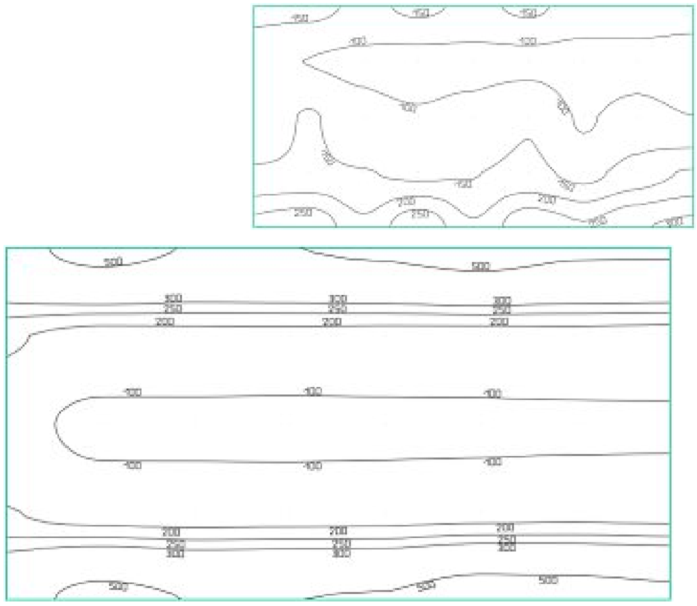


Figure 70: Isoluxlines Base case, Swimming Pool Hall Hietzing (figure by the author)

Optimization suggestion number 1: Increasing ceiling surface reflectance.

The elevated ceiling above the main pool has a dark wooden finish. The surface reflection value is expected to be 17%. It can be assumed that a higher reflectivity would improve the illumination of the main pool area. The ceiling at the rest of the hall is painted with light pastel-yellow colour and measures a surface reflectance of 79%. In the optimization simulation 79% surface reflectivity is assumed for the dark elevated ceiling as well. Additionally, one spotlight above the paddling pool was defected during the measurement process. It is considered switched on this scenario. The effect on lighting levels is tested in the model and documented in Figures 71 and 72.

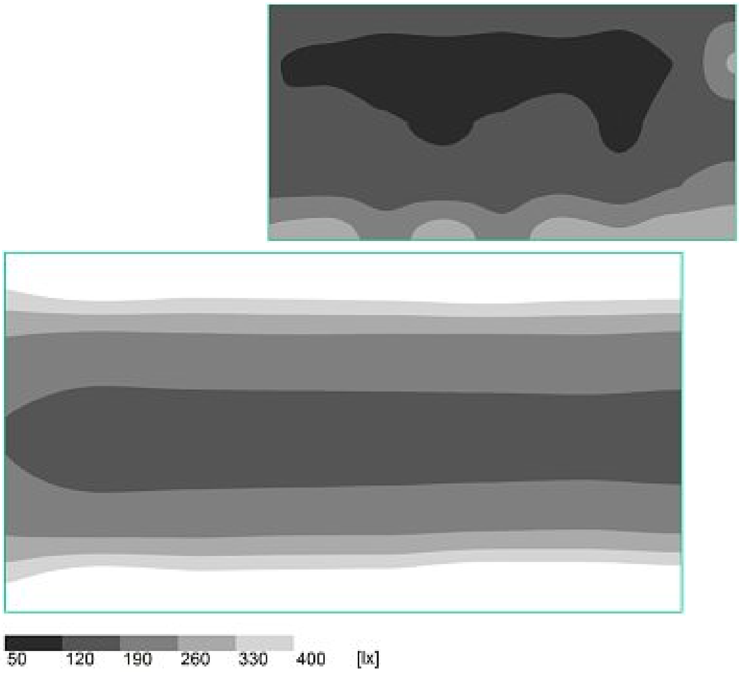


Figure 71: Greyscale Optimization #1, swimming pool hall Hietzing (figure by the author)

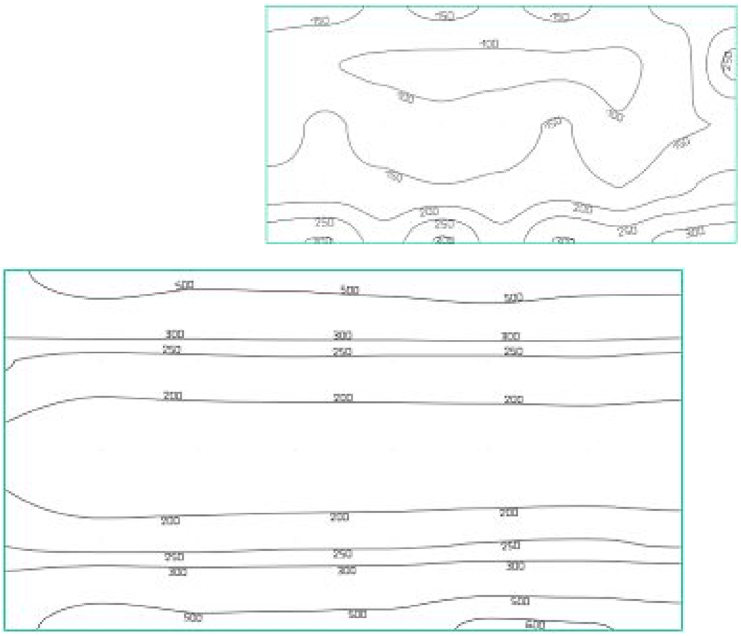


Figure 72: Isoluxlines Optimization #1, swimming pool hall Hietzing (figure by the author)

The simulation results in improved average lux levels of the main pool basin by 46%, those of the teaching pool by 6%. The lighting distribution stays identical to the base scenario. The uniformity of the teaching pool appears uneven. For the main pool the highest illuminance values are received at the outer calculation points of the pool basins, close to the installed lamps. While the average illuminance of the pool basin grid points surpassed 200 lux, minimum values below 150 lux are registered along the centre axis of the main pool.

The reference surface of the teaching pool does not improve significantly by the simulated optimization measure. The as functional considered small spotlight above the paddling pool increases average illumination of this area slightly. Each calculation point of the teaching pool still falls short of the required minimum value of 200lux.

Optimization suggestion number 2: Installation of additional luminaires.

The number of additional luminaires is chosen to fulfil required illuminance and uniformity standards. The positioning is in line with the architectural design. One additional row of six luminaires is mounted centrally above the main pool at a height of +3.75m above floor level. Three additional luminaires in a linear constellation are assumed to be installed at +2.90m above the teaching pool. The utilized lamp types are assumed identical to the existing luminaires. The positions and the optimization effect can be seen in Figure 73 and 74. The simulation is building on optimization proposal 1.

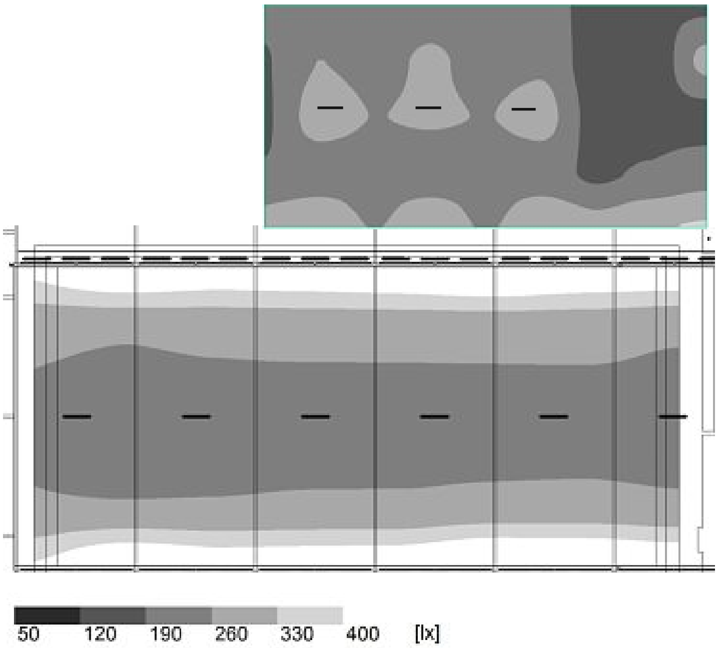


Figure 74: Greyscale Optimization #2, swimming pool hall Hietzing (figure by the author)

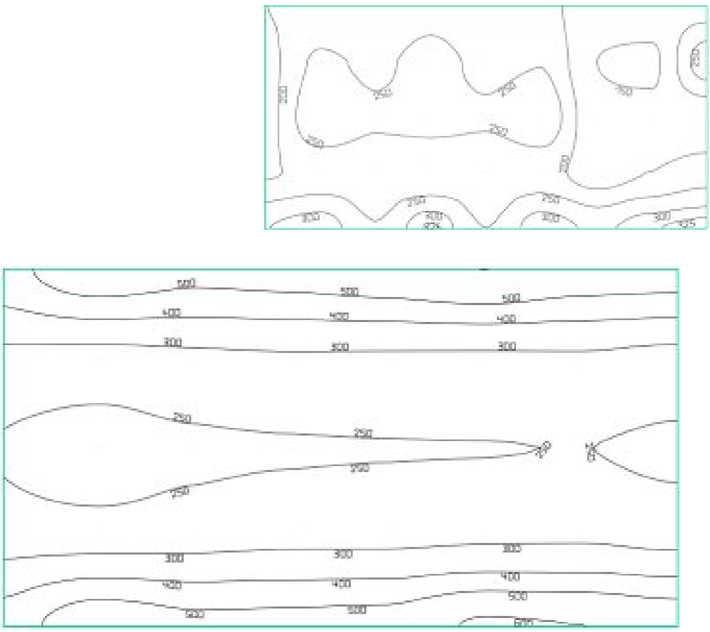


Figure 73: Isoluxlines Optimization #2, swimming pool hall Hietzing (figure by the author)

The approach was based on the built-in tool in Dialux for estimation of required number of luminaires to achieve desired illuminance levels. The installation of additional luminaires drastically improves the illumination of the swimming pool hall. The average visual performance of the main pool basin increases by 29% and of the teaching pool by 88%.

All calculation points register sufficient light input. Illuminance levels of the main pool basin range between 230 lux and 296 lux, those of the teaching pool basin between 206 lux and 295 lux. The minimum illuminance value of 151 lux of the overall hall is to be found at the paddling pool area. The uniformity of both pools meets the standard requirements in this scenario.

Comparison of optimization proposals

Figure 75 and Table 37 and 74 visualize improvements of the simulated optimization scenarios for both pool areas. The simulation runs are building on the previous optimization proposal.

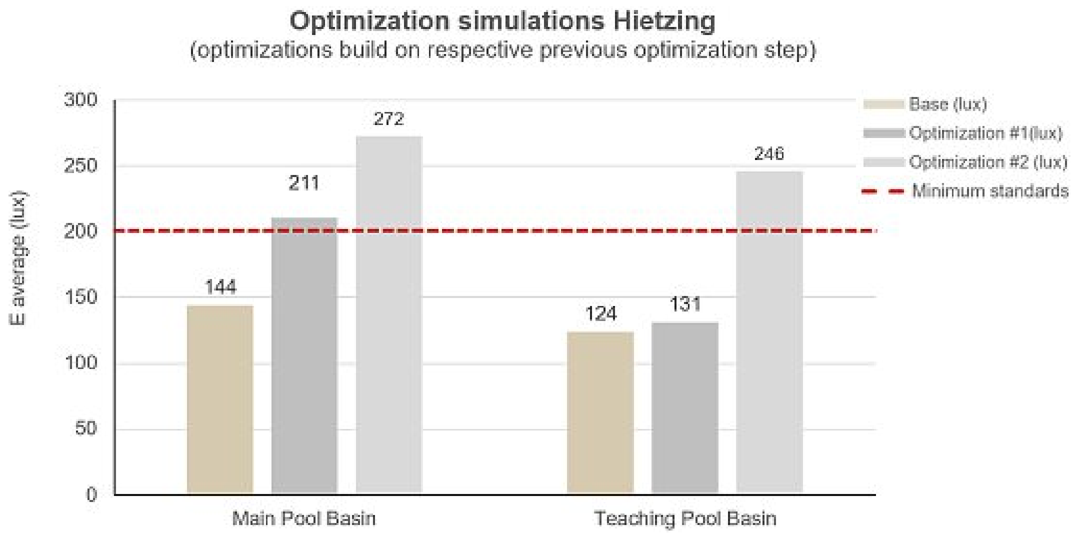


Figure 75: Optimization scenarios results, Hietzing main pool (figure by the author)

Table 73: Optimization scenarios results, Hietzing main pool

Main pool basin Hietzing, optimzation steps				
Indicators	Base model	Optimization #1 (building on base)	Optimization #2 (building on #1)	Minimum standards
E min [lux]	76	143	230	-
E max [lux]	185	252	296	-
E avg [lux]	144	211	272	200
Uniformity	0.53	0.68	0.84	0.5
E avg improvement (to respective previous optimization step)	-	46%	29%	-

Table 74: Optimization scenarios results, Hietzing teaching pool

Teaching pool basin Hietzing, optimzation steps				
Indicators	Base model	Optimization #1 (building on base)	Optimization #2 (building on #1)	Minimum standards
E min [lux]	84	88	206	-
E max [lux]	163	174	295	-
E avg [lux]	124	131	246	200
Uniformity	0.68	0.67	0.84	0.5
E avg improvement (to respective previous optimization step)	-	6%	88%	-

General optimization suggestions

It can be assumed that necessary actions that aim to fulfil required lighting standards increase electricity consumption. However, the optimization proposals considered in this contribution strive for ensuring safety and enhancing overall visual comfort.

According to technical staff of pool hall *Hietzing* all artificial lights have been upgraded to state-of-the-art LED technology in 2017 as part of the conducted contracting project.

Additional energy savings of contemporary lighting design could result from installation of control schemes. Since the measurements suggest daylight availability throughout the pool hall, implementation of daylight-based control in the pool hall could reasonably improve energy efficiency. The technology detects areas where sufficient illumination is provided by natural light and dims luminaires in that specific area. Viable savings should be accurately calculated in advance of any refurbishment project. However, further calculations are beyond the scope of this thesis.

3.3 Comparison of Object 1 and Object 2

Status Quo

On-site inspections of the two indoor swimming pool buildings revealed high similarities between the artificial lighting system layouts. The geometry of both buildings is almost identical. Small deviations of luminaire arrangement occur in positioning of spotlights.

Within the framework of Energy Contracting, all light sources of *Hallenbad Hietzing* were replaced with LED light sources in recent years. The pool building *Donaustadt* uses fluorescent-based energy-saving luminaires. An upgrade to LED luminaires might improve cost efficiency while simultaneously reducing environmental impact. According to literature and manufacturer recommendations the investment seems to be beneficial only in long-term view. In *Hietzing*, the staff can control light colours of the spotlights to illuminate patterns and materials differently and generate interesting moods in the swimming pool hall. Dimming control is not possible in either of the case studies.

During the measurement process of *Donaustadt* pool hall six tubular fluorescent lights were defected, which impacted the illumination considerably. In *Hietzing* the artificial light system seemed better maintained, all lights were functional.

Illuminance levels

The visual performance of artificial lighting systems (excluding daylight influence) in both case study buildings is summarised in Figure 76. The graph includes the night-time measurement and simulation results of individual building zones expressed as average horizontal illuminance. Simulation results are included in the figure to illustrate the deviation from the status quo.

In this thesis, swimming pool basins have been considered with highest priority as they incorporate the main purpose of the buildings. The first conclusion drawn from the graph is that under the described conditions the measurements of main pool and teaching pool of both analysed buildings clearly fall short of the minimum requirements of 200 lux. It is strongly suggested to implement optimization measures to the artificial lighting system in both swimming pool halls.

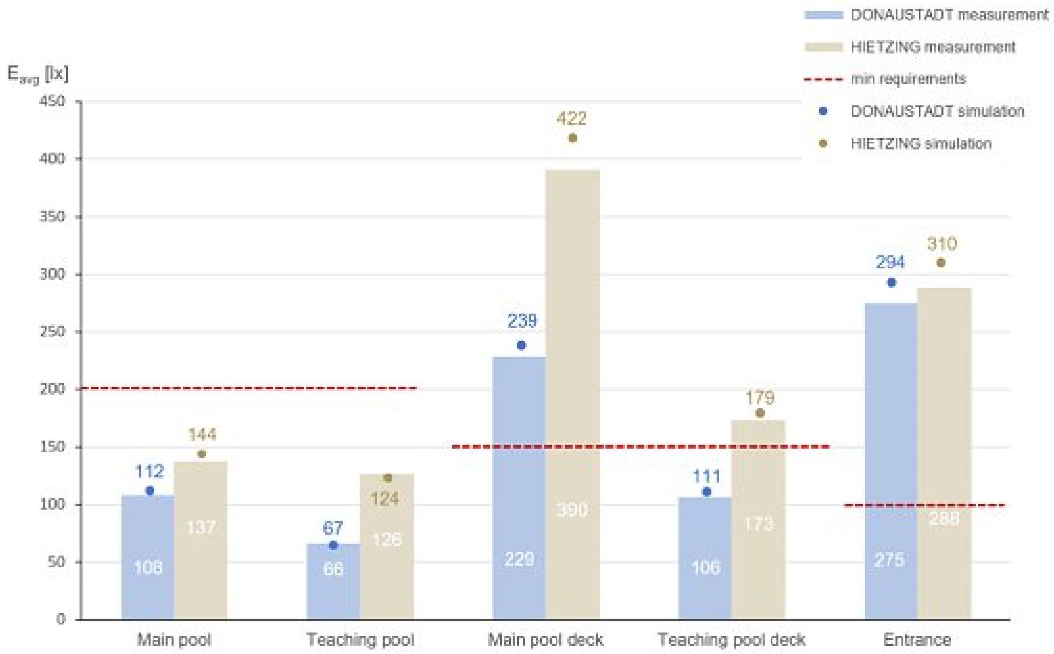


Figure 76: Average illuminance of artificial lighting system, Donaustadt and Hietzing (figure by the author)

The second main information derived from the graph is that *Hallenbad Hietzing* registers overall higher illumination values than *Donaustadt* in all compared areas of interest. The average illuminance of the teaching pool in *Donaustadt* is about half the quantity of its' equivalent in *Hietzing*. The significant difference might be traced back to the fact that a considerable number of luminaires surrounding the pool basins of *Donaustädter Hallenbad* have been defected (not running) during the night-time measurement, whilst in *Hallenbad Hietzing* all luminaires except for one small spotlight were fully functionable. The first optimization of *Hallenbad Donaustadt* in chapter 3.1.5 considers all defected luminaires functional. The average illuminance of the first optimization run for the main pool results in 127 lux and for the teaching pool in 121 lux. Both values, although considerably higher than those of the base case with defected luminaires, are still unsatisfactory compared to the standards but seem to be in a comparable range to the measurements of *Hietzing* which features 137 lux for the main pool and 126 lux around the teaching pool area. It would be advantageous to repeat measurements with all luminaires in operation to verify the simulated results.

The pool's circumferential areas require a minimum illumination of 150 lux. Except for the teaching pool deck in *Donaustadt* the standards are met. Again, the simulation run with all luminaires in full operation theoretically improves the average horizontal illuminance to 141 lux in this area. Therefore, it can be assumed that the low effort of exchanging all defected light sources would result in improved and almost satisfactory illuminance levels in this area as well (if one considers the standard suggestion as satisfactory). In comparison, the average illuminance of *Hietzing*'s main pool deck amounts to 390 lux and thus exceeds the minimum requirement of 150 lux significantly, as well as it exceeds the corresponding results of the *Donaustädter Hallenbad*.

In the entrance hall, both artificial lighting systems perform well above the minimum requirements. In correspondence to the swimming pool hall, *Hallenbad Hietzing* reveals higher average illumination values in this area than *Donaustadt*.

Besides the number of not running luminaires, another explanation for the overall significantly higher illuminance data might be based on the architectural colour scheme of the swimming pool halls. The dominant design feature for wall and ceiling surfaces in *Hietzing* is a light-cream colour. In *Donaustadt* walls are blue and the ceilings are of different shades of wooden brown. Estimated surface reflectance of *Hallenbad Hietzing*'s ceiling is 71%, in *Donaustadt* it is only 17%. The values have been derived from luminance and corresponding illuminance measurements. Based on the *Donaustadt* optimization scenario 2 in chapter 3.1.5, an increased ceiling surface reflectivity demonstrates the vast effect on the overall illuminance levels. By manipulating the ceiling's surface reflectance from 0.17 to 0.80 in the second optimization scenario, the average illuminance levels of the teaching pool rose by 35% compared to the calibrated model and assuming all luminaires functional. This supports the aforementioned assumption that the visual performance of the *Hallenbad Hietzing* in as-is condition is in advantage over its equivalent in *Donaustadt* in achieving higher illumination levels.

The uniformity of both pool halls based on night-time measurements meets the requirements of international standards. Out of the two case studies, the results suggest a slightly more uniform lighting distribution in swimming pool hall *Donaustadt*.

Correspondence of simulation models

According to Figure 77 the simulation models' results appear to widely correspond with the night-time measurements. The simulation of the *Donaustädter Hallenbad* results in marginal differences to the measured values, the average relative deviation is below 6%. The simulation model of the *Hallenbad Hietzing* does not correspond to the measurements that well. Especially *Hietzing* main pool stands out with a 29% deviation. Whilst 80% of calculation points in *Hallenbad Hietzing* are within deviation ranges of lower than 11%, a few grid cells next to interior furniture distort the average result and validity of the virtual model significantly. During the measurement process obstructions such as interior trees, plant pots and permanent furniture impacted the measurements, but were not considered in the simplified simulation model. The maximum outlier in *Hietzing* deviates +340% from the measured value. Those grid points are assumed as statistical outliers. By excluding these mentioned outliers, the average relative deviation of the main pool grid would amount to 6%, more specifically 17 lux, which is about the same range of deviation from the measurements as *Hallenbad Donaustadt*.

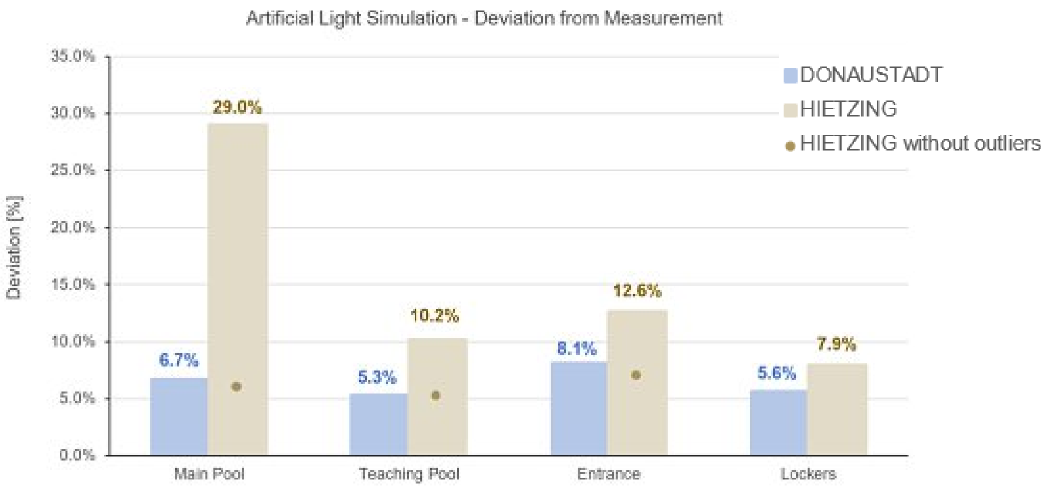


Figure 77: Deviation of simulations to measurements, artificial lighting performance (figure by the author)

Daylight integration

The geometry and external dimensions of both pool buildings are close to identical. As mentioned in the Introduction, the main geometry difference is the height of the raised flat roof and the accompanying skylight constellation above the main pool. Cross sections of daylight input are illustrated in Figure 78.

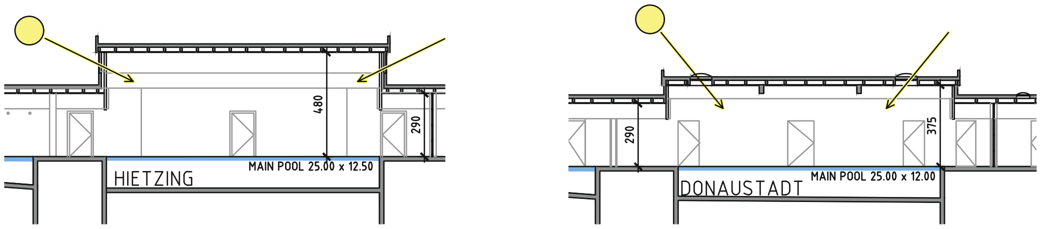


Figure 78: Skylight design cross sections, left: Hietzing, right: Donaustadt (figure by the author)

The swimming pool hall *Donaustadt* features a room height of 3.75m combined with 24 horizontal skylights. In contrast, the swimming pool hall in *Hietzing* has a room height of 4.80m, providing the possibility to include vertical skylights strips along the lengths of the façades of the roof elevation. Therefore, the *Hallenbad Hietzing* features a higher overall window-to-wall ratio. The comparison of average measurement-derived daylight factors (Figure 79) informs about the geometry's impact on daylight availability at the swimming pool basin's measurement points. As can be expected, the larger window area from the skylights in *Hietzing*'s geometry results in higher natural light input.

TEACHING POOL

Hietzing

1.6%	1.6%	1.6%	1.7%	1.6%
1.1%	1.1%	1.1%	1.1%	1.1%
0.9%	1.0%	1.1%	1.0%	1.0%
			DF avg	1.2%

Donaustadt

0.5%	0.5%	0.6%	0.6%	0.6%
0.3%	0.3%	0.4%	0.3%	0.4%
0.2%	0.2%	0.2%	0.2%	0.2%
			DF avg	0.4%

MAIN POOL

Hietzing

1.7%	1.7%	1.7%	1.8%	1.7%	1.6%
2.1%	2.2%	2.3%	2.4%	2.4%	2.3%
1.4%	1.4%	1.4%	1.4%	1.3%	1.3%
				DF avg	1.8%

Donaustadt

2.7%	1.7%	1.4%	1.3%	1.1%	1.1%
1.9%	1.0%	0.6%	0.5%	0.4%	0.4%
2.5%	1.9%	1.5%	1.3%	1.2%	1.2%
				DF avg	1.3%

Figure 79: Daylight Factor Pool Basin results, Hietzing and Donaustadt (figure by the author)

As a sidenote, the simulated daylight values stray noticeably further from the measurements than the night-time simulations. Based on experiences obtained during this work the exclusion of daylight influence leads to more reliable simulation results. Potential reason could be the larger set of uncertainties of influencing parameters for the daylight simulation in comparison to the artificial light simulation, such as transmittance of the transparent envelope of the buildings, surrounding outdoor obstructions, and deviating characteristic of the daylight characteristics influenced by the sky model in the simulation in comparison to the measurements' days sky conditions.

Table 75 provides an overview of daylight factor assessment of both pool reference grids via measurement and simulation. It also includes information about the sky model utilized from the software for simulation. For both buildings, exterior illuminance is significantly underestimated by the software. The average exterior illuminance reaches fractions of 32% (*Donaustadt*) and 48% (*Hietzing*) compared to the on-site measurements. Subsequent exterior illuminance adjustments addressing the deviation ratio from simulation to measurement improve the correspondence of average daylight factors considerably. The results are illustrated in Figure 80.

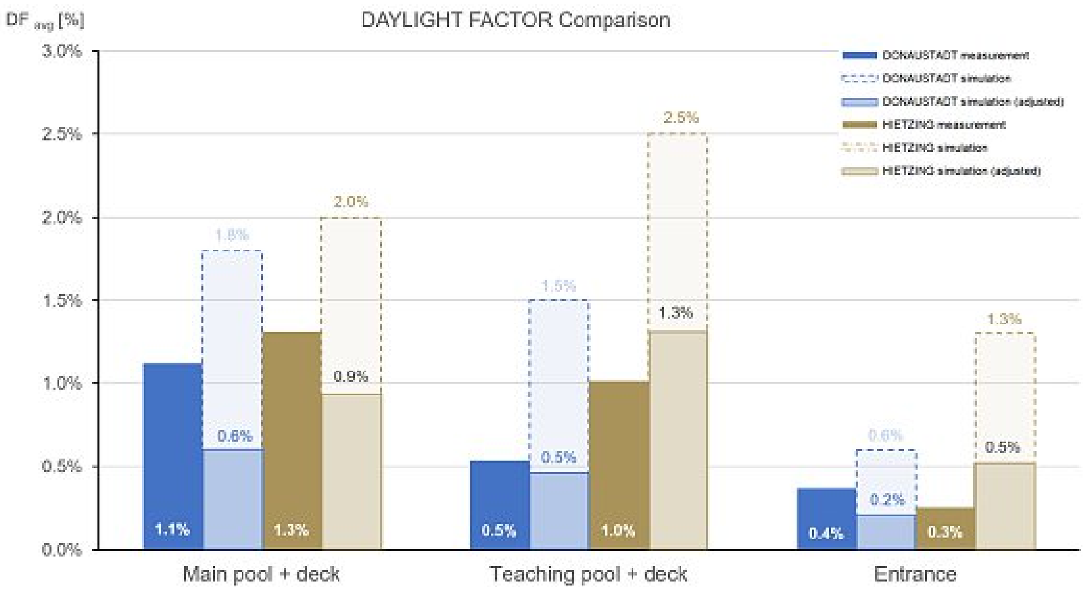


Figure 80: Average daylight factors, comparison of measurements and simulations (figure by the author)

Table 75: Average daylight factors, comparison of measurements and simulations

DF_{avg} [%]	Measurement	Simulation	Simulation (Avg. Ext. illuminance deviation adjusted)	Measurement	Simulation	Simulation (Avg. Ext. illuminance deviation adjusted)
Main Pool + deck	1.1%	1.8%	0.6%	1.3%	2.0%	0.9%
Teaching Pool + deck	0.5%	1.5%	0.5%	1.0%	2.5%	1.3%
Entrance	0.4%	0.6%	0.2%	0.3%	1.3%	0.5%
E exterior average (lx)	43 234	13 732	41 928	34 600	16 560	33 600
E exterior average ratio to measurement	-	32%	97%	-	48%	97%

Glare

In the district pool of *Hietzing* large plants are positioned in front of the façade, assumingly to reduce daylight penetration. In *Donaustadt* the natural light enters the swimming pool hall unfiltered and less controlled. In both buildings there are no glare control devices such as e.g. interior blinds. According to my subjective impressions, the additional application of glare devices is not a primary necessity. I visited the swimming pool halls numerous times for photographs, masking off the measuring grids and measuring processes under the most varied lighting conditions, both inside and outside. Additionally, I have known the *Donaustädter Hallenbad* for a long time since I also did my primary school swimming course in the hall. I have not experienced any negative problems with glare. Both *Hietzing* and *Donaustadt* pool halls are covered with light-coloured ceramic tiles on the floor and walls, which causes the surfaces to reflect light strongly and create "shiny" spots. These light reflections are noticeable in the pool hall. However, they do not lead to visual discomfort or visual impairment by glare in any way.

Furthermore, the UGR calculations via Dialux considered almost identical positioning of calculation points within both pool halls. Although lateral glazing poses a major risk for glare occurrence in pool facilities, the simulations (overcast as well as clear sky) suggest low incidence for visual disturbance by direct or indirect glare.

4 CONCLUSION

The main objective of this thesis is acquisition and analysis of current state of lighting conditions of contemporary swimming pool buildings in Vienna. Evaluations are based on artificial lighting systems and daylight availability of two case study buildings that are representative for a group of municipal pool facilities. The focus is on how the visual performance of the 40-year-old sports facilities compares to modern lighting standards. Additionally, it was set as a goal to find out how the two almost identical buildings behave in comparison to each other. Part of this thesis addressed the question of how good the level of correspondence of the simulation models is by individual calibration measures using measurement data. Derived results and detected deficiencies are likely to be widely and directly applicable to all district pool buildings in Vienna.

The approach included on-site measurements as well as modelling and simulation of the lighting conditions via state-of-the-art simulation tools. Measurement processes were conducted in different setups to assess daylight and artificial lighting performance individually. Evaluations are based on external and internal illuminance measurements and luminance measurements of interior surfaces.

To summarize, the *Hallenbad Hietzing*, the building from the first district pool construction stage performs superior to the district pool *Donaustadt* in view of lighting availability and illumination levels during day- and night-time. The geometry with vertical skylight strips is beneficial and results in higher natural light input. The design detail of a high ceiling surface reflectance is assumed to be the pool facility *Hietzing*'s main driver of increased illumination levels. Additionally, the artificial lighting system uses advanced LED technology and is assumably more energy-efficient and optimized towards operational and maintenance costs.

Nevertheless, both buildings express clear deficiencies in required illumination provided by the artificial lighting systems. While uniformity results can be considered as sufficient and glare potential as minimal, the relevant illuminance standards are not met in both swimming pool halls. Therefore, it is strongly recommended to implement refurbishment actions that increase the artificial lighting performance in the swimming pool hall. Optimization scenarios were simulated using the two generated virtual models. Both can be considered as rather reliable due to low deviations to the measured status quo. In general, simulations with the exclusion of daylight interference proofed to be of higher accuracy to the measurements mainly due to default skylight assumptions by the simulation software. The optimization results determine that the installation of additional luminaires in the 40-year-old lighting designs would be necessary to meet contemporary standards. Nevertheless, inexpensive and simple to implement optimization measures, such as exchanging all defected luminaires and painting dark ceiling battens with a light colour of high surface reflectance would already result in a noticeable illumination increase.

Daylight availability within both pool halls is ensured via numerous skylights and glass façade surfaces. The measurement-based daylight factors of the swimming pool areas mainly indicate the necessity of supplementary artificial lighting during daytime to provide a well-lit-space.

Limitations as well as opportunities were caused by restrictions due to the current pandemic. As the baths have not been opened for public use since March 2020 the water was drained from the swimming pools (the basins were empty). The absence of uncontrollable reflections of turbulent water surface contributed to a more exact measurement process. Illumination values in the pool basins could be conducted efficiently as the equipment was not at permanent risk of water damage and no issues to reach specific points of the measurement grids were experienced. Instead, it was precisely adjusted to the designated grid position by tripod and water level. On the other hand, the pool building is per se not designed to be used without water. The impact on illumination by specular reflections and underwater lights could therefore not be considered in the measurement procedure. Both might have substantial impact on the visual quality of the swimming pool hall. Even though the water and its corresponding surface reflectivity can be modelled in the simulation software it is advantageous to repeat the measurement under usual operational conditions (including all lights in operation) to verify the simulation results.

The simulation models represent simplifications of the real situations. The pool halls' surface information was reduced and averaged in the modelling process. Interior objects such as plants and benches were not considered. Additionally, the utilised software might show limitations when it comes to the complex process of rendering daylight, given the larger set of uncertainties regarding the required input information. Even though weather conditions and time of each measurement point were precisely documented the exterior illuminances and resulting daylight simulation results stray far from the measured values. Most significant deviations occur close to the glass facades. Another limitation was the lack of data of existing structures such as exact lamp/luminaire type and performance data and external physical obstructions. Luminaires of the integrated *DIALux* catalogues from ordinary manufacturers were chosen carefully to approximate the measured lighting situation and prevailing lighting equipment. The angle and exact height of the suspended spotlights was as good as possible determined from plans and on-site visits, but its fine positioning yet had to be estimated.

Sports facilities such as swimming pool halls are regularly known for a high level of energy usage in comparison to other building typologies. They are indispensable for public recreation, exercise and health. Despite considerable saving accomplishments within Energy-Contracting projects since 2000, information about current strengths and deficiencies for composing efficient future strategies need to be continuously evaluated.

Thus, future research in this area should encompass the collection of diversified information about the overall building physical behaviour of swimming pool facilities, e.g. how thermal performance based refurbishment actions affect visual and acoustical conditions. Generating long lasting building information models that are adjustable with time seem a promising approach for future work. Information that contributes to comprehensive building physical behaviour enables more accurate simulation-based predictions for future refurbishment processes.

This thesis is a contribution to the current discourse of developing environmentally conscious and energy-efficient public buildings. The detected shortcomings should be understood as impulses and inspiration for re-evaluation and future strategies that should strive for cost optimization and simultaneous reduction of the ecological footprint while keeping up high levels of user satisfaction.

Furtherly, research in the lighting performance industry research could take place in extension or adjustment of the lumen method. The calculation aims to provide a method for an efficient lighting design. For optimization proposals within this thesis, the implementation was barely possible, since existing structures such as skylights and beams had to be taken into consideration.

5 INDEX

5.1 List of Figures

5.2 List of Tables

All tables without mention of references are created by the author.

5.3 List of Equations

6 LITERATURE

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7 APPENDIX

A. Tables

Further daylight measurement processes (daylight and partly artificial light):

Donaustadt, 14.05.2020, 09:25 to 11:10

5	out	2 027	1 943	4 507	5 461	4 687	4 542	4 606	4 505	4 407
	in	1 594	650	1 053	904	807	667	743	635	635
4	out	1 980	3 357	2 826	2 048	1 633	1 302	1 325	1 641	3 714
	in	1 707	920	695	480	360	300	300	330	575
3	out	1 863	3 076	2 809	2 176	1 503	1 309	1 359	1 557	3 818
	in	1 850	776	420	265	170	150	140	150	229
2	out	2 204	1 780	2 692	2 997	1 440	1 330	1 374	1 510	3 761
	in	2 150	920	650	565	350	320	310	348	730
1	out	18 790	2 058	2 164	2 824	3 146	3 378	3 745	4 364	4 780
	in	1 870	1 016	540	591	493	468	507	560	587
main pool, w artif.		A	B	C	D	E	F	G	H	I

5	out		1 879	3 082	2 865	2 296	4 450	4 574	4 911	4 911	453	4 696	5 047	5 668	8 440
	in		835	835	700	430	740	980	850	930	950	1 100	1 064	1 100	700
4	out	1 841	2 006	2 441	2 392	2 259	4 325	3 178	3 136	3 094	3 062	3 073	5 833	3 923	
	in	1 800	850	570	430	240	304	362	385	420	410	440	460	480	
3	out	2 106	2 004	3 136	3 398	2 364	3 583	3 344	3 400	3 446	3 491	3 547	5 410	3 980	4 574
	in	1 930	695	334	180	190	170	182	173	190	173	191	220	170	227
2	out	3 506	1 796				3 973	3 942	3 809	3 746	3 678	3 615	4 516	4 410	4 183
	in	1 220	423				180	200	191	183	186	186	177	145	85
1	out	4 791	1 758				2 368	2 821	3 028	3 263	3 857	4 491	5 318	4 968	1 909
	in	1 173	333				257	285	158	245	205	290	300	300	230
teaching pool, w/o spotli		A	B	C	D	E	F	G	H	I	J	K	L	M	N

4	out	4 352	4 507	4 570	4 747	4 650
	in	475	493	535	500	430
3	out	4 257	4 302	4 346	4 304	4 457
	in	230	220	240	225	208
2	out	4 297	4 296	4 404	4 709	6 479
	in	315	315	305	325	300
teaching pool, w spotlights		G	H	I	J	K

6	out	2 462	2 596	2 652	2 697	2 790
	in	146	156	131	164	146
5	out	4 477				2 907
	in	166				165
4	out	4 236				3 169
	in	111				187
3	out	4 080	6 707	4 668	4 316	3 682
	in	81	176	131	320	280
2	out				4 704	4 398
	in				65	56
1	out				4 187	4 410
	in				93	75
entrance		A	B	C	D	E

Hietzing, 15.05.2020, 08:30 to 10:20

8	out		4 471	4 093						
	in		457	510						
7	out		4 498	4 348						
	in		408	240						
6	out									
	in									
5	out	11 051	11 008	5 114	4 984	4 743	4 529	4 305	4 282	4 419
	in	1 102	574	70	76	75	71	74	64	67
4	out	10 872	10 165	5 007	4 965	5 430	5 645	5 542	5 593	4 591
	in	1 092	465	123	108	120	121	128	112	115
3	out		10 311	5 001	4 983	5 382	5 665	5 565	5 674	4 819
	in		461	157	161	171	169	172	167	158
2	out	9 992	10 201	4 974	5 016	5 347	5 668	5 577	5 704	4 997
	in	892	424	242	245	256	249	251	253	262
1	out	10 120	4 229	3 952	3 878	3 916	4 050	4 334	4 706	4 943
	in	183	488	538	522	542	549	548	535	533
main pool, w/o artif.		A	B	C	D	E	F	G	H	I

4	out	4 430	4 555	5 025	5 068	5 079	5 254
	in	266	267	265	280	258	261
3	out	4 359	4 648	4 992	5 064	5 066	5 313
	in	191	191	198	207	209	211
2	out	4 279	4 743	4 943	5 055	5 054	5 400
	in	261	243	246	257	255	260
main pool, w/ artif. light		C	D	E	F	G	H

5	out	2 453	2 936	2 956	2 968	2 994	2 994	3 027	3 159	3 277
	in	212	180	174	178	190	194	180	176	176
4	out	2 498	4 511	4 541	4 588	4 662	4 682	2 997	3 721	3 421
	in	127	207	179	184	190	196	120	147	186
3	out	2 582	4 484	4 532	4 570	4 625	4 657	2 988		
	in	113	108	160	136	167	173	97		
2	out	2 677	4 354	4 334	4 315	4 310	4 311	2 977	3 532	3 284
	in	108	139	118	98	117	125	84	111	136
1	out	2 864	2 936	2 951	2 957	2 967	2 978	2 991	3 207	3 238
	in	77	63	66	58	67	60	56	110	72
teaching pool, w/o art		A	B	C	D	E	F	G	H	I

4	out	5 479	5 454	5 423	5 422	5 454
	in	196	184	186	189	179
3	out	6 974	7 145	7 382	7 538	7 609
	in	227	203	184	213	229
2	out	8 410	8 309	8 325	8 281	8 181
	in	234	229	199	227	234
teaching pool, w/ artif. Lig		B	C	D	E	F

Extract from calibration process

Simulation model without any calibration / initial model Donaustadt pool hall:

5	Simulation	182	287	359	344	343	349	358	339	332
	Measurement	56	123	320	336	333	207	300	285	305
4	Simulation	186	152	144	145	146	152	148	143	126
	Measurement	110	99	115	147	138	105	123	126	122
3	Simulation	172	120	92	99	103	104	101	98	85
	Measurement	129	88	72	81	80	77	80	81	81
2	Simulation	182	141	126	145	146	156	154	156	142
	Measurement	133	110	108	124	116	116	123	140	144
1	Simulation	165	263	264	357	361	371	399	406	401
	Measurement	128	176	188	360	252	245	294	336	331
main pool, artificial light		A	B	C	D	E	F	G	H	I

5	Sim. / Measurem.	225%	133%	12%	2%	3%	69%	19%	19%	9%	54.6%
4	Sim. / Measurem.	69%	54%	25%	-1%	6%	45%	20%	13%	3%	26.3%
3	Sim. / Measurem.	33%	36%	28%	22%	29%	35%	26%	21%	5%	26.2%
2	Sim. / Measurem.	37%	28%	17%	17%	26%	34%	25%	11%	-1%	21.9%
1	Sim. / Measurem.	29%	49%	40%	-1%	43%	51%	36%	21%	21%	32.4%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		78.6%	60.2%	24.5%	8.7%	21.3%	46.9%	25.4%	17.1%	7.9%	

Average deviation from Simulation to Measurement	
32.3%	**45lux**

5	Simulation		202	201	130	65	104	159	158	168	158	162	165	130	134
	Measurement		164	158	115	59	72	103	105	115	118	115	116	113	115
4	Simulation	189	184	186	72	44	83	130	143	135	149	129	133	89	87
	Measurement	172	163	158	64	42	47	58	61	63	62	61	58	63	83
3	Simulation	188	149	85	36	25	89	117	126	125	126	121	102	71	133
	Measurement	161	130	80	33	22	49	57	56	54	56	55	54	45	139
2	Simulation	171	148				150	167	171	167	163	168	128	89	31
	Measurement	126	90				85	89	81	73	82	80	75	65	30
1	Simulation	107	133				189	238	97	244	205	247	222	206	192
	Measurement	82	91				167	182	63	144	134	172	155	180	187
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N

5	Sim./Measurem.		23%	27%	13%	10%	44%	54%	50%	46%	34%	41%	42%	15%	17%	38%
4	Sim./Measurem.	10%	13%	18%	13%	5%	77%	124%	134%	114%	140%	111%	129%	41%	5%	97%
3	Sim./Measurem.	17%	15%	6%	9%	14%	82%	105%	125%	131%	125%	120%	89%	58%	-4%	93%
2	Sim./Measurem.	36%	64%				76%	88%	111%	129%	99%	110%	71%	37%	3%	80%
1	Sim./Measurem.	30%	46%				13%	31%	54%	69%	53%	44%	43%	14%	3%	36%
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N	
							58%	80%	95%	98%	90%	85%	75%	33%	6%	

Average deviation from Simulation to Measurement	
69.1%	**53lux**

Simulation model calibration process, Dialux default surface reflectance and adaptions of luminaire defects, Donaustadt pool hall:

5	Simulation	66	128	328	335	327	212	331	331	329
	Measurement	56	123	320	336	333	207	300	285	305
4	Simulation	145	106	126	135	130	115	132	138	123
	Measurement	110	99	115	147	138	105	123	126	122
3	Simulation	158	101	75	84	85	84	88	92	82
	Measurement	129	88	72	81	80	77	80	81	81
2	Simulation	166	114	97	120	110	120	132	150	138
	Measurement	133	110	108	124	116	116	123	140	144
1	Simulation	143	191	197	323	256	273	346	399	396
	Measurement	128	176	188	360	252	245	294	336	331
main pool, artificial light		A	B	C	D	E	F	G	H	I

5	Sim. / Measurem.	18%	4%	2%	0%	-2%	2%	10%	16%	8%	7%
4	Sim. / Measurem.	32%	7%	10%	-8%	-6%	10%	7%	10%	1%	10%
3	Sim. / Measurem.	22%	15%	4%	4%	6%	9%	10%	14%	1%	9%
2	Sim. / Measurem.	25%	4%	-10%	-3%	-5%	3%	7%	7%	-4%	8%
1	Sim. / Measurem.	12%	9%	5%	-10%	2%	11%	18%	19%	20%	12%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		22%	8%	6%	5%	4%	7%	11%	13%	7%	

Average deviation from Simulation to Measurement	
9.1%	**15lux**

5	Simulation		198	197	128	65	85	120	127	129	130	130	140	121	129
	Measurement		164	158	115	59	72	103	105	115	118	115	116	113	115
4	Simulation	186	178	182	70	42	56	69	75	75	78	76	73	69	82
	Measurement	172	163	158	64	42	47	58	61	63	62	61	58	63	83
3	Simulation	176	128	82	34	24	56	66	68	65	69	69	67	53	127
	Measurement	161	130	80	33	22	49	57	56	54	56	55	54	45	139
2	Simulation	141	91				93	108	91	84	95	95	96	75	25
	Measurement	126	90				85	89	81	73	82	80	75	65	30
1	Simulation	86	103				167	194	61	156	158	200	199	197	191
	Measurement	82	91				167	182	63	144	134	172	155	180	187
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N

5	Sim./Measurem.		21%	25%	11%	10%	18%	17%	21%	12%	10%	13%	21%	7%	12%	15%
4	Sim./Measurem.	8%	9%	15%	9%	0%	19%	19%	23%	19%	26%	25%	26%	10%	-1%	19%
3	Sim./Measurem.	9%	-2%	2%	3%	9%	14%	16%	21%	20%	23%	25%	24%	18%	-9%	19%
2	Sim./Measurem.	12%	1%				9%	21%	12%	15%	16%	19%	28%	15%	-17%	17%
1	Sim./Measurem.	5%	13%				0%	7%	-3%	8%	18%	16%	28%	9%	2%	10%
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N	
							12%	16%	16%	15%	19%	20%	25%	12%	8%	

Average deviation from Simulation to Measurement	
15.9%	**13lux**

Simulation model calibration process, adaptions of surface reflectance values from measurement data

5	Simulation	72	134	330	341	331	211	330	335	341
	Measurement	56	123	320	336	333	207	300	285	305
4	Simulation	147	111	129	139	133	115	133	144	132
	Measurement	110	99	115	147	138	105	123	126	122
3	Simulation	170	108	78	88	87	85	88	93	89
	Measurement	129	88	72	81	80	77	80	81	81
2	Simulation	186	126	101	123	116	124	134	155	145
	Measurement	133	110	108	124	116	116	123	140	144
1	Simulation	170	200	194	329	258	279	347	408	406
	Measurement	128	176	188	360	252	245	294	336	331
main pool, artificial light		A	B	C	D	E	F	G	H	I

5	Sim. / Measurem.	29%	9%	3%	1%	-1%	2%	10%	18%	12%	9%
4	Sim. / Measurem.	34%	12%	12%	-5%	-4%	10%	8%	14%	8%	12%
3	Sim. / Measurem.	32%	23%	8%	9%	9%	10%	10%	15%	10%	14%
2	Sim. / Measurem.	40%	15%	-6%	-1%	0%	7%	9%	11%	1%	10%
1	Sim. / Measurem.	33%	14%	3%	-9%	2%	14%	18%	21%	23%	15%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		33%	14%	7%	5%	3%	9%	11%	16%	11%	

Average deviation from Simulation to Measurement	
12.0%	**19lux**

5	Simulation		231	222	144	75	90	122	126	129	129	131	130	128	138
	Measurement		164	158	115	59	72	103	105	115	118	115	116	113	115
4	Simulation	220	208	204	83	50	57	68	70	70	72	73	71	70	86
	Measurement	172	163	158	64	42	47	58	61	63	62	61	58	63	83
3	Simulation	203	151	100	42	31	56	61	61	58	63	65	61	51	131
	Measurement	161	130	80	33	22	49	57	56	54	56	55	54	45	139
2	Simulation	165	108				92	90	83	78	87	91	89	75	28
	Measurement	126	90				85	89	81	73	82	80	75	65	30
1	Simulation	109	107				167	194	57	153	153	198	198	204	222
	Measurement	82	91				167	182	63	144	134	172	155	180	187
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N

5	Sim./Measurem.		41%	41%	25%	27%	25%	18%	20%	12%	9%	14%	12%	13%	20%	16%
4	Sim./Measurem.	28%	28%	29%	30%	19%	21%	17%	15%	11%	16%	20%	22%	11%	4%	15%
3	Sim./Measurem.	26%	16%	25%	27%	41%	14%	7%	9%	7%	13%	18%	13%	13%	-6%	11%
2	Sim./Measurem.	31%	20%				8%	1%	2%	7%	6%	14%	19%	15%	-7%	9%
1	Sim./Measurem.	33%	18%				0%	7%	-10%	6%	14%	15%	28%	13%	19%	12%
teaching p., artificial l.		A	B	C	D	E	F	G	H	I	J	K	L	M	N	
							14%	10%	11%	9%	12%	16%	19%	13%	11%	

Average deviation from Simulation to Measurement	
12.7%	**12lux**

Simulation model without calibration / initial model Hietzing pool hall

5	Simulation	432	469	586	540	540	558	605	556	550
	Measurement	211	350	478	478	491	469	490	492	484
4	Simulation	464	223	192	196	199	195	196	196	181
	Measurement	88	120	157	173	158	160	153	164	171
3	Simulation		150	84	86	86	88	89	90	85
	Measurement		69	73	79	81	80	83	82	79
2	Simulation	459	221	194	195	197	199	201	202	187
	Measurement	105	129	162	159	166	158	179	195	194
1	Simulation	397	469	596	551	556	566	627	603	573
	Measurement	185	388	512	508	514	527	554	548	545
main pool, artificial light		A	B	C	D	E	F	G	H	I

5	Sim. / Measurem.	105%	34%	23%	13%	10%	19%	23%	13%	14%	28.15%
4	Sim. / Measurem.	427%	86%	22%	13%	26%	22%	28%	20%	6%	72.22%
3	Sim. / Measurem.		117%	15%	9%	6%	10%	7%	10%	8%	22.76%
2	Sim. / Measurem.	337%	71%	20%	23%	19%	26%	12%	4%	-4%	57.22%
1	Sim. / Measurem.	115%	21%	16%	8%	8%	7%	13%	10%	5%	22.70%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		245.9%	65.9%	19.2%	13.2%	13.8%	16.8%	16.9%	11.2%	7.2%	

Avergae Deviation from Simulation to Measurement		Average Deviation without outliers row A and B	
41%	**38lux**	**14%**	**39lux**

5	Simulation	447	298	159	162	130	160	128	156	128	156	169
	Measurement	351	256	154	154	136	161	142	155	142	136	137
4	Simulation	409	134	91	62	52	49	50	50	49	80	223
	Measurement	284	181	112	100	87	88	88	93	71	71	68
3	Simulation			84	111	80	65	80	108	57	112	107
	Measurement			110	161	128	100	128	141	80	66	44
2	Simulation			119	113	107	93	104	113	93	141	167
	Measurement			153	171	158	129	157	164	131	169	192
1	Simulation			240	262	173	261	168	260	232	270	278
	Measurement			275	287	192	262	185	284	264	301	276
teaching pool, artificial l.		a	b	A	B	C	D	E	F	G	H	I

5	Sim. / Measu.	27%	16%	3%	6%	3%	-2%	-1%	1%	-10%	15%	23%	7%
4	Sim. / Measu.	44%	-26%	-19%	-38%	-40%	-44%	-43%	-46%	-31%	13%	228%	56%
3	Sim. / Measu.			-24%	-31%	-38%	-35%	-38%	-23%	-29%	70%	143%	48%
2	Sim. / Measu.			-22%	-34%	-32%	-28%	-34%	-31%	-29%	-17%	-13%	27%
1	Sim. / Measu.			-13%	-9%	-10%	0%	-9%	-8%	-12%	-10%	1%	8%
teaching pool, artificial l.		a	b	A	B	C	D	E	F	G	H	I	
				16%	24%	25%	22%	25%	22%	22%	25%	82%	

Average Deviation from Simulation to Measurement	
29%	**32lux**

Simulation model calibration process, adaptions of surface reflectance values from measurement data, Hietzing pool hall:

5	Simulation	492	503	603	557	559	580	622	578	573
	Measurement	211	350	478	478	491	469	490	492	484
4	Simulation	478	247	197	199	200	196	195	198	192
	Measurement	88	120	157	173	158	160	153	164	171
3	Simulation		169	90	88	85	87	89	92	94
	Measurement		69	73	79	81	80	83	82	79
2	Simulation	474	243	197	193	196	197	202	206	202
	Measurement	105	129	162	159	166	158	179	195	194
1	Simulation	444	495	606	558	560	571	643	633	604
	Measurement	185	388	512	508	514	527	554	548	545
main pool, artificial light		A	B	C	D	E	F	G	H	I

5	Sim. / Measurem.	133%	44%	26%	17%	14%	24%	27%	17%	18%	35.54%
4	Sim. / Measurem.	443%	106%	25%	15%	27%	23%	27%	21%	12%	77.67%
3	Sim. / Measurem.		145%	23%	11%	5%	9%	7%	12%	19%	28.96%
2	Sim. / Measurem.	351%	88%	22%	21%	18%	25%	13%	6%	4%	60.91%
1	Sim. / Measurem.	140%	28%	18%	10%	9%	8%	16%	16%	11%	28.39%
main pool, artificial light		A	B	C	D	E	F	G	H	I	
		266.9%	82.1%	23.0%	14.8%	14.5%	17.6%	18.1%	14.3%	12.9%	

Avergae Deviation from Simulation to Measurement		Average Deviation without outliers row A and B	
47%	**45lux**	**16%**	**47lux**

5	Simulation	476	328	200	199	170	193	168	192	161	177	168
	Measurement	351	256	154	154	136	161	142	155	142	136	137
4	Simulation	433	179	143	113	102	95	96	97	92	87	76
	Measurement	284	181	112	100	87	88	88	93	71	71	68
3	Simulation			139	167	133	118	131	158	107	148	118
	Measurement			110	161	128	100	128	141	80	66	44
2	Simulation			180	175	168	154	163	177	152	194	225
	Measurement			153	171	158	129	157	164	131	169	192
1	Simulation			299	318	240	318	233	315	286	326	339
	Measurement			275	287	192	262	185	284	264	301	276
teaching pool, artificial l.		a	b	A	B	C	D	E	F	G	H	I

5	Sim. / Measu.	36%	28%	30%	6%	3%	-2%	-1%	24%	13%	30%	23%	15%
4	Sim. / Measu.	52%	-1%	28%	13%	17%	8%	9%	4%	30%	23%	12%	16%
3	Sim. / Measu.			26%	4%	4%	18%	2%	12%	34%	124%	168%	44%
2	Sim. / Measu.			18%	2%	6%	19%	4%	8%	16%	15%	17%	12%
1	Sim. / Measu.			9%	11%	25%	21%	26%	11%	8%	8%	23%	16%
teaching pool, artificial l.		a	b	A	B	C	D	E	F	G	H	I	
				22%	7%	11%	14%	9%	12%	20%	40%	49%	

Average Deviation from Simulation to Measurement	
20%	**27lux**

Daylight factor simulation results (including calibration)

Donaustadt pool hall:

5	2.0%	1.0%	0.6%	0.6%	0.6%	0.5%	0.5%	0.6%	0.5%
4	2.2%	1.2%	0.7%	0.7%	0.6%	0.6%	0.6%	0.6%	0.6%
3	2.1%	1.0%	0.4%	0.3%	0.3%	0.2%	0.2%	0.3%	0.2%
2	2.3%	1.3%	0.9%	0.7%	0.7%	0.7%	0.6%	0.7%	0.6%
1	2.0%	0.9%	0.6%	0.5%	0.5%	0.5%	0.4%	0.4%	0.4%
main pool, DF, sim	A	B	C	D	E	F	G	H	I

5	0.8%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.0%
4	0.4%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	
3	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	
2	0.2%	0.2%	0.2%	0.2%	0.3%	0.2%	0.2%	0.2%	0.1%
1	0.2%	0.3%	0.3%	0.3%	0.3%	0.2%	0.3%	0.3%	0.2%
teaching p., DF, sim	F	G	H	I	J	K	L	M	N

6	0.1%	0.1%	0.2%	0.3%	0.4%
5	0.1%	0.1%	0.1%	0.2%	0.4%
4	0.2%	0.2%	0.2%	0.2%	
3	0.1%	0.2%	0.1%	0.2%	0.2%
2				0%	0%
1				0%	0%
entrance, DF, sim	A	B	C	D	E

Hietzing pool hall:

5	3.0%	1.2%	0.7%	0.6%	0.5%	0.5%	0.4%	0.4%	0.4%
4	3.5%	1.9%	1.3%	1.1%	1.1%	1.0%	1.0%	1.0%	0.9%
3		2.0%	1.3%	1.1%	1.1%	1.0%	1.0%	1.0%	0.9%
2	3.5%	1.9%	1.2%	1.1%	1.0%	1.0%	1.0%	0.9%	0.9%
1	2.8%	1.2%	0.7%	0.5%	0.4%	0.3%	0.3%	0.3%	1.2%
main p	A	B	C	D	E	F	G	H	I

5	2.2%	2.8%	3.0%	2.8%	3.0%	2.8%	2.9%	2.7%	2.5%
4	1.4%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.4%	#DIV/0!
3	0.9%	0.9%	1.0%	1.0%	1.0%	0.9%	0.9%	1.1%	0.5%
2	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.4%	0.4%
1	0.6%	0.6%	0.7%	0.6%	0.7%	0.6%	0.5%	0.4%	0.4%
teachin	A	B	C	D	E	F	G	H	I

6	0.4%	0.4%	0.4%	0.4%	0.4%
5	0.7%	0.9%	0.5%	0.9%	0.7%
4	0.6%	0.9%	0.5%	0.9%	
3	0.4%	0.4%	0.4%	0.4%	0.2%
2				0%	0%
1				0%	0%
entrance, DF, sim	A	B	C	D	E