Doctoral theses at NTNU, 2023:194

Ole Øiene Smedegård

Optimizing Energy and Indoor Climate Systems in Swimming Facilities

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Department of Civil and Environmental
Engineering

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Trondheim, June 2023

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ISBN 978-82-326-7090-1 (printed ver.)
ISBN 978-82-326-7089-5 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

Doctoral theses at NTNU, 2023:194

Printed by NTNU Grafisk senter

Optimizing energy and indoor climate systems in swimming facilities

Abstract

The awareness of climate change is well established worldwide and the European Union has defined a long-term goal of zero greenhouse gas emissions by 2050. Increased energy efficiency in buildings is defined as one of the most important tools for achieving this, a so-called “renovation wave”. In addition, the EU encourages a focus on buildings that support education and public health. Swimming facilities, a building type designed for improving public health and well-being, are documented in the literature as having considerable potential for reducing energy consumption. This makes swimming facilities especially attractive in this context. Considering swimming facilities as a complex building category, with all their inherently connected variables and processes, it is important to focus on both the design and the operational phases.

The goals of the PhD project have been as follows:

1. Identify the knowledge-gap in the research on energy and indoor environmental systems in swimming facilities,

2. Increase the possibility of optimized operation and investigate operating tools for tracking real-time energy performance for swimming facilities, and

3. Improve the design phase, thus reducing the threshold of using building performance simulation in the planning of these facilities.

In this work, a literature review revealed the major trends in research during the past few decades. Areas like solar heating for outdoor swimming pools, energy consumption, and air quality stand out; however, except for air quality and disinfection by-products, research was found to be highly fragmented. Regarding tools for optimized operation of swimming facilities the literature lacks benchmarks and rating systems. A continuous rating system, as an operating tool, can prevent costly operational flaws in energy use by quickly disclosing and improving the overall quality of the operation which are the primary functions of a facility - the indoor environment and energy use.

In the context of energy use an energy prediction model was developed in this work that represents the baseline for the energy use in a swimming facility. The baseline represented the expected energy use for the considered time period. The model was developed by applying multiple linear regression analysis of operational data collected from a swimming facility in Norway. The model was found to be a powerful tool for continuous supervision of the energy performance of the facility. By applying this model, an operator can quickly reveal possible operational disruptions/irregularities. In the case study, the statistically significant independent variables were found to be the pool usage time and the outdoor dry-bulb temperature. The energy prediction model produced in this work can easily be deployed either in a spreadsheet or in the building automation reporting system. It is therefore applicable for existing and new buildings which are equipped with thermal and electric energy meters.

Regarding the design phase, this research addressed the paradox in the complexity of the building. While complex buildings such as swimming facilities should be analyzed by dynamic simulation tools in the planning phase, this is seldom done due to the demanding and time-consuming task of modeling such complex systems and phenomena. Therefore, a simplified model for simulation-based design of swimming facilities was developed and compared with a validated detailed model of a swimming pool air handling unit (AHU), which is the most complex device in a swimming facility. The detailed model was a replica of a real AHU, and the system was simulated in a fully-coupled approach and operated using complex heuristic rule-based control. It was found that despite the introduction of three different simplification measures in the detailed model, the accuracy of the simplified model

was still satisfactory, bearing in mind the overall uncertainty at this design stage. The measures were defined by (1) A detached model approach between the building and the AHU, (2) Using an ideal control system and, (3) Simplifying the component equations.

In conclusion, the results of this PhD project can contribute to more sustainable swimming facilities in existing and new buildings. However, there are numerous topics in this context that need to be investigated further, such as developing a continuous holistic rating system that comprises the performance of the facility, including air and water quality, water usage, thermal comfort, and energy consumption. For the design phase the calculation of the evaporation rate stands out and should be further investigated. This is the most energy intensive process in a swimming facility and has a large impact on the predicted energy use.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been carried out as an industrial PhD at the Department of Civil and Environmental Engineering, NTNU, Trondheim, and COWI AS, Trondheim, with Amund Bruland as the main supervisor and Laurent Georges, Bjørn Aas and Salvatore Carlucci as the co-supervisor and Jørn Stene as the company supervisor.

The work was funded by the Research Council of Norway and COWI AS and received grants from COWIFonden. The initiative for the project came from the Centre for Sports Facilities and Technology (SIAT) at NTNU as a part of their work within this field.

When I started in 2017, HVAC systems in swimming facilities were an unknown area for me. Although I had long-term experience within the field, an extensive period of experiencing and training was necessary to attain in-depth knowledge in this technical field. Fortunately, I was surrounded by an experienced team of supervisors, each of them a specialist in their areas. I quickly started with fieldwork and data collection to become familiar with the multiple processes in a swimming pool. Nevertheless, I discovered the great challenge of moving from investigation and mapping to publishing scientific work.

I believe that the extensive process of developing holistic knowledge improved my thesis significantly, especially with respect to the development of the research questions. After some time, investigating new and old, large and small, good and poor swimming facilities, the required improvements within the field were clearly revealed and defined. However, using existing buildings as laboratories is not easy. Dealing with insufficient equipment, insufficient feedback from the user group, incorrectly reported or missing data and disguised flaws represented a time consuming and exhausting part of the work.

The final part of the PhD project, the submission of papers to scientific journals, being peer reviewed and accepted was an interesting experience.

Overall, this doctoral work has been an fascinating period of my life, developing myself along with one of the most interesting fields within the HVAC area.

Ole Øiene Smedegård

May 2022, Trondheim, Norway

Acknowledgements

In 2016, I received a very significant phone call from Bjørn-Åge Berntsen, the head of the Centre for Sports Facilities and Technology (SIAT) at NTNU. Together with the swimming pool specialist at the Centre, Bjørn Aas, we arranged a meeting where they presented a project proposal for me and COWI. The proposal was an Industrial PhD project within the field of HVAC in swimming facilities. After several meetings COWI accepted the proposal and established the project, which I commenced in 2017.

I was quickly and effective included in the community at SIAT which treated me as an equal colleague, even though my employer was COWI. I appreciate the help of Wolfgang Kampel, getting me on track when I started my PhD, Bjørn-Åge Berntsen for his help and positive attitude and of course Bjørn Aas, the Centre's specialist and creative "epi center".

I also want to acknowledge Maria Therese Bergan, Maren Berg Grimstad and Kjerstina Røhme, who were always available and willing to solve any administrative problems, and Beate Sørensen at COWI for solving all the issues by including such a project into an unprepared project system. I want also to thank Thomas Jonsson, Laurent Georges and Per Olav Tjelflaat for the excellent courses they arranged at NTNU.

My supervisors, Amund Bruland, Bjørn Aas, Laurent Georges, Salvatore Carlucci and Jørn Stene provided excellent guidance meetings during this long project period. Amund, with his long academic experience, Laurent with all his valuable guidance and knowledge, Bjørn, with his extensive experience from industry, Salvatore for his academic guidance and Jørn, for his patience during the project, were all irreplaceable. I also acknowledge the assistance from Stewart Clark at NTNU in editing my published papers and this thesis.

Early on in the PhD project Bjørn Aas gave me full access to his extensive network within industry, including both suppliers and operators of swimming facilities. They all welcomed me and gave me full access to their facilities and equipment. This made the technical basements of the swimming facilities maybe my most important "offices" during the PhD period. Jan Arne Løvås, Linda Stæhli, Kjetil Øvretveit, Hallgeir Revhaug, Trond Sigernes, Thomas Hjertenes, Hallvard Haukenes and Nic Holm all shared their valuable knowledge and gave me access to their equipment and facilities. This thesis is built on this knowledge and experience provided by all these colleagues within the field. Breathing and feeling these spaces, crawling in ventilation ducts, inspecting air handling units, wading inside the equalization tanks and inspecting the inside of the filters all contributed to the highly important part of understanding these strange facilities to the full.

I also have to particularly thank my hard-working and clever master's students who I supervised during my PhD. Clemet Perisse, Julie Jørgensen, Marianne Ruud, Henrik Alvestad and, last but not least, Vegard Skinnes. Thank you for your contribution and all the interesting experiments, results and discussions during your specialization projects and master's work.

Most of all I am very thankful for all the support from my wife Veronika Mari, and for sticking with me. And to our two teenage daughters Sunniva and Nanna Marie for all the smiles and for brightening our everyday life.

Contents

1 Introduction

1.1 Problem Outline

In the wake of the Intergovernmental Panel on Climate Change (IPCC) report in 1990 (1), and the following periodic reports, awareness of climate change has been well established worldwide. The Kyoto Protocol, 1997, established the baseline for the developed countries, where the European Union defined their target in the EU Energy and Climate Package (CARE). The EU gave the member states directives to fulfil each of the key targets in the package. For building stock the EU implemented the Energy Performance of Buildings Directive, EPBD (2), which was a part of the energy efficiency target in CARE.

By the end of the second commitment period of the Kyoto Protocol, 2013- 2020, the EU reported to be on track with respect to its target of reducing greenhouse gas (GHG) emissions by 20 % (3). The work towards the next goals is initiated as a part of the EU's 2030 climate and energy framework and the contribution to the Paris Agreement where the EU has defined a reduction of net emissions by at least 55 % compared to 1990 levels (4). The long-term goal is defined as “no GHG emissions” by 2050 (5). Energy efficiency in buildings is defined as one of the most important tools for both short-term and long-term targets (6), where a renovation wave of the existing building stock is defined as one of the “key actions” (5).

The EU recommends particular attention regarding energy reducing refurbishment of buildings that support education and public health (5). In the literature, swimming facilities are recognized to have considerable potential for energy reduction. This type of facility is associated with high energy use, as well as a large dispersion in energy use within the building category. The specific energy use is reported to range from about 400 $kWh/(m^2·a)$ to 1 600 $kWh/(m^2·a)$ (7-10) where the variations in age, technology and the different maintenance routines are defined as the most important explanatory variables. However, the figures represent a large energy savings potential (8), and for swimming facilities in Norway, figures in the range of 28 % are mentioned (7).

Swimming facilities are recognized as a complex building category due to the multiple and inherently connected variables and processes. This can be described with respect to the distinctive indoor environment and the number of controlling parameters, the processes, and the required technical equipment within this building category.

The indoor environment is represented by the extreme thermal conditions with high air temperature and high relative humidity as well as the presence of water aerosols including disinfection by-products (DBPs).

The thermal conditions are decided by the requirements to achieve satisfactory thermal comfort for the user and minimize energy use by controlling the evaporation rate for the pools. However, in cold climates this high temperature and relative humidity is a challenge for the construction elements and the building envelope where issues like condensation on surfaces, corrosion and mold may contribute to degradation of the construction.

The technical equipment for the HVAC system is designed to keep the processes in the swimming facilities under control. This includes the water treatment system, the ventilation system, the heating system and the water supply and sewage system. These systems control variables like the thermal indoor environment (air temperature, relative humidity), pool water conditions (temperature and disinfection), evaporation from the pools and required consecutive dehumidification, heat recovery and water usage, as well as air quality (fresh air supply). Chapter 2 provides an in-depth presentation of this topic. Figure 1 shows a principle illustration of a typical swimming facility found in Scandinavia, i.e. climate zone D according to the climate zones definition of Köppen and Geiger (11).

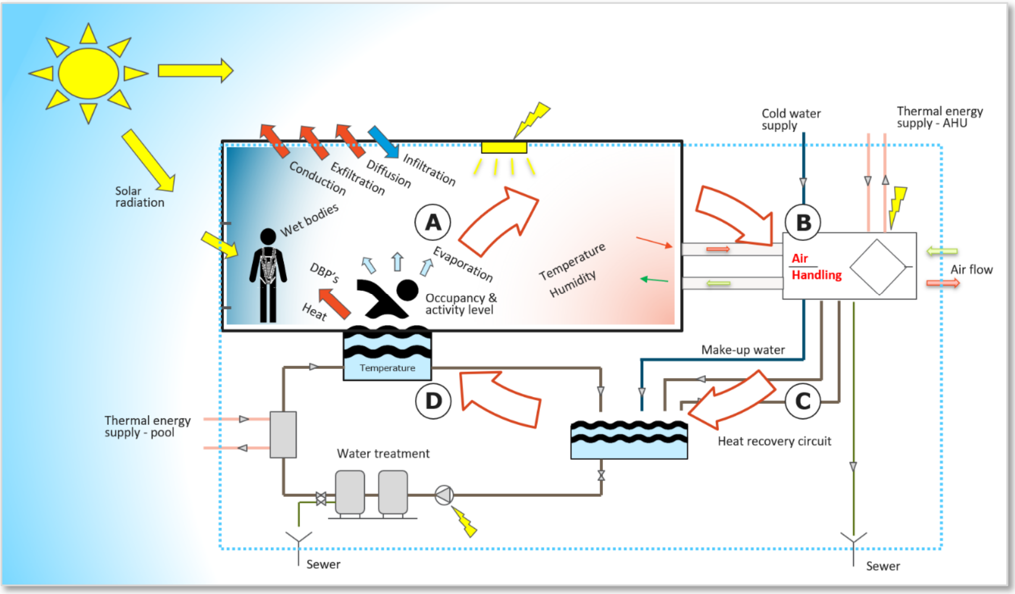


Figure 1 Principle illustration of a swimming facility in a Scandinavian climate with key elements related to space and water heating, ventilation, air conditioning and dehumidification as well as water treatment; (A) Indoor environment, (B) Air handling, (C) Heat recovery circuits and (D) Water treatment system. The arrows illustrate the typical direction of the net energy flows (12).

Considering the complexity of swimming facilities, the considerable range in specific energy use not unexpectedly takes into account an increasing amount of technical components (13). There is a substantial risk of excessive energy use and an improper and possibly harmful indoor environment if the technical systems are poorly designed and/or operated. For example, the operation of the air handling unit (AHU) with its integrated heat pump for ventilation, dehumidification and heat recovery influences both the energy use for the pool circuit, due to the heat recovery system, and the control of the water temperature in the pool. Poor operation may result in inferior air quality, high energy use and improper thermal conditions in the pool or in the swimming hall. The dependency of the energy use on the operational phase (14), where both behavioral and operational management are important (15), addresses the importance of the operational quality of the building. Due to this, the importance of well-trained and qualified operational personnel (16) cannot be underestimated (16). In buildings with non-skilled operational staff, the performance of the facility is vulnerable to improper operation (17). Considering the lack of operational tools in existing swimming facilities, this addresses an important area of potential improvement toward reduced energy use in this building category.

In addition to the large range in specific energy use, Kampel et al. (18) found that the most energy efficient swimming facilities use an advanced heat recovery system with multiple heat sinks. It is therefore recommended to install advanced heat recovery technology in swimming facilities to minimize annual energy use. Since the optimal energy plant design depends on investment costs, energy prices and local climate, heat pumps are recommended for heat recovery in Norwegian swimming facilities. Kampel et al. emphasized the importance of a well-designed heat sink side of the heat recovery system. However, designing and optimizing complex buildings requires extensive calculations during design. In Norway the prevailing building code (TEK17) for complex buildings like swimming facilities requires dynamic calculations for documentation of approved energy performance measures (19, 20). Paradoxically this is seldom done for swimming facilities. Due to its complexity the modeling is time consuming and also requires highly skilled engineers with in-depth knowledge regarding both advanced/detailed modeling of the facility and the system itself (21). This addresses an unexplored potential for improved design of swimming facilities.

This thesis covers three different aspects, each represented by an article in a scientific journal. See Figure 2.

1. Define the knowledge-gap in the research of energy and indoor environmental systems in swimming facilities
2. Operational tool - Tracking energy performance by comparing actual and expected short-term energy use
3. Design tool – Analyzing and proposing a model complexity of the BPS-model for a swimming facility

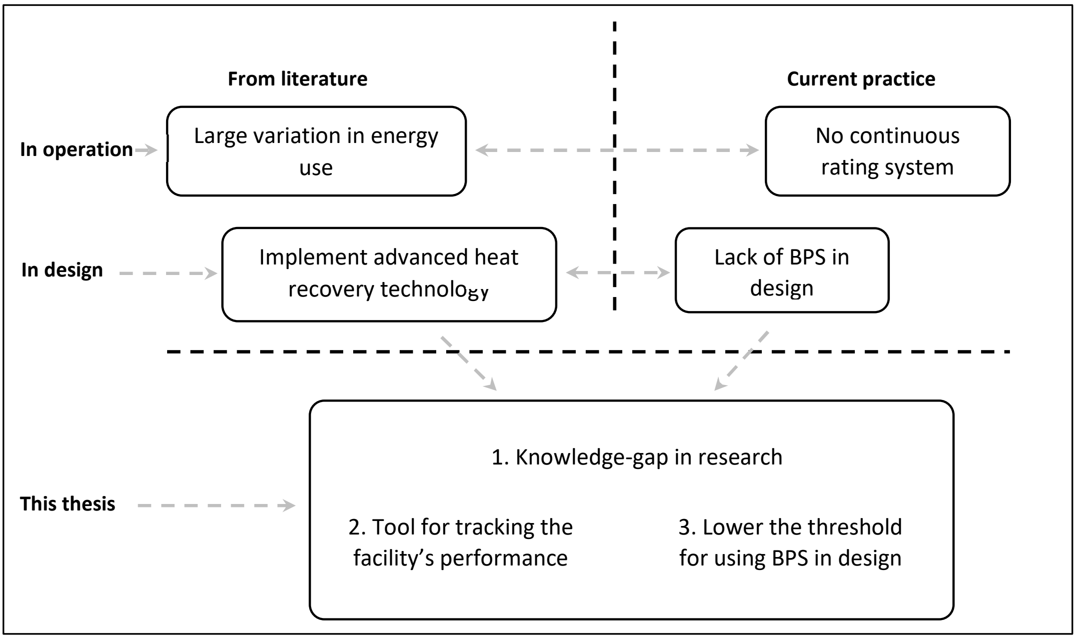


Figure 2 The different aspect of the thesis, derived from current practice and current research literature.

1.2 Research funding and environment

COWI, which is an international consulting group operating in multiple technical fields, is the owner and main funder of this PhD project. The project has been carried out in close cooperation with The

Centre for Sport Facilities and Technology (SIAT), within the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). This project is one of COWI's initiatives for developing knowledge within the field of complex buildings, to enhance sustainable building design in order to reduce GHG emissions. The project is also a part of SIAT's effort toward improved performance of sport facilities. The Research Council of Norway and COWIFonden are co-funders.

1.3 Research Questions

This PhD project is a continuation of the work by Wolfgang Kampel regarding energy use in swimming facilities (8). His findings regarding excessive energy use in Norwegian swimming facilities and his recommendation regarding implementation of extensive heat recovery systems are emphasized in his thesis. The concentrated statement of his work is "design energy effective facilities and be sure it is operated with the expected performance". The initial extensive literature review presented in Paper I show that a vast number of articles provide research concerning swimming facilities but there is no research regarding this topic.

The large variation in energy use among swimming facilities indicates a widespread in energy efficiency. Some of this can be explained by the differences in the technical systems as well as the overall design. However, with the amount of technical equipment in a swimming facility, the probability of flaws in operation is considerable, and this must be considered carefully when operating the facility. This thesis discusses the knowledge gap in research, how the operational personnel can obtain the expected performance of the facility and how complex the designers must keep their BPS model when designing a swimming facility.

These existing research gaps led to the following research questions:

RQ1: What are the research gaps within the field of energy and indoor climate systems in swimming facilities?

RQ2: Is there a potential for keeping the swimming facilities within the expected energy performance, and how can this be achieved?

RQ3: Is there a potential for reducing the threshold for applying building performance simulation tools in the planning- and design-phase of a swimming facility, and how can this be implemented?

1.4 Research Approach

This thesis is based on an experimental and a numerical part. Extensive data have been collected from my own experiments and by logged historic data and technical information from Norwegian swimming facilities. The experimental data have been analyzed using statistic methods while the technical information has been used to program advanced numerical models of an air handling unit (AHU) operating in a swimming facility.

1.5 Thesis Structure

The thesis summarizes the research work conducted during the PhD work. The thesis is structured in the following chapters: the State-of-the-Art Analysis, Methods, Results, Discussion and Conclusions. The chapters are based on the scientific papers attached in the Appendix.

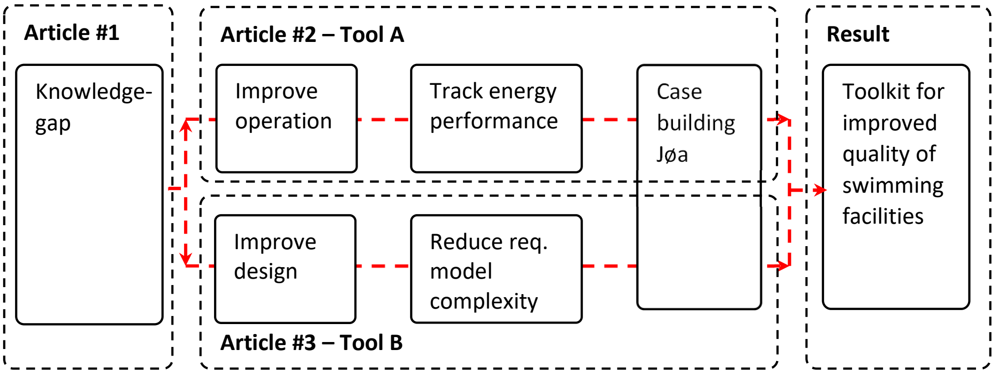


Figure 3 The definition of the main subjects treated in the thesis.

Paper I

Smedegård, O. Ø., Aas, B., Stene, J., Georges, L., Carlucci, S. (2021). *A Systematic and Data-Driven Literature Review on the Energy and Indoor Environmental Performance of Swimming Facilities*. Energy Efficiency Journal, 14:74. Published 2021.09.18.

> **Relevance to the thesis:** This paper addresses RQ1. A comprehensive literature review was carried out with bibliometric and thematic analyses of the research in swimming facilities from a heating, ventilation, and air conditioning (HVAC) perspective. This paper presents a holistic analysis of previous research in swimming facilities and defines research gaps.
> **My contribution**: Conceptualization, development of the methodology, formal analysis, investigation, visualization and main author of the journal paper.

Paper II

Smedegård, O. Ø., Jonsson, T., Aas, B., Stene, J., Georges, L., Carlucci, S. (2021). *The Implementation of Multiple Linear Regression for Swimming Pool Facilities: Case Study at Jøa, Norway*. Energies, 14(16), 4825. Published 2021.08.07.

> **Relevance to the thesis:** This paper addresses RQ2. A method and a data-driven model for calculating the energy baseline for swimming facilities was introduced and applied to a real case study. This model was trained and validated by collected operational data from the swimming facility at Jøa, Norway. The model is simple both in development and use and can be important to support the operational personnel to keep the facility within the expected range of energy performance.
> **My contribution**: Data collection, cleaning, development and application of the method, analysis and discussion of results and main author of the journal paper.

Paper III

Smedegård, O. Ø., Aas, B., Stene, J., & Georges, L. (2021). *Analysis of Model Complexity of Air Handling Units in Swimming Facilities*. [Unpublished article]. Under review in journal.

> **Relevance to the thesis:** This paper addresses RQ3. Calculation results from two building performance simulation (BPS) models of an air handling unit for a swimming facility were compared and analyzed. The simulation models were a simplified model with ideal control

and an advanced model serving as a replica of the real AHU. The outcome of the numerical investigation found the simplified model provided results with satisfactory accuracy for early-stage design. This initiative will lower the threshold for using BPS in this design stage. The paper derives useful guidelines for BPS design of AHU, which is the main energy-intensive component in indoor swimming pool facilities.
My contribution: Development of the pool model in IDA ICE and validation using field measurements. Development and implementation of the detailed AHU model in IDA ICE and development of the simplified model. Development of the framework of comparison between both models. Generation of the simulation results and comparison of models. Analysis and discussion of the results and writing the journal paper.

2 Theory and State-of-the-Art Analysis

2.1 General

Swimming facilities can be defined as a complex building type due to their distinctive indoor environment, the wet surfaces and the required technical equipment concerning both water and air treatment, and the heat recovery and energy supply system. Working with this building category therefore requires a high level of holistic knowledge both in design and research. Figure 1 illustrates a typical swimming facility, with its circular dependencies, that can be found in Scandinavian.

The indoor environment in the pool, shown in the zone A in Figure 1, is normally controlled by a ventilation system with fixed set-points for indoor (dry-bulb) air temperature and relative humidity. In addition to eliminating the risk of condensation on the building envelope and structural systems which may cause significant damage, the system is also designed to provide a healthy and thermally comfortable indoor environment.

The air handling unit (AHU), shown in the zone B of Figure 1**,** is controlled with the purpose of keeping a fixed air state in the facility, which normally is assumed to be equivalent with the extract air state due to the mixed ventilation concept. This is controlled by varying the amount of circulated air and the state of the supplied air.

In order to keep the air in the swimming facility fully mixed, issues including air stratification, condensation on building surfaces, non-homogeneous concentration of pollutants and regions with high air age in the facility are important. The circulated air flow rate is normally kept within the range between approx. 75 % to 100 % of the nominal air flow rate when the swimming facility is in use (i.e., “bathing mode”). This share of the airflow rate is identified as the “Recirculated air” in Figure 4. When required, the fresh air flow is directed into the facility by modulating bypass dampers. The control system calls for fresh air supply on several occasions, such as providing the minimum amount of fresh air during operation or the required amount of dehumidification or cooling in the pool. For this reason, the facility can either operate at full or minimum fresh air supply during the same type of pool usage (i.e., occupancy and activity) depending on the outdoor conditions. The facility will have the best air quality when it is operated with full fresh air supply due to maximum dilution of air pollution (DBPs). However, this would result in extremely high energy usage. It would also preferably require an air humidifier since indoor air is dryer and will increase the evaporation rate from the pool surface considerably and degrade the thermal comfort of the user.

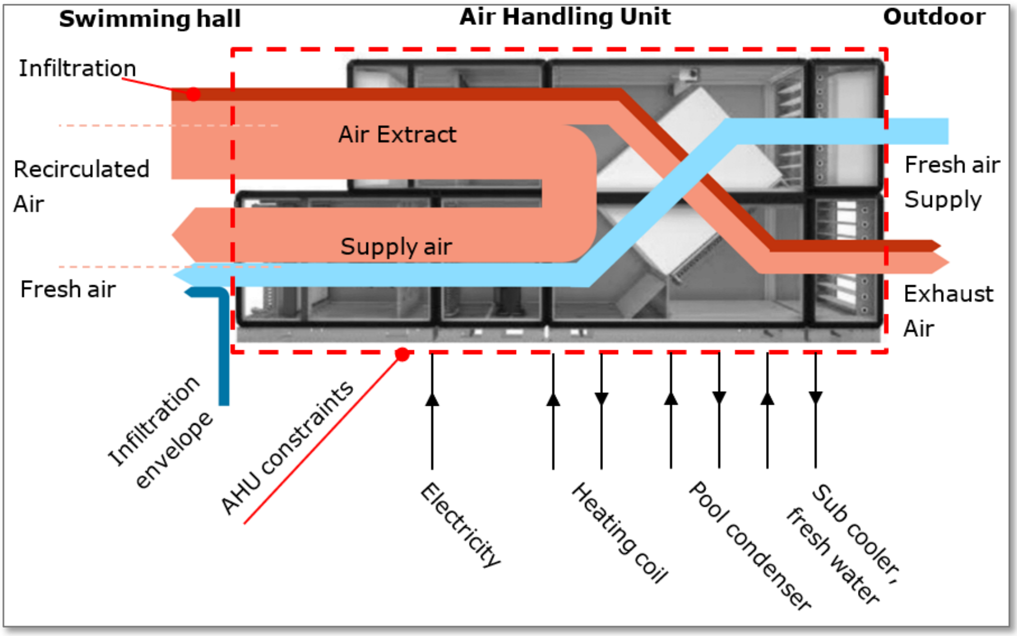


Figure 4 Illustration of the airflows through the air handling unit in "bathing mode".

The evaporation rate from pools is one of the most important phenomena influencing the operation of the AHU in a swimming facility. While the evaporation rate greatly depends on the number of users (i.e., occupancy) and to the occupants' activity level, the air movement, pool water temperature and the indoor air state are also important. The evaporation rate is energy intensive and is controlled by the AHU. Due to the high enthalpy level of the indoor air, the operation of the AHU distinguishes between the operation mode of the swimming facility, defined as "bathing mode" and "night mode". In "bathing mode", the latent heat from the extracted air is recovered by a heat pump while in "night mode", with no required fresh air supply, the entire air flow is recirculated with the purpose of keeping the indoor thermal environment at setpoint. The desired indoor temperature and relative humidity is traditionally kept at a level where the evaporation rate is minimized, since evaporation is a highly energy intensive process. The thermal comfort also needs to be considered with regard to the multiple user groups present in this kind of facility (e.g., swimmers, staff, spectators).

Since the ventilation system normally covers the demand for heating, cooling and dehumidification, the enthalpy level of the supply air varies both in accordance with the outdoor conditions, the operating mode of the facility and the degree of occupancy. This may cause fluctuations in the net energy flow during operation, meaning the energy difference between the supply air and the extract air in the swimming hall. This is due to the variations in latent and sensible heat. Concerning modern swimming facilities, the net energy flow in the air flow will normally be negative.

The heat recovery circuit is a crucial connection in the energy supply of the facility. The connection between the AHU and the water circuit (see the zone C in Figure 1) circulates pool water with the purpose of utilizing the recovered latent heat from the exhaust air. The recovered heat can be used for either air heating and/or water heating. Figure 4 illustrates a typical connection to the AHU, identified as pool condenser and sub-cooler/fresh water.

The pool water circuit comprises a water treatment system, a water refill system and a pool water heater, as illustrated in zone D in Figure 1. This loop keeps the pool water quality and temperature within the required range. The water is purified in order to remove pathogens and disinfection by-products which are demonstrated to be harmful for the swimmers.

The key elements summarized above, and their interconnection illustrates the complexity of the system which makes the operation error prone to where flaws in operation may cause both excessive energy use and result in an improper and possibly harmful indoor environment. The operation of the AHU influences the indoor environment, the evaporation rate, the energy use, the pool heating, the pool water temperature and heat recovery. In addition, the operation of the pool water circuit influences the air quality to a large extent. The pool water quality is determined by filtering, disinfection, and disinfection by-products. Finally, the evaporation rate which extensively depends on the water and air temperatures requires a well-controlled pool water temperature.

A high evaporation rate increases the fresh air demand in the swimming facility, which increases the energy losses. An improper control system or an inappropriate system design may cause relative humidity to rise. This increases the risk of condensation on the internal surfaces of the building envelope. In addition, due to the air density the pressure gradient will get steeper inside the pool hall, which may cause degradation of the construction due to increased exhilaration and moist diffusion. Problems like corrosion and possible accumulation of moisture inside envelope components may also occur.

These internal dependencies show that understanding swimming facilities is important to be able to optimize, improve or investigate their operation. For example, when evaluating the air quality inside the hall, knowledge regarding the control system of the AHU is crucial. During operation, the fresh air supply flow rate fluctuates continuously, which has a direct impact on the dilution of the airborne contaminants. Another example is the multiple elements in the HVAC system where the effect of multiple flaws in operation may counterbalance. This may lead to an acceptable overall energy use and the operational staff may find that flaws are hard to identify. As flaws in the water refill system can hide problems with the AHU and the fresh air supply, there is a need for an operational tool, like a continuous rating system or a fault-detection and diagnostic (FDD) tool, as well as the need to design the system accurately.

2.2 Operation Support of Swimming Facilities

Due to the strong connection between the operation and the energy consumption for buildings (14), the need to pay attention to optimal operation cannot be underestimated. Behavioral and operational management are important (15), as well as well-trained and qualified operational personnel (16). This is especially important for complex buildings with extensive technical installations, like swimming facilities (16). However, for many buildings this is not the case (12), and without a dedicated operational tool, it is a considerable task to run such a facility with satisfactory performance, even for skilled operational staff.

Ruparathna et al. (22) presented a performance rating system for public buildings based on the Level of Service (LOS) index. The index is a qualitative measure, initially developed to assess the quality of traffic services for motor vehicles but applied to buildings in the study. The index indicates the level of operational performance in a holistic perspective, including the building users, society and the environment. In the perspective of operating swimming facilities, this kind of rating system can be a useful tool for the operational staff as a continuous reporting system.

Due to the complexity of a swimming facility, the required amount of performance indicators is considerable. Some, like the level of some airborne disinfection by-products cannot be monitored in real time. Ruparathna et al. (22) implemented measures like user satisfaction, indoor environmental quality, water quality and energy use, among others in their case study. Saleem et al. (23) investigated the required amount of performance indicators to monitor buildings including swimming facilities. Compared to Ruparathna et al. (22) who proposed a set of 22 indicators, Saleem et al. proposed a set of 63 indices. They also considered the above-mentioned water quality, indoor environmental quality, energy efficiency and user satisfaction.

Energy efficiency is considered to be the most important criterion in sustainability rating systems. However, it is the least achieved (24). The need for a system for monitoring the energy performance for the main functions of the building is therefore obvious. Due to the large internal energy flows in swimming facilities, for example caused by heat recovery or the multiple units of equipment, the need for energy monitoring is important due to the increased probability of operational flaws.

2.3 Designing Swimming Facilities

Even with the implementation of a rating system including continuous tracking of the energy performance and the additional adequate performance indicators, a strict monitoring system will only be able to keep the building at the designed level.

Kampel et al. (18) found that the technical system within the swimming facility had a major impact on the energy consumption. They recommended complex heat pump recovery systems with multiple condensers and an integrated design. However, they also recognized the potential for improved energy performance even for the best performing swimming facilities.

In design, complex system layouts require detailed sizing and optimization in order to ensure a well-operating system that serves both the user and the building management as expected. This is also reflected in the building codes, where the Norwegian authorities require dynamic calculations for documenting approved energy performance measures (19, 20). In comparison, for buildings like dwellings, a simplified calculation methodology of monthly averaged data is in accordance with the building code. Paradoxically, dynamic calculations are seldom performed for swimming facilities due to the complexity of the system and the lack of predefined BPS models for the different subsystems. The detailed modeling is both costly in terms of modeling time and it also requires a modeler with in-depth knowledge regarding both advanced/detailed modeling of the facility. The latter includes the control system for the complex indoor environment with water surface(s), multiple interacting HVAC sub-systems, and the heat recovery system. Consequently, technical systems for swimming facilities are usually designed using engineering rules-of-thumb and simple calculation methods. This current practice may lead to significant deviation between the real and expected performance of the building.

In research, the performance of a swimming facility has been widely investigated using building performance simulation (BPS). Regarding energy saving measures, the use of BPS is widely used to support the implementation of different heat recovery concepts and to improve the control strategy. Ribeiro et al. (25-27) investigated the development of a possible energy saving strategy. They studied the benefit of using dynamic set-points for temperature and relative humidity and by customizing the control strategy in a swimming facility by analyzing a case study with the BPS tool ESP-R (25, 27). The same approach was adapted in their study regarding the potential for demand response in swimming facilities (26). However, the study did not specify the model complexity of neither the controllers, the control algorithms nor the actuators. In addition, the case study was carried out for a Mediterranean climate zone where the energy systems differ significantly from the facilities located in northern

Europe. The study reported evaporation as the main energy loss of the facility, accounting for as much as 70 % of the total losses. For facilities in northern Europe, these heat losses are normally considerably lower due to the heat recovery system which partly recovers this internal energy transfer.

The control system of swimming facilities was also treated in the study of Delgado et al. (28). The study estimated energy savings by applying predictive control algorithms in a swimming facility and defined the control settings by using a BPS model of a specific facility (28). Like the studies by Ribeiro et al., this case study was also carried out in a Mediterranean climate, namely in south-east Spain. In addition, the study only considered the thermal behavior of the swimming pool basin and it assumed stable conditions in the swimming pool hall (29). Compared to northern Europe, the HVAC system differs significantly with respect to the interconnection between the pool system and the ventilation system, due to the need for heat recovery. The main reason for the general difference in system design is the large difference in energy costs. While exhaust air heat pump technology is frequently used in northern Europe, facilities in the Mediterranean climate favorize solar energy, due to its availability and low operational cost.

Regarding studies in northern Europe, Westerlund et al. (30-32) investigated the use of heat recovery systems integrated in the AHU in the 90s and early 2000. They presented a calculation method for predicting the annual heating demand. The method was based on calculation in hourly time-steps (30) and was performed with a margin of 5 %, even with an ideal control system, which demonstrated that detailed modeling has only a minor impact on the annual energy use. They also evaluated different concepts of heat recovery systems integrated in the AHU and found that the absorption system achieves the best performance (31), compared to a mechanical heat pump. However, as in the above-mentioned studies, the control system was not introduced in detail. The considered system layout of the AHU does not represent the present design of the AHU in new swimming facilities in northern Europe.

Ratajczak and Szczechowiak (33) investigated the room demands in a swimming facility located in the Polish climate. They divided the swimming hall into zones, each defined and categorized based on its different needs. The holistic study considered the ventilation system and compared different solutions and system layouts. The recommended system was based on several virtual zones where each zone was served by a dedicated ventilation system. The study also considered a traditional ventilation system, i.e., one air handling unit serving the entire swimming facility. The component layout of this system was based on two by-pass-dampers (mixing chambers), an integrated heat pump heat recovery system with both air and pool condenser, a counter crossflow air heat exchanger and a heating coil, which is in accordance with most AHUs in Norwegian swimming facilities. However, the control algorithms differ, and the complexity of the controllers was not treated in the study. The study included a short-term validation of the model over a period of 85 hours and showed good agreement. Due to the northern European climate of Poland, solar energy was not treated (33). The use of an AHU with an integrated heat pump heat recovery system was found to be the most beneficial solution in an economic and ecological perspective for an indoor swimming pool facility (34).

Taebnia et al. (35) investigated the energy performance of air handling units for ice rinks arenas in Finland. Ice rink premises share the technical complexity of swimming facilities. The study was carried out by short-term validation in the BPS-tool IDA ICE (36), which they also applied in their study regarding the development of a simplified calculation method for energy demand (37). They identified a possible reduction of the dehumidification demand by almost 60 %, by precise planning of the AHU layout. This considerable impact of the design process on the energy consumption, indicates the importance of the high-quality BPS model when assessing complex systems.

In addition to the presented studies, several other studies also treat the energy performance of swimming facilities by the use of BPS tools. Each BPS tool was represented with assumptions and complexities applied for both air and water heat recovery systems (38-43), where none of the studies were treating the impact of the model complexity of the controllers. However, Claußand Georges (44) investigated the BPS model complexity of the control system of a residential heat pump. They found that the modeling complexity of the system had a significant impact on the performance and stated that this aspect should not be overlooked. The investigation was carried out as a case study modeled in the BPS tool IDA ICE (36).

3 Method

This chapter describes the research methods and the workflow followed in the thesis to generate results.

3.1 General Approach and Core Idea

The thesis is a part of the activity at the NTNU Centre for Sports Facilities and Technology (SIAT) and is a continuation of Kampel's thesis (8). The main goal is to contribute to improved design and operation of swimming facilities. Kampel disclosed the amplitude of the excessive energy use in Norwegian swimming facilities and compared the energy performance of swimming facilities. He also disclosed how high performing facilities could be recognized.

The workflow of this thesis comprises three main activities: (A) Status of the research in swimming facilities, (B) Improvements in operation and (C) Improvements in the design phase. Figure 5 illustrates the structural overview. This three-fold approach is based on the findings of Kampel (8) where the large variation in energy performance among swimming facilities, and the identification of the characteristics of the best performing facilities, were the key elements. The large variation in energy use between facilities indicates the significant potential for optimizing the operation of the swimming facilities while the complex heat recovery system indicates a need for optimizing the design process.

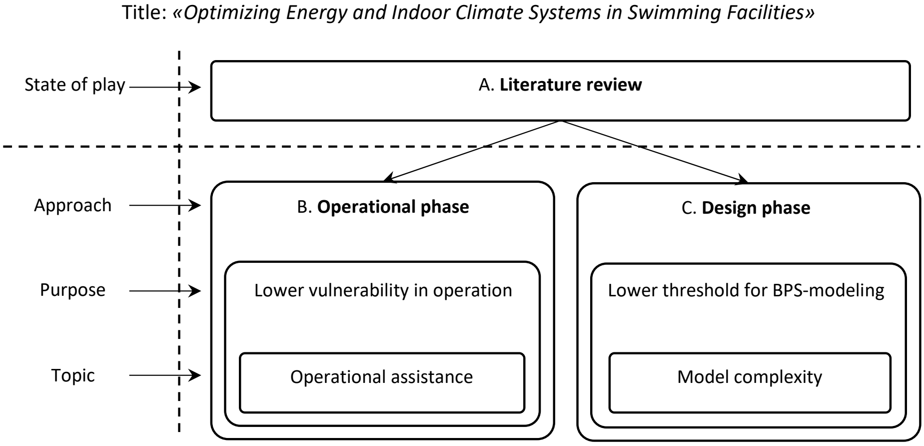


Figure 5 Structural overview of the workflow method of the thesis.

3.1.1 Operational Assistance

Research question #2 addresses energy-intensive operational problems and how to effectively avoid them in swimming facilities. In order to quickly identify and correct operational problems, the basic requirement is that they need be identified immediately. The operator will then be able to take measures and avoid large energy losses. This means that the operator must always have knowledge of the actual energy performance.

The energy performance of any building is defined by the deviation between the actual energy use and the expected energy use. Therefore, to keep the building on track with respect to its expected energy performance it is required to identify actual energy use and to compare this to the expected energy use (benchmark). While the first is straight forward, and solved by implementing energy meters into the system, the latter is not. Inaccurate methods like the average key performance indicators (KPI) for annual energy use are commonly used. For energy intensive buildings like swimming facilities, this method possibly involves a large amount of excessive energy use since the method treats annual energy use. This can be avoided by implementing a tracking system for the energy performance treating shorter periods of time. For new buildings, a tracking system can easily be implemented when constructing the building but for the building stock this possibly requires additional installation of sensors, energy meters and a system for collecting and storing data.

Introducing an energy prediction system with the potential of extensive implementation within the building stock requires simplicity at all levels. The energy prediction will represent the baseline (reference) in the energy performance system. The challenge when developing such a system includes the complexity of the development/method, the implementation and the everyday use (Figure 6). An energy prediction system will help the operational staff to identify flaws in operation and to keep the facility “on track” with regard to energy use and indoor environment.

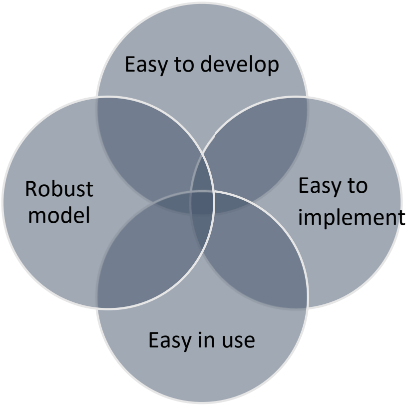


Figure 6 The main constraints of an effective energy performance method.

3.1.1.1 Multiple Linear regression - Developing the Baseline Model

There are several methods for predicting the energy use in buildings including physical/engineering methods as well as statistical and artificial intelligence methods (45). However, considering the above-mentioned constraints the method should be easy to develop. The statistical method "multiple linear regression" (MLR) fulfils this purpose. The method adapts to the characteristics of the building by using measurements as training data and is regarded to be an easy-to-follow statistical method (46). In addition to the simplicity of the developing the MLR model the method can easily be implemented by operational staff even without technical academic competence. A comprehensive description of the method is presented in Paper II.

3.1.2 Model Complexity

Research question #3 address the threshold for applying building performance simulation tools (BPS) in the planning- and design-phases. Paper III aims to solve the question of whether the model complexity of the building performance simulation (BPS) model of an air handling unit in a swimming facility has a major influence on the simulation results. By reducing the model complexity, the time use of energy simulations of such complex systems would be reduced for industry. This will make it easier for the designer to design an energy efficient holistic system. Considering the current lack of requirements in the building code regarding energy use in swimming facilities, the multiple technical systems are usually sub-optimized. This includes the air handling unit, the water treatment system, and the general HVAC system.

In swimming facilities, the air handling unit is the key device in the energy and indoor environment system. This unit controls the thermal environment, the humidity level and the air quality, and recovers thermal energy from the exhaust air. Due to the multipurpose function of the device the control system is complex. Paper III describes the high level of complexity of the control system including several controller groups, demand-controlled ventilation, integrated heat pump, several mixing chambers etc. and answering the question by comparing the calculations results from two BPS models with different complexity. A detailed model serves as a replica model of the real AHU, including a closed loop model approach. The simplified model is defined as a modified version of the detailed model, but with a set of simplifications including an ideal control system, a detached model approach and simplified codes. These models are referred to as the detailed model and the simplified models respectively. The comprehensive description of the development of the physical-based models and the approach is presented in Paper III of this thesis.

3.2 Literature Review Methodology

A systematic literature review can be described as the process of gathering research, filtering records and summarizing the content (47). The purpose of this part of the thesis is to investigate the present research related to HVAC systems in swimming facilities. The literature review was based on the Systematic Literature Review methodology which includes both empirical and theoretical literature (48, 49).

The publications were collected from major databases: Scopus, Web of Science (WoS) and Compendex (Elsevier). The search string was developed with the purpose of mapping the scientific landscape of publications with respect to the research regarding the technical part of swimming facilities. The technical areas of interest were defined as the fields of HVAC and indoor environmental quality (IEQ). The search string was divided into two parts, one describing the facility and describing the field. Figure 7 illustrates the process of creating the raw and unfiltered dataset of records.

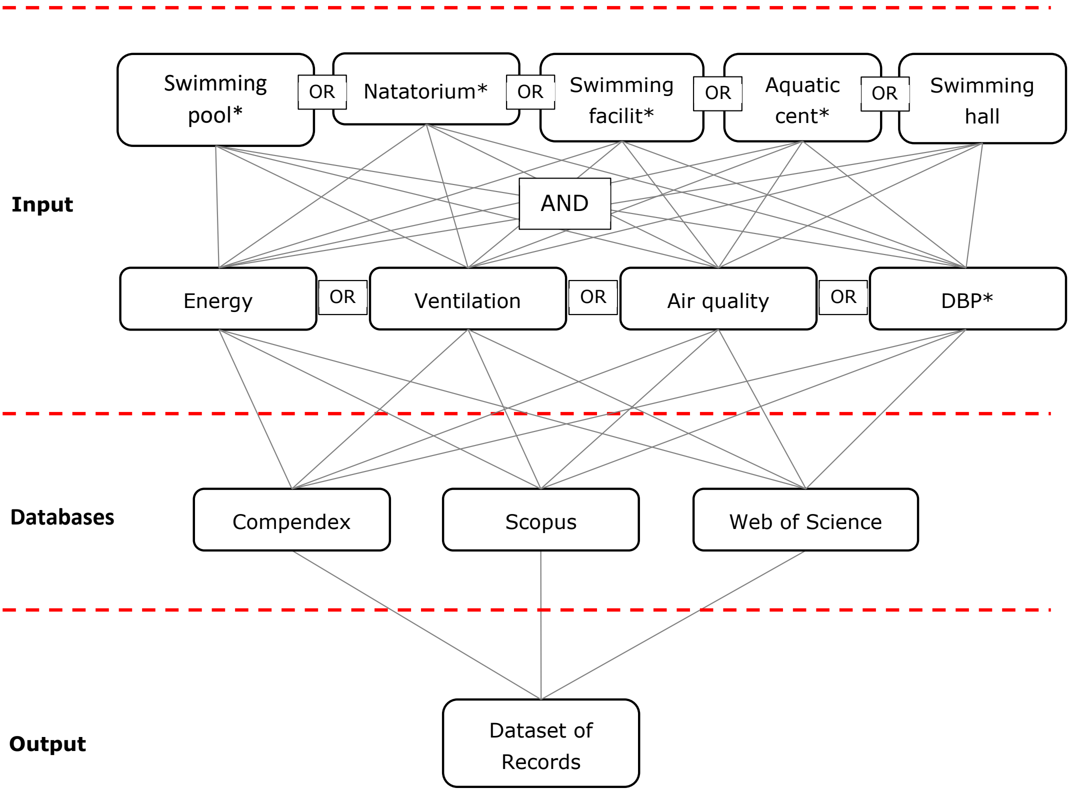


Figure 7 *Illustration of the process of establishing the dataset. *Refer to the truncation symbol in the search string. The truncation symbol allows you to search for all the various endings of a word (12).*

3.2.1 Processing of the Dataset

The dataset of records originally consisted of 1993 scientific articles, which was reduced to 524 articles during the filtering process. The process was divided into four stages:

1. Document type: the records were limited to journal or conference articles,
2. Language: the records were limited to documents written in English,
3. Duplicates: removing duplicates,
4. Relevance: excluding irrelevant records.

During this process, the dataset was analyzed with respect to the source of the records. The relative distribution of databases within the raw dataset was 50 % (Scopus), 25 % (WoS), 25 % (Compendex). After the filtering process, the distribution changed to 80 %, 10 % and 10 %, respectively. The dataset was further analyzed both bibliometrically and thematically in order to map the scientific landscape and depict major trends within the defined broad topic.

3.3 Experimental Data

Papers II and III introduce new methods that are tested using one case study. The selection of the reference facility was based on the need for a facility with well-defined boundary limits and a well-instrumented automation system recording measurement data as well as state-of-the-art technical installations. In addition, the case study should represent a swimming facility representative for the Norwegian building stock and be available within reasonable distance for the author to allow field inspections. Based on these criteria, the multipurpose community center at Jøa, Fyret, was chosen, see Figure 8. The center includes a typical Norwegian swimming pool used for education and activities promoting public health. In Norway this kind of swimming facility represents considerable potential for energy conservation. Buildings with a swimming pool surface area below 300 m^2 constitute approx. 550 out of the 850 existing (65 %) facilities in Norway (8).

Figure 8 The multipurpose sports center at Jøa, Fyret.

3.3.1 Data Collection

The analyzed experimental data for this project was extracted from both the inbuilt building automation system (BAS) and by measurements from additional sensors installed temporarily by the author. In addition, the usage of the pool (e.g., number of users) was collected manually by the operational manager. The collected data had two purposes: (a) Developing a statistical model (Paper II) and (b) the validation and input data for the BPS models in Paper III. The time step for the collected data was 1 minute.

To ensure the development of an accurate prediction method, the number of independent variables was maximized. In the context of question RQ2, identifying the most influencing variables on the energy consumption requires a statistical analysis.

For the physical-based modeling in BPS for RQ3, measurements regarding the important thermal processes in the swimming facility were collected for the investigations. This included both the air state at several locations in the AHU, the pool water temperature, the room air temperature and humidity, the evaporation rate, the air flow rates, and the controller signals. These measurements made it possible to compare the performance of the different components in the AHU with the physical-based models.

3.3.2 Data Processing

For the statistical analysis, the dataset ranged from November 2017 to June 2019, and the dataset was processed by time-averaging the data. Prior to the regression analysis, the minimum period of averaging was identified by investigating the autoregression function of the dependent variable. The partial autocorrelation function (PACF) was applied for this purpose.

Outliers and periods with operation flaws were identified manually by investigating the logged operational data for each of the subsystems in the facility. The training dataset, ranging from November 2017 to June 2018, was cleaned by extracting these periods. The validation dataset, ranging from September 2018 to June 2019, was processed by averaging with the same time steps as the training dataset and by identifying operational flaws. In the validation dataset, flaws were kept in the dataset in order to check if these periods can be identified by the method.

3.4 Numerical Study

3.4.1 Building Model

The analysis of the model complexity was based on a numerical study of the building test case. The building model, presented in Figure 9, has a simple shoebox geometry. It has a ground surface of 266 m^2, a room volume of 1 090 m^3 and a swimming pool surface of 106 m^2 with dimensions of 12.5 m x 8.5 m. Three of the vertical walls and the roof are exposed to the outdoor climate. The model calibration was done using the local climate during a short period of time (160 hours) while the comparison between the detailed and simplified models were done using the typical meteorological year taken at Værnes near Trondheim, in Norway.

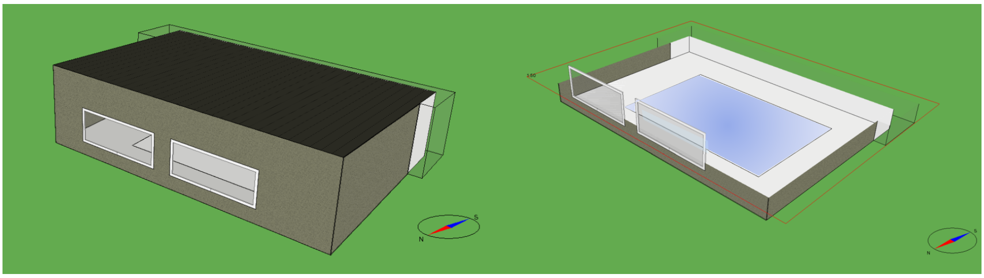


Figure 9 The building model - screenshots from the graphical user interface of IDA ICE.

The swimming facility is heated and dehumidified by the AHU. In reality, the air is supplied along the windows, by the floor, and by textile ducts beneath the ceiling. The air is extracted through an exhaust grill placed on the inner wall. The nominal air change rate at rating conditions is approx. 10 h^{-1}. The air change rate is demand controlled as a function of the evaporation rate, the heating demand and the usage. The air is perfectly mixed in the building model in IDA ICE disregarding the location of the ventilation air supply and exhaust.

3.4.2 BPS Models for the Air Handling Unit

The consequence of simplifying the AHU BPS model was investigated in Paper III which compared the simulation results of two separate BPS models for the case building:

1. A detailed model, serving as a replica and reference of the real air handling unit
2. A simplified model, developed to support the design phase of swimming pools

The detailed model, which was modeled in the BPS software IDA ICE, was based on the collected information and knowledge from the document study. The AHU layout can be recognized as a standard but with some additional components like bypass dampers and an integrated heat pump. The AHU also comprises supply and exhaust fans, a crossflow plate heat exchanger (i.e., not a rotary heat recovery wheel), a heating coil, fresh air and exhaust air dampers. The schematic of the model is presented in Figure 10, and the control system is briefly illustrated in Figure 11. More detailed descriptions of the models can be found in Paper III.

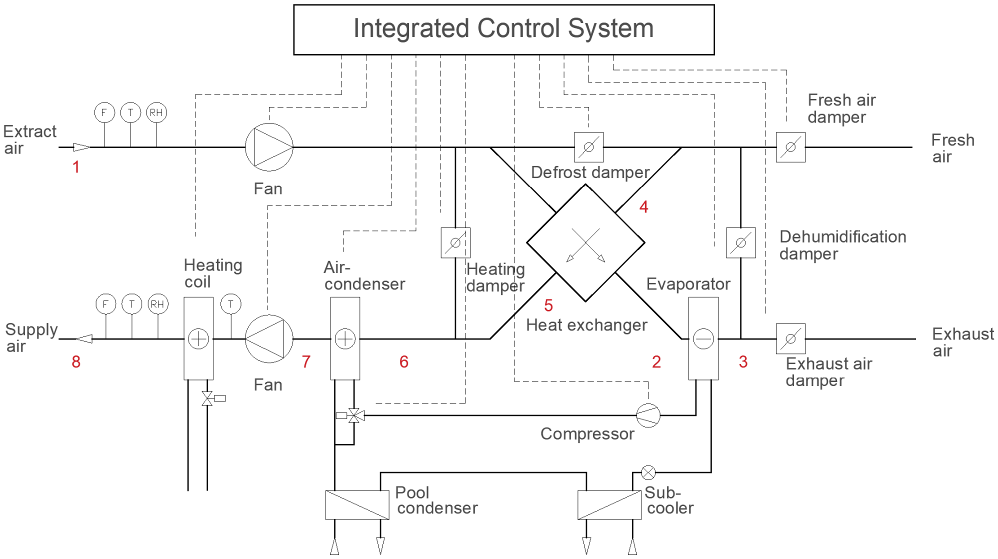


Figure 10   Principle of the design of the BPS-model of the air handling unit (AHU).

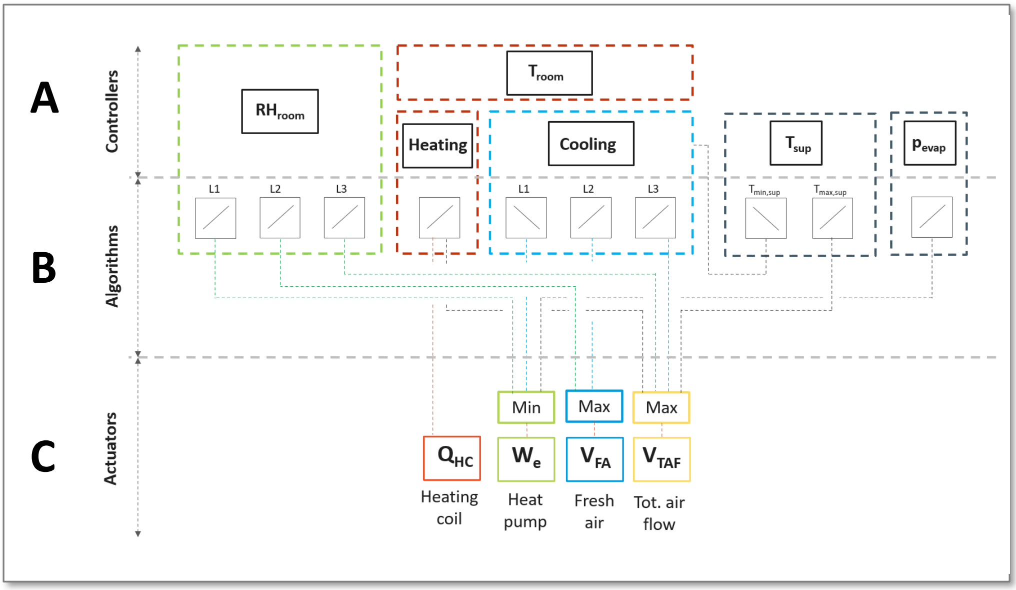


Figure 11   Schematic layout of the control system for a swimming pool AHU. Level A – Controllers; Level B – Algorithms; Level C – Actuators and components.

3.4.3 Verification and Validation

The modeling of several processes needs special attention as they strongly influence energy use. Three key processes were identified: the evaporation rate from the pool and the heat recovery by the air heat exchanger and by the heat pump. Concerning the evaporation rate, this topic is widely discussed in the scientific literature where several correlations and algorithms are presented. However, there is currently no consensus in the literature regarding the best method for predicting the evaporation rate. Some of the most commonly used equations are the ASHRAE equation (16), the VDI equation (50) and the equations developed by Shah (51). In the present study, the ASHRAE equation was used. Several studies have investigated the accuracy of these equations. Shah (51) found that the ASHRAE equation performs fairly well with high occupancy (52) while his own algorithm was found to be the most accurate. Li et al. (53) presented the same conclusion for both the ASHRAE correlation (54) and Shah's correlations for both unoccupied (55) and occupied pools (52). Ciuman et al. (56) found the VDI equations (50) calculated the most accurate evaporation rate in their study. They were comparing the calculation results from Carrier (57), Smith et al. (58), Shah (51), ASHRAE (54), VDI (50) and Biasin and Krumme (59). These discordant results illustrate the uncertainty when calculating the evaporation rate.

The air heat recovery effectiveness is another key variable in the AHU of a swimming facility. In ventilation systems without variable air flow control (i.e., constant air volume, CAV), the efficiency may be reasonably assumed to be constant. However, applying the same approach to swimming facilities with a variable air flow rate (VAV) will lead to large modeling errors, leading to erroneous air states within the AHU and energy consumption. For swimming pool AHU, the heat exchanger is normally a crossflow plate heat exchanger due to corrosion issues. These are delivered with a supply air side thermal efficiency of about 60 %, calculated with Equation (1):

$$\theta = \frac{(t_{sup} - t_{outdoor})}{(t_{ext} - t_{outdoor})} \tag{1}$$

Due to the continuous variation in the fresh air supply, and thus the airflow rate through the heat exchanger, the thermal effectiveness will vary accordingly. In operation, the airflow rate ranges from 60 to 100 % of the nominal value. Figure 12 shows the measured supply air side temperature efficiency of the heat exchanger. The presented data are averaged values for 15-minute periods, collected over a period of one week, from May 3, 2019 to May 10, 2019. The outdoor dry-bulb temperature ranged from approx. 0°C to 15°C for the presented series of data. The presented data also illustrate the efficiency variation of the heat exchanger, and the large portion of time the device is operating at part-load with respect to the fresh air supply. However, Figure 13 and Figure 14 illustrate the calculations results from the IDA ICE model and the NTU model implemented in the simplified method, respectively. While the IDA ICE model overpredicted the heat exchanger efficiency, the NTU method underpredicted it. However, since the deviation increased when the air flow rate dropped, the result of this can be limited. This is discussed further in Chapters 4 and 5.

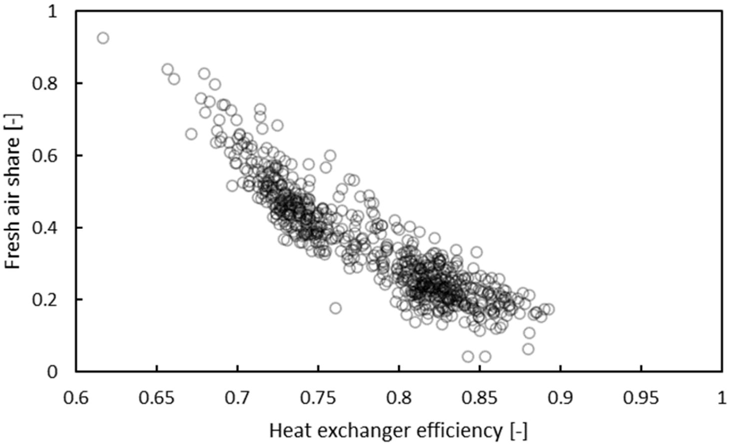


Figure 12 Supply air side heat exchanger efficiency. 15 minutes averaged data for a period of one week.

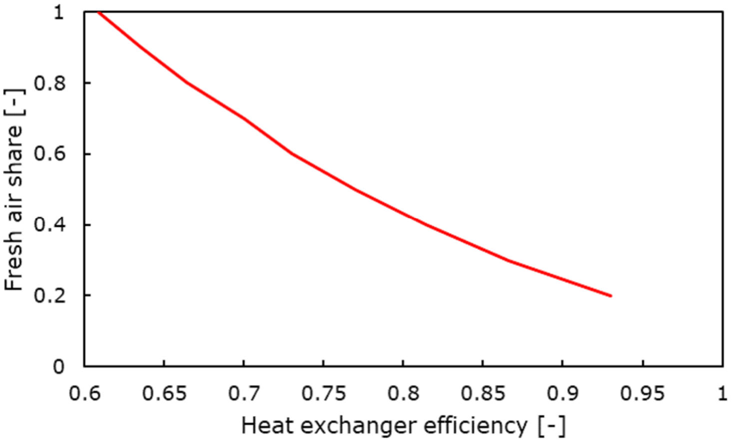


Figure 13 Supply air side heat exchanger efficiency. Calculation results from IDA ICE.

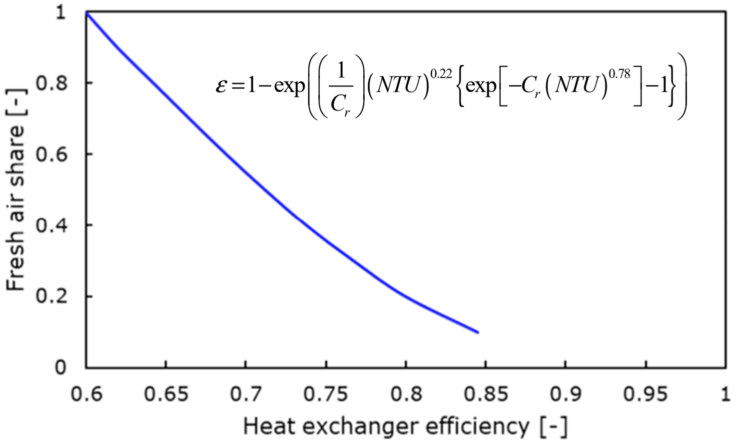


Figure 14 Supply air side heat exchanger efficiency. Calculation results from the simplified NTU model.

3.5 Document Study

A document study was carried out prior to the investigation of the case study. Typical documents of interest were manuals and technical specifications of the equipment in the case study. These documents specify rating conditions and sizes of components and devices but are not complete in their description. The limitations concerning incomplete descriptions are due to the intellectual properties related to some equipment where the suppliers want to protect their technology from their competitors.

4 Results

4.1 Literature Review (Paper 1)

While the title of the PhD defines the focus and the field of the project, the literature study defined the gaps within the research area and the path for the subsequent work and studies. This involves both the technical areas included in the present research and the scientific landscape.

Swimming facilities are defined by their requirements regarding air quality, water temperature and quality, thermal comfort both in the room and in the water, and its considerable thermal and electric energy demand. All topics, as defined in Figure 15, can be found in the context of swimming facilities in research.

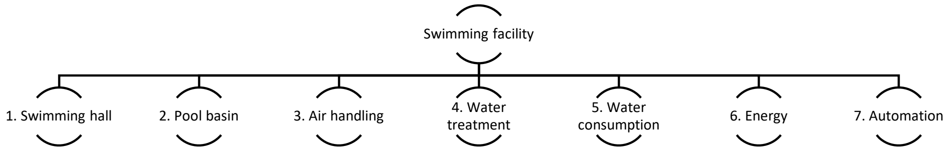


Figure 15 The defined main topics of swimming pool research (12).

For these specific areas, a large number of scientific publications have been published worldwide through the years. In general, the area is found to be relatively new and 75 % of the articles were published within the last two decades. This demonstrates the considerable relevance of the research. However, this also challenges the industry to keep track of the relevant findings that need to be implemented. The gap between the research findings and the current practice in industry has been identified. Regarding the origin of the research, it was discovered that 80 % of the scientific publications can be found in the scientific database Scopus, and for the last two decades this has increased to 85 %. The last 15 % of the records can exclusively be found in either Compendex or Web of Science. However, the area of HVAC is fragmented both with respect to the journals and by research groups (involved in multiple publications). This selection of publications represents 154 publications for the past two decades, written by 290 authors where only five authors are represented by three or more publications. Worldwide, only two research groups are found to have a focus on multiple publications. These groups have both focus on energy use in swimming facilities and are represented by Rajagopalan (60-66) in Australia and Bruland (7, 67, 68) in Norway.

Regarding the research topic, the articles can be categorized by their main focus, either disinfection by-products (DBP), solar energy or HVAC. In total, DBP-related publications represent almost half of the research found in the literature. However, while the found research is in the context of swimming facilities some relevant records may be missing. This may be general areas that do not necessarily address swimming facilities, such as ventilation in large spaces, disinfection, and humid air. In addition, the dataset is also limited to not include all technical areas in a swimming facility.

Areas which are not included are acoustics, corrosion, specific tasks related to building physics, construction, lighting systems and illumination/glare etc. This consideration is within the objective of the project.

The energy topic was found to be the most focused area in the selection of HVAC-related publications. The keyword “energy” was found in about 80 % of the publications, which was expected due to the climate challenge and the worldwide focus on energy and greenhouse gas reduction.

Taking into account the urgent need for GHG reduction (69), measures should have an immediate effect, also for existing buildings. Swimming facilities are recognized as a type of building with both energy intensive properties and a large variation in energy use within the category (7-10, 70), which implies a considerable potential for energy reduction. In general, energy use is considered to be the most important criterion in sustainability rating systems but the least achieved (24). In addition, the present rating system, like the energy labelling (71), is only a tool and an instrument for the design phase of the building and not in operation. This issue is addressed in RQ2 in Paper II.

However, the design phase of swimming facilities has a considerable impact on the energy performance of the building, where the layout of the most energy effective system includes a high level of complexity (18). For such complex buildings it is required by regulations to provide documentation of the energy performance of the building carried out by dynamic simulations (19, 20). For swimming facilities, this is seldom done in the Norwegian building industry due to the complexity of the buildings. This issue is addressed in RQ3 in Paper III.

4.2 Monitoring real energy performance using in-situ measurements

An energy prediction model based on the MLR method was developed where the case study building was used as an example. For training data purposes, usage data were extracted from the building automation system (BAS) for the first year of operation after the building was approved and commissioned. However, a newly commissioned building may have flaws in operation, which the process of cleaning of the dataset confirmed. The original training dataset ranged from November 2017 to June 2018, but due to flaws in operation the training dataset was reduced to March 2018 to June 2018. The dependent variable, the energy consumption of the swimming pool facility, was investigated for autocorrelation where the variable was found to be independent in time when averaging the data for time steps above three days. In the final dataset prepared for training the model consisted of 29 datapoints.

4.2.1 The Variables

The independent variables were chosen due to relevance and availability, considering the constraints defined in Figure 6. From the known dependency between the energy consumption in buildings and outdoor climate (72) and user-interference (8, 61, 72), these variables were defined.

The outdoor climate, with respect to dry-bulb temperature and relative humidity, is normally monitored, and historic values are usually stored in the building automation systems of swimming facilities. From these measurements the following variables were introduced in the regression analysis as independent variables:

- Outdoor dry-bulb temperature [°C] - measured
- Absolute moisture content [g/g] - calculated
- Enthalpy content [kJ/kg] - calculated

The outdoor dry-bulb temperature influences the sensible heating demand with respect to conduction losses and heating of the fresh air flow into the building. With the distinct hot and humid thermal environment in swimming facilities, it is obvious that this variable has a major impact on the energy use. However, the fresh air supply in swimming facilities is controlled by the indoor humidity level where the dehumidifying is based on dilution of the indoor air volume with the dry outdoor air. This implies that the moist content of the outdoor air has a major impact on the energy usage as well as the enthalpy content. As Table 1 summarizes, these variables are strongly correlated even though they represent different properties and combinations of properties of the outdoor air. The single most correlating variable with the power consumption is found to be the moist content of the outdoor air.

Concerning the user interference in swimming facilities this is both due to evaporation from the pool and wetted surfaces (73) and to the minimum required fresh air flow. In addition, the user intensity also has an impact on the water usage including the make-up water after filter flushing and evaporation. Regarding the evaporation rate, a high activity level will increase the evaporation rate. The following independent explanatory variables were defined:

- The pool usage factor, i.e., the relative portion of time the pool is occupied
- Number of adults in the pool
- Number of children in the pool
- Water supply to the pool circuit

Registration of the occupancy identified both the number of adults and children. Since this only addressed the number of users and the date of the bathing activity, the exact bathing period was not provided. For this purpose, the historic data regarding the water level in the equalization tank was collected and utilized. Figure 16 visualizes an example of 2.5 hours of operation, where the water level is shown to reflect the usage of the pool. This information formed the "Pool usage factor".

Table 1 Correlation matrix. The internal correlation between the variables included in the dataset, given as the Pearson correlation coefficient. Based on the dataset averaged for 2-week periods.

	Power consumption	Outdoor temperature	Enthalpy difference	Moist content	Water flow	Number of adults	Number of children	Pool usage
Power consumption	1							
Outdoor temperature	-0.75	1						
Enthalpy difference	0.79	-0.95	1					
Moist content	-0.82	0.96	-0.97	1				
Water flow	0.07	0.40	-0.19	0.18	1			
Number of adults in pool	0.11	-0.44	0.38	-0.40	-0.15	1		
Number of children in pool	0.21	-0.28	0.29	-0.34	0.09	0.52	1	
Pool usage, bathing time	-0.21	0.25	-0.17	0.24	0.18	-0.18	-0.35	1

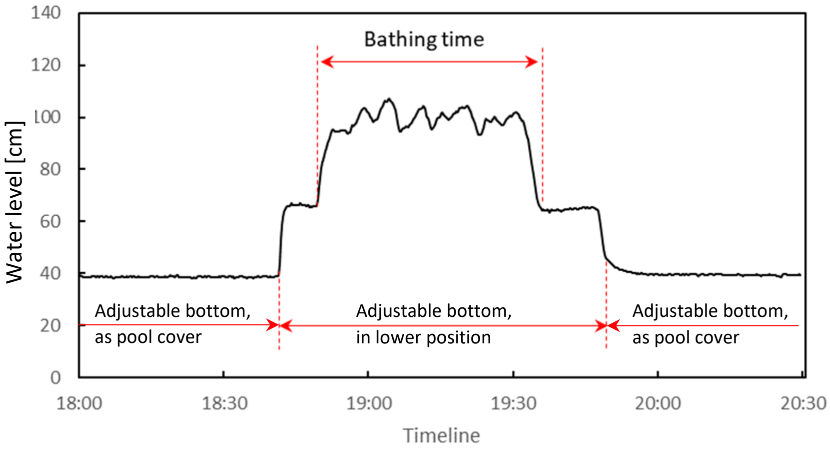


Figure 16 Water level in the equalization tank located in the pool water circuit.

4.2.2 Analyzing the Data and Training the Model

The historic data indicate that the total power consumption of the swimming facility is greatly dependent on the operating mode of the facility, "bathing mode" or "idle mode". By plotting the power consumption against the outdoor temperature two clusters were identified, Figure 17. Since the operation of the swimming facility is defined by the dehumidification method, where the integrated heat pump is operated as an energy recovery unit in "bathing mode" and as a pure dehumidification device, the entire amount of waste heat from the dehumidification process is recovered in the facility. Besides the programmed operation of the facility, the users are also influencing the energy consumption by the increased evaporation rate from the pool which adds up the difference in power consumption between the operation modes.

As Table 1 describes, the power consumption correlates with the outdoor conditions. For this dataset it can been illustrated as shown at Figure 18 where the power consumption is sorted and presented with the corresponding outdoor temperature. Also, this chart identifies the two operation modes by their influence on the power consumption.

The best fitted model describing the power consumption of the swimming facility was found to consist of two variables, the outdoor temperature and the pool usage factor (17). These variables were found to describe the 3-day average power consumption with an R^2 at 0.87 and a prediction interval at 1.86 kW. Figure 19 gives the resulting equation of the regression analysis, which describes the relationship between the power consumption and the two variables.

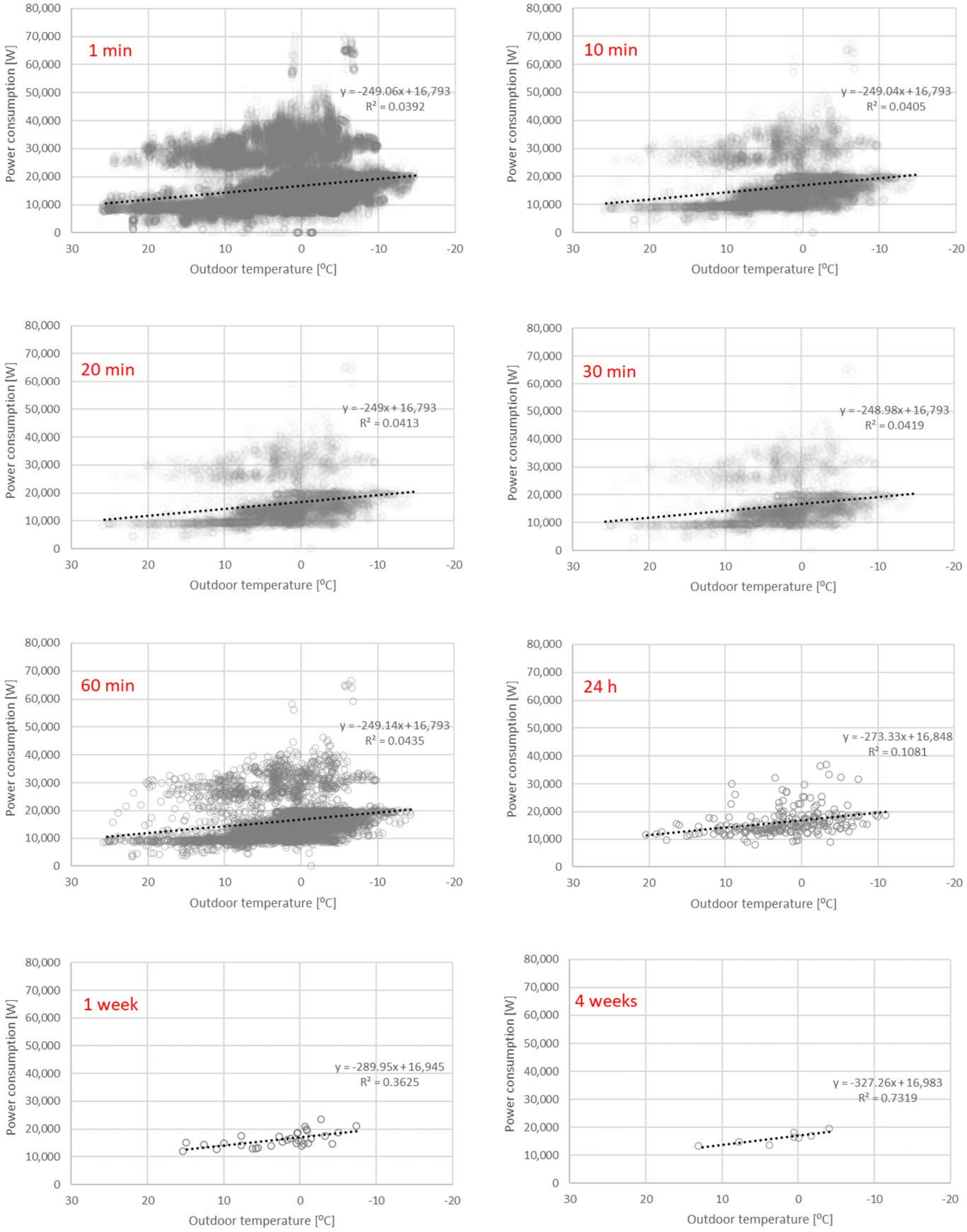


Figure 17 *Averaged total power consumption plotted against averaged diurnal outdoor dry-bulb temperature when the dataset is averaged from 1 min to 4 weeks (17).*

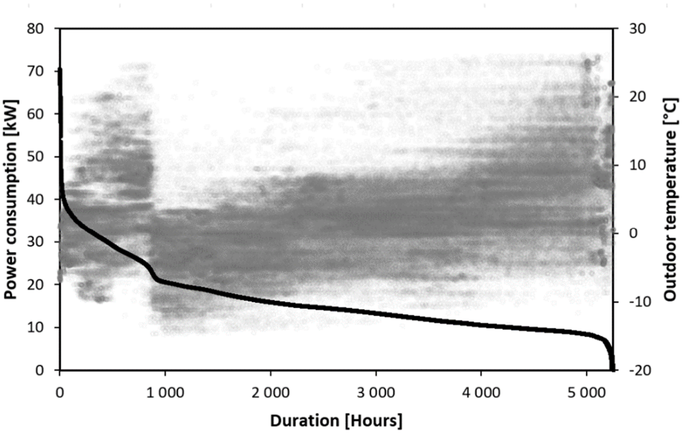
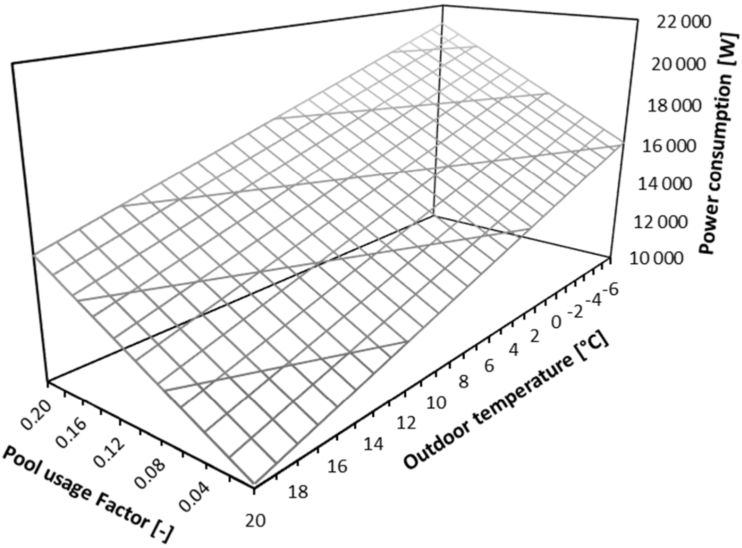


Figure 18 Power consumption presented as a duration curve along with the corresponding outdoor dry bulb temperature.



$$\dot{E}_{tot} = 17{,}715 - 227.8 \cdot T_{out} + 24\,790 \cdot t_{pu}$$

Figure 19 3D-plot of the regression equation from the regression analysis. Variables as three-day averaged values. $\dot{E}_{tot}$ = Power consumption, T_{out} = Outdoor dry-bub temperature, t_{pu} = Pool usage factor.

4.2.3 Validation and Application

The applied value of the baseline equation in Figure 19 is shown in Figure 20 where the baseline equation is validated against the consecutive operating year. The energy prediction equation was shown to predict the energy consumption well when the facility is operating without flaws. This means that when the energy consumption deviates from the expected energy use, the baseline, this is caused by operation disruptions. For the whole year validation several operation flaws were identified, referring to Figure 20:

(A) Uncontrolled water refill

(B, C) Issues with the control system of the water temperature

(D) Issues with the control of the indoor environment and the water refill system, leading to a consecutive lockdown of the facility

(E) Issues related to the control of the air handling unit and the air flow supply.

The flaws were identified by in-depth investigation of the dedicated AHU-control system, the pool circuit system and the overall building automation system (BAS). The prediction model was able to identify the disruptions as illustrated.

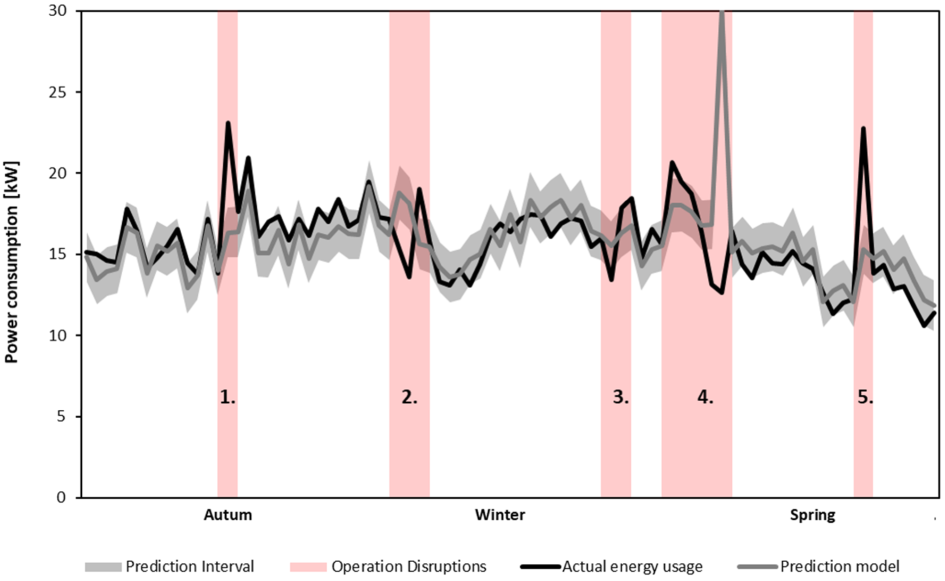


Figure 20 Visual validation of the prediction model from September 2018 to June 2019. The prediction model includes the prediction interval in gray, measured power consumption in black and periods associated with operational disruptions in red (17).

4.3 Model Complexity

The detailed model was initially validated with measurements from the case study over a period of approx. one week. The validation showed good compliance between measurements and calculations, Figure 21, and based on that it was used as a baseline in the comparison with the simplified model.

The validation data were divided into three main variables:

- Air temperature, supply and extract air flow [°C]
- Vapor pressure, supply and extract air flow [°C]
- Air flow rate, extract air [m^3/h]

The calculations were in compliance with the measurements. The extract air temperature was represented with a minor deviation. However, this was expected since the extract air temperature is controlled to have a fixed level. The supply air temperature was seen to deviate in periods. This deviation partly addresses the user interference of the system. This means that during an inspection of the facility it was observed that doors were left wide open. Such actions lead to an undesirable increase in energy use since the air handling unit had to operate with higher supply air temperatures. Such effects are obviously not a part of the detailed model operation schemes.

Since the case study facility lacks a weather station for recording of the outdoor humidity, solar radiation and wind, and the location of the facility is rural without any nearby meteorological weather station, the validation weather data was generated (74). The compliance between the generated weather data were evaluated by comparing measurements with generated data of the outdoor dry-bulb temperature measurements. Figure 22 shows the comparison, where the deviation is represented by an approximately 0.4 K difference in the average temperature during the validation period.

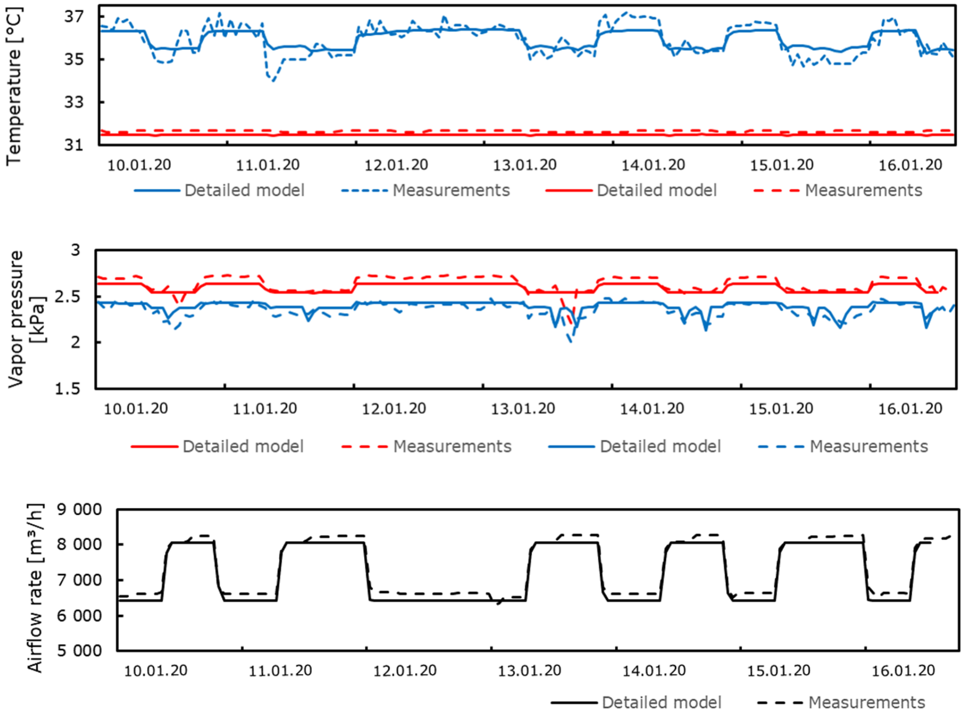


Figure 21 Validation results for the supply air (blue) and extract air (red) – temperature and vapour pressure – as well as the air flow rate for the extract air.

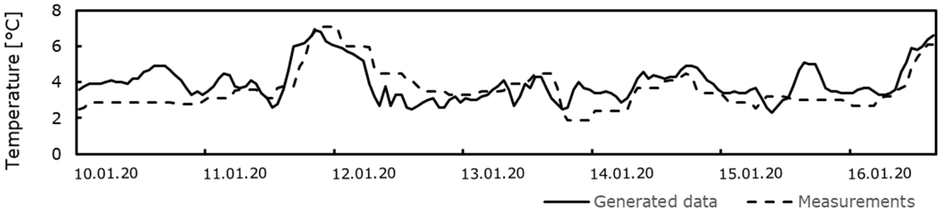


Figure 22 Validation results for the weather data. Comparison of measured and generated outdoor dry-bulb temperatures.

4.3.1 Comparison

Paper III investigated the performance of the detailed model and the simplified model. For the simplified model an initially dynamic whole year simulation was carried out with the purpose of identifying extraordinary operating modes. Based on controller signals four scenarios were chosen for the steady-state investigation, as illustrated in Figure 23. The scenarios were summer and winter conditions in both "bathing mode" and "idle mode". The models were investigated by:

- Airflow rates and air states in the air handling unit
- Coefficient of performance (COP) and power consumption for the heat pump
- Thermal power consumption for the heating coil
- Fan power
- Waste heat potential
- Energy consumption for the heating coil, compressor, fans and waste heat potential

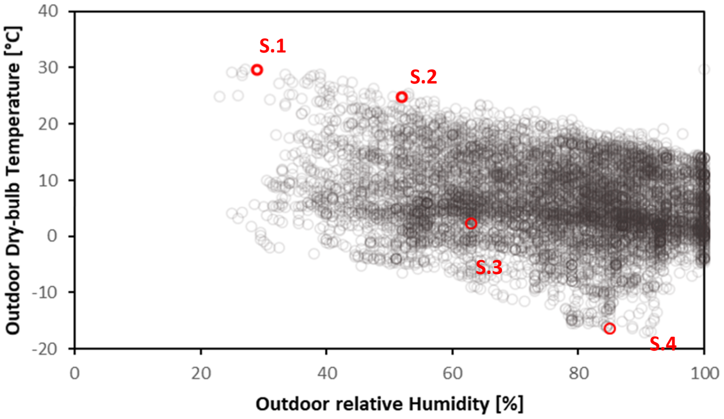


Figure 23 Outdoor dry-bulb temperature vs. outdoor relative humidity for the weather file. The identified scenarios are marked in red.

4.3.2 Analysis and Results

The results from the comparison were evaluated with respect to airflow calculations, air states and energy use. Summarized, the accuracy of the simplified model was found to be in good compliance with the detailed model, when applied to the facility at rating conditions. The fresh air ratio and volume flow rate were both found to be within a deviation of 5 % for all scenarios, see Figure 24. Moreover, the accumulated deviation of the calculated enthalpy level was in all cases below 5 kJ/kg, for both airflow sides in the air handling unit (AHU), Figure 25. When considering the energy use over a whole year only minor deviations were found between the models, Figure 26. Bearing in mind the room heating and dehumidification demands dependencies on the AHU and vice versa, this demonstrated that the detached approach only gives minor discrepancy in all the extreme cases. However, due to the simplified component models, idealized control system and the detached model approach, some considerations should be made when applying this model. Even with the good compliance between the models the detached approach should be applied with caution. For evaluation of distinct operation conditions, it is necessary to include the response of the building model due to the influence of the AHU on the indoor environment variables (temperature, RH and airflow). In such cases the detailed model should be applied due to the closed-loop approach and the AHU with its controller groups that influence the indoor variables (temperature and relative humidity). The closed-loop approach includes the interaction between the AHU and the swimming hall and is therefore suited for including the performance where the lay-out of the controller groups is included. For example, the use of the integral-term in the PI-controller, which is controlled (on/off) in the detailed model, has a direct impact on the state of the system and propagates into to both sensible and latent energy demand.

Even though the simplified model was found to provide calculation results in accordance with the detailed model, it was found to underpredict the air flow rate through the air heat recovery exchanger, with minor deviation. This is due to the above-mentioned steady-state error in the detailed control system which interfere with the design conditions with respect to both temperature and relative humidity. This affects the evaporation rate and therefore the supplied fresh air supply rate to the swimming hall. For scenario 4, Figure 23, bathing mode in winter condition, the simplified model was found to slightly overpredict the air flow rate by 5 % deviation.

The heat exchanger models were also found to differ in performance, where the simplified model calculated a lower heat recovery rate than the detailed model. This was as expected, ref. Figure 12, Figure 13 and Figure 14. However, since the deviation increased when the airflow rate decreased, it will not lead to any significant discrepancy. This is also shown for the calculated accumulated deviation in enthalpy level in Figure 25.

The deviation in energy demand for the key components is illustrated in Figure 26, where the accumulated deviation over a whole year simulation is presented, Figure 26E. Despite the overall good compliance, the calculated amount of waste heat was seen to stand out. In the simplified model the waste heat potential was overpredicted in "bathing mode" and underpredicted in "idle mode". The deviation was both due to very different calculations concerning evaporator and condenser capacities (heat transfer to air and pool water) and a more accurate waste heat circuit modeled in the detailed model, where the pool water temperature had a large impact on the condenser temperature in the heat pump. Since the pool water heater including the control system was not included as part of the analysis in this study, the waste heat presented in Figure 26 was calculated as the maximum amount of waste heat, without considering the heat sink. In the case study building this was handled by also controlling the heat pump by the availability of a heat sink, i.e., the potential for air heating or pool water heating. However, this underlines the importance of a well-designed system which preferably is prepared for utilizing this amount of heat. Regarding the latter, the operating strategy for the heat recovery system was found to prioritize itself without any consideration of the value of the alternative heat sources. This can be the optimal strategy for swimming facilities located in regions with a high energy cost such as electricity. For facilities with alternative heat sources like high-efficiency heat pumps, natural gas, district heating and industrial waste heat this is not necessarily the optimal control and should preferably be modified. However, during the completion of the study, the obstacle regarding business secrecy was revealed. To implement the exact control strategy was therefore found to be impossible. This study used all available information along with the knowledge collected during onsite inspection of the device. This is usually not possible in ordinary engineering projects and such modifications need to be carried out by the manufacturer. This also makes it impossible for the research community to investigate these highly complex control systems.

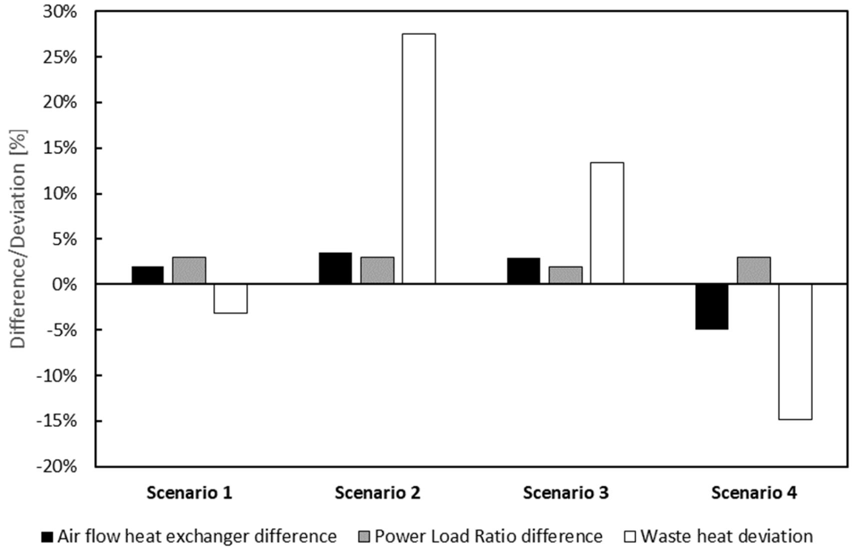


Figure 24 Discrepancy between the calculation results for the "detailed model" and the "simplified model" with regard to air flow rates and waste heat. The differences in air flow rates are given as the absolute difference in the calculated air flow ratio while the calculated waste heat is given as the deviation in the detailed model results, compared to the simplified model.

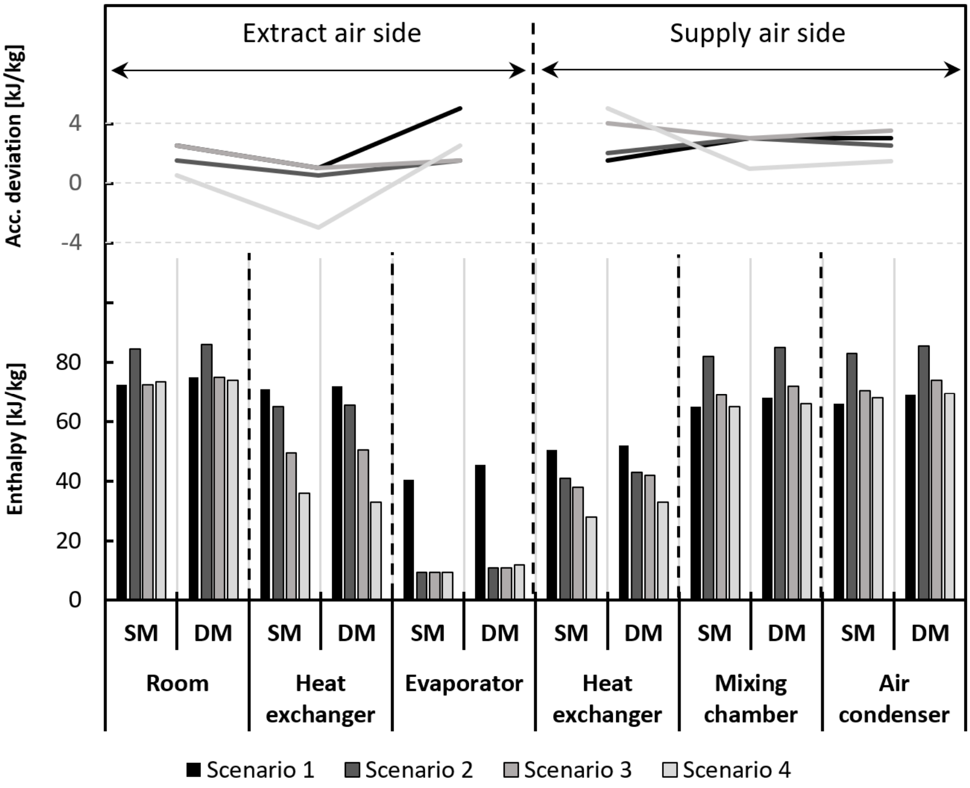


Figure 25 Enthalpy levels for each stage in the air handling unit presented for each scenario and model. Deviation is given as relative to the simplified model. SM = simplified model, DM = detailed model.

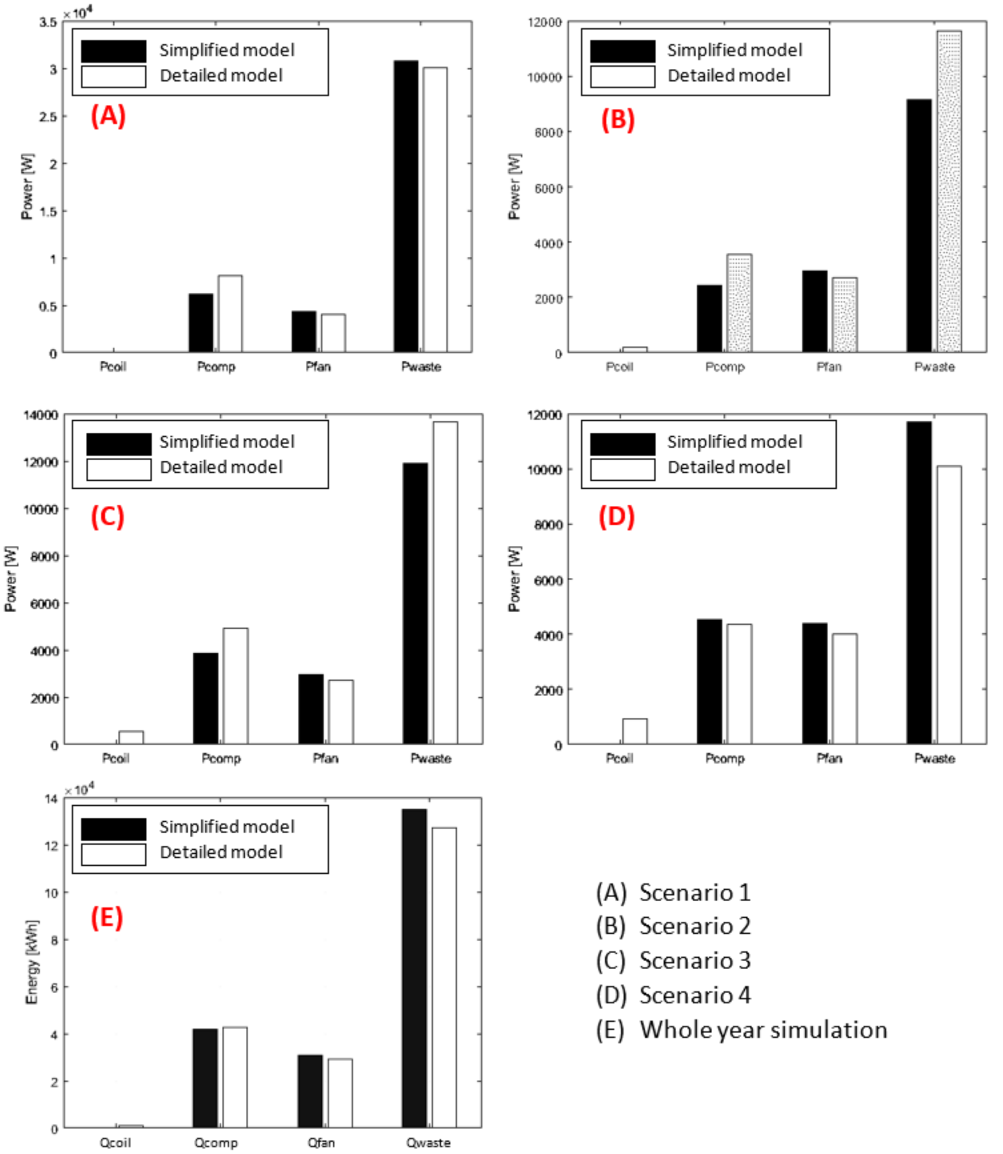


Figure 26 *Power supply related to essential components in the AHU (P_{coil} = heating coil, P_{comp} = heat pump compressor, P_{fan} = AHU fan, P_{waste} = pool condenser heat). Annual energy use is given as Q_{coil}, Q_{comp}, Q_{fan} and Q_{waste}.*

5 Discussion

5.1 Methodological Considerations

This study includes a wide range of calculated and collected data from the field. This chapter provides a detailed discussion regarding the method and how the encountered challenges were treated.

5.1.1 Data Collection

The data collection was a major challenge in this study. In order to develop concrete tools that were suitable for industry and the building sector, the research design included the use of a case study to answer RQ2 and RQ3. This required basic information and knowledge regarding operation, system design and usage, collected from the test facility.

The strength of the case study is demonstrated by the detailed information from the in-depth investigation and exploration of a swimming facility in operation. This gave valuable information regarding both potential issues in operation and actual performance. However, the challenge with case studies is to establish general relevance of the results due to the uniqueness of the building, the outdoor climate, the usage and the quality of operation. The case study building was chosen due to its generality since swimming pools at this size range represent approx. 65 % of the swimming facilities in Norway (8). The newly commissioned case buildings also had an extensive building automation system, which made it possible to collect a wide range of measurement data.

Furthermore, swimming pools in schools are also characterized by the simplicity of the technical system which makes it transferable to larger swimming facilities. The system contains the same basic components as larger facilities but has a sparser layout which is an advantage when evaluating the system.

A challenge regarding the selected case study building was the age of the building. Since this is a newly commissioned building, which is provided with the latest in commercial technology and with building requirements beyond the requirements in the prevailing building code, the building does not represent the average swimming pool facility within the building stock. However, for the purpose of this study this was considered as an added value. The state-of-the-art facility provides the possibility to evaluate and optimize the process regarding design and operation of today's swimming facilities. Also, in the state-of-the art building automation system (BAS) in the case study all the operating data in the system is logged into one top system. This made it possible to extract historical data from the facility for a long period of time. In addition, the manufacturer has carried out annual service including calibration of sensors, which makes the logged data in the system reliable for the purpose of this study.

One of the challenges with swimming pools in schools is the logging of the occupancy, i.e., number of users and period of use. While larger facilities normally are provided with entrance systems which log both the number of visitors and residence time and the duration of the stay in the facility, school pools normally do not do this. However, for the case study building the users were instructed to complete handwritten registration for every visit. By combining the digitalization of the handwritten log and by utilizing the logged measurements of water level in the equalization basin, see Figure 16, the usage of the pool could be included into the dataset of measurements. This two-fold process also contributed as mutual quality control. The same process of quality checking was also applied to the collection of operating data that was either extracted from different sub-systems or external parameters, like weather data.

5.1.2 Document Study

To answer RQ3, which aims to help the designer overcome the obstacle of model complexity, all available documentation regarding the air handling unit was collected. This information contributed to the foundation of the modeling of the replica model. The information included technical documentation of the air handling unit, which gave key information about the controller with their tuning parameters (gain and integral-time) and the control strategy itself. However, some essential information regarding the control system was not provided in this documentation due to trade secrets. In order to get the building performance simulation (BPS) model to be as similar as possible to the real device, an in-depth inspection of the device was carried out along with conversations with the supplier and the operator. The model was validated over a short period and found to provide calculations close to the measurements. However, the model must be considered as an interpretation of the real device.

5.1.3 Measurements

Measurements for Papers II and III were collected from the case study building. For the purpose of the study presented in Paper II measurements were collected from the building automation system for both the training dataset and the validation dataset. Since it was required to have data ranging over two operating years due to the need for seasonal variations in the outdoor conditions and an extensive validation period, the data were collected from the building itself. For the purpose of training data this added value for other facilities where all the data were collected from the facility itself without requiring additional equipment. However, the system was not prepared for extensive data collection, and measurements had to be downloaded manually for every half week. This added an additional source of human error uncertainty to the dataset. A quality control of the downloaded dataset was therefore carried out after each session of data extraction.

Due to the lack of weather data measurements in the case study, building data from the nearest meteorological weather station was collected and applied to the training dataset. The meteorological weather data was compared to the local outdoor dry-bulb temperature which proved satisfactory compliance. Only the humidity component from the meteorological weather data was applied in the dataset. The atmospheric pressure was set to constant 1013 mbar.

For the short-term validation applied in Paper III, the weather file containing information regarding temperature, relative humidity, solar radiation and wind was generated (74). The weather data for the validation period were compared to the outdoor dry-bulb temperature and found to have acceptable compliance considering the purpose.

The investigation of the performance of the cross-flow heat exchanger was highly dependent on the sensor placement in the outlet airflow due to the non-uniform temperature profile. This issue was solved by measuring the temperature profile and averaging the temperature. The resulting calculated performance is shown in Figure 12.

Another source of the overall uncertainty when evaluating the swimming facility and validating the BPS model, was the measurement of the room air temperature, since it was measured in the extract air duct and not in the swimming hall. In order to fulfill this assumption, it was required that the ventilation system provides a fully mixed air distribution. The case study facility is represented with an air change rate per hour (ACH) ranging from approx. 10.8 (nominal) to 6.5 (idle mode). Taking into account the placement of the air supply and extract terminals, this is considered a correct assumption. The fully mixed room air was also proven in the tracer gas experiment of the case study (75).

5.1.4 Statistics

One of the important assumptions when applying multiple linear regression in Paper II is a linear dependency between the dependent variable and the independent variables. This assumption is also applied in this study. It was also assumed that the variables are normally distributed. The distribution of the three-day averaged power consumption from September 2018 to June 2019 is presented in Figure 27. Based on the visual inspection of the chart, the assumption of normal distribution was confirmed, even though the distribution was not perfectly bell shaped. The Pearson correlation coefficient was applied for the evaluation of the multicollinearity.

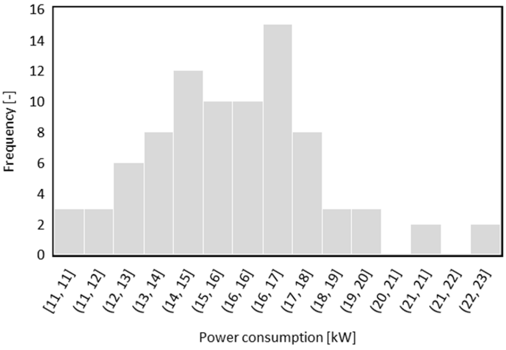


Figure 27 The distribution of the three-day averaged power consumption for the case building at Jøa from September 2018 to June 2019.

When applying the multiple linear regression method, the chosen dependent variable should be independent of itself. This means that the method cannot be applied for energy use in buildings over a short period. This is due to the time constant of the building where the thermal mass makes the energy use dependent on itself. This can be avoided by averaging the data over a time period. For this study the minimum averaging time period was found by applying the partial autocorrelation function, which specifies the number of past lags that has an influence on the dependent variable.

5.1.5 Choice of Input Data

The chosen input data for Paper II was the energy use for the technical systems of the swimming facility, and included the supplied thermal and electric energy to both the pool circuit system and the air handling unit – heating of pool water and the supply air as well as electric energy to pumps, fans, compressor in the heat pump unit and water treatment.

5.1.6 Limitations

Paper II was limited to the part of the building with the swimming pool facility, i.e., only the swimming hall which was ventilated by the swimming pool air handling unit and not the technical areas and wardrobes.

5.1.7 Building Performance Simulation Modeling

Paper III was based on simulations of the case building with a detailed model of the building using software IDA ICE version 4.8 SP1, which is a dynamic building simulation software that applies equation-based modeling (36). Due to the complexity of the air handling unit this paper addressed the model complexity of the BPS model without interfering with the rest of the system. The paper considered two sources of data and results: calculations with a simplified model and with a detailed model.

The challenge with a study comparing unvalidated calculations is the possibility of comparing irrelevant operating conditions. To ensure the relevance, the detailed model was validated with the case building, and the validation included measurements over a short period of time. The choice of short-term validation was due to the limited access to operating data. The model was in good compliance with the case building with respect to the air states and the air flow rate. This means that both the heating demand and the dehumidification demand followed the case building, including the calculation of the evaporation rate.

For the whole year comparison, the simplified and the detailed model were applied with a simplified assumption regarding the activity level of the occupants. This means that the compared facility was represented with a user group with similar activity level. Since the activity level is proportional to the evaporation rate this influenced both the heating demand of the pool water and the air states and potential air flow rate. However, the evaporation rate was reported as a step-function (76) since it was observed to increase considerably when the pool was in use, with only a minor rise when increasing the number of swimmers. Taking into account the large room volume which buffers potential changes in the evaporation rate, this was considered a correct assumption within the scope of this study.

Both the detailed model and the simplified model contain steady-state equations. The heat pump models in both the detailed model in IDA ICE and in the simplified model have some shortcomings. They are both steady-state models and no transient effects were considered, i.e., losses during start-up and shut-down periods. In addition, neither defrosting of the evaporator nor the air heat exchanger was included in the models. Regarding the condenser side some simplifications were applied. The simplicity of the black box-models in IDA ICE does not allow detailed modeling of the condenser side circuit, e.g., with multiple condensers and a sub-cooler. This was solved with a modeled water circuit at the heat sink side, connected to the air handling unit and the water circuit. This means that the model was an interpretation of the real device. However, the control system of heat sink/heat supply was modeled in accordance with the specifications found in the document study.

The sensible heating demand in the building envelope model is both dependent on the outdoor climate and the heat transfer to the adjacent rooms in the building. During operation the room temperature in the adjacent rooms will vary as well as the heat transfer. In the building envelope model the surface temperature of the adjacent side of the inner walls/floor was fixed. This was considered a correct assumption with respect to the purpose of the study.

5.1.8 Applicability

The results from the energy prediction study in Paper II can be applied worldwide. The study investigated the case building where the method was proven to be a well-suited tool for this building type. For buildings located in other climate zones the resulting equations will obviously differ due to different outdoor climate, usage, technical systems and building standard. It can also be applied to both new and existing buildings as a tool for helping the operational staff and facility management to keep the swimming facility within the expected energy performance. However, a continuous rating system in swimming facilities should not solely focus on energy performance but also include metrics regarding the core purpose of the facility.

The results presented in Paper III can also be applied worldwide. There will be differences in design due to available energy sources, building standard and the local energy price structure but this does not change the conclusion of the study even though the computer models included a heat recovery unit. Thus the influence of the modeling of the controller still applies.

5.2 Operation Phase – Tracking the Energy Performance

RQ2 addresses the topic of keeping the facility at the expected energy performance level. Paper II answered the question by introducing the use of a method based on continuous comparison of the actual energy use and the expected energy use over a period of only three days. Figure 20 illustrates the practical outcome with its potential for revealing operational flaws.

The main challenge with the method is to establish a reliable estimate for the expected energy use over a short period of time. Due to the energy use dependencies on climate and usage the estimate must be calculated. In order to avoid long lasting operating flaws with the potential of a large energy loss, the energy estimate should be calculated over as short a period as possible. This will reflect the operator's response time if operational flaws occur. Paper II used the case building as an example for both developing equations and testing its application. The finding of the paper is defined by the development of a reliable and robust baseline equation for the expected energy use of a swimming facility. By applying the well-recognized multiple linear regression method, the equation was developed with a clean dataset of only 29 datapoints. The proposed equation consisted of only two predictors (variables) with a R^2= 87 % and a prediction interval of 1.86 kW. Figure 19 illustrates the equation with the influence of the predictors.

The final regression equation confirmed the initial analysis of the energy use of the facility, which indicated both the pattern of usage and seasonal dependencies. Figure 28 presents the averaged power consumption plotted against the averaged outdoor temperature over a period of 30 minutes and 24 hours. The 30minute data clearly show indications of two operating modes, each represented by a cluster in the plot. This pattern is diminished when the data is averaged over a period of 24 hours.

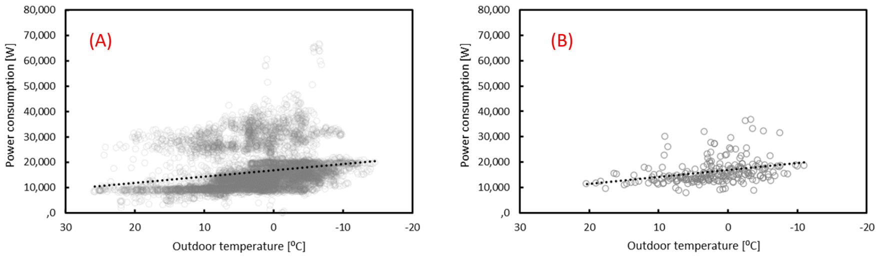


Figure 28 Averaged total power consumption plotted against averaged outdoor dry-bulb temperature when the dataset is averaged for 30 minutes (A) and 24 hours (B).

Figure 28A also gives an impression of the density of these two operating modes, where the energy intensive cluster is less dense. This is also confirmed in Figure 29, where the pool usage factor gives a pool usage of maximum 17 % of the time. This means a maximum of 4 hours use a day.

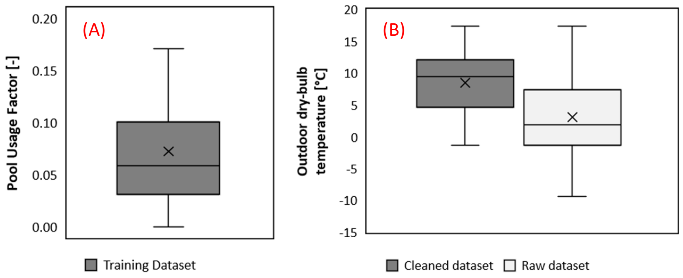


Figure 29 The spread of the usage data and the outdoor dry-bulb temperature. Averaged data for three-day periods.

The findings indicated a robust model with few variables describing as much as 87 % of the variance. However, this also indicates stable operation with few adjustments to central variables, like the pool temperature, within the dataset. For swimming facilities varying indoor variables and several predictors can be required. For the case building such adjustments will produce discrepancy in the evaluation of the energy performance, but the operator will be aware of the incident due to the simplicity of the equation which is transparent. Another important reason for the robustness of the model is the training data. The raw dataset from the facility was carefully cleaned for operational flaws before it was applied as a training dataset. Due to the purpose of the study the training dataset should not include flaws or disruptions. This process was not introduced without implications. Even with the newly commissioned building considerable operational flaws were revealed during the data cleanup. This excluded a large part of the dataset, approx. 55 %, and the final dataset ranged from March to June 2018. This had implications regarding the range of the variables. As Figure 29B shows, the minimum outdoor dry-bulb temperature was reduced from approx. -9 °C to -1 °C (three days averaged) which means that the model must extrapolate. However, the validation process did not find this was a problem, and the model performed well also when extrapolating down to the lowest outdoor temperature (-6 °C) during the validation year (three-day averaged).

The transparency of the equation is one of the strengths of the presented method but also the simplicity in development and in use along with the minimal required measurement equipment. The method is well-recognized for engineers and does not require any computer scientists or experts in statistics to develop or interpret the results. Further, the final energy prediction model is simple, with its algebraic expression, and can be deployed either in a spreadsheet or in the building automation reporting system.

5.2.1 Continuous Rating System

The proposed method has great potential for industry since operational irregularities are common in buildings and the energy performance is seen to be the most focused but the least achieved parameter in rating systems. The importance of the operating phase when minimizing the environmental impact should obviously not be underestimated. However, for swimming facilities operational flaws can have additional harmful consequences, beside excessive energy use, such as degradation of the technical equipment and the building construction as well as the occurrence of the sick building syndrome. For this reason, a continuous rating system including evaluation of the most central parameters regarding usage and service should be included to avoid improper and harmful operation. Parameters like air quality, sensible energy losses, evaporation, water quality and thermal environment should also be included in order to maintain the overall quality of the facility within the expected range, for both the user and the owner. Figure 30 presents an example of an interface of a continuous rating system for a swimming facility. The concept has the potential to reveal possible operational flaws quickly and direct the operator in the on-site fault detection. The additional parameters beside the energy performance should be evaluated at the same level as the energy performance. However, the energy performance is by far the most difficult variable to evaluate during operation due to its fluctuation and influencing variables. This can be traced by applying the method and results presented in Paper II.

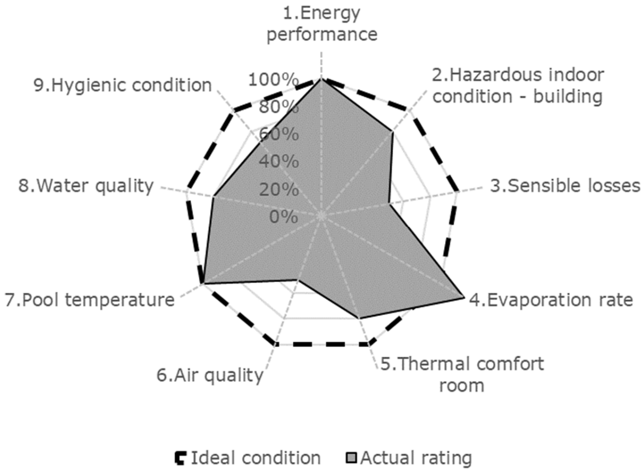


Figure 30 An example of an interface layout of a continuous rating system for a swimming facility where the most important operational parameters are displayed. The gray area represents the actual rating and the dashed line represents the expected "optimum" operation.

5.3 Design Phase – BPS Model Complexity

RQ3 addresses the design phase by reducing the threshold of using building performance simulation (BSP) tools. The threshold is represented by the required time and level of knowledge to model technical systems in swimming facilities. Threshold energy simulations are rarely performed in swimming pool projects and rule of thumb, simple calculations and statistics regarding annual energy demand and calculation of rating conditions define the layout of the system. With respect to the complexity this represent a considerable potential for improvement in the design of the water, energy and climate system in the facility. Paper III approached the question by analyzing the required model complexity of an air handling unit model. The air handling unit is the key device in the HVAC system of a swimming facility and has a very complex control system. The outcome of the study validated the simplified model approach as appropriate for the design phase.

The challenge and main concern in reducing the model complexity is the reduced accuracy of the model and misprediction of the demands. However, modeling a large system with a complex model structure requires well-functioning quality systems including verification ensuring that the model is performing close to reality, since validation obviously is not possible. Due to this, large complex models are more vulnerable to miscalculation compared to simple and transparent models, while the simplified model is more inaccurate due to its simplicity and assumptions. Considering this there is a trade-off when it comes to model complexity. Paper III treated this by introducing a new level of model simplifications, recognized as level 2 in Figure 32 and verified it against a short-term validated detailed model. The challenge of introducing a new level of simplification is both the reduced accuracy as well as the practical implications to ensure an increased implementation in building projects.

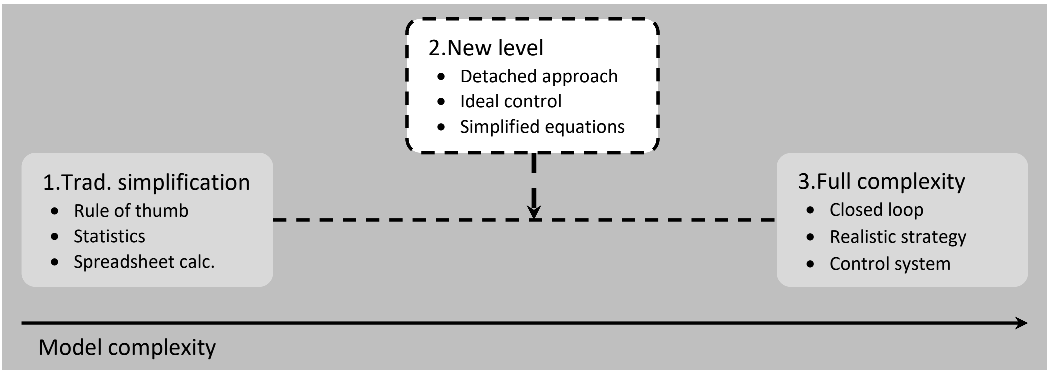


Figure 32 The defined levels of model complexity. The new level of complexity refers to the simplified model.

The simplified BPS model is a stand-alone model where the thermal demands were provided as input variables, i.e., the model calculates in a detached approach. This is in contrast to the detailed model which is modeled in a closed loop approach where the thermal demands and the model are interacting. The implication of this simplification is the non-versatility of the model. However, the impact of this is shown to be minor. Considering the amplitude of the deviation and the purpose of the simplification this approach with its added deviation is within the accepted range. Also, the non-versatility of the model is considered acceptable in the design process. For more complex projects or research activities including the response of the facility to the operation, the simplified approach could not be applied.

The challenge by simplifying the model is to conserve the key element of the modeled device while the complexity is reduced. For this case the key element is the control strategy. With several control variables the main purpose of the algorithms is kept unchanged in the simplified model. The total circulated air flow rate, temperatures, fresh air flow rate are controlled with several purposes. This influences the delivered energy by the operating time for the integrated heat pump and also by the fresh air supply rate which both have a large impact on the energy use of the facility.

A considerable part of the complexity is located at the controller level, identified as level A in Figure 11. This level includes groups of controllers, working both in serial connection (as cascade) and in parallel. These are tuned to obtain stable operation and no fluctuation and are therefore specific to each facility. In the simplified model this level is replaced by ideal control. Along with the above-mentioned detached model approach, it is required to customize this level since the concept of such controllers is based on the feedback. A problem with the idealized control system is the lack of control regarding the heat supply since the model calculates without power limitations. However, since the inertia of the building is considered when calculating the thermal demands this will not contribute as an issue with extreme peak power demand. The results from the comparison confirmed this. However, this last simplification contributes considerably by reducing modeling time and thereby the threshold for increasing the implementation of BPS in the design phase.

The threshold towards increased use of BPS in design also addresses the component equations, which concern the accuracy of each component. In this study the equations regarding the air heat exchanger are simplified, along with the heat pump model. In swimming facilities, the calculation of the air heat exchange is not straight forward. The normal operation of a swimming facility AHU deviates considerably from the rating conditions due to the demand-controlled fresh air supply. While the rating parameters, such as the heat exchanger efficiency, refer to dry operation and with the full fresh air rate the unit is normally operated with only a fraction of this and normally in wet operation, i.e., heat recovery of both sensible and latent heat. As discussed in the Chapter 4, this simplification does not contribute much to the deviation in the results, since the deviation in energy performance increases with the decreasing air flow rate. However, the reduced complexity makes the model easily applicable for manual implementation in programming and numeric computing platforms such as Matlab.

Overall, the simplification of the model and the reasonably good accuracy for all steps, the proposed simplifications are considered to be an important initiative towards increased use of building performance simulation (BPS) models in the design of swimming facilities. The knowledge regarding the required complexity of BPS models has great potential for industry as well as for designers, contractors and owners of facilities.

6 Conclusion

Research Question #1:

"What are the research gaps within the field of energy and indoor climate systems in swimming facilities?"

The research gaps were found by collecting records with a wide search string.

The first research gap was identified as lack of knowledge regarding initiatives about how the considerable variation in energy use, which also is recognized as very high, should be closed.

The second research gap was identified as the lack of knowledge regarding the BPS model complexity of the air handling unit (AHU) in swimming facilities.

Research Question #2: *"Is there a potential for keeping the swimming facilities within the expected energy performance, and how can this be achieved?"*

It was found that a baseline equation for the energy use effectively could be developed with the multiple linear regression analysis method. The method proved to perform well in the case study, and its strength was proven by early and quickly disclosing flaws during operation. The strength of the method is also demonstrated by its potential for application in both existing and new swimming facilities as well as its simplicity in development, implementation and in use. The presented equation consisted only of two variables, the outdoor dry-bulb temperature and the fraction of time the pool was in use. This two-variable equation was found to precisely predict the 3-day averaged energy use with an $R^2 = 87\%$.

Research Question #3:

"Is there a potential for reducing the threshold for applying building performance simulation tools in the planning- and design-phase of a swimming facility, and how can this be implemented?"

The threshold of applying BPS tools in the planning and design phase is identified by the model complexity, which is considerable for swimming facilities. A new and simplified model was defined and validated by comparing it with calculations for a validated detailed model. The validation of the simple model was found to give reasonably good results and the model can successfully be applied in the design phase of swimming facilities. By applying a BPS model at this stage the designer's ability to plan complex energy systems will improve, where the energy flow through the system fluctuates a lot over a year.

6.1 Contributions

The purpose of this project has been to improve the function and the operation of swimming facilities. It has a pragmatic approach and proposes practical improvements for both existing and new buildings. The project is in three parts, each part defined with a research question and a paper.

The literature review was carried out with its entire focus on the HVAC system in swimming facilities with a holistic approach. To the knowledge of the author no such holistic study has previously been carried out. Although several literature reviews have been published none of them have dealt with the holistic focus. The project has contributed with new knowledge to the swimming facility research community and has also contributed regarding the knowledge gaps for HVAC systems in swimming facilities.

Energy use in swimming facilities is a widely discussed topic in the literature. During the literature review, studies were found characterizing the distinct structure of energy use in swimming facilities and others proposing energy efficient measures. However, no studies were found that treated the subject of keeping the existing and new swimming facilities effectively at their best energy performance. The presented study found the use of a regression analysis to be effective in the development of an energy performance baseline. The findings can be applied to any swimming facility and help the operational staff to keep their facility within the range they expect and enable them to minimize their response time in fault detection.

Building Performance Simulation (BPS) is widely used in research for investigating energy reducing measures and indoor climate in swimming facilities. The author has not found any utilization of the potential of the tool when designing the facilities. Despite this, the model complexity was not found as a topic in the literature, although the complexity of the systems is high. The findings in the analysis of the model complexity will help the industry to overcome the threshold of using BPS in design and also make the research community aware of the consequences of simplifying the BPS model.

6.2 Future work

6.2.1 Energy Rating System

The fault detection and diagnostic tools for swimming facilities should be further developed to maintain a high level of performance during the operational lifetime of a swimming pool. The findings concerning the energy performance identification produced a method that was able to provide a model with good accuracy in the estimation of the energy baseline of a swimming facility. The method is easy to develop and easy to implement and has widespread potential. However, the latter should be focused to maximize its extent to the market. Thus the transferability of the model should be further investigated both concerning the selection of predictors and the coefficients. The baseline equation should preferably be generalized and validated in several swimming facilities.

The study presented a model trained by measurements and data collected during operation. For facilities lacking measurements as well as historic usage and operating data, this will be a major obstacle in implementing an energy baseline model. The possibility of training the model by using energy calculations from a BPS tool should be investigated and validated. This will have the potential to quickly provide an energy prediction model without requiring any invasive initiatives in the system or energy plant.

The energy performance model should be a part of a continuous holistic rating system for the facility. This system should also include the quality of service provided to the user that includes components such as the indoor environment, water quality, air quality, and water usage. Guidelines for development and implementation should be provided.

6.2.2 BPS Models

The analysis of the model complexity concluded with a set of simplifications defining a simplified model which should overcome the threshold of the BPS use in industry. However, the study was limited to one case study. The simplified model should also be validated against other brands of air handling units as well as larger swimming facilities.

The study emphasized the need for further validation of key components in the simplified as well as the detailed model. The heat pump models should preferably be validated to the distinct operation of heat recovery of saturated moist air with a large temperature difference. Research is also required on heat pump modeling in BPS tools. A complex energy system as in swimming facilities challenges current heat pump models in BPS and it should be able to model advanced heat pump circuits. Current practice regarding this topic is too simplified and can lead to misprediction of energy use. This is especially the case if CO_2 heat pumps or configurations with multiple condensers and/or evaporators are used.

Guidelines for implementation of the model should be provided to ensure implementation by industry. This will lower the threshold for applying the simplified model and make it easier for the designer in the planning of such facilities.

6.2.3 Technical system

The overall control system for swimming facilities should be optimized in order to utilize the waste heat from the AHU delivered to the pool circuit. This should be analyzed and improved by modeling the whole system with a BPS tool improve the control or the system lay-out.

The BPS models can also be used to study the supervisory control of the pool, for instance, how the set-point temperature of the pool temperature can be changed in time to perform load shifting. The large thermal mass of the pool can typically be used for peak shaving which can be important in future grid tariffs.

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Appendix

Paper I

Energy Efficiency
https://doi.org/10.1007/s12053-021-09985-6

REVIEW ARTICLE

Systematic and data-driven literature review of the energy and indoor environmental performance of swimming facilities

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Received: 20 January 2021 / Accepted: 14 August 2021

Abstract During the last few decades, focus on measures for energy conservation in buildings has increased considerably. The European Commission implemented the Energy Performance of Buildings Directive, which gave instructions to the member states about how to reduce energy consumption in residential and non-residential buildings. In the process of making the building sector more energy efficient, the building codes generally have become stricter with some simplifications applied in the requirements. For swimming facilities in Norway, these simplifications are undermining the purpose of the code by excluding the energy use related to the operation of swimming pools, which is the main part of the energy use in this building category. In other words, the energy use related to operation of the facility is not regulated. Furthermore, guidelines for the planning and operation of these types of facilities are outdated and research for this building category is sparse. These three aspects mean that there is a considerable potential for improvement. This paper presents a comprehensive literature review with bibliometric and thematic analyses of the contextualized research in swimming facilities from a heating, ventilation, and air-conditioning perspective. It maps the

Highlights

- A total of 524 scientific papers on heating, ventilation, and air conditioning in swimming facilities are identified, selected, and reviewed.
- Bibliometric and thematic analyses are performed for the selected 524 papers.
- Swimming facilities are complex buildings which require numerous interacting disciplines.
- The research field of disinfection by-products in swimming facilities appears to be mature.
- The coverage of energy and indoor environmental quality in swimming pools is, so far, fragmented and non-comprehensive.
- Research is required to bridge the entire knowledge chain from the physico-chemical reactions in the pool water to the overall facility energy consumption.

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major trends during the past few decades, where areas like solar heating for outdoor pools, energy consumption, and air quality stand out. Except for air quality and disinfection by-products, research on these facilities is highly fragmented without any strong contributors to the various fields.

Keywords Swimming facilities · HVAC · Energy · Indoor environmental quality · Disinfection by-products

Introduction

Background

The global climate change has been disclosed over the past 30 years and has been periodically stated by the Intergovernmental Panel on Climate Change (IPCC), since their first report in 1990 (Tegart et al., 1990). As a consequence and after the establishment of the Kyoto protocol in 1997, the European Union implemented the Energy Performance of Buildings Directive, EPBD (European Commission, 2006). EPBD was partly designed to meet the 20% indicative target for energy efficiency improvement defined by the EU Energy and Climate Package.

Within the European Commission's vision of climate neutrality by 2050 (European Commission, 2019b) and the proposed raising of the greenhouse gas reduction target to at least 50% toward 2030 (European Commission, 2019a), a "renovation wave" of the building sector has been defined in the related action plan. For the specific case of swimming facilities, research has revealed a large span in energy use for the buildings. Their specific energy use, expressed as delivered energy per square meter and annum, has been reported to range from 400 kWh/(m^2.a) to almost 1600 kWh/(m^2.a) (Kampel et al., 2013; Kampel, 2015; Røkenes, 2011; Swim England, 2016). Kampel (2015) investigated the energy use of Norwegian swimming facilities and found its range to be wide even if it was normalized to different variables, like number of visitors or pool's water surface. This variation can partially be explained by the variety of subcategories within swimming facilities, the age of the building, the difference in installed technology, and the maintenance routines. This all represents a large energy savings potential (Kampel, 2015). Considering that modern office and residential buildings are characterized by a specific delivered energy use below 100 kWh/(m^2.a), swimming facilities represent an energy-intensive building category. Consequently, in the context of the EU Roadmap 2050 (European Commission, 2019b), it is a paradox that swimming facilities are not treated exclusively, rather just included as a sub-category of "sport facilities," which are characterized by totally different size, uses, period of operation, and, of course, energy consumption (European Union, 2010).

Motivation

Due to the range in energy use, Kampel et al. (2013) called for increased research activity regarding the development of representative Final Annual Energy Consumption (FAEC) indices. Duverge et al. (2017) pointed to the complex nature of swimming facilities as a reason for the lack of research and standards related to this kind of facility. The research field regarding energy performance and water usage is suffering from the lack of worldwide research activity (Duverge et al., 2018). However, research and design in swimming facilities require a high level of holistic knowledge due to the multiple and inherently connected subjects, like indoor environmental quality, chemo-physical reactions in both water and air, water treatment and management, technical building systems for environmental control, and energy efficiency, among others. The complexity of these facilities is also reflected by the number and typologies of the technical systems required in a typical swimming pool. Figure 1 shows a general illustration of the typical circular dependencies in swimming facilities found in Scandinavian conditions (i.e., zone D according to the climate zones definition of Köppen & Geiger, 1930).

Referring to Fig. 1:

1. The indoor environment (1) is normally controlled by fixed set-points for indoor (dry-bulb) air temperature and relative humidity. The ventilation system is dedicated to handle all issues related to the indoor environmental quality and provide a healthy and thermally comfortable indoor environment. The air distribution is typically also designed to eliminate condensation

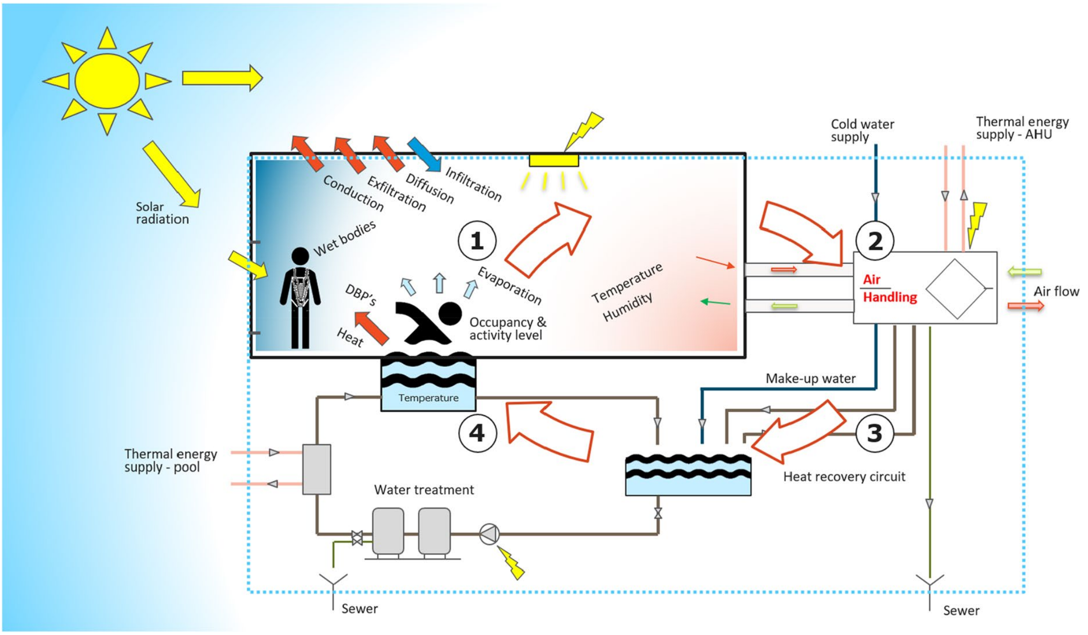


Fig. 1 Schematic operation concept of a swimming facility within Scandinavian conditions with key elements related to space and water heating, ventilation, air conditioning and dehumidification, and water treatment; (1) indoor environment, (2) air handling, (3) heat recovery circuits, and (4) water treatment system, where the arrows illustrate the typical direction of the net energy flow

problems on the facility envelope and structural systems.

2. The evaporation rate for pools greatly depends on the occupancy and activity levels. The air handling unit (AHU, 2) controls the humidity and air temperature in the pool hall by heating and varying the state of the supplied air. Depending on the operation mode, bathing or night mode, the AHU recovers the latent heat from the extracted air, normally with an integrated heat pump. In night mode, most of the air flow is recirculated into the hall, with the purpose of maintaining the room temperature and humidity set-points in reasonable ranges. Since the energy level in the supply air flow depends on the thermal losses of the pool hall, and the energy level in the extract air depends on the evaporation from the pool surface, the direction of the net energy flow may vary in operation. However, the net energy flow related to the ventilation system in modern swimming facilities, with high energy performance, will normally be negative, as illustrated in Fig. 1.
3. The heat recovery circuit (3) is connected to the AHU and the recovered latent heat is used for either air or water heating. This represents a crucial link in the energy loop of the facility.
4. If required, additional thermal energy and water refill are supplied in the water treatment system (4). This loop circulates the water through the pool where the water quality is strictly monitored and controlled, along with its temperature.

The relationship between the different key elements in the swimming facility illustrates the vulnerability of the system and the risk of both excessive energy use and an improper and possibly harmful indoor environment. For example, the performance of the AHU influences the indoor environment and the energy use as it controls the indoor environment and recovers latent heat from the extracted air. The performance of the AHU also influences the energy use for the pool circuit due to the heat recovery system and the control of the water temperature in the pool.

The performance of the pool circuit influences the indoor environment by the water quality, filtering, disinfection and disinfection by-products, and thereby the air quality, but also by the temperature control, which is crucial for controlling the evaporation rate. The latter is greatly dependent on the water and air temperatures. A high evaporation rate increases the energy content in the pool air, which in turn will increase the ventilation losses. High humidity will also increase the risk of condensation on building envelope surfaces and make the pressure gradient steeper inside the pool hall. This may cause degradation of the construction due to corrosion and possible exhilaration and increased diffusion and possible accumulation of moisture inside envelope components.

The illustrated interconnections show the importance of understanding the varied and complex nature of swimming facilities when dealing with optimization or improvements. For example, the importance of in-depth knowledge regarding the AHU's control system is crucial when evaluating the air quality inside the hall since the fresh air supply flow rate typically fluctuates during operation and together with it the dilution of the contaminants in the hall. Another example is the consequences of the interconnected heat recovery and energy system. Even if the facility has satisfactory overall energy performance, multiple issues may be present. For example, issues related to the water refill system can disguise problems with the air handling unit and the fresh air supply.

Considering the lack of regulations related to the energy use in swimming facilities, it is beyond doubt that the different technical systems are very often sub-optimized.

Purpose

Within the field of swimming facilities, several literature reviews were carried out in the past decade. They include themes regarding prediction of the evaporation rate during natural convection (Poós & Varju, 2019), disinfection by-products in swimming pools (Carter & Joll, 2017; Chowdhury et al., 2014; Manasfi et al., 2017), and heating technologies for swimming pools (Li et al., 2020). Motivated by the reported potential for energy optimization, and the need for research, regulations, and guidelines addressing the complexity of these facilities, this paper presents and discusses a systematic literature review of the energy and the indoor environmental performance of swimming facilities. It presents new knowledge, regarding the present contextualized research related to HVAC systems in swimming facilities, and depicts the scientific landscape, which is based on both bibliometric and thematic analyses. This work describes the state of the art regarding the multidisciplinary field of HVAC systems in swimming facilities in cold climate regions such as northern Europe.

Methodology

Swimming facilities represent a building type where research addresses either the technical aspects of the facility or the activities carried out in the facility (biomechanics, swimming techniques, statistical studies regarding drowning etc.). This literature review deals with the technical and engineering aspects of the facilities with a focus on those aspects related with the indoor environmental quality (IEQ) and heating, ventilation, and air conditioning (HVAC).

The literature review has been carried out following a three-step methodology illustrated in Fig. 2. The methodology uses a systematic and data-driven bibliometric analysis to collect and investigate data from publications available in the scientific literature. The outcome of each step is analyzed in "Methodology" section, where an analysis of the identified and collected publications is presented.

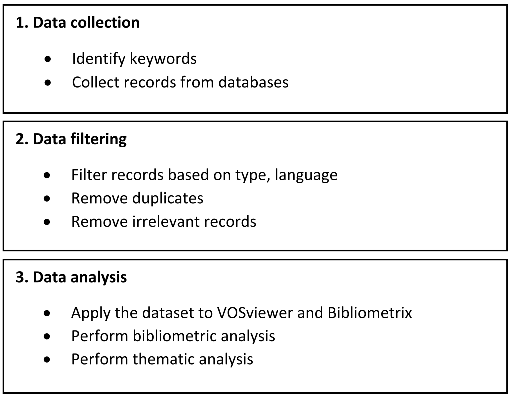


Fig. 2 Holistic methodology workflow chart

The data collection

The development of the search string, box no. 1 in Fig. 2, is based on the aim of the study, a mapping of the scientific landscape of publications with respect to the technical part of swimming facilities. This approach defines a broad system boundary which makes it possible to conduct an analysis of the facility-relevant research in this field. The technical areas of interest, defined from the field of HVAC and IEQ, include.

- Energy,
- Air quality,
- Ventilation,
- Disinfection by-products.

The following major databases were used in the analysis:

- Scopus,
- Web of Science (WoS),
- Compendex (Elsevier).

Figure 3 illustrates the workflow related to the establishment of the dataset of raw data, box no. 1 in Fig. 2 (Data collection).

The search string was applied to the databases and the bibliometric data were collected on February 23, 2020. The search was carried out by searching in title, keywords, and abstract (topics). The search resulted in a dataset of bibliographic data with 1993 records. The distribution of the records before filtering was approximately 50% Scopus, 25% Web of Science, and 25% Compendex.

Filtering data

The filtering process was carried out in four steps:

1. Document type: limit the records to journal or conference articles,
2. Language: limit the records to documents written in English,
3. Duplicates: excluding duplicates in the dataset,
4. Relevance: excluding irrelevant records.

Figure 4 illustrates the impact of the individual filtering steps on the number of records, and the distribution.

Figure 4 reveals a distinct change in the distribution between the databases at filtering step 3, “Removing duplicates.” This change is due to the prioritized order of removing objects. During this step, articles with origin from Compendex were removed

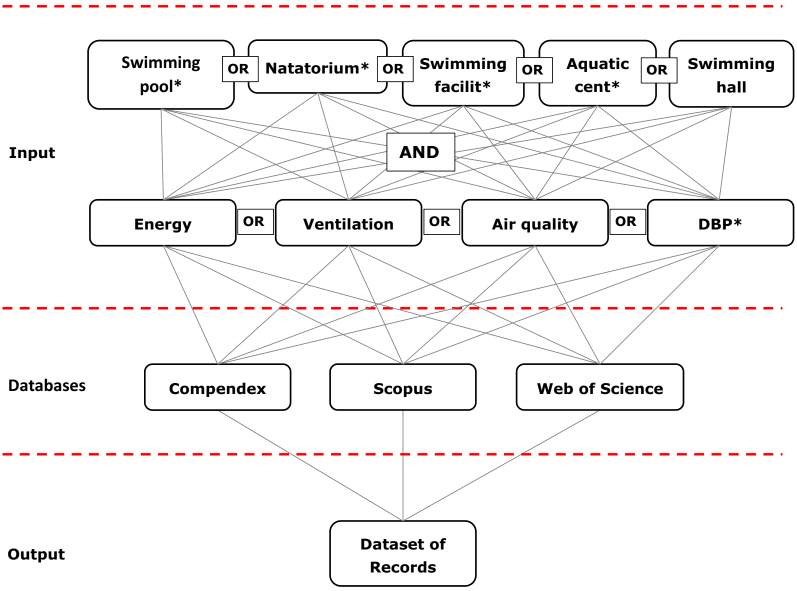


Fig. 3 Illustration of the process of establishing a raw dataset. *Refer to the truncation symbol in the search string. The truncation symbol allows you to search for all the various endings of a word

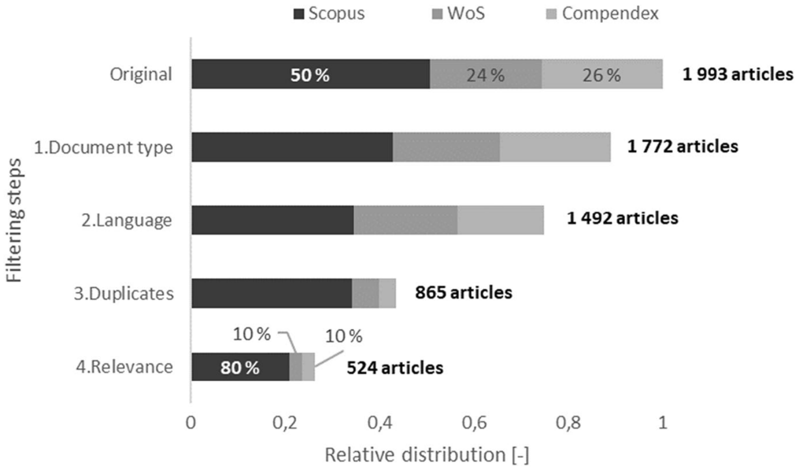


Fig. 4 The impact of the filtering steps on the original dataset

first, and second the records from Web of Science. The reason for this order was the lack of information which is provided in the bibliometric extraction by Compendex.

Regarding the last filtering step 4 "Relevance," the dataset was reduced by almost 40%. This reduction was due to the broad search string. Irrelevant records were filtered out manually by screening the title and abstract. If the research presented outcomes, which were not in the scope of our study, they were excluded from the dataset and subsequent analyses.

Analyzing data

Identification process

Prior to the analyzing section, extensive identification was required. The facilities were mapped, and subsystems and key-areas were identified by a unique tag. By screening titles and abstracts for the dataset of 524 articles, a tag was assigned to each article. The aim of the tagging system, the structural map, was to further reduce the dataset to investigate the research within the field. Figure 5 illustrates the overall topography of the structural map used for tagging the articles.

In addition to the tag system previously described, the articles are categorized both by the type of facility and the approach of the study, deterministic or analytical. The type of facility has been identified by public or residential indoor and outdoor pools since these categories differ significantly in design, operation, and typical issues.

The analysis

The analysis has been divided into two parts: (1) bibliometric analysis and (2) thematic analysis. The bibliometric one provided information about the knowledge structure and development of the research field in the context of swimming facilities. This involved analysis of authors' productivity, affiliations, and publication year and publication countries (of their affiliated organizations) as well as co-occurrence of words in a text and the co-occurrence of the keywords listed under the abstract. The thematic analysis was based on a quantitative analysis of each of the publication's

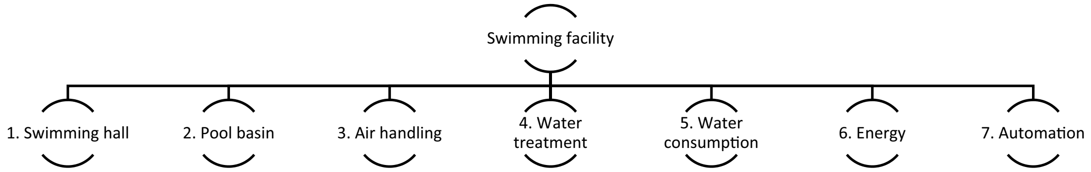


Fig. 5 The overall topography of the structural map. Each category was represented with several sub-categories

finding. This was identified by full-text review of the publications and structuring/discussion in the context of the HVAC system.

The bibliometric analysis comprises 524 documents published between 1930 and 2019. The dataset is created according to Fig. 4, as the outcome of step 4. The dataset has been investigated by the use of VOSviewer (van Eck & Waltman, 2010) and Bibliometrix (Aria & Cuccurullo, 2017), and the results are reported in several perspectives and subsections.

Results of bibliometric analysis

This section provides information about the knowledge structure and the scientific landscape of the respective research fields.

Publication trends and structural analysis

The dataset can be divided into public and residential swimming pools. Studies regarding residential swimming pools almost entirely comprise outdoor pools with energy-related focus in the dataset (Harrington & Modera, 2013; Nouanegue et al., 2011; Ruiz & Martínez, 2010; Song et al., 2018). This is also the case for public outdoor swimming pools, where about 80% of the studies deal with the energy system. The dominant topic within the energy subcategory is solar energy, represented by about 40% of the articles. This dominance is reasonable because solar energy has been an important heat source for open-air swimming pools for decades (Ruiz & Martínez, 2010).

By arranging the dataset with respect to the year of publication, as illustrated in Fig. 6b, the interest in solar energy (regardless of the type of swimming facilities) is observed to be constant since the 1980s, with the exception of a drop during the first period in the new millennium. This in relation to the absolute publication rate, where the solar energy–related studies dominate the number of publications in the pre-millennial period. Figure 6a illustrates the dataset divided into three main categories:

1. HVAC and engineering in public indoor facilities,
2. Disinfection by-product (DBP)–related studies,
3. Outdoor and public swimming pools.

The remaining part of the records, apart from the studies regarding outdoor and/or residential swimming facilities, represents 15% of the publications in the last two decades, as illustrated in Fig. 6a. These publications include DBPs, HVAC, and engineering-related topics, all technical, constructional, and operational. Figure 6a illustrates the distribution between the defined groups, where the last two are represented by approximately 40 and 45%, respectively. Bearing in mind the importance of proper air quality and the toxicity of the DBPs, which have been linked to adverse health effects (Richardson et al., 2010), as well as the parallel worldwide focus on energy use and consequent environmental impact, this distribution is expected.

When looking into the publication trend, the publication rate versus the publication year, the strong increase of the DBP-related publications rate in the last decade is revealed. This increase can be seen for the whole dataset as well, where 75% of the articles are published after 2000. By comparison, looking exclusively at the DBP publications, 90% of the DBP-related articles are published in the last 15 years.

Publication year and average publication year

In the last two decades, there are only 154 publications within the HVAC and engineering category. The average publication year is 2013, which indicates an increasing number of publications toward this period. This pattern is illustrated in both Fig. 6b and c. This offset of the average publication year for the last two decades makes this a state-of-the-art study. Figure 6b Illustrates the distribution for the entire dataset which confirms this conclusion.

Sources

For the HVAC and engineering category, 85% of the publications in the last two decades can be found in the Scopus database. Approximately one third are conference papers and the dominating scientific journal source is “Energy and Buildings” with about 10% of the publications (Fig. 7). Only 5 out of 84 sources in this dataset have published more than 2 articles. This indicates a fragmented research field where no specific scientific journals, besides “Energy and Buildings,” emphasize contextualized research about swimming facilities.

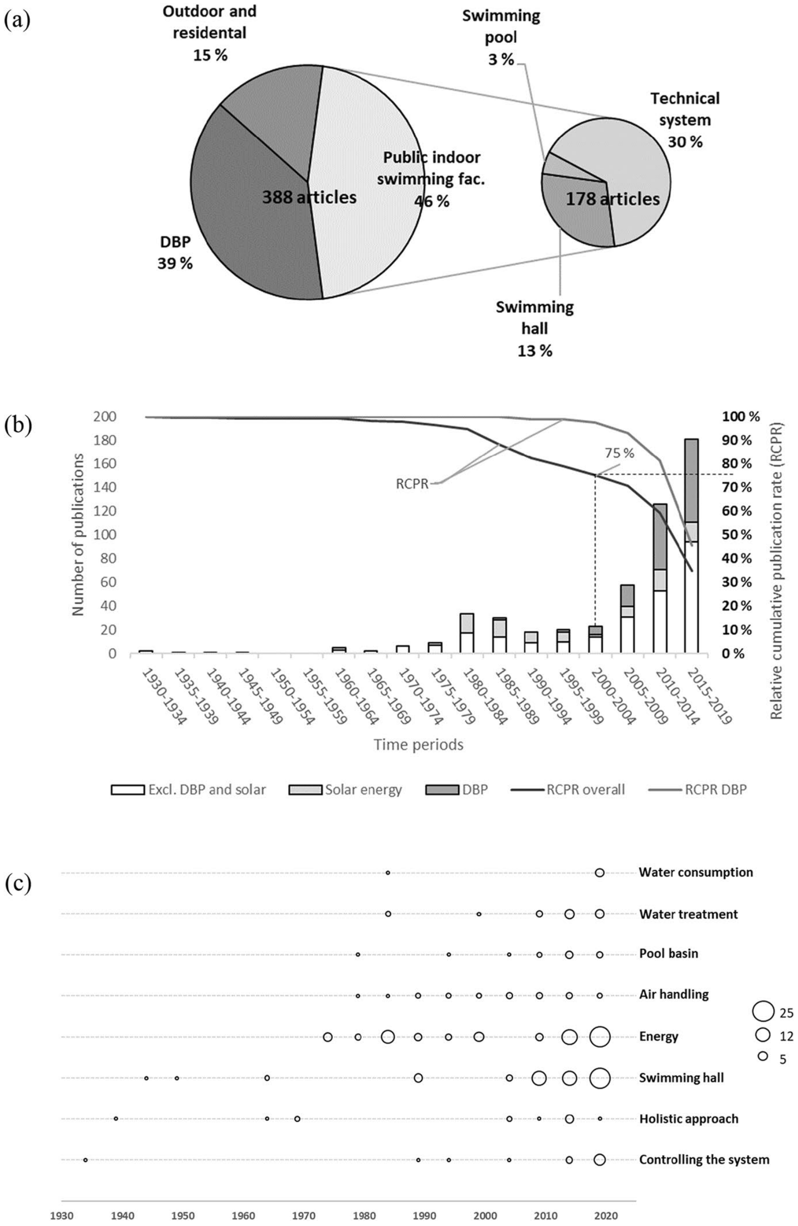
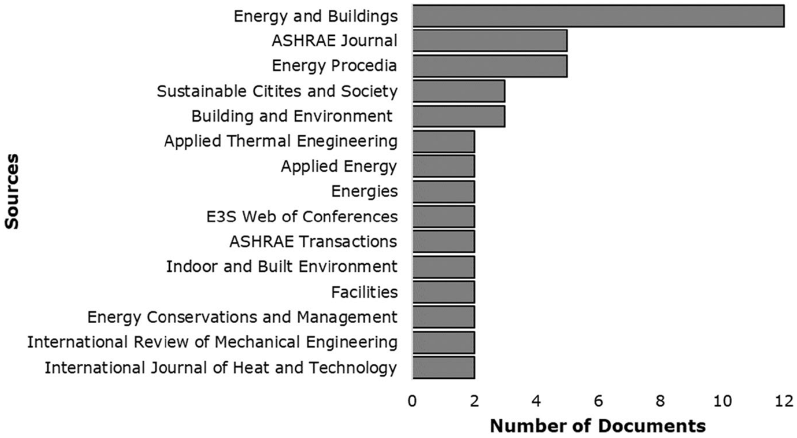


Fig. 6 The structural overview of publications with respect to **a** main topics; **b** publication timeframes; **c** research topics

Authors and institutions

Research in the context of swimming facilities is a field of growing interest. The publication rate has been constantly increasing over the last two decades, cf. Figure 6b. For the bibliometric dataset of Scopus records related to the HVAC and engineering category, a total of 290 authors are represented. The distribution of the authors' publication rate depicts a field identified by many occasional authors where approximately 90% have only one publication. The pattern of a fragmented field can also be seen in the

Fig. 7 Most relevant sources with number of published articles



distribution of authors as well. A comparison with Lotka's law, which describes the publication frequency by the authors, demonstrates that the respective field is identified by few authors with multiple publications. Lotka's law is one of the basic laws of informetric and explains the distribution of the scientific productivity within a field. It shows that the relation between the number of authors publishing a certain number of articles is a fixed ratio to the number of authors publishing one article. The relation is approximately inverse square.

Parallel to this, the group of core authors is equivalently small, where only five authors are represented by three publications. This wide dispersion is scrutinized in Fig. 8b, which depicts the total amount of publications for the whole pool of authors ($n = 290$). The overall picture of this distribution is the occasional pattern. Rajagopalan from Australia is by far the most contributing author and, along with Bruland's group at the Norwegian University of Science and Technology (NTNU), represents the core group of authors. Both Rajagopalan's and Bruland's groups have publications with a comprehensive approach, each with PhD theses within the subject (Duverge, 2019; Kampel, 2015). Both research groups focus on the energy use in swimming facilities.

Contributing countries

The popularity and significance of a research field can be identified by tracing the span of the geographical area and the contributing countries. The dataset of the HVAC and engineering research area for the last two decades represents 154 articles. By rearranging these with respect to the corresponding author, this contextualized research is of special interest in the developed countries. Europe is the main contributor by 76 articles and North America second by 34 articles, together representing over 70% of the publications. Figure 9 illustrates the distribution over the continents. The publication intensity is well distributed in Europe, where 19 countries have contributed with publications. Portugal and Italy are the most contributing countries, each with nine articles followed by Germany and UK with seven publications each (Fig. 10). This depicts a research area with good bibliometric dispersion.

Key areas

Even though the published articles in this predefined field apparently seem fragmented, the pool of records is closely connected in the thematic perspective. This is illustrated in a Sankey diagram (Riehmann et al., 2005) organized as a three-field plot in Fig. 11 (Aria & Cuccurullo, 2017). This plot shows the most frequent words in abstracts, author's keywords, and sources (scientific journals), illustrated by the size of the boxes. The strength of the connections is identified by the line between the boxes. The most frequent words identified in the abstracts give the main terms of the research questions while the field of the author's keywords gives the main concepts on which the domain is built (Carlucci et al., 2020). The terms "energy efficiency," "heat pump," and "indoor air quality" stand out in the abstracts, besides the obvious

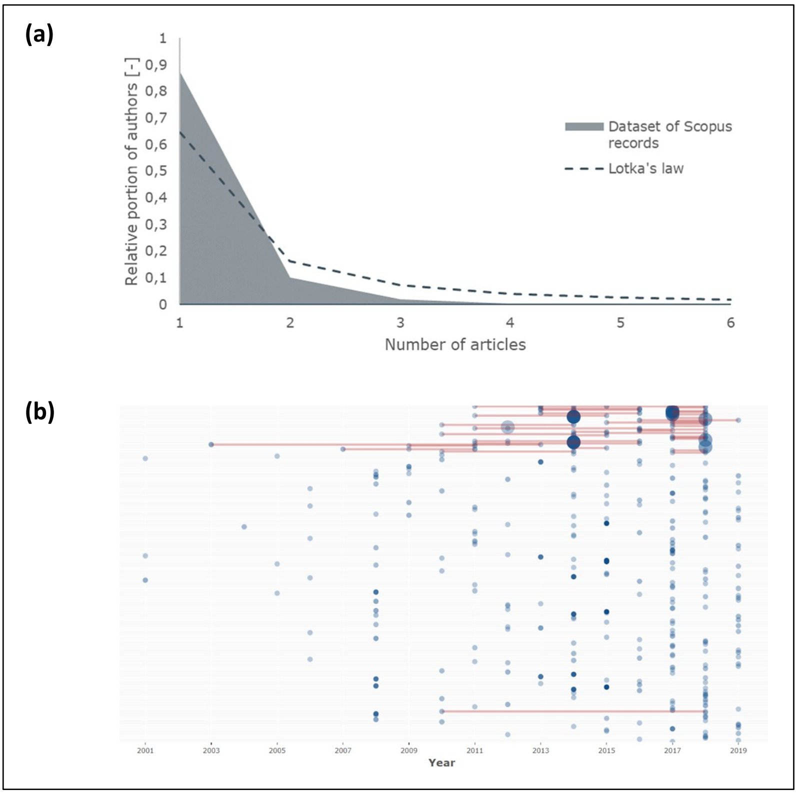


Fig. 8 The distribution of the authors publication rate in the Scopus dataset

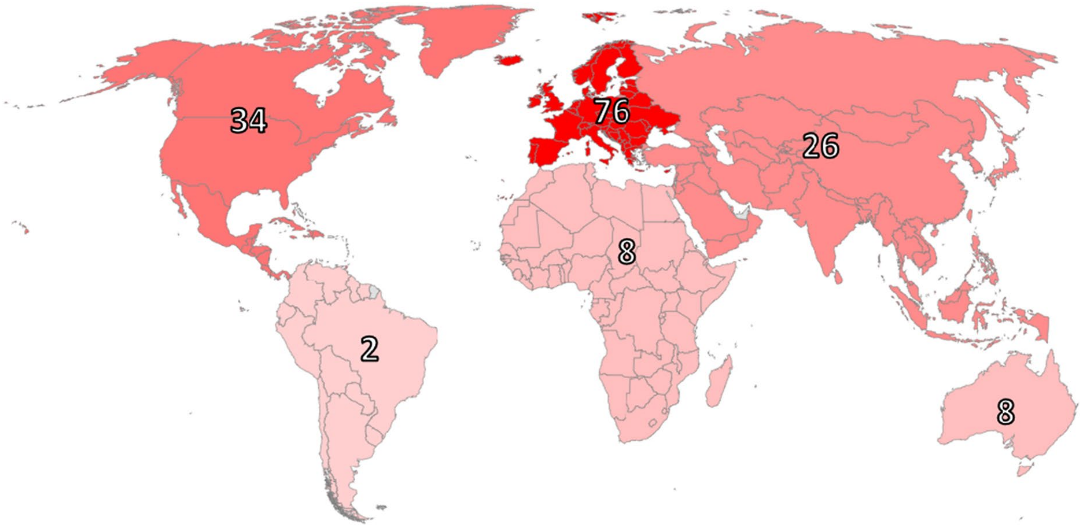


Fig. 9 The most contributing continents with respect to publications. Based on the affiliation of the corresponding author

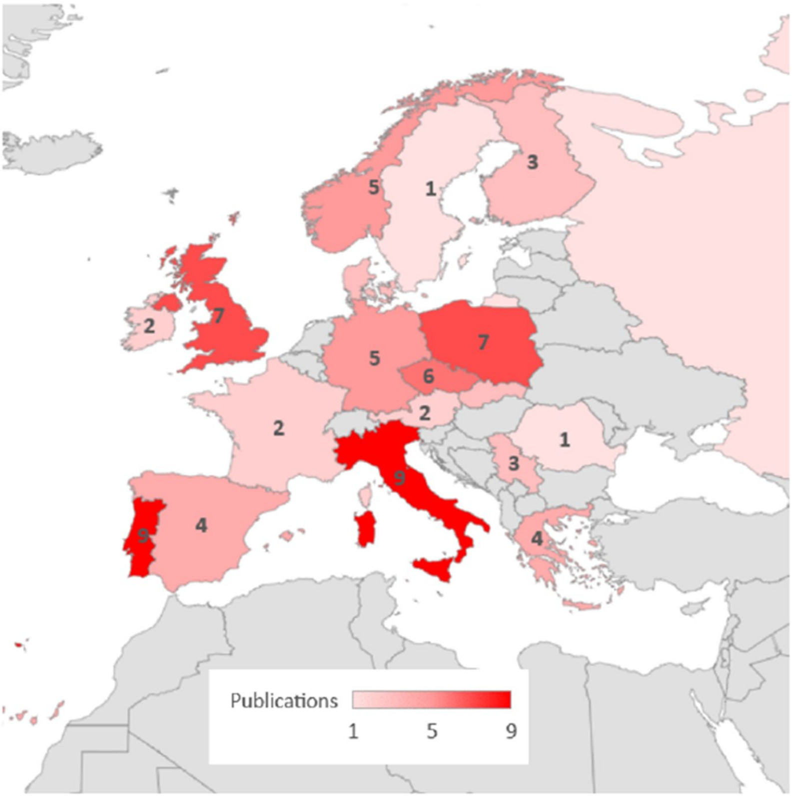


Fig. 10 The most contributing European countries with respect to publications. Based on the affiliation of the corresponding author

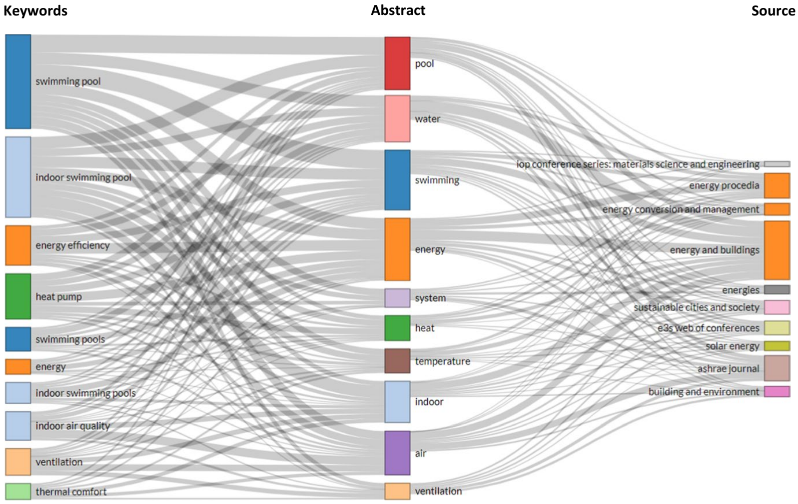


Fig. 11 Three-field plot of the building specific records found in Scopus

terms "swimming pool" and "indoor swimming pool." Regarding the concept of the studies, given in the field of author's keywords, the term "energy," "water," and "air" are distinguished. The scientific journal "Energy and Buildings" is once again seen to involve all of the combinations, but mostly "energy" and "water." The "ASHRAE Journal" is found to include most articles distinguished by the term "air."

Considering the Scopus dataset of HVAC and engineering specific records, and inspecting the occurrence of central terms, the following result is found:

- "Energy" occurs in 80% of the topics (title, keywords or abstract).
- "Ventilation" occurs in 30%.
- "Air quality" occurs in 20%.
- "Thermal comfort" occurs in 10%.

This indicates that most of the publications have an energy-related approach where energy efficiency is a central part of the research.

Results of thematic analysis

With the complex thematic structure of swimming facilities, the fragmented research area found in the bibliometric analysis is expected. Due to the multiple purposes of these facilities, many issues during operation will occur as well. The primary function of the facilities is to offer the user groups swimming pools in a comfortable and harmless indoor environment. Within this task, multiple topics are present, such as thermal, acoustic, actinic, and atmospheric comfort. In addition, the water quality is crucial, with respect to temperature (thermal comfort), water treatment, and air quality affected by Disinfection By-Products (DBPs). Second, these main functions should be fulfilled without harming the building envelope (issues regarding building safety and life cycle cost), for example, preventing corrosion and condensation. Finally, these tasks should preferably be achieved with minimum energy use.

Considering these factors together frames a research area with a large potential for optimizing and improving performance. The research communities have approached all these fields to a different extent. This section summarizes some of the most important research in the context of each discipline, for indoor swimming facilities. Figure 12 provides the structure of the analysis in this section.

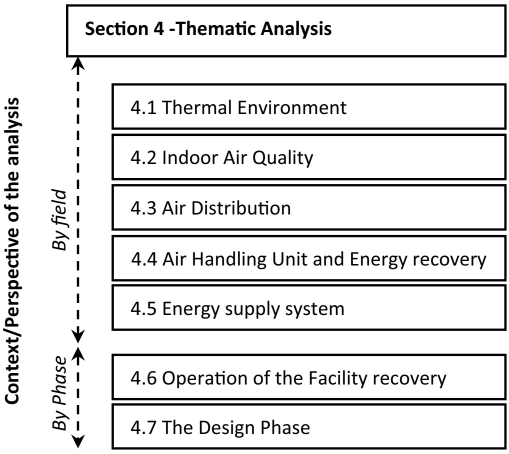


Fig. 12 Section 4—graphic table of content

Indoor thermal environment

When evaluating the indoor environment in a swimming facility, the complexity appears in full scale. For the thermal comfort part, the diversity of the user groups is significant and ranges from experienced swimmers using the facility for training purposes, to water activities and swimming for kindergarten children and the disabled. In addition, there are spectators and lifeguards present where the latter are present for hours. In other words, the diversity is present in both the activity level, ranging from high to low, the clo factor (from swimwear to normal clothing), as well as wet and dry bodies. Hence, the task of providing a good thermal environment for every user group is challenging (Rajagopalan & Jamei, 2015).

Rajagopalan et al. (Rajagopalan & Jamei, 2015; Rajagopalan & Luther, 2013) investigated the occupants' perception of thermal comfort and found a high level of discomfort in natural and hybrid ventilated facilities in temperate climates during hot weather with the use of predicted mean vote (PMV) and thermal sensation vote (TSV). Even though the indoor environment is extreme with respect to air temperature and humidity, the thermal perception of the staff and spectators (dry bodies) was found to correlate well with the indoor temperatures and PMVs. For the wet bodies, the case was different. Swimmers act as multiple thermal objects during the period of presence, both with dry and wet bodies. Since the occupants' thermal comfort is a result of human heat balance (Abel et al., 2003) and wet skin is a special case, an additional evaporation term is required in the energy balance equation. This is not applied in the PMV method.

Revel and Arnesano (2014b) investigated the perception of the thermal environment in sport facilities, where a swimming pool environment, including participants with wet skin, was among the considered user group. In this study, a good correlation was found between PMV and TSV for swimmers with wet skin when applying an evaporation term in the proposed heat balance equation when calculating the PMV (Standard Norge, 2006). For this specific study, the Stolwijk model for the evaporation term (Lammers, 1978) was applied with good results. It was also shown that the PMV and predicted percentage dissatisfied (PPD) indexes can be used to evaluate the thermal perception of the swimmers and to make the facility management informed of the facility's performance with respect to thermal comfort. This may give the facility more satisfied users and also the possibility to optimize the energy performance of the facility (Revel & Arnesano, 2014a). By continuously monitoring and evaluating, a satisfying thermal environment may be obtained through the lifespan of a swimming facility. However, measurements are no better than the total uncertainty of the measurements. For example, in Norwegian swimming facilities, the sensors are placed in the extract chamber in the central air handling unit (AHU) or in each AHU if multiple. This does not take the indoor air distribution in the facility into account (Arnesano et al., 2016) and may not display the indoor thermal environment in a proper way. Arnesano et al. (2016) showed a significant improvement in the measurements inside a swimming facility by optimizing the sensor placement. In the specific case, the conventional system performed within acceptable limits for 60% of the period, whereas the improvement with an optimized sensor placement performed satisfactorily for almost the entire period.

Indoor air quality

Indoor air quality is mainly evaluated by the level of airborne particulate matter and contaminants. The research has provided considerable knowledge regarding air quality to the HVAC community, mostly through descriptive studies. This includes studies regarding.

- Numerous disinfection by-products (Richardson et al., 2010; Weaver et al., 2009),
- Occurrence and human consequences (Shaw, 1986; Benoit & Jackson, 1987; Kim et al., 2002; Righi et al., 2014; Lévesque et al., 2015; Zhang et al., 2015; Chowdhury, 2016; Nitter et al., 2018; Gabriel et al., 2019; Nitter & Svendsen, 2019a),
- Formation of DBP (Jmaiff Blackstock et al., 2017; Kim et al., 2017; Fakour & Lo, 2018),
- The impact of water treatment (Weng et al., 2012; Hansen et al., 2012; Weng et al., 2013; Spiliotopoulou et al., 2015; Nitter & Svendsen, 2019b),
- Impact on the users and the user's uptake (Chu et al., 2013; Fernández-Luna et al., 2013; Font-Ribera et al., 2016; Hang et al., 2016; Parrat et al., 2012; Xiao et al., 2012).

Due to the humid environment and the ventilation intensity, dust is not found to be a problem in swimming facilities (Kic, 2016). On the other hand, DBPs from chlorine-based disinfection are associated with such facilities and of particular concern (World Health Organization, 2006). This water treatment method, which is the most common in swimming facilities, secures the absence of pathogens (viruses and fungi) in the water, which may cause severe health effects if not removed (World Health Organization, 2006). The reaction between chlorine and organic matter from the occupants, such as hair, sweat, skin cells, urine, and lotions, creates DBPs. The presence of DBPs in the poolroom has been linked to a variety of health issues (Liviac et al., 2010; World Health Organization, 2006; Manasfi et al., 2017). Within the DBP research area, the necessity of proper ventilation is often emphasized, but without any design specifications or suggestions (Berg et al., 2019; Dyck et al., 2011; Erdinger et al., 2004; Nitter et al., 2018). Due to the complexity of these kinds of HVAC systems and the need for specific ventilation, energy, and building physics expertise, this is not surprising. Anyway, the different studies underline the awareness regarding the ways DBPs penetrate the human skin, among which inhalation plays the most important role. It is impossible to eliminate the formation of DBP, but it can be limited by, for example, reducing the DBP precursors and diluting the pollution by enhanced air supply or improvement of the water treatment system (Manasfi et al., 2017; Ratajczak & Piotrowska, 2019).

The traditional ventilation concepts are designed to avoid condensation on surfaces (Nitter & Svendsen, 2019a). The air is normally supplied below the window surfaces and extracted from a centrally placed extract air grill. This concept is applied even in newly commissioned swimming facilities where the surface temperatures theoretically never will drop below the dew point (Ratajczak & Piotrowska, 2019). Even though the DBP research community generally has not provided any specific design codes or guidelines, only emphasizing the importance of proper ventilation to minimize hazardous inhalation, some of the studies have recommendations.

The performance of the ventilation system, in relation to its intended function, depends on the fresh air supply and air distribution. The traditional design has been exclusively focused on protection of the building construction and keeping the indoor environment within a given range of temperature and humidity. Since the main source of air pollution in swimming facilities is the water surface, there is consensus that the design of the ventilation system is one of the most important tasks in the work regarding improving the indoor air quality for swimmers (Berg et al., 2019; Nitter & Svendsen, 2019a; Ratajczak & Piotrowska, 2019; Saleem et al., 2019).

In the present studies, the operation of the ventilation system is rarely reported. While some report a fresh air share between 20 and 100% of the total air flow and a maintenance staff demonstrating a great degree of uncertainty (Gabriel et al., 2019), others report 4 to 6 air changes per hour (ACH) and a ventilation control strategy based on controlling the air flow by both temperature and humidity, aiming to prevent condensation, and due to an annual large enthalpy difference (Nitter & Svendsen, 2019b). Another study reported that details regarding the ventilation system were not known, neither the air flow rate nor the system topography (Erdinger et al., 2004). This lack of technical knowledge is of course expected due to the complexity of the facility and the technical system. Consequently, this underlines the need for interdisciplinary cooperation between the HVAC and DBP research fields to get precise design guidelines which can make a difference.

Despite the general lack of practical and useful recommendations for design parameters and system topography, exceptions exist. There are three possible ways to improve the air quality (Ratajczak & Piotrowska, 2019):

1. Reduce precursors,
2. Apply better disinfection methods,
3. Improve ventilation in the occupied zone.

Reduce precursors DBPs are an unintended consequence when the aim is to inactivate pathogens in swimming pools. Since many of the DBPs found in swimming pools are formed by the reaction of disinfectants, like chlorine, and natural organic matter from humans (Richardson et al., 2010), an obvious priority toward improved air quality is to reduce the precursors. Since this is a result of human hygiene, such as showering before swimming and avoiding the discharge of urine during swimming, the task of reducing this is not trivial or technical, but a socio-anthropological task where guiding/informing and possibly the layout of the shower room play an essential role. Even though urine is sterile itself, mixing with pool water represents a public health concern. Urine contains many compounds that can react with disinfectants, as chlorine, and may form DBPs (Jmaiff Blackstock et al., 2017). Since the potential limitation of the introduction of organic matter may not have an immediate effect on the DBP levels due to the slow reactions with chlorine, the facility management should emphasize continuous public awareness campaigns (Parrat et al., 2012).

Apply better disinfection methods Although the precursors are minimized, a complete elimination of organics is impossible. Urine has a massive chloroform DBP formation potential (Berg et al., 2019) which is likely to end up in the pool's air (Berg et al., 2019). In addition, results have shown that removing the volatile DBP trichloramine across the water treatment train is not a feasible strategy due to the high formation rate in the pool (Skibinski et al., 2019). Thus, the ventilation concept and fresh air supply for the facility are crucial to reduce the negative health impacts for the occupants. The layout of the water treatment train is of major importance in minimizing the harmful DBPs. For example, the use of granular activated carbon filtration is shown to remove trihalomethane (THM), and the use of UV treatment is shown to increase the air concentration of THMs (Nitter & Svendsen, 2019b).

Improve ventilation in the occupied zone Removing airborne pollutants can be done by either mixing ventilation concepts, by source capture through replacement ventilation, or a combination of both. Traditionally, the ventilation systems in Norwegian swimming facilities are based on mixing ventilation with low ventilation effectiveness, where the air is supplied in the vicinity of the glazing façade and a centrally placed extract air grill (Nitter & Svendsen, 2019a; Polak, 2008b). The concept is based on the perception that the main purpose of the ventilation system is to prevent condensation on the inner surface, supply sensible heat to the facility, and to dehumidify the air. The concept is found in Norwegian guidelines, as well as foreign references and standards, where the importance of stagnant air or low air velocities by the water surface is emphasized (Norges byggforskningsinstitutt, 2003; Polak, 2008a; ASHRAE, 2015; Bøhlerengen et al., 2004; Saunus, 2008; Standard Norge, 2019a). This is due to the air velocity impact on the pool evaporation rate. Since the space above the water surface is the occupant zone by definition, the traditional ventilation concept provides low ventilation efficiency and consequently relatively high values of DBP have been observed (Nitter et al., 2018). However, this design is in accordance with the present HVAC guidelines.

Air flow distribution

The air distribution in a swimming facility is of major importance. A properly designed system will supply fresh air to the breathing zones, remove airborne contaminants and disinfectant by-products, and prevent condensation, corrosion, and stratification (Lochner & Wasner, 2017). In the case of the latter, improper design may cause severe damage to both the building envelope and structures, like staircases, diving platform towers, handrails, and the technical equipment. In combination with adverse material properties, pitting corrosion may occur (Sedek et al., 2008; Szala & Łukasik, 2018).

Regarding the building envelope, exfiltration and infiltration may result in moisture accumulation that conceal deterioration of the building materials (Ananian et al., 2019). Condensation inside the facility may also cause corrosion, and in combination with poor ventilation efficiency the prevalence of fungi may occur (Viegas et al., 2010). The ventilation system should also maintain the thermal and hygroscopic environment within the preferred range and minimize the level of DBPs. There is consensus within the research community regarding the importance of good ventilation in order to avoid harmful environment for the pool users (Berg et al., 2019; Manasfi et al., 2017; Nitter & Svendsen, 2019a; Nitter et al., 2018; Ratajczak & Piotrowska, 2019; Zhang et al., 2015). Due to the complexity of swimming facilities and the multi-functionality of the ventilation system, a refinement is not straightforward. There are three possible approaches to improve the ventilation concept:

1. Improve ventilation efficiency (distribution),
2. Increase fresh air supply (dilution),
3. Remove DBP by source (concept).

Improving ventilation efficiency must be carried out by supplying more fresh air into the occupancy zone, which is against the present international guidelines, where air flow in the vicinity of the water surface is discouraged. Despite this, Cavestri and Seeger-Clevenger (2009) found a top-level ventilation concept in combination with a deck-level exhaust system to be successful in maintaining DBPs at low levels (Cavestri & Seeger-Clevenger, 2009; Baxter, 2012). By utilizing the physical properties of one of the most important DBPs, trichloramine, the system showed low levels of this DBP with the same fresh air flow rate as suggested by ASHRAE (2015; ASHRAE & ANSI, 2013). The concept is based on a principle of displacement of the polluted layer of air above the water surface, and the exhaust air is completely extracted from the facility, without being included in the air recirculating system, which is usual in swimming facilities. However, some technical issues regarding the energy efficiency of the facility must be solved when implementing this ventilation design.

As a part of the increased focus on reducing energy consumption in the building industry during the last decade, the Norwegian legislation has approached high energy efficiency building codes and the passive house concept (Standard Norge, 2012; The Norwegian Ministry of Local Government and Modernisation, 2017). This includes swimming facilities as well. An improved building standard reduces the heating demand and exfiltration/infiltration losses, increases the inner surface temperature, and reduces disparity in air supply/extraction. Rojas and Grove-Smith (2018) have taken this into account in their numerical study of possible ventilation concepts in energy-efficient swimming facilities carried out with CFD simulations. While the traditional high recirculation air change rate in swimming facilities is due to the need for good air distribution throughout the entire hall in order to avoid condensation and obtain a satisfying indoor thermal environment, the air change rate may be reduced and air circulation may be avoided (Rojas & Grove-Smith, 2018). The proposed optimal system, a "top level supply–low level extract" system with swirl diffusers with vertically discharging air, achieved the best air exchange and contaminant removal efficiency. Despite the uncertainty with an unvalidated CFD model, the importance of the low vertical location of the extract air opening was emphasized, as Cavestri and Seeger-Clevenger did (Cavestri & Seeger-Clevenger, 2009; Baxter, 2012). Regarding the supply air design in general, Limane et al. found improved air quality, improved thermal comfort, and reduced air stratification and age of air by increasing the air impulse and redirecting the air jet toward the occupied zone (Limane et al., 2018).

The complexity of the air supply and air flow patterns in large halls is considerable. Several microzones may easily occur, with stratification and dead spots, which can lead to severe corrosion, as previously mentioned. Areas with swimmers, people on the deck, spectator areas, and exteriors that need condensation and corrosion prevention need to be taken into account in the design (Lochner & Wasner, 2017). Ratajczak and Szczechowiak (2020) did just this in their study, while zoning the swimming facility with three virtual zones, each with dedicated ventilation systems: spectator zone, wall and roof as well as a source capture system for the occupant zone in the pool environment. This solution was proven to perform with a possible energy savings of maximum 36% as well.

Numerical investigation

Regarding investigation of air flow distribution, several numerical and experimental studies have been carried out, each with a distinctive approach. The phenomena of water evaporation and how to implement this in a CFD model was treated by both Ciuman and Lipska (2018), Blázquez et al. (2017), and Blázquez et al. (2018). Here, empirical relationships and the use of predefined boundary conditions were proposed. When modeling the indoor environment of a swimming facility, the calculated evaporation rate is of major importance due to its impact on air density, the dew point, and, last but not least, the overall energy use in the facility.

Lebon et al. (2017) used a validated zonal model developed in TRNSYS to investigate the indoor airflow patterns and occupants' perception of thermal comfort. They documented inadequate air renewal in the occupant zone and poor thermal comfort, with a too hot and humid environment in this specific pool hall including a semi-Olympic swimming pool. Limane et al. (2017) further investigated this specific facility by the weather effect on the indoor environment and documented a very small impact. Furthermore, the effect of the swimmers in the swimming pool was evaluated and found to be of great importance for the indoor environment. The main advantageous effect was found to be less stratification and better air mixing, and the adverse effect was increased specific humidity in the swimming zone. This underlines one of the main obstacles when modeling air flow in swimming facilities, where most studies present results from cases without occupant behavior.

Air handling unit and energy recovery

Along with the ventilation concept and the fresh air supply, the air handling and the mechanical design have a considerable impact on energy use. The AHU plays a central role in swimming facilities since it maintains the required thermal and atmospheric indoor environment and is an important tool to maintain safety (Standard Norge, 2019a). Since a standard AHU for a swimming facility provides temperature and humidity control as well as atmospheric control, the main part of the internal energy flow passes through the AHU, due to the absorbed moist air related to the evaporation. As a result of this, the design of modern swimming facility–dedicated AHUs includes the mechanical concept, the control system, and the energy recovery concept. The latter normally includes heat transfer between the air and water circuits, which is crucial for maximizing energy recovery.

For climatization and ventilation of swimming facilities, there are mainly two concepts for dehumidification and air supply:

1. Outdoor air dehumidification—maximizing fresh air supply,
2. Mechanical dehumidification—minimizing fresh air supply by refrigeration dehumidification.

The first concept, combined with mechanical energy recovery and dehumidification, is most widely used in Scandinavian countries (Johansson & Westerlund, 2001). These systems have been investigated in multiple studies, in several setups with heat pumps in several layouts as well as absorption systems with absorbent (Johansson & Westerlund, 2001; Liu et al., 2014; Qiu & Riffat, 2010; Ratajczak & Szczechowiak, 2020; Sun et al., 2011). Johansson and Westerlund (2001) proved the importance of a heat recovery system in the air circuit in their study and reported approximately 20% reduction in the total energy demand for this application. As Liu et al. concluded (Liu et al., 2014), Johansson and Westerlund also identified an absorption system to be the most efficient of the two concepts. Due to the well-established technology in the market, the heat pump system should normally be the preferred equipment in new projects (Johansson & Westerlund, 2001). This recommendation is based on the importance of optimal continuous operation of equipment that is both operator-friendly and supplied with well-defined supplier-directed responsibilities due to the overall functioning over the lifetime span of operation.

The energy supply system

The energy systems in swimming facilities are complex even in the basic layout; they include water circuits, air circuits, makeup-water system, and often multiple heat pumps and complex control strategies due to the demanding indoor environment and the need to control the evaporation phenomena. Since the energy performance of the swimming facility depends both on the technical layout and the presence of a heat recovery system (Kampel et al., 2014), predesigned energy recovery systems are available on the market. These are for the heat recovery of exhaust air and waste water. Generally, the design of these systems requires a highly conscious designer, with respect to the layout to the selection of equipment since high energy use is related to weaknesses in the building design and maintenance (Kampel et al., 2016). Kampel et al. found that the Norwegian swimming facilities had an excessive energy use, approximately 30% above the expected level (Kampel et al., 2013). In addition, they found considerable variation in the specific energy use. Comparing this to the specific energy use per visitor, presented by Rajagopalan (2014), no consensus regarding energy use is observed. There may be many reasons for this, but the operation of the facility is obviously one of them.

The dispersion in energy use and the complexity of the facility underline the importance of an operational and maintenance tool for the operation staff. Kampel et al. emphasized the importance of this by using benchmarking in operation for identifying operational irregularities. He proposed a “key performance indicator” based on energy usage data for 43 Norwegian swimming facilities (Kampel et al., 2016). This general approach can be regarded as a “first help aid” for operating swimming facilities because of its general approach and the accuracy of the method. While Kampel et al. claimed that overall water usage is the most correlated variable to the energy usage, the literature differs in the use of “key performance indicator” for energy use in swimming facilities. Other studies did not find any strong correlation to water usage (Duverge et al., 2018) but found the strongest correlation to the bather load and the number of opening days (Nitter et al., 2019), or referring to usable area (kWh/m^2.a) (Rajagopalan, 2014; Swim England, 2016) or water surface area (kWh/ws.a) (Trianti-Stourna et al., 1998). This indicates that this benchmarking tool, based on statistical data from multiple facilities, could not be the optimal solution as an operational guidance tool for securing optimal operation of the facility. This is mainly due to the accuracy and the variety of facility types, and the fact that the concept of benchmarking is “looking backwards” and comparing annual energy use of existing swimming facilities to avoid operation disruption in new facilities.

Operation of the facility

The overall energy consumption of the building and the consequent environmental impact is dependent on the operational phase of the building (Rincon et al., 2013), and this should be emphasized. The lack of supervision of a building's performance after commissioning and during the operational stage as well as the complexity of rating systems are identified as some of the major obstacles associated with building performance assessment systems (Namini et al., 2014; Rincon et al., 2013). Despite this, the literature generally lacks rating systems as operational support, both as tactical and operational tools (Ruparathna et al., 2017). In swimming facilities, the complexity of the rating system and the impact of the operation may be expected to be substantial. The consequence of inappropriate operation of the HVAC system in swimming facilities may cause problems like degradation of equipment and the occurrence of the sick building syndrome (Pietkun-Greber & Suszanowicz, 2018), in addition to increased water and energy usage.

The complexity of creating such a rating system for swimming facilities is well illustrated by the estimation of the energy use, which is crucial in a rating system for this building category. Several researchers have proposed calculation methods for this by introducing physical models (Lu et al., 2015), machine learning tools (Yuce et al., 2014), and building performance simulation tools like IDA ICE (EQUA Simulation AB, 2020) or TRNSYS (Calise et al., 2018; Mancic´ et al., 2014), each represented by pros and cons. However, none of these calculation methods can be easily implemented into average operation management.

The design phase

Besides the importance of the facility operation, the design phase is crucial for the performance of the facility. The engineers design a system that aims to fulfill the building-defined energy usage ambitions and the user demand regarding the indoor environment. This task is a multi-objective optimization problem including technical issues and the construction of the building envelope where holistic and in-depth knowledge is required. For example, research has established that an improvement in the thermal properties of the building envelope is proven to have the potential of reducing the energy consumption by 20%, considering a refurbishment project (Isaac et al., 2010). The dependence between the indoor environment and energy use is also found by Westerlund et al. (1996), where the air temperature and humidity had a considerable impact on energy use. Due to the influence of an open water surface, the indoor temperature may have the opposite effect on the energy use compared to conventional "dry" buildings. Depending on the type and extent of the heat recovery system in the AHUs, the temperature level will affect the energy use differently. A system without a heat recovery system will profit from a relatively high indoor air temperature (Johansson & Westerlund, 2001) whereas a concept with a highly developed heat recovery system will profit from a lower indoor air temperature. This is due to the interaction between thermal losses in the swimming hall, the air flow losses, and evaporation from the pool surface. Ribeiro et al. treated this interaction in their work, where the use and selection of set-point temperature and humidity was investigated and discussed (Ribeiro et al., 2011, 2016). By introducing alternative control variables, dew point and wet bulb, as well as alternative ranges, they proved an energy cost savings for the specific case study of about 8% (Ribeiro et al., 2016). This indicates a large energy savings potential just by adjusting the software for the building energy management system.

The control system and the choice of controller is another important topic. Normally, the HVAC system is equipped with P, PI, and PID controllers, depending on the purpose. The use of predictive control, in combination with solar systems, with early shut-off, proved to reduce the energy demand by approximately 20% and the fuel consumption by approximately 40% (Delgado Marín et al., 2019). This improvement was due to the successful task of maximizing the applied solar energy into the system. The concept of predictive control is especially suited for making the system operate with an economically optimal regime, where the heat supply can be directed to periods with high electricity charges (Zemtsov et al., 2017).

Taking into consideration the thermal mass of the swimming pool, the proper selection of the control parameters is associated with reduced operational cost, similar to the case for outdoor swimming pools (Venkannah, 2002). This thermal mass may either be utilized in the energy plant locally, with the purpose of reducing energy consumption and for effect peak shaving purposes (Woolley et al., 2011) or for peak shaving for district heating systems for neighborhoods (O. Kim et al., 2018).

When taking the pool into account, with an active approach as mentioned above, the importance of evaporation cannot be underestimated. The consequences of misjudging the magnitude of the evaporation rate will result in either a dysfunctional HVAC system (in case of the design phase) or excessive energy use (if uncontrolled in the operation phase). Due to the complex nature of these phenomena, calculation is not a straightforward task. Numerous articles have been published over the last century regarding this subject, all of them based on Dalton's first empirical investigation that determined the law of partial pressure which was published in the early nineteenth century (Dalton, 1802). Although there is a lack of consensus regarding one particular calculation method, some major methods stand out.

The widely known correlation which Carrier proposed in 1918 (Carrier, 1918) was based on results from a set-up with an unoccupied water surface and by experiments using forced air flow. Even though the set-up only included forced convection, the equation has also been used for natural convection by setting the velocity term to zero. The equation has been widely used throughout the century for all sorts of facilities, and applied in the ASHRAE handbooks (ASHRAE, 2015), where an additional activity factor is applied to the equation.

Smith et al. investigated the evaporation rate for both indoor and outdoor swimming pools, as well as occupied and unoccupied pools (Smith et al., 1993, 1994, 1998). They confirmed the form of the Carrier equation but proposed a correction factor for unoccupied cases and an activity factor for the occupied cases. They found that the Carrier equation overpredicted the evaporation rate when applied in cases with unoccupied pools.

Hanssen and Mathisen (1990) performed experiments in a school swimming pool in Trondheim, Norway, and proposed a semi-empirical equation for estimation of the evaporation rate. The equation has been important for Norwegian engineers since it was published in 1990, and has been referred to in the academic literature by Stensaas (1999) and in the NBI engineering guidelines (Norges byggforskningsinstitutt, 2003). The equation is valid for both occupied and unoccupied pools using a proposed activity factor. Even though the activity factor is proportional to the number of swimmers in the pool, it was emphasized in the study that the evaporation rate increases more like a step function, even with a few swimmers present.

During the last three decades, Shah has published several articles regarding his work on evaporation correlations (Shah, 1992, 2002, 2003, 2008, 2012, 2013, 2014). The equations presented are based on physical phenomena, theory, and empirical data. Shah validated his formulas with all available test data and compared the accuracy with several present correlations (Shah, 2014). His equations and calculation algorithms predicted evaporation for unoccupied and occupied pools with a mean deviation of approximately 21 and 16%, respectively (Shah, 2012).

Other empirical equations of major importance to industry are provided by the VDI guidelines (Verein Deutscher Ingenieure, 2010). VDI applies to heating, room air, sanitary installations, and electrical systems in public indoor swimming pools and for Germany can be considered as ASHRAE is for the USA.

Prediction of performance

Several studies regarding evaluation of the present evaporation equations have been carried out. While Shah (2014) evaluated the performance in his own algorithm to be the most accurate, Ciuman and Lipska (2018) found the most accurate correlation to be the VDI correlation (Verein Deutscher Ingenieure, 2010), by comparing the performance of Carrier (1918), Smith et al. (1993), Shah (2014), ASHRAE (2007), VDI (Verein Deutscher Ingenieure, 2010) as well as Biasin and Krumme (1974). Li and Heiselberg (2005) found that the ASHRAE correlation (ASHRAE, 2007) gave a good prediction for higher occupancies, while Shah's correlation for unoccupied pools (Shah, 2002) and occupied pools (Shah, 2003) gave the best prediction. This underlines the uncertainty when dealing with evaporation. This challenges the designer of the HVAC system because this uncertainty affects the overall system efficiency. Taking into account the overall complexity when including the energy plant and the ventilation system when predicting the annual energy consumption, the use of building performance simulation (BPS) tools is crucial for optimizing and sizing the systems. Concerning prediction of evaporation in multizone network, the BPS tool IDA ICE (EQUA Simulation AB, 2020) has implemented the ASHRAE equation (ASHRAE, 2007) while Transsolar's TRNSYS pool add-on (Auer, 1996) has applied the VDI equation for occupied pools (Verein Deutscher Ingenieure, 2010).

Regarding the design of the energy plant, improvements regarding the layout can be done by optimizing the configuration. An optimal configuration and capacity of a polygeneration system gives good solutions for a specific case, but are often based on the present energy demand (Mančić et al., 2018). The task is not trivial and knowledge with respect to detailed information regarding the performance is crucial (Luo et al., 2019). There are numerous possible sources; some are especially adapted to the specific building and location and some are not. For example, the use of a solar roof has been proved successful (Archibald, 2017) as well as buildings interacting with each other and sharing energy (Abo Elazm & Elsafty, 2011; Kuyumcu et al., 2016).

Chow et al. (2012) used TRNSYS (Klein et al., 2017) to investigate the use of a solar-assisted heat pump for a public swimming center located in Hong Kong. They found that the installation performed well with an economical payback period less than 5 years. Even though tropical and subtropical areas are assumed to be favorable, solar energy systems are not the preferred energy source for public swimming facilities in all areas (Fuller et al., 2017). Fuller et al. (2017) assessed the viability for a solar heating system in the southern part of Australia and found the investment to be relatively favorable with a payback of about 7 years. However, the system was found not to be common in public facilities, where the barriers were unchanged for the last 30 years. These studies illustrate the need of a BPS tool in the design phase.

Along with the improvement in the building standard for the whole building stock, and the consecutive reduction of the energy consumption, the implementation of power-demanding devices has been substantial. Due to this, peak demand tariffs have been introduced. This encourages the end users to reduce their power demand. By applying demand control strategies, studies have shown a reduced peak power cost by approximately 15% by the use of battery storage in a medium-sized swimming facility which includes a grid-connected photovoltaic system (Berglund et al., 2019). The potential for optimizing these kinds of facilities seems substantial but is highly complex. Consequently, software and modeling techniques for the engineering community must be developed further.

Conclusions

This paper presents a review of the research in the area of swimming facilities in the context of heating, ventilation, and air conditioning (HVAC). Different aspects of swimming facilities have been covered including air quality, ventilation, and energy performance. The contribution in each field has been presented as well as the research focus. The understanding of swimming facilities as a building type is a highly complex task as it is a system involving numerous interacting disciplines. The aim of this paper has been to create a better understanding of the topic and reveal the weak spots in the current state of the art.

Air quality and ventilation

The research field of disinfection by-products (DBPs) in swimming facilities appears to be mature and has evolved to be the most important research area during the past decade given the largest number of publications.

In general, the gap between research and engineering is wide in this field. If designers are to use the findings related to this topic, precise recommendations must be provided and the close relation to the interaction with the HVAC system must be precisely described. Future studies that aim to provide knowledge for improved design should be carried out by multidisciplinary research teams in order to ensure that the results are possible to implement and interpret in the context of HVAC and system architecture. However, there is consensus that DBPs in indoor air in swimming facilities should be dealt with by an effective ventilation system:

- *The ventilation concept* of source capture has proven to perform well (Cavestri & Seeger-Clevenger, 2009; Baxter, 2012), even though this design is in contradiction to national and international guidelines which recommend to avoid, or minimize, the air movement in the swimmers' breathing zone, due to its effect on evaporation. However, applying the concept of source capture leaves the challenge to the present design of AHUs with large internal flow of recycled air, which must be modified in order to ensure high energy efficiency for the facility.

- *The fresh air flow rate* is found to correlate with the dilution of contaminates and the concentration of DBPs (Nitter & Svendsen, 2019a). However, no consensus is found regarding the recommended fresh air flow rate. Some studies call for "100% fresh air" (29), another "a large air volume" (Parrat et al., 2012). A few studies recommend a customized control system for the fresh air supply by including variables like "water quality" and "bather load" (Nitter & Svendsen, 2019a). State-of-the-art AHUs dedicated for swimming pools have complex control systems where the supply air flow rate is decided by variables like operating mode, supply air temperature, extract air temperature, air humidity, and heat supply. New additional variables must be precisely evaluated due to the increased complexity, the additional risk of excessive energy use, and the overall vulnerability of the system. In general, an increased fresh air supply will reduce indoor humidity and result in greater evaporation and energy use, in addition to the impact on thermal comfort.
- The lack of *prediction models* for the generation rate of DBPs has been identified since this is an important index when designing ventilation systems. Present guidelines and regulations, like the national guidelines (Bøhlerengen et al., 2004; Norges byggforskningsinstitutt, 2003; Polak, 2008b), international guidelines (ASHRAE & ANSI, 2013; Verein Deutscher Ingenieure, 2010; ASHRAE, 2015; World Health Organization, 2006; Standard Norge, 2019b), and Norwegian codes (The Norwegian Ministry of Local Government and Modernisation, 2017; The Norwegian Ministry of Labour and Social Affairs, 2011), are all divergent with regard to recommendations, and a proper calculation tool for optimized fresh air flow rate should therefore be developed.

In addition to the abovementioned key elements and considering that a complete stop of the applied DBP's precursors is unattainable, a hygienic control and improved water treatment should be emphasized in swimming facilities.

Energy

Several studies have treated alternative control strategies in swimming facilities and emphasized the potential in the building energy management systems (BEMS). For example, the use of alternative control variables like dew point and wet bulb temperature in alternative ranges proved an energy cost savings of about 8% for the specific case (Ribeiro et al., 2016). This indicates a large energy savings potential only by adjusting the software for the BEMS. The concept of predictive controls has also proved to be especially suited for making swimming facilities with solar systems operate with an economically optimal regime due to the thermal mass of the pool. However, the research field of energy systems in swimming facilities in cold climates is found to lack research on solar energy applications despite the considerable potential represented by the constant high electric load and the large thermal mass represented in the pool.

The system design defines the operational boundary constraints. Due to the multiple disciplines represented in the building, the need of predicting and optimizing the performance is considerable, both by means of dynamic and steady-state simulations considering the overall energy performance of the facility. This also includes modeling the complex phenomena of evaporation where there is a lack of consensus in the research.

Operation

Even a well-designed swimming facility is no better than its operation. The operation of swimming facilities is a multi-objective optimization problem that requires tactical and operational management. The probability of operational failure is substantial if only annual energy consumption and water usage measurements are included in the operators' benchmarks for the facility. The literature lacks benchmarks and rating systems, and both indexes and easily implementable methods should be developed. A rating system, as an operational tool, would ensure better operation concerning the facility's primary functions, the indoor environment, and the energy use.

Acknowledgements This work is a part of a doctoral project entitled "Optimizing Energy and Climate Systems in Buildings with Swimming Facilities," which is carried out as a cooperation project between the Centre for Sport Facilities and Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, and the engineering company COWI AS. The project is funded by COWI AS, The Research Council of Norway and COWIFonden.

Funding Open access funding provided by NTNU Norwegian University of Science and Technology (incl St. Olavs Hospital - Trondheim University Hospital).

Declarations

Conflict of interest The authors declare no competing interests.

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Paper II

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The Implementation of Multiple Linear Regression for Swimming Pool Facilities: Case Study at Jøa, Norway

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Abstract: This paper presents a statistical model for predicting the time-averaged total power consumption of an indoor swimming facility. The model can be a powerful tool for continuous supervision of the facility's energy performance that can quickly disclose possible operational disruptions/irregularities and thus minimize annual energy use. Multiple linear regression analysis is used to analyze data collected in a swimming facility in Norway. The resolution of the original training dataset was in 1 min time steps and during the investigation was transposed both by time-averaging the data, and by treating part of the dataset exclusively. The statistically significant independent variables were found to be the outdoor dry-bulb temperature and the relative pool usage factor. The model accurately predicted the power consumption in the validation process, and also succeeded in disclosing all the critical operational disruptions in the validation dataset correctly. The model can therefore be applied as a dynamic energy benchmark for fault detection in swimming facilities. The final energy prediction model is relatively simple and can be deployed either in a spreadsheet or in the building automation reporting system, thus the method can contribute instantly to keep the operation of any swimming facility within the optimal individual energy performance range.

Keywords: swimming facilities; energy prediction; fault detection; multiple linear regression analysis

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Citation: Smedegård, O.Ø.; Jonsson, T.; Aas, B.; Stene, J.; Georges, L.; Carlucci, S. The Implementation of Multiple Linear Regression for Swimming Pool Facilities: Case Study at Jøa, Norway. *Energies* **2021**, *14*, 4825. https://doi.org/10.3390/en14164825

Academic Editor: Marcin Kamiński

Received: 28 June 2021
Accepted: 4 August 2021
Published: 7 August 2021

1. Introduction

1.1. Background

The EU has defined a target for reducing GHG emissions by at least 40% by 2030 compared to 1990 levels [1]. Their long-term goal is defined as "no GHG emissions" by 2050 [2]. Increased energy efficiency in buildings is defined as an important tool for both the short term and long term [3]. One of the "key actions" in the Action Plan related to the 2030 framework is a "renovation wave" of the existing building stock [2].

Within the "renovation wave", the European Commission recommends paying particular attention to energy-reducing refurbishment in types of buildings that support education and public health, such as schools and hospitals [2]. In swimming facilities, which support education and public health, the potential for energy reduction is considerable [4] and the literature associates these facilities with high specific energy use [5] and a large dispersion in energy use. The specific energy use ranges from 400 kWh/(m^2·a) to almost 1600 kWh/(m^2·a) [6–9]. This can be partially explained by the variations in age, technology and the different maintenance routines [7], but the numbers also represent a large energy saving potential [7]. Regarding the building stock of swimming facilities in Norway [6], the overall excessive energy use is estimated to be 28%. This provides a considerable incentive for improvement initiatives.

1.2. Motivation

Since the energy consumption of any building is highly dependent on the operational phase [10], particular attention has to be given to providing optimal operation [11]. Here, both behavioral and operational management are important [12]. It is crucial to emphasize the importance of well-trained and qualified operating personnel [13], especially in buildings with extensive technical installations like swimming facilities [13]. However, this is not always the case [14], and even with skilled operating staff, it is a considerable task to run a facility that has satisfactory performance. In the case of non-skilled operating staff, the performance of the facility is vulnerable if there is improper operation and possible excessive energy use and low indoor environmental quality. The complexity of the operation increases if there are more and more technical components [15]. In addition, during the operation phase, such factors will degrade the building and the technical systems, and the performance of the building will be lower than when it was commissioned [16]. This may lead to a poor indoor environment and increase the energy use. For buildings with extensive technical systems, such as swimming facilities, multiple operational interruptions may conceal other malfunctions and make it difficult for the operating staff to find them. The result is a building with low overall performance compared to the design level. This means that there is a need for strict holistic control and a supervision system for the performance of the building.

Ruparathna et al. [17] proposed a rating system for public buildings based on a level of service (LOS) index. This index is a qualitative measure that is traditionally used to compare the quality of motor vehicle traffic services. When applied to public buildings, the LOS index indicates the level of operational performance provided to building users, society and the environment, based on the assessment of the defined performance indicators in the building. For the operating staff, this kind of rating system can be applied as a useful tool if it is used as a continuous reporting system for the performance of the building. With the implementation of adequate performance indicators, this kind of system will contribute to keeping the technical installations “on track” as a lifetime commissioning system and a tool for fault diagnosis.

For swimming facilities, the number of performance indicators may be considerable and some are impossible to track directly in real time, for example, the level of some airborne disinfection by-products. Ruparathna et al. [17] implemented a set of 22 performance indicators in their case study, including measures like user satisfaction, indoor environmental quality, water quality and energy use, among others. Saleem et al. [18] investigated the choice of performance indicators for aquatic centers in Canada, and proposed a set of 63 indices, including water quality, indoor environmental quality, energy efficiency and user satisfaction.

Energy efficiency is an important aspect in these rating systems and is considered the most important criterion in sustainability rating systems as well as the least achieved [19]. This underlines the importance of a strict system for monitoring the energy performance along with the main functions of the building. Due to the large internal energy flow in swimming facilities, this is even more important because of the increased probability of operational faults and increased energy use.

1.3. Theoretical Background

Continuous assessment of building energy performance is a process of analyzing residuals. Here, the residual is the difference between the monitored energy use and the prediction of the expected energy use of a dynamic benchmarking system. Contrary to “snapshot” rating systems, such as energy labeling of buildings [20] or documentation for fulfilling the passive house standard [21,22], a dynamic benchmarking system depicts the continuous energy performance of the facility.

The prediction of the expected energy use is a complex task which depends on a large set of variables and parameters. The task should preferably be solved in a way which could easily be implemented in existing facilities and control systems. It should also be easy to adapt and be transparent for the operating staff. The importance of easy implementation is related to the increasing climate threat which can also be found in the short-term goal defined as the EU 2030 GHG reduction goal [1].

As they are different from other building types, swimming facilities are characterized by complex energy systems required to maintain appropriate conditions in the swimming hall and pool(s) and provide suitable water quality. Swimming halls are facilities with complex and energy-intensive technical systems [23], with several interacting subsystems. Figure 1 illustrates the extent of the technical systems and how they are connected internally and to external variables. These systems provide functions like fresh air supply, air heating, dehumidification, water heating and water treatment. The thermal and electric power/energy consumption levels of the different systems are logged in the building automation system.

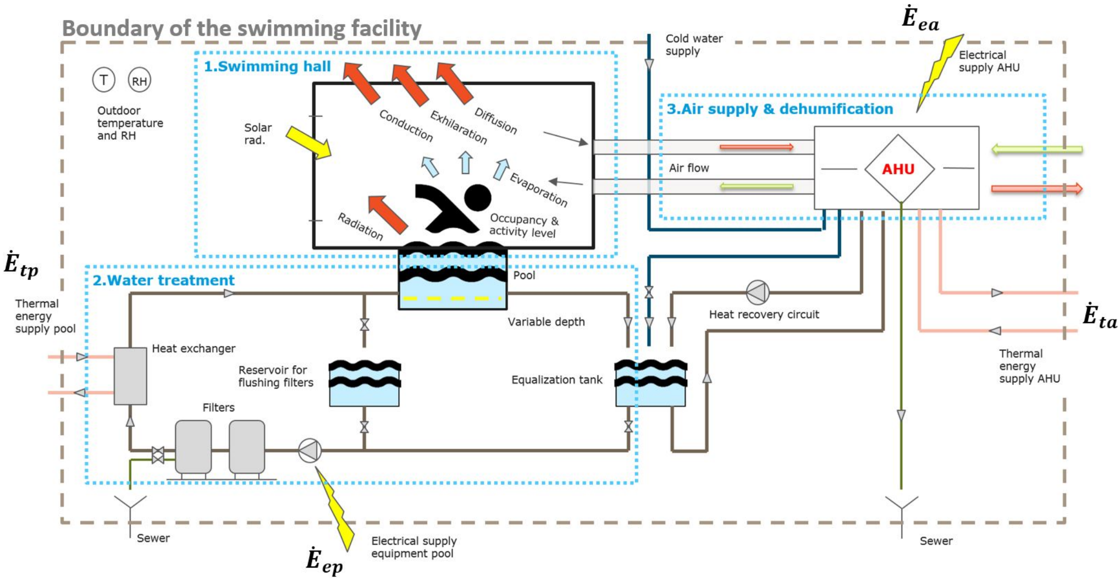

Figure 1. An overview of the extent of the technical systems in a typical swimming pool facility.

The task of predicting the energy use in swimming facilities is complex due to constantly fluctuating variables such as evaporation of water from the pool and surrounding surfaces, the required amount of makeup water and the filter flushing intervals. Energy prediction has been treated in several studies where methods regarding outdoor and indoor swimming facilities have been presented.

1.4. Energy Prediction Methods

The energy prediction methods include physical/engineering methods as well as statistical and artificial intelligence methods [24]. Lu et al. [25] addressed the design and analysis stage and proposed a physical model for a sports facility. Despite the challenge related to the required numbers of parameters, the model performed with a coefficient of correlation (R^2) of 0.934. Westerlund et al. [26] showed that the engineering approach for estimating annual energy use gave satisfactory results in swimming facilities as well.

The results from this study, with a prosaic and simple technical structure, illustrates the importance of heat recovery, where evaporation dominates the energy demand. The same observation was also revealed in the study by Lovell et al. [27] where an engineering model for the prediction of thermal performance for an outdoor Olympic swimming pool in Australia was developed. The model was based on the heat balance and performed with an accuracy of 67% of the predicted heating capacities. This was within a range of ±100 kW, which proved to be the most accurate model compared to other equivalent models. The study confirmed that evaporation dominated the energy demand of an outdoor swimming facility. The same physical and empirical equations are also applied in building performance simulation tools such as TRNSYS [28], ESP-R [29] and IDA ICE [30], among others. Mančić et al. [31] determined the energy losses for a pool hall and pool, and later the optimal configuration of a polygeneration system [32], by modeling the system via physical and empirical equations in TRNSYS. Moreover, Duverge and Rajagopalan [33] investigated the energy and water performance of an aquatic center in Australia. They modeled the facility with the BPS tool EnergyPlus and recommended both solar heating and the use of vacuum filters in their study.

Yuce et al. [34] presented an artificial neural network approach for predicting the energy consumption and thermal comfort in an indoor swimming facility. The prediction was an application for an optimization-based control system for swimming facilities. Kampel et al. [35] proposed a statistical model for predicting the annual energy use of swimming facilities. It was developed through a multiple linear regression (MLR) analysis, and its purpose was to establish a tool for calculating energy performance indicators for the benchmarking of swimming facilities. In addition, the MLR method was also applied in the study by Duverge et al. [36]. One of the outcomes was that the usable floor area and the number of visitors were among the most influential variables for annual energy use.

While the simulation tools based on physical models and artificial neural networks, with different topologies and learning algorithms, can provide useful insights and efficiently predict target values, both frameworks are computationally costly and need case base adaptation. In the context of the practical use and implementation of energy prediction features among existing buildings, MLR has the potential to be in the middle ground with respect to computational cost and the opportunity to adapt it to the different target cases. MLR represents an easy-to-follow statistical method [37] which can explain a dependent variable, using multiple independent variables, but does not require in-depth knowledge of physical processes or training algorithms. It is easy to develop and implement [38] and is widely used in the prediction of energy use. For example, Safa et al. [39] presented a method to predict energy use in office buildings for the purpose of energy auditing. The study showed the capacity of simple models where the final regression model was based on outdoor temperature and occupancy with a monthly resolution. The model performed well with acceptable error, when assessing each of the four buildings in the study individually. Catalina et al. [40] developed a regression model for predicting the monthly space heating demand for residential buildings while another approach developed a generic equation of three variables for predicting the heating demand in apartments blocks [41]. The MLR method has also been applied with success in energy forecasting for swimming pool buildings [38,39].

The objective of this paper is to investigate and propose a method for energy prediction in swimming facilities, based on the MLR method. This approach has considerable potential for reducing the annual energy demand of both existing and new buildings by making the operating staff conscious of the performance of the building in relation to the design level. Buildings are only sustainable if they are operated and maintained properly [15].

2. Method

This study investigates the impact of several independent variables on the energy use of a swimming facility. The analysis has been carried out by applying the multiple linear regression method with the purpose of developing a reliable energy prediction model. Figure 2 illustrates the workflow of the study, where the main topics are identified.

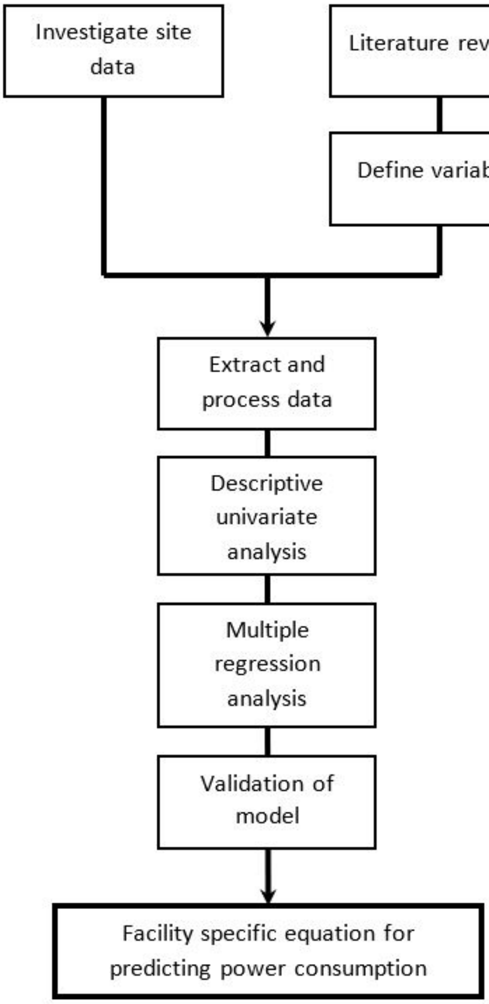

Figure 2. Block diagram representing the workflow of the study.

2.1. The Building

The investigated building is a multi¬purpose sports center located at Jøa, an island in the municipality of Namsos in Norway. It is located at 64.6 N, 11.2 E, 65 m above mean average sea level. It is defined as part of the Marine West Coast climate zone according to the climate zone definition of Köppen and Geiger [42]. The sport center was commissioned in autumn 2016 and contains several facilities besides the swimming pool facility, such as a sports hall, a shooting range, a library, a café, a gym and an outdoor ice rink. Figure 3 shows a photograph of the north-oriented façade for the swimming hall. The swimming hall has a usable area of 266 m^2 (13.7 m × 9.43 m), including the 8.5 m × 12.5 m swimming pool. Key quantities are presented in Appendix C. This paper investigates only the part of the building with the swimming facilities.

Figure 3. The northern façade of the building.

2.2. The Technical Systems

The swimming facility at Jøa is a state-of-the-art swimming facility which complies with the Norwegian passive house standard [22]. It includes a ventilation heat recovery system equipped with a heat pump, as recommended in the literature [5,43], and conventional water treatment, which research has found to be the most effective water treatment train [44].

2.3. The Dataset

The dataset ranges from November 2017 to June 2019 and is separated into two parts. The training dataset and the validation dataset are, respectively, from November 2017 to June 2018 and September 2018 to June 2019. The size of the datasets was decided based on three main factors: (1) The training dataset should not be too large, due to the purpose of the study; it should be a quick and easy to implement a dynamic energy benchmark for swimming facilities. (2) The validation dataset should be large enough to cover all the seasons and several operation disruptions. (3) It should be preferably based on continuous operation data, without including lockdowns for maintenance.

2.4. The Variables

The objective of the study is to predict the energy use (dependent variable) as a result of several independent variables. The selected independent variables used in this study are listed in Table 1.

The dependent variable was defined by applying the energy conservation Equation (1) at the boundary defining the swimming facility as presented in Figure 1.

$$\frac{dE_{net}}{dt} = \dot{E}_{net} = \dot{E}_{ea} + \dot{E}_{ta} + \dot{E}_{ep} + \dot{E}_{tp} \tag{1}$$

where $\dot{E}_{net}$ is the net delivered energy to the facility, $\dot{E}_{ea}$ is the delivered electricity to the air handling unit, $\dot{E}_{ta}$ is the delivered thermal energy to the air handling unit, $\dot{E}_{ep}$ is the delivered electricity to the pool circuit and $\dot{E}_{tp}$ is the delivered thermal energy to the pool circuit. The units for the variables are given in Table 1.

The independent variables were defined as the meteorological data, ambient air temperature and relative humidity and the usage data. This choice was due to the availability in the respective building and to the known correlation between energy use and outdoor climate [45] and user interference [7,36,45]. In addition, this group of indicators is represented as logged values in conventional building automation systems (BASs). Due to the highly insulated building envelope and the orientation of the façades, the assumption of negligible effects of wind pressure and solar radiation was applied.

The dataset was created by:

1. Extracting historic data from the BAS.
2. Collecting weather data from the national database of the Norwegian Meteorological Institute [46].
3. Digitalizing handwritten occupancy data due to lack of electronic occupancy registration.
4. Calculating new variables based on indirectly monitored data. This is reported for the respective variables in Table 1.

Due to implications within the BAS, extracting data prior November 2017 was not possible. In addition, only a limited part of the variables was logged in June 2018. Table 1 summarizes the variables in the dataset, the units and the origin of the data.

Table 1. The selected variables that have been used in the analysis.

N	Variable	Unit	Type	Source	Comment
$\dot{E}_{ea}$	Electric energy consumption, AHU	$\frac{\text{kWh}}{\text{h}}$	Dependent	BAS	Fans, compressor, pumps and control system
$\dot{E}_{ta}$	Thermal energy consumption, AHU	$\frac{\text{kWh}}{\text{h}}$		BAS	Supplied thermal energy for air heating
$\dot{E}_{ep}$	Electric energy consumption, pool circuit	$\frac{\text{kWh}}{\text{h}}$		BAS	Related to pumps, disinfection, etc.
$\dot{E}_{tp}$	Thermal energy consumption, pool circuit	$\frac{\text{kWh}}{\text{h}}$		BAS	Supplied thermal energy for pool heating
$\dot{E}_{tot}$	Total thermal and electric energy consumption	$\frac{\text{kWh}}{\text{h}}$		Calculated	Summarized load pt. 1–4
T_{out}	Outdoor dry-bulb temperature	°C	Independent	BAS	Measurement from the site
	Moisture content outdoor air	$\frac{\text{g}}{\text{g}}$		Calculated	Meteorological data
	Enthalpy difference indoor/outdoor	$\frac{\text{kJ}}{\text{kg}}$		Calculated	Combining meteorological data and indoor air measurements and by applying the ideal gas law
t_{pu}	Pool usage factor (proportion of time the pool was in use)	-		BAS/ Calculated	Calculated by utilizing water level data in the equalization tank
	Number of adults bathing	adults		Handwritten	Manually digitalized and implemented in the dataset
	Number of children bathing	children		Handwritten	Manually digitalized and implemented in the dataset
Q_w	Water supply flow rate to the pool circuit	$\frac{\text{l}}{\text{s}}$		BAS /Calculated	Calculated by utilizing water level data, flushing reservoir

2.4.1. Cleaning the Dataset

The resolution of the original training dataset was 1 min time steps for all the variables. The dataset was cleaned and preprocessed by detecting and analyzing outliers manually, caused by broken sensors, miscoded values, operation disruption (e.g., unintended operation due to mechanical flaws, software errors or mistakes by the operator), etc. Outlier detection can also be carried out statistically, for example, by using approaches such as standard deviation or the interquartile range [47]. Both techniques identify outliers by comparing each value/measurement to its population. Due to the purpose of this study, outliers are of special interest (fault detection). For the training dataset, operation disruptions were identified and excluded prior to regression analysis, while operation disruption was a part of the validation process.

The process of identifying and categorizing operation disruptions was carried out by an in-depth investigation of the historic data, stored in the BAS and in the dedicated control systems of the air handling unit and heat recovery system.

2.5. Statistical Methodology

The choice of the multiple linear regression method was based on its strength as a statistical data handling tool and its simplicity in development, implementation and operation. The latter is crucial if the building owners and the industry are to be able to minimize the energy use, related to undesired operation, over a short period of time. Regarding practical issues, the developers (the engineers) recognize the method in their university education and the operation management can easily evaluate the energy performance in a spreadsheet [41], or it can be easily implemented in any report system, due to its simple algebraic equation.

The dataset was imported and analyzed with IBM SPSS statistical software [48].

2.5.1. Multiple Linear Regression

The MLR method was used to predict the dependent variable y, here the total power consumption, averaged over a certain period. This period was taken to be sufficiently long so that the method only focused on physical effects as processes in the steady state for each time step. The regression equation was trained by the ordinary least square method where the sum of the root square error was minimized. The corresponding regression coefficients, β_0 and β_i, were determined. These comprised the slope coefficient for the independent variables.

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \epsilon \tag{2}$$

where y_i is the dependent variable, β_0 is the intersection with the y-axis when x is zero, β_i is the regression slope coefficient in the linear equation, x_i is the predictor—the independent variable—and ϵ is the error term.

2.5.2. Assumptions

In the development of the model, several assumptions were adopted. The data source was time series data, and, initially, its autoregressive properties or the order of the autoregressive process were not known. These were identified by applying the partial autocorrelation function (PACF), which specifies the number of past lags influencing the dependent variable (i.e., the order of the autoregressive process). The application of the PACF in time series analysis is analogous to deciding the number of independent variables to be included in a multiple linear regression analysis [49]. The dataset was initially investigated for autoregressive properties and reduced by averaging the data and centered in time to eliminate any autoregressive properties in the dependent variable. Each observation in the training dataset was then treated as independent.

2.5.3. Evaluation of the Prediction Model

The "goodness of fit" was evaluated by the coefficient of determination R^2 and the adjusted R^2, which considers the number of explanatory variables and the possibilities of overfitting. R^2 is defined by the relationship between the explained sum of squares and the total sum of squares.

The multiple linear regression equation was validated by analyzing the variance with the F-test. The test operator, F, which is defined by the ratio between the explained sum of squares and the residual sum of squares, was applied to the F-distribution. A significance level of 5% was chosen as the required level.

The coefficients in the equation, the impacts of the independent variables, were evaluated by applying the T-statistic, with the *t*-test, which is similar to the F-test, but which describes the probability of nonlinear correlation by applying the test operator to the T-distribution. The test operator is defined by the relation between the coefficient and its standard error.

The fundamental assumptions for using linear regression were investigated, such as a lack of multicollinearity, no heteroskedasticity, normally distributed residuals and no autocorrelation among the residuals [50], which were fulfilled for each case in the presented analysis. The multicollinearity among the variables was investigated by manually applying the independent variables in a correlation matrix. Potential heteroskedasticity was evaluated visually. The autocorrelation among the residuals was tested with the Durbin–Watson statistic, which assumes a maximum lag of one. The lag of the residuals was investigated by determining the autoregressive process by applying the PACF.

2.5.4. Validation

The prediction model was tested and validated by comparing the prediction and measurement for the whole validation dataset. The criteria for a passed validation process were defined as (1) all the measurements identified as normal operation should be predicted within the prediction interval defined in the training process and (2) all of the operation disruptions should be clearly identified by the validation process.

3. Results and Discussion

3.1. Description—The Training Dataset

The dataset used for training the regression analysis comprises approximately 350,000 observations. Figure 4 shows the collected data for the dependent variable and the total electric and thermal power consumption, plotted together with the outdoor dry-bulb temperature. The average power consumption for the whole dataset is approximately 16 kW and energy supply for the period is 93,000 kWh. The daily average energy use ranges from approximately 190 kWh to nearly 900 kWh, with a corresponding daily average power consumption ranging from approximately 7.9 kW to 37 kW. The registered average diurnal dry-bulb temperature ranges from −11 °C to 20 °C. During this period, nearly 2000 swimmers used the facility, equally divided between adults and youngsters/children.

Figure 4 reveals a seasonal trend, a minor dependency between the energy use and the outdoor temperature, with some spikes in energy use distributed over the period. By visual inspection, it seems that the outdoor temperature variable can explain some of the variations in energy use, but additional variables influenced the variation in daily total energy usage.

3.1.1. The Energy Performance of the Facility

Regarding the energy performance, the swimming facility at Jøa was identified as having an energy performance indicator (EPI) of 44.8 kWh/visitor, calculated over the period of the investigated dataset presented in Figure 4. In comparison, Norwegian swimming facilities are associated with an average EPI for a typical year of approximately 26 kWh/visitor,and a median EPI of approximately 22 kWh/visitor, where the dispersion is reported to range from 10 to 80 kWh/visitor [51]. The EPI has been recommended by Kampel [7] who found that visitors are the single variable that explains most of the variation in the energy performance of swimming facilities [35]. The poor EPI-value of the swimming facility at Jøa can be explained by the low user intensity, on average only 235 visitor/month, compared to Kampel's dataset representing a median annual user intensity of 94,261 visitors (average of 7855 visitors per month). Additionally, the outdoor climate can explain this performance indicator since the data are not climate corrected.

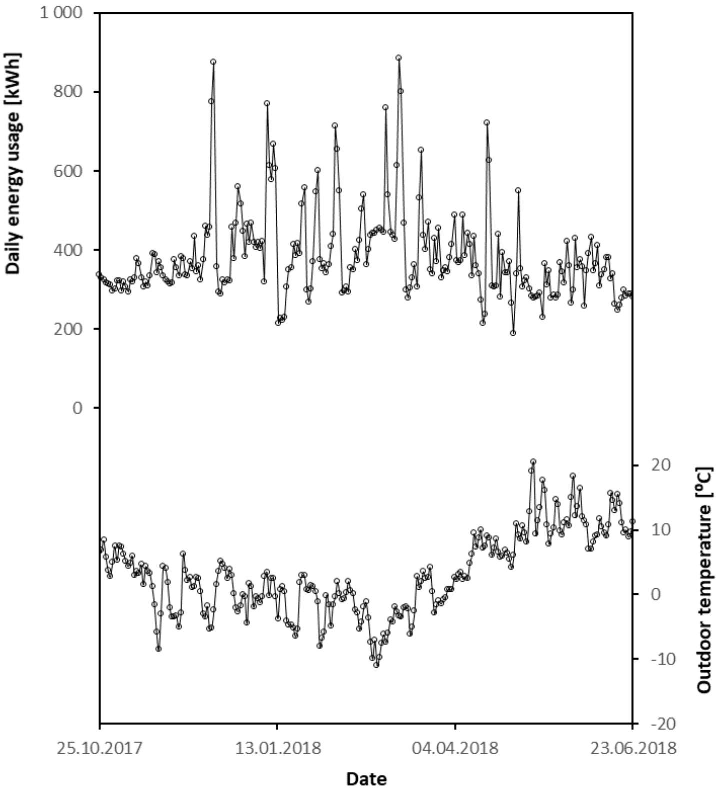

Figure 4. Energy usage for operation of the swimming facility vs. the outdoor temperature, both daily averaged.

3.1.2. Energy Distribution

The delivered energy to the swimming facility is almost evenly divided between electricity and thermal energy. Figure 5 depicts the energy distribution of the building section with the swimming pool. The low thermal energy consumption for the air handling unit (AHU) in comparison with the thermal load of the pool circuit has two major causes. The low overall user intensity for the period of collected data implies that the system operates in air recycling mode (night mode) without fresh air supply for a long period of time, which reduces the air dehumidification and heating demands considerably. Another reason is the operation of the heat recovery system which recovers the latent heat in the exhaust air and supplies heat to the facility, where the order of priority is air heating and pool heating. The building automation system neither collects data regarding the performance of the subsystems nor the thermal efficiency of the heat recovery system.

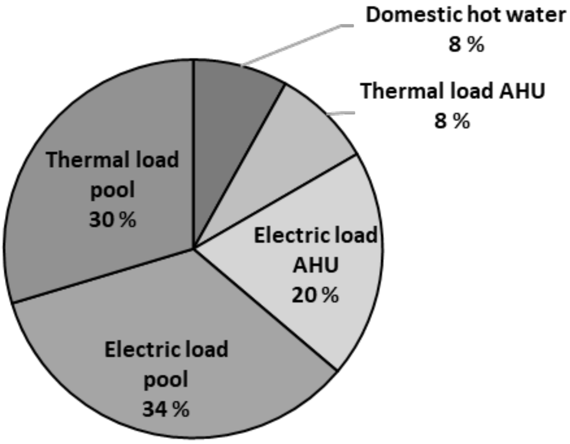

Figure 5. Energy distribution for the swimming facility incl. the energy use for domestic hot water heating.

3.1.3. Time Step Analysis

When treating time series data of energy use in buildings with linear regression, the inertia of the building must be considered due to this impact on the autoregressive process of the variables. This is because the energy use (the dependent variable) is logged with a short time step (1 min). For the swimming pool at Jøa, this impact is partly illustrated using a duration curve depicted in Figure 6, where the data are sorted by decreasing power consumption. The range of outdoor temperatures associated with each step of power demand is wide and can be partly explained by inertia of the building. A short time step resolution will not give any significant correlation, since the process depicted is not steady state. The impact of the time lag can be minimized by averaging the dataset, and thereby reducing the time step resolution (see Section 2.5.2).

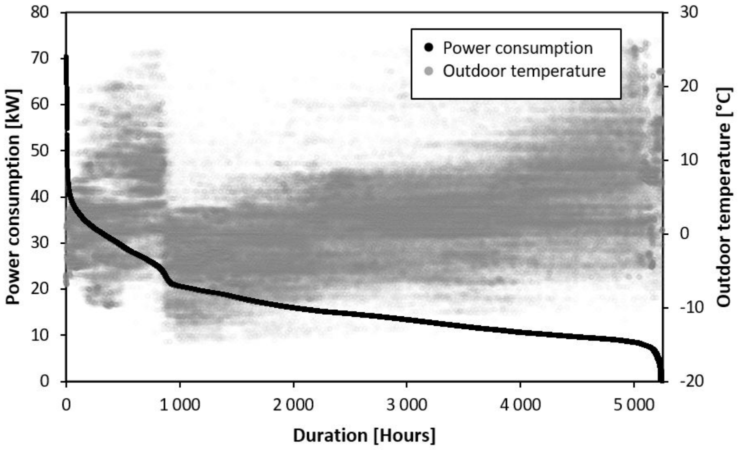

Figure 6. Scatter plot—sorted power consumption presented as a duration curve along with the corresponding outdoor temperature.

Figure 7 illustrates the consequences of averaging the dataset and reducing the time step resolution. The figure presents the dataset with time steps ranging from 1 min to 4 weeks. Both the power consumption and outdoor temperature are presented as time-averaged values centered in time. Firstly, the figure gives an indication of two possible different states in the operation of the facility, represented as a pattern of a divided dataset (clouds of datapoints), for time-step resolution from 1 min up to 60 min. The same can be observed in Figure 6, which represents a pattern of two different duration curves overlapping. Secondly, without considering the significance of the simple linear regressions, a considerable increase in the coefficient of determination, the R^2, is observed when averaging the dataset. This implies that the time step should be maximized in order to obtain the best fitting model if prediction is the main purpose. Concerning the purpose of this study, the time step should correspond to the swimming facility operating staff's requirement to identify and handle possible operational disturbances during a reasonable period of time.

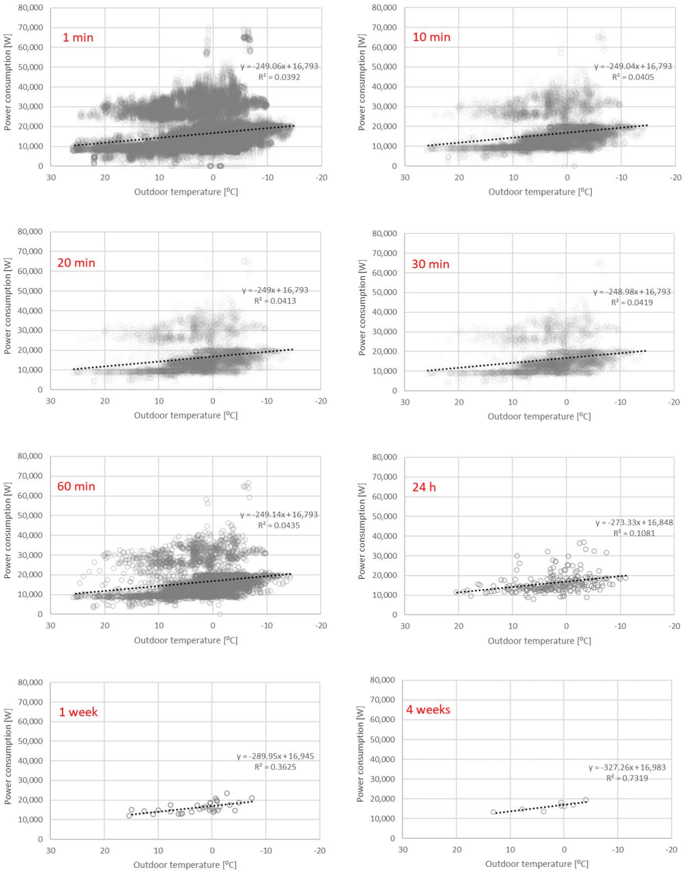

Figure 7. Averaged total power consumption plotted against averaged diurnal outdoor dry-bulb temperature when the dataset is averaged from 1 min to 4 weeks (see Appendix A for higher resolution).

3.2. Statistical Analysis—Developing the Model

Since the training dataset consists of operation data from the first period after the building was commissioned, several irregularities may occur. By detecting and excluding observations associated with irregular operation events, the training dataset is optimized to only represent flawless operation. A predictive model trained by this dataset should be able to provide accurate predictions.

By investigating historical operating data from both the BAS and the internal control system of the air handling unit, a major change in operation was found. The consequence of this is illustrated in Figure 8, which depicts the thermal load for the pool heating system, where a change in operation is identified in late March 2018. The reason for the considerable change was issues related to the control of the integrated dehumidification system and the pool temperature, possibly a problem with a mixing valve. However, since this flaw in the operation has implications for both the pool temperature and the heat recovery system, the whole period from 25 October 2017–22 March 2018 must be excluded from the training dataset.

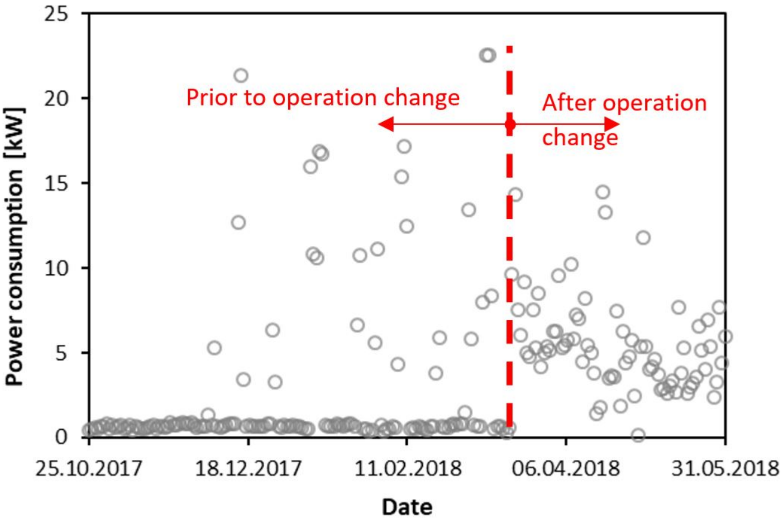

Figure 8. Thermal load for the pool circuit, plotted against the timeline, in averaged 1-day time step resolution.

3.2.1. New Training Dataset

By excluding the period associated with operational irregularities, prior to 22 March 2018, the prediction model was developed. The new training dataset, ranging from 22 March to 24 June 2018, consisted of three-day averaged values, for a total of 29 datapoints. The analysis of the autoregressive properties of the dataset showed no autocorrelation when averaging data for 72 h, or 3 days.

The results of the regression analysis are expressed in Equation (3). The key output from the regression analysis is given in Table 2. Regarding possible problems with overfitting, 15 datapoints per predictor are recommended [52] to obtain reliable fitted regression, which means a maximum of two predictors for a dataset of this size. The two independent variables which are found to explain most of the variance are the outdoor dry-bulb temperature (T_{out}) and the pool usage factor (t_{pu}) (see description of variables in Table 1). This combination has a statistical effect on the energy use, with almost similar impact, and both were identified by a significance level $p < 5\%$. The chosen combination of variables is in accordance with the physics, where the outdoor temperature represents the thermal losses through the envelope and ventilation, and the pool usage represents the water usage and the operation mode of the facility. The number of swimmers was not found to have a statistical effect on the overall power consumption, despite the impact of evaporation on the energy use. This may be explained by the phenomenon of evaporation, which is observed as a step function where a few bathers have a significant impact, but a further increase only gives a small additional contribution to evaporation [53]. However, the combination of weather conditions and usage/occupancy is also found to have a statistically significant effect on energy use in office buildings [38], despite the difference between these building categories.

$$\dot{E}_{tot} = 14,715 - 227.8T_{out} + 24,790t_{pu} \tag{3}$$

where $\dot{E}_{tot}$ is the predicted power consumption [Watt], T_{out} is the outdoor temperature [°C] and t_{pu} is the pool usage factor.

Table 2. Key outputs from the regression analysis.

	Unstandardized Coefficients				
	B	**Error**	**Standardized Coefficients**	**T**	**Significance**
Constant	14,715	2410.7		16.387	
Outdoor temperature	−227.8	27.2	−0.591	−8.38	0.000
Pool usage	24,790	2607.5	0.671	9.507	0.000

The ability of the model to explain the variance is given by R^2 = 87%. The ability of the prediction model to reproduce the power consumption is illustrated in Figure 9, where the predicted power consumption is plotted along with the training data, the actual power consumption and the corresponding prediction interval. The prediction interval of 95% is the interval where there is 95% confidence of there being an observation within it. It depends on factors like sample size, number of predictors and the significance level. For the range of independent variables given in the training dataset, the mean prediction interval is identified to be ±1.86 kW. Figure 10 shows the linear relationship between the training dataset and the data produced by the prediction model where the Pearson correlation coefficient is 0.93.

Regarding the fundamental assumptions in linear regression, the residuals from the training process, given in Figures 11 and 12, are approximately normally distributed. There are no signs of heteroskedasticity and the residuals are represented with a mean value of approximately 0. The autoregressive process is not found to be on an order higher than 1, but the Durbin–Watson coefficient is approximately 1.4, which possibly indicates some autocorrelation. However, the possible autocorrelation, or the lack of autocorrelation, is not found to be statistically significant. The regression equation is considered to be reliable within the given goodness of fit.

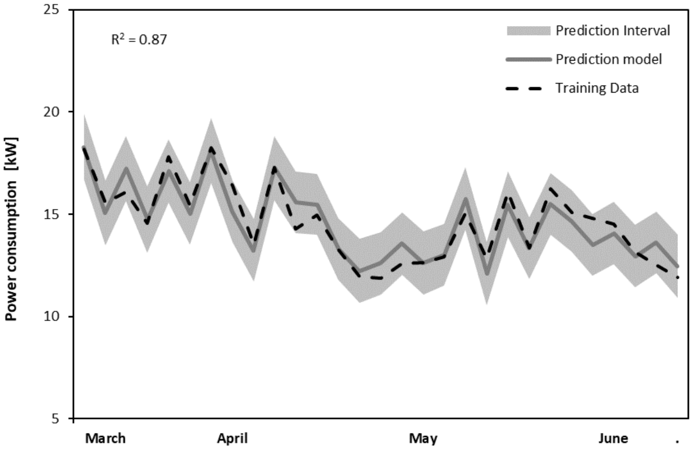

Figure 9. The predicted power consumption plotted against the training data and with the corresponding prediction interval.

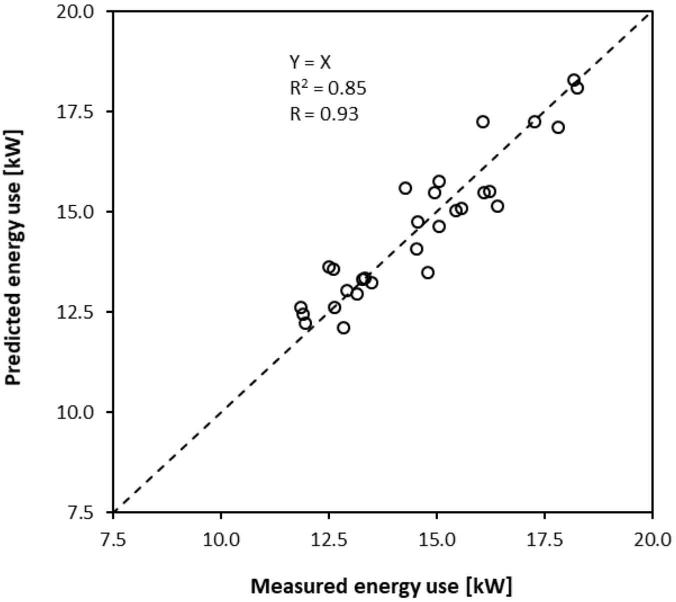

Figure 10. The predicted power consumption plotted against the measured power consumption. The Pearson correlation coefficient is given as the R-coefficient.

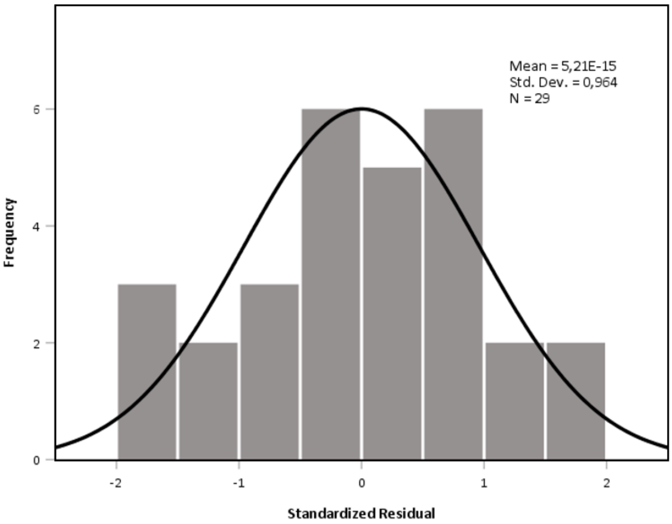

Figure 11. The distribution of the residuals.

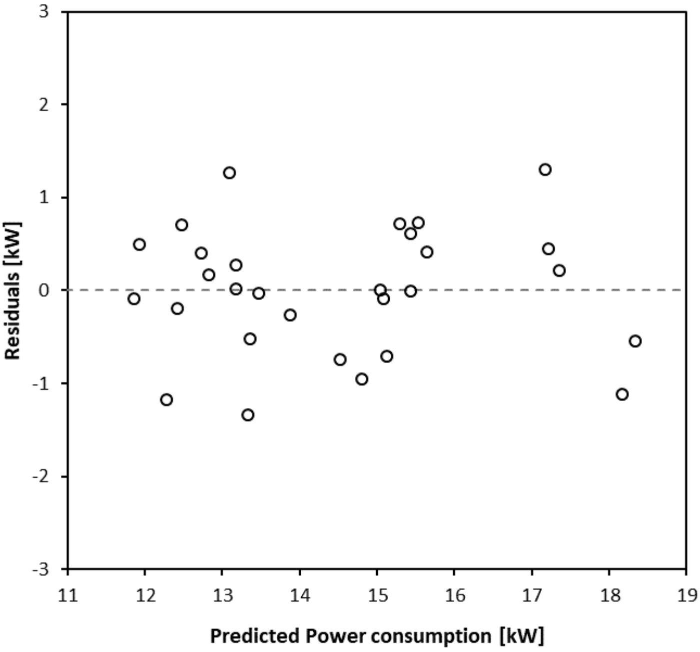

Figure 12. Residuals plotted by power consumption.

3.3. Validation and Application

The validation of the prediction model is illustrated in Figure 13 as a comparison between the predicted and actual data from the validation dataset. The predicted power consumption, including the prediction interval, is the gray shaded area and the measured power consumption is the black line. The numbered red areas are the identified periods with operational disruption, and they include 14 datapoints out of a total of 85 in the validation dataset. The given operation disruptions have been identified as (A) uncontrolled water refill, (B,C) issues with the control system of the water temperature, (D) issues with controlling the indoor environment and water refill system, leading to a consecutive lockdown of the facility and (E) issues related to the control of the air handling unit and the air flow supply. The prediction model identifies all of the disruptions as illustrated. When the facility operates without flaws and faults, the facility performs within the operational baseline provided by the prediction model. Each of the operational disruptions are identified as major deviations from the baseline.

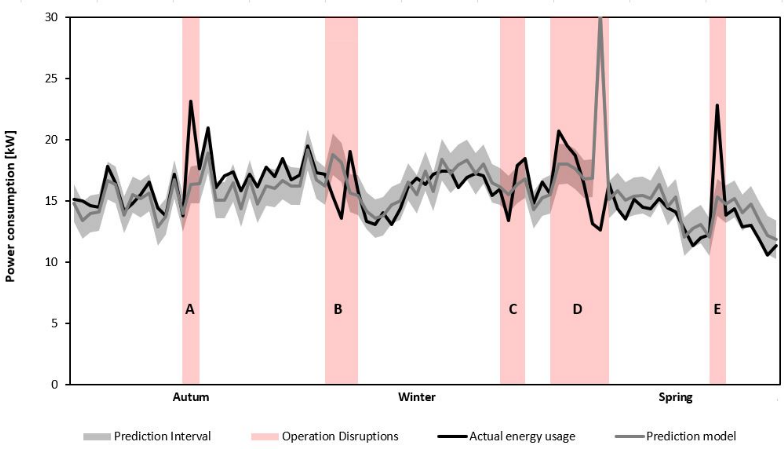

Figure 13. Visual validation of the prediction model from September 2018 to June 2019. The prediction model includes the prediction interval in gray, measured power consumption in black and periods associated with operational disruptions in red (see Appendix B for higher resolution).

When excluding the data associated with operational disruptions, 14 datapoints in total (approximately 16% of the dataset), the predicted operation fits the actual performance well. Figure 14 illustrates the correlation between the predicted and measured power consumption exclusive of the operation disruptions. The Pearson correlation coefficient is 0.85. However, there are periods where the models seem to consistently over- or underpredict the performance model, and this may have to do with the lack of explanatory variables in the model. However, this deviation is within the prediction interval, which corresponds with no detection of operational disruption for the relevant period. Figures 15 and 16 present the range of the independent variables used in the prediction model. Even though the range of the training dataset was initially significantly reduced to only three months of data (29 datapoints), the dispersion of the variables within this dataset corresponds with the validation dataset.

In the perspective of applying the presented method to industry, the combination of a short-term training dataset and the few predictors makes this method especially useful. This means that a facility can develop a model over a short period of time, with a minimum of sensors. However, the transferability with regard to the choice of independent variables must be further investigated in order to obtain a universal method for industry.

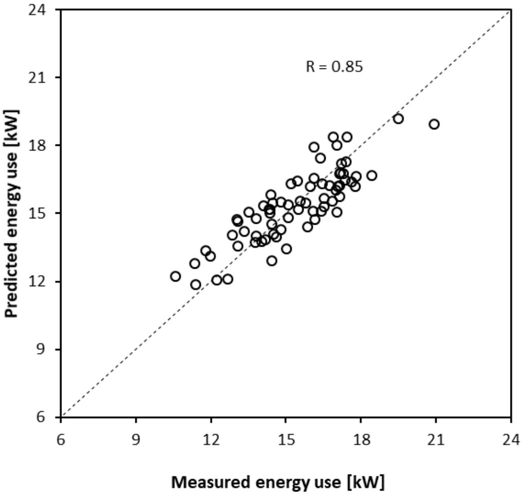

Figure 14. The predicted power consumption plotted against the measured power consumption for the validation dataset. The Pearson correlation coefficient is given as the R-coefficient.

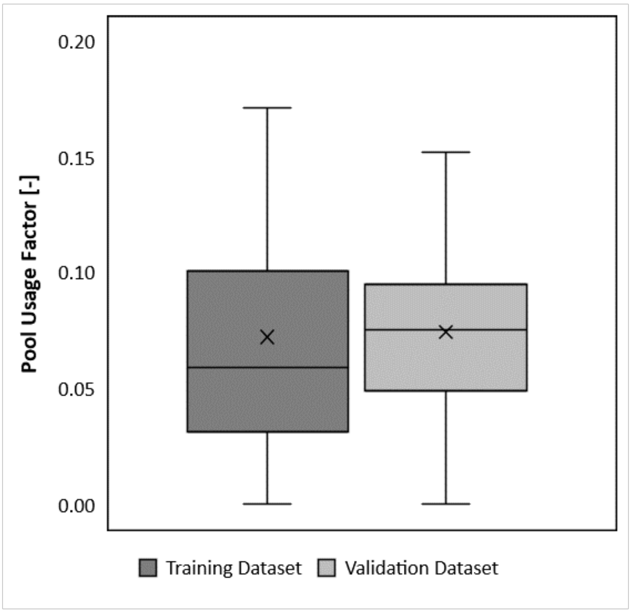

Figure 15. The dispersion of the independent variables in the prediction model, for each dataset used in the analysis.

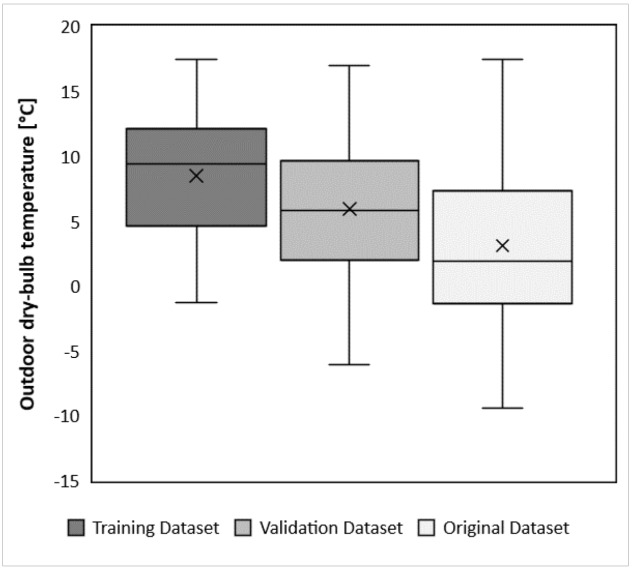

Figure 16. The dispersion of the independent variables in the prediction model, for each dataset used in the analysis.

4. Discussion and Opportunities for Deployment of the Created Model

Due to the importance of focusing on the operating phase when minimizing the environmental impact [10,54], and because operational irregularities are common in buildings [55], an implemented operational tool may have great potential for industry. For swimming facilities, this is especially important since inappropriate operation may also cause problems such as degradation of equipment and the occurrence of the sick building syndrome [56]. When applying the presented method to industry, the combination of a short-term training dataset and a few predictors makes this method especially useful. It means that a facility can develop a personalized model in short period of time with a minimum of sensors. In addition, the final energy prediction model is simple and can be deployed either in a spreadsheet or in the building automation reporting system. This method can therefore contribute instantly to keep the operation of a swimming facility within the optimal and expected individual energy performance range, which is fundamental for achieving the energy target for any building [57]. The MLR method, which is applied in this study, has formerly been recognized for predicting energy use in buildings [39] and has also been applied to determine the parameters of thermal equations for outdoor swimming pools [58]. With respect to the specific case of Jøa, the operational staff have to download the energy usage, the outdoor temperature and the pool usage. The deviation between the prediction and the measured energy use will give the operational staff an alarm if there is a potential flaw in the operation and enable them to detect the fault within a short period of time. However, the transferability with respect to the choice of independent variables must be further investigated in order to obtain a universal method for industry. Additionally, guidelines with respect to the implementation of the model should be provided.

5. Conclusions

This paper presents a model for predicting energy consumption in swimming facilities. The energy prediction model aims to become a dynamic energy benchmark for fault detection in swimming facilities. The investigation has been carried out by using multiple linear regression analysis (MLR) for a specific swimming facility located in Norway. The MLR method has formerly been recognized in predicting energy use in buildings but has also been applied to determine the parameters of thermal equations for outdoor swimming pools. The main findings of this study are:

- The study has shown that it is possible to develop an accurate energy prediction model for swimming facilities with a minimum of variables and datapoints.
- The results from the analysis of the training dataset underlined the importance of investigating the training data prior to training of the model. The original dataset was based on raw data from 7 months of operation after the building was commissioned and approved by the building owner. The modified and preferred dataset was reduced after an in-depth investigation that revealed comprehensive operational disruptions. The final training dataset consisted of only 29 datapoints of 3-day averaged data ranging over a period of 3 months, March to June 2018.
- The statistically significant independent variables were found to be the outdoor dry-bulb temperature and the pool usage factor, which predicted the average power consumption accurately in the validation process. In the validation period from September 2018 to June 2019, the equation correctly identified all the critical operational disruptions.
- The model has been shown to be a suitable tool for helping operating staff in continuous evaluation of the energy performance of a facility and quickly disclosing possible operational disruptions. By identifying possible operational irregularities at an early stage, excessive energy use in operation can be avoided. Operational irregularities occur in a high percentage of new buildings. The importance of focusing on the operating phase and the overall energy consumption is crucial when minimizing the environmental impact. In addition, the knowledge of the energy performance of buildings is fundamental in achieving the energy targets. For swimming facilities, inappropriate operation of technical installations may also cause problems such as degradation of equipment and the occurrence of sick building syndrome.
- This study only investigated one specific facility and future work should address the robustness of the model and transferability to other swimming facilities.

This study illustrates the strength of multiple regression analysis when applied as a dynamic and continuous energy benchmark. By applying simple input variables, an estimate of the expected power consumption, within an acceptable error range, can be made that reveals potential operational disruptions. The energy prediction model is simple and can be easily implemented in the automation system of a building. The prediction model does not require an operator with an engineering background and may serve as first-line supervision for the use of a dynamic energy benchmark for a facility. By applying this method in existing swimming facilities, the overall energy use may be greatly reduced as it provides the building management with improved knowledge about the energy performance of the building.

Author Contributions: Conceptualization, O.Ø.S.; methodology, O.Ø.S and T.J.; software, O.Ø.S.; validation, O.Ø.S.; formal analysis, O.Ø.S.; investigation, O.Ø.S.; data curation, O.Ø.S.; writing—original draft preparation, O.Ø.S.; writing—review and editing, O.Ø.S., T.J., B.A., J.S., L.G. and S.C.; visualization, O.Ø.S.; supervision, T.J., B.A., L.G. and S.C.; project administration, O.Ø.S. and J.S. All authors have read and agreed to the published version of the manuscript.

Funding: The project is funded by COWI AS, the Research Council of Norway and COWIFonden.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This data collection campaign was performed within the framework of a PhD study by COWI AS and NTNU SIAT. All the data are privately stored and will not be disclosed until the end of the study.

Acknowledgments: This work is a part of a doctoral project entitled “Optimizing Energy and Climate Systems in Buildings with Swimming Facilities”, which is carried out as a cooperation project between the Centre for Sport Facilities and Technology at the Norwegian University of Science and Technology in Trondheim, Norway, and the engineering company COWI AS.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

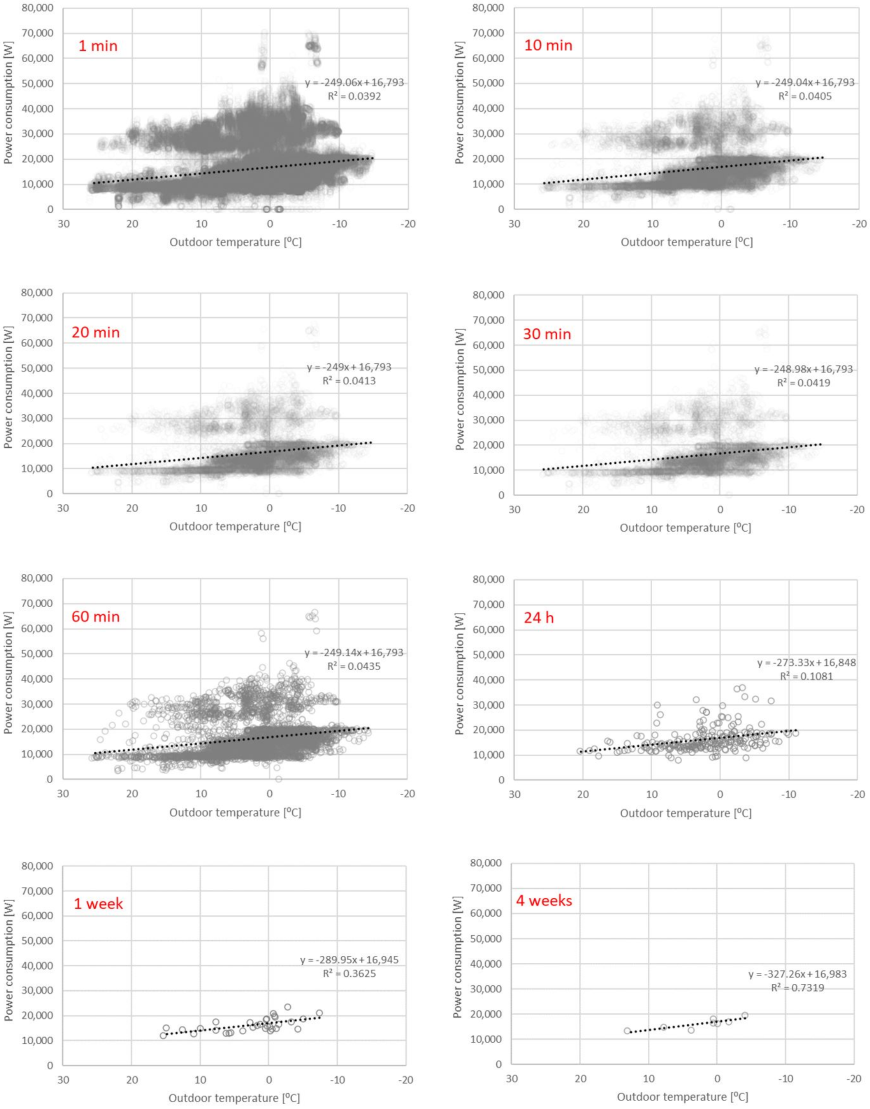

Figure A1. Averaged total power consumption plotted against averaged diurnal outdoor dry-bulb temperature when the dataset is averaged from 1 min to 4 weeks.

Appendix B

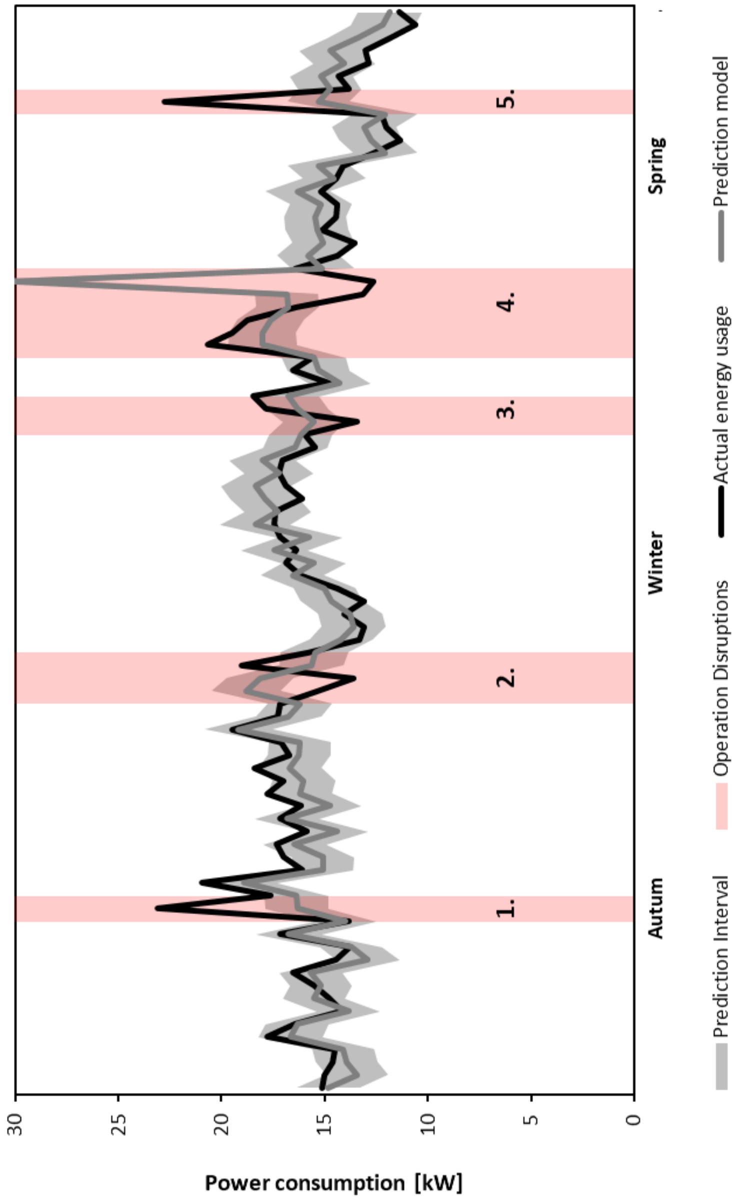

Figure A2. Visual validation of the prediction model from September 2018 to June 2019. The prediction model includes the prediction interval in gray, measured power consumption in black and periods associated with operational disruptions in red.

Appendix C

Subject	Quantity
Window surface area	30 m^2
Water surface	12.5 m × 8.5 m
Useable area	266 m^2
Nominal air flow, air handling unit	11,000 m^3/h
Nominal thermal power, air condenser	26 kW
Nominal thermal power, pool water condenser	34 kW
Nominal water flow circulation pool circuit	60 m^3/h
Rating condition pool circuit	300 visitors/day
Nominal power pool heater	70 kW

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Paper III

Analysis of the Model Complexity of Air Handling Units to Support Energy-Efficient Design of Indoor Swimming Pool Facilities

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Abstract

Building performance simulation (BPS) is a powerful tool for building design including heating, ventilation, and air-conditioning systems (HVAC). Several research studies have used BPS to investigate the potential of energy savings measures for swimming facilities. The technical complexity of swimming facilities is a considerable challenge for BPS since many complex phenomena occur in the various sub-systems –water treatment system, energy recovery systems, energy-intensive ventilation system with air handling units (AHU) and a complex control system. The building industry traditionally plans and design these complex buildings by heuristic rules of thumb, and these empirical design rules may lead to significant differences between real and predicted performance. Therefore, it's important to develop simplified models with acceptable accuracy for simulation-based design of swimming facilities. The paper investigates the model complexity of the AHU by comparing a novel simplified model and a detailed model for a Norwegian swimming facility. The simplified model uses a decoupled approach between the building and the AHU that is operated by an optimal control (OC). The detailed model is a replica of a real AHU and the system is simulated in a fully-coupled approach and operated using a complex heuristic rule-based control (RBC). In addition, the paper describes the implementation of the comprehensive heuristic RBC in BPS tools, using IDA ICE. The detailed heuristic RBC accurately approximates the OC where the system is designed for minimizing the energy use when waste heat is accounted for. The simplified decoupled model with OC has acceptable accuracy for early-stage design, bearing in mind the overall uncertainty at this design stage. However, when carrying out a detailed investigation of a swimming facility, the complex heuristic RBC should be applied, especially considering the impact of thermal-coupling effects between the swimming pool and the AHU such as the offset error of the controllers which influences the entire facility. In conclusion, the paper derives useful guidelines for BPS design of AHU, which is the main energy-intensive component in indoor swimming pool facilities.

Keywords:

- Indoor Swimming pools
- Air handling unit
- System modeling
- Model complexity

Nomenclature

Q_h	Heating and cooling needs
$Q_{cond,\ max}$	Total condenser power, heat pump
Q_{evap}	Evaporator power
Q_{waste}	Waste heat energy
P_{coil}	Heating coil power
P_{waste}	Waste heat power
P_{comp}	Heat pump compressor power
P_{fan}	Fan power
W	Dehumidification needs
RH	Relative humidity
RH_{out}	Outdoor relative humidity
T	Dry-bulb temperature
p_{evap}	Evaporator pressure
V	Airflow volume
m_{ext}	Exhaust air mass flow rate
S	Air state
H	Enthalpy
COP	Coefficient of performance, heat pump
Ω	Absolute humidity
Θ	Airflow rate imbalance
ξ	Mass fraction air from air heat exchanger to condenser
H	Heat exchanger efficiency function of C_R and NTU

Subscripts

HP	Heat Pump
RH	Relative humidity
Temp	Temperature
Sup	Supply air
Evap	Evaporator
HC	Heating coil
FA	Fresh air
TAF	Total airflow
S	Saturated
Out	Outdoor

1 Introduction

1.1 Background

The European Union is targeting a greenhouse gas (GHG) reduction by at least 55 % by 2030, compared to 1990 levels (1), as the next milestone in approaching the long-term goal of “no GHG emissions” by 2050 (2). In the achievement of both long-term and short-term goals, increased energy efficiency for the building stock is defined as an important remedy (3). One of the “key actions” in the Action Plan of the 2030 framework defines a “renovation wave” as a tool for approaching this (2).

The European Commission recommends particular attention to types of buildings that support education and public health (2), swimming facilities represent a considerable potential for energy reduction (4). Recent research associates these facilities with both high specific energy use and a large dispersion in energy use, ranging from 400 kWh/(m²·a) to almost 1 600 kWh/(m²·a) (4-7). This can be explained by the variations in building age, technology, operation and maintenance routines (4). The overall energy reduction potential of Norwegian swimming facilities is found to be approx. 30 % (5). Also, in the Mediterranean climate swimming facilities are found to be energy intensive and defined to have the highest energy baseline (8). However, the approach for energy efficiency strategies differs substantially from northern swimming facilities since the southern climate provides high thermal and electric energy supply from solar systems (9).

1.2 Motivation

Concrete action is necessary for achieving the potential of energy savings in buildings (10). However, in the design phase when estimating the energy performance of the building, the authorities provide requirements concerning model complexity. For swimming facilities it is required to carry out dynamic calculations to document the energy performance measures (11, 12). Paradoxically this task is seldom implemented in the Norwegian building industry because of the complexity of the buildings. Modeling swimming facilities is both time consuming and requires highly skilled staff with in-depth knowledge regarding both advanced modeling and in-depth knowledge of all the sub-systems in the facility.

1.3 Theoretical Background

Unlike other building types, swimming facilities are defined by a complex energy system that is required to maintain an appropriate indoor environment in the swimming hall and pool water quality. Figure 1 illustrates the main components of the various technical systems and their interconnection. The purpose of these systems is to provide fresh air supply, air heating, air dehumidification, water heating and water treatment.

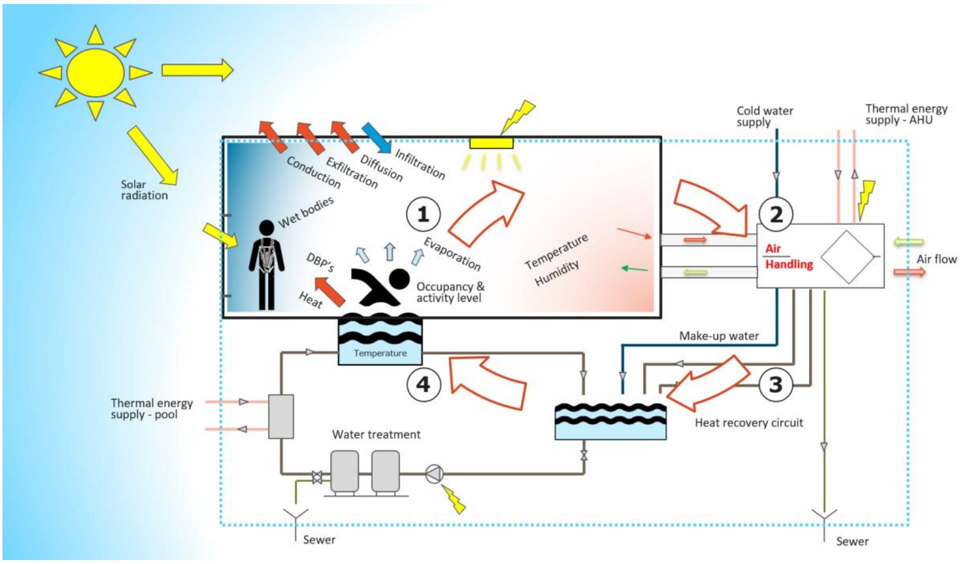

Figure 1 Schematic operation concept of a swimming facility with key elements related to space and water heating, ventilation, air conditioning, air dehumidification and water treatment; (1) Indoor environment, (2) Air handling, (3) Heat recovery circuits and (4) Water treatment system, where the arrows illustrate the typical direction of the energy flow.

Referring to *Figure 1*:

1. The indoor environment (1) is typically controlled by tracking fixed setpoints for the indoor dry-bulb temperature and relative humidity (RH). The air handling unit (AHU) and the air distribution system are dedicated to handle all issues related to the indoor air quality and provide a healthy and comfortable thermal indoor environment. The task of eliminating condensation problems on the building envelope and structural systems is also handled by the air distribution system.
2. The evaporation rate from the pool greatly depends on the type of activity. The air handling unit (2) controls the humidity and air temperature in the facility by supplying sensible heat and removing latent heat. When the swimming pool is occupied, the facility runs in “bathing mode”. Then, latent heat is recovered from the exhaust air, normally with a heat pump integrated in the AHU. When the swimming pool is not occupied, the facility runs in “night mode”. Most of the air flow is recirculated into the hall in order to maintain the room temperature and humidity setpoints within reasonable ranges. Since the state of the extracted air is constant and therefore its enthalpy, the enthalpy of the supply airflow depends on the heat losses for the pool hall and the evaporation rate from the pool surface. For this reason, the net energy flow related to the airflow in the ventilation system of swimming facilities, will vary between positive and negative values.
3. The latent heat recovery from the AHU (3) is supplied to the air heating or to the pool water heating. This connection between the AHU and the pool represents a crucial link in the energy supply system.
4. Additional thermal energy is supplied as well as water refill to the water treatment system (4). This loop circulates the water through the water treatment train where the water is filtered and disinfected. There, the water quality is monitored and controlled. The relationship between the different key components in the swimming facility illustrates the vulnerability of the system as well as the risk of prediction error in the energy performance.

For example, the performance of the AHU influences the indoor environment and the energy use as it controls the waste heat recovered from the exhaust air. For this reason, the AHU also affects the energy use for the pool circuit.

The operation of the water treatment system influences the indoor environment by the water quality, filtering, disinfection, and disinfection by-products, and thereby the air quality, but also by the temperature control, which is crucial for controlling the evaporation rate from the pool. The evaporation rate is among other things greatly dependent on the water and air temperatures. A high evaporation rate increases the enthalpy in the pool air, which in turn increases the ventilation losses. High indoor relative humidity will also increase the risk of condensation on the building envelope and make the pressure gradient steeper inside the pool hall. This may lead to degradation of the building construction, possible corrosion and possible accumulation of moisture inside the envelope components due to exfiltration.

These interconnections show the importance of understanding the dynamic and complex nature of swimming facilities when modeling the facilities in BPS tools. For example, the importance of in-depth knowledge regarding both the pool usage, in relation to the evaporation rate and the control system of the AHU is crucial when treating the connection between the heat recovery and the energy system. An incorrect layout in the computer model may lead to satisfactory overall energy performance, despite multiple errors and issues related to systems such as water refill system which can hide problems with the air supply system. This paper analyzes the model complexity of the AHU model and the consequences when simplifying the control system of the heat recovery and air supply systems.

1.4 Previous Work

A vast number of studies focus on the design and operation of swimming facilities. Westerlund et al. (13-15) investigated swimming facilities and air handling units in the 1990s and early 2000. They developed a calculation method for estimating the heating demand in swimming facilities. The method predicted the annual heating demand, while the calculations were performed in hourly time-steps (13). Ribeiro et al. (16-18) investigated the benefits of introducing dynamic setpoints and by customizing the control strategy in a swimming facility. The study was carried out by modeling the facility in the BPS tool ESP-R, where the focus of the study was entirely built around the development of possible energy savings strategies.

Delgado et al. (19) also investigated the benefit of improving the control system of swimming facilities. By implementing predictive control algorithms, they estimated the energy savings and defined the control settings using a BPS model for a specific facility (19). However, the model only considered the thermal behavior of the swimming pool and assumed stable conditions in the swimming pool hall (20).

Regarding the indoor environment and the different demands for a swimming facility, Ratajczak and Szczechowiak (21) investigated and suggested a new technical system architecture. This was based on a concept where the swimming facility was divided into zones, each defined by requirements regarding dehumidification as well as the thermal and indoor environment. The authors proposed an overall system layout where each zone was served by a dedicated AHU. The component layout of the traditional ventilation system was based on two by-pass dampers (mixing chambers), an integrated heat pump with both air- and pool condensers, a counter-crossflow air heat exchanger and a heating coil and was in accordance with the usual layout of AHUs in present Norwegian swimming facilities. However, the control algorithms were different. The BPS model was validated by comparing the energy results with short-term measurements, in total 85 hours. The comparison showed good agreement, even with the idealized control system of the AHU in the BPS model. Ratajczak and Szczechowiak (22) also investigated the AHU as an economic and ecological source of heat for an indoor swimming pool facility, and they concluded that the use of a heat pump was the most beneficial solution.

Taebnia et al. (23) applied the same approach as Ratajczak and Szczechowiak (21) in their study where the energy performance of AHUs for ice rink arenas was investigated with regard to the system layout. Ice rink premises share the same complexity of the HVAC system as swimming facilities. The study investigated the AHU layout and identified a possible reduction of the dehumidification demand. The study was carried out by modeling the premises in the BPS tool IDA ICE. Like Ratajczak and Szczechowiak (21), Taebnia et al. validated their model by short-term measurements, which they also applied in their study regarding the development of a simplified calculation method for energy demand (24). The considerable impact the AHU layout has on the energy demand, indicates the great importance of an accurate BPS model when assessing these complex systems.

In addition to the above-mentioned studies, several others have treated the energy performance of swimming facilities by using BPS tools (25-30). To the knowledge of the authors, no studies have addressed the importance of the model complexity of swimming facilities.

1.5 Research Questions

This paper investigates the influence of the BPS modeling complexity for an AHU in a swimming facility. The objective of the study has been to:

1. Develop a simplified decoupled model of the swimming pool facility using optimal control for the AHU.
2. Compare the control actions for the heuristic rule-based control (RBC) vs. an optimal control.
3. Identify the physical phenomena that can only be addressed by a detailed model.

The results support the design of complex control systems for the AHU in swimming facilities. Section 2 introduces the workflow of the study, the strategy for the model comparison and the case study. It also presents the assumptions and inputs applied in the study. Section 3 presents the analysis of the results and Section 4 presents the discussion of the calculation results. Conclusions are presented in Section 5.

2 Method

2.1 Simplified vs. Detailed models

This study presents an analysis of the complexity of AHU models in a swimming facility. Both the detailed and simplified approaches are compared:

- **The detailed model** is a replica of the actual swimming pool. A model component is dedicated to the states of the indoor air and pool water while a second component models the states in the AHU. In the detailed model, both components are coupled. It translates the fact that the state of the room air in the swimming pool influences the AHU, namely the heating and cooling needs (Q_h) and the dehumidification needs (W). In turn, the operation of the AHU also influences the state of the room. Typically, the airflow rate to the room is modulated by the AHU (i.e., VAV system). Large variations in the airflow rate can alter the convection coefficients along walls as well as the evaporation rate from the pool water surface. This influences Q_h and W. Unlike the AHU, the room air and water in the pool have strong dynamic effects and cannot be modeled in steady-state. Therefore, implementing an idealized controller, such as optimal control, is a demanding task. Consequently, the detailed model rather implements the detailed heuristic control of the AHU. In our study, the detailed model is implemented in the commercial BPS package IDA ICE v.4.8 SP1 (31). This tool has been validated using experimental data from the IEA BESTEST cases included in the ASHRAE and CIBSE procedures (24). It has a dedicated add-on to model the swimming pool hall (the “Ice Rinks and Pools” add-on), namely the room air and the water in the pool.

- **The simplified model** decouples the room and AHU models. In the first step, the humidity and thermal balances of the pool room are computed using an ideal heater and cooler to track the temperature setpoint and a dehumidification to track the setpoint relative humidity. Due to the decoupling, the mechanical airflow rate is kept constant. The main assumption is that variations of ventilation airflow rate only influence the Q_h and W moderately, making the decoupling possible. The validity of this assumption is tested later in the paper. In a second step, the AHU model should satisfy the pre-computed Q_h and W. The AHU is typically modeled as a nonlinear steady state model, such as in IDA ICE. It is therefore easier to implement an optimal control for the operation of the AHU. During early-stage design, this removes the need to collect detailed information regarding the AHU control. For the sake of the simplicity, the AHU model is implemented in MATLAB (32) which enables direct access to optimization algorithms. The objective function to minimize is the energy use of the AHU.

For the sake of consistency, the model of pool room and water are modeled in IDA ICE in the exact same way when comparing of the detailed coupled and simplified decoupled approaches. In order to obtain realistic results it is important that there is proper modeling of the interface between the room air and the water. The modeling of the evaporation rate here uses the ASHRAE equation. The equation is introduced in the Appendix and its accuracy compared to other models is discussed.

The analysis has been carried out following the scheme presented in Figure 2.

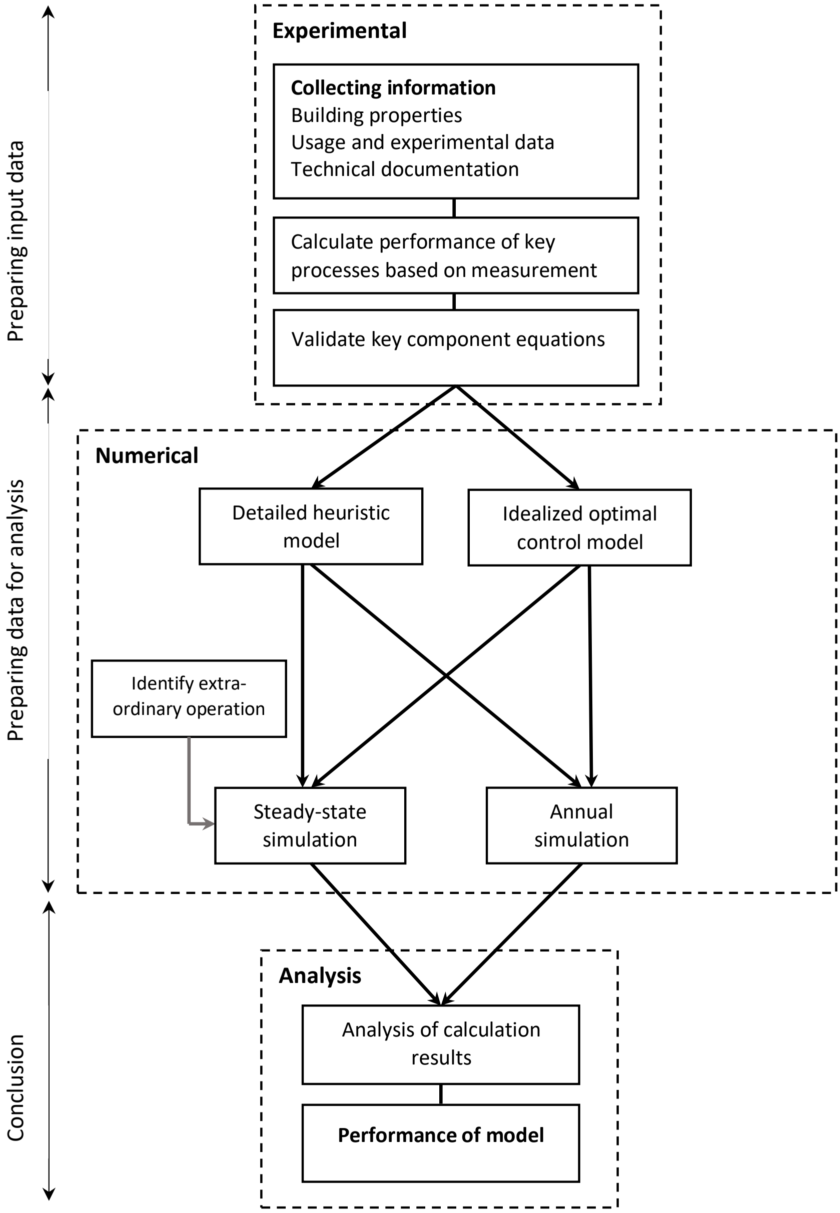

Figure 2 Block diagram representing the workflow of the BPS study comparing the detailed and simplified models.

2.2 Implementation of a Detailed Air Handling Unit Model

This section describes in detail the heuristic rule-based control (RBC) of the selected swimming pool AHU along with its implementation. The selection of the brand for the AHU was based on its extended use in the Norwegian swimming facilities market and its availability in the case study. Defining all the details of the heuristic RBC was a demanding process and is not compatible with the early-phase design of a swimming pool. Information was found in the AHU documentation, through conversations with the AHU supplier and operators, and by detailed inspection of the device.

2.2.1 General Description

The purpose of the AHU in a swimming facility is to provide adequate temperature and humidity levels in the facility and to supply fresh air for hygienic reasons. Due to the energy intensive characteristics of the facility, and therefore the risk of excessive energy use, these tasks are done with several energy-reducing measures such as heat recovery, demand-controlled airflow rates, several operating modes with different operating strategies as well as interconnection with the pool water circuit. The importance of these energy-reducing measures is due to the considerable energy content in room air and the continuous evaporation from the pool and wet surfaces.

The overall system layout of a swimming pool AHU is based on a standard AHU layout with some additional components, see Figure 3. The AHU comprises supply and exhaust fans, a crossflow plate heat exchanger (i.e., not a rotary heat recovery wheel), a heating coil, fresh air and exhaust air dampers as well components specific to swimming pools: an integrated heat pump unit (evaporator, pool and air condensers, sub-cooler, compressor, etc.), several by-pass dampers which enable mixing of air flows and an advanced control system. In addition, there are some differences regarding practical properties such as enhanced corrosion resistance.

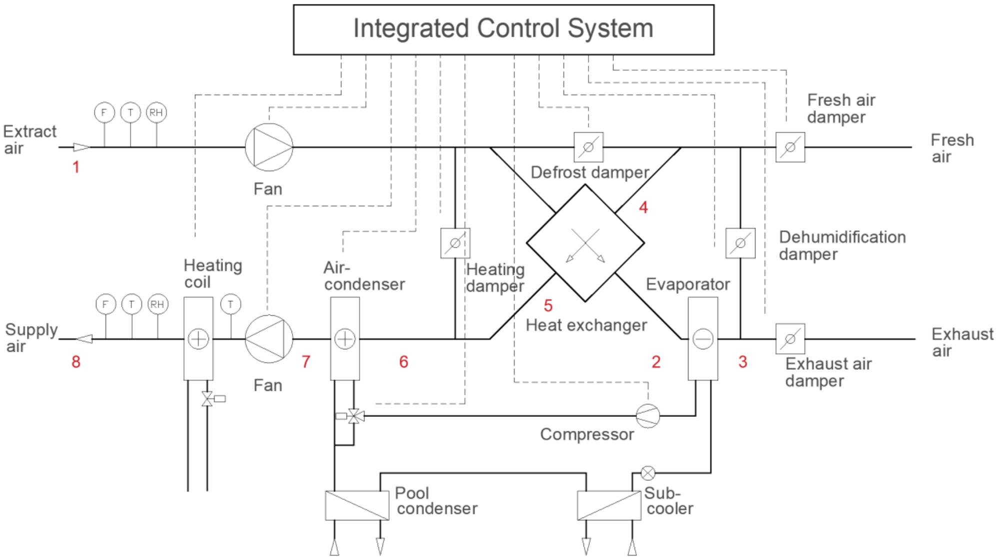

Figure 3 *Principle of the design of an air handling unit (AHU) and a schematic representation of the integrated control system for swimming facilities.*

2.2.2 Detailed Rule-Based Control

The control system for the swimming pool AHU is divided into three levels: (1) the controllers, (2) the control algorithms and (3) the actuators and components. The layout is illustrated in Figure 4.

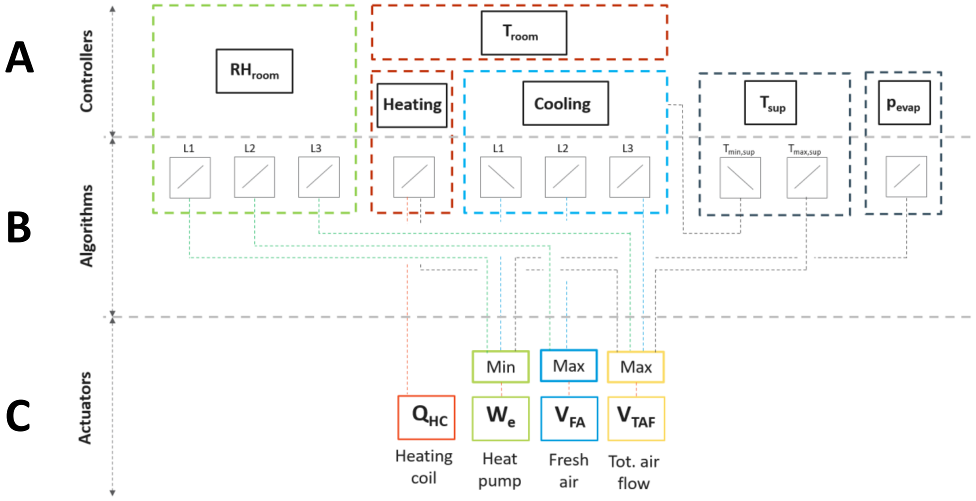

Figure 4 Schematic layout of the control system for a swimming pool AHU. Level A – Controllers; Level B – Algorithms; Level C – Actuators and components.

2.2.3 The Controllers

At the controller level (Level A in Figure 4), the controlled variables are each represented by a group of controllers. There are two main groups of controllers dedicated to either indoor relative humidity or indoor temperature. In addition, the accepted area of operation is defined by the operation mode of the facility, i.e., “bathing mode” or “idle mode”, which defines both minimum and maximum air flows (demand controlled), relative humidity (setpoint), type of controller (PI or P controller) and operation mode for the heat pump (dehumidification or heat recovery mode).

The set-up for the controller groups can be explained as follows:

- **Relative humidity (RH) controller**

  The RH controller is a PI controller where the integral-term is switched off on two occasions, (1) when the facility is operated in “idle mode” or (2) when the deviation from the set-point exceeds ± 2 % (proportional range) in “bathing mode”.

- **Temperature controllers**

  The temperature controller group is represented with a cascade control, where the extract air temperature is taken as a proxy for the room air temperature. When the extract air temperature deviates from the setpoint, the controller identifies a heating demand ("heating mode"). Then, the output of the extract air controller is used for identifying the setpoint for the supply air temperature controller which controls the two-way valve for the heating coil. Both controllers operate with a proportional range of ± 1°C.

  In "cooling mode", a cooling controller substitutes the supply air controller for heating, which means that the heating coil is switched off. However, in periods with high cooling demand, the supply air temperature is kept above the minimum threshold, a task dedicated to a separate controller. The threshold is defined as a function of the outdoor temperature and the purpose is to avoid draft in the facility. This controller is operated in the same manner as the cooling controller with the same P range and is reducing the output of the cooling controller. The cooling controller operates with a P range of ± 1°C.

- **Airflow rate controllers**

  The airflow rate is controlled by both the cooling and humidity algorithms. In addition, it is also controlled by the supply air temperature and the position of the heating coil valve. The airflow is increased linearly to the maximum airflow if the air supply temperature is between 45 and 53°C (i.e., maximum airflow rate reached at 53°C) or the valve position is between 90 and 100 % open (i.e. maximum airflow rate when valve is fully open).

- **Heat pump controller**

  The heat pump has two possible operating strategies depending on the overall operation mode of the facility. In "bathing mode", the heat pump is operated as a sole heat recovery device, while in "night mode", it is operated as a dehumidification device since there is no fresh air requirement. In addition, to the control signal from the humidity and temperature control algorithms, the heat pump capacity is controlled by the evaporator pressure in the heat pump circuit if the swimming facility is operated with fresh air supply. The latter is due to the variable fresh- and exhaust airflow and occurs when the facility is operated in "bathing mode" or in “idle mode” if the humidity or the temperature controller is calling for fresh air supply. This is described in detail in the next section. The evaporator pressure controller is represented as a P controller in the model.

  The high-pressure side of the heat pump is controlled by the temperature controller and a supply air temperature controller, dedicated to the air-cooled condenser. These controllers prioritize air heating and only direct heat to the pool condenser if there is no air heating demand.

Due to the use of P controllers, PI controllers, cascade controllers and several operation modes, the issue with integral windup of PI controllers must be addressed. This issue occurs when the integral term in the controller no longer affects the controlled variable. This is represented multiple times in the controller groups, as in the choice of RH controller in "bathing mode" and "idle mode" or when dealing with a deviation within the given P range. These issues must be addressed in the computer model, which increases the modeling time considerably. This issue was also addressed by Clauß and Georges (33) in their analysis of the model complexity of a BPS model for a residential heat pump. In their work, the performance of different controllers was compared, and the importance of anti-windup was demonstrated. The analysis was based a case study implemented in the BPS tool IDA ICE (31).

An anti-windup circuit with an on/off-switch is implemented for each controller. Figure 5 shows the schematic of the controller which was applied in the detailed model.

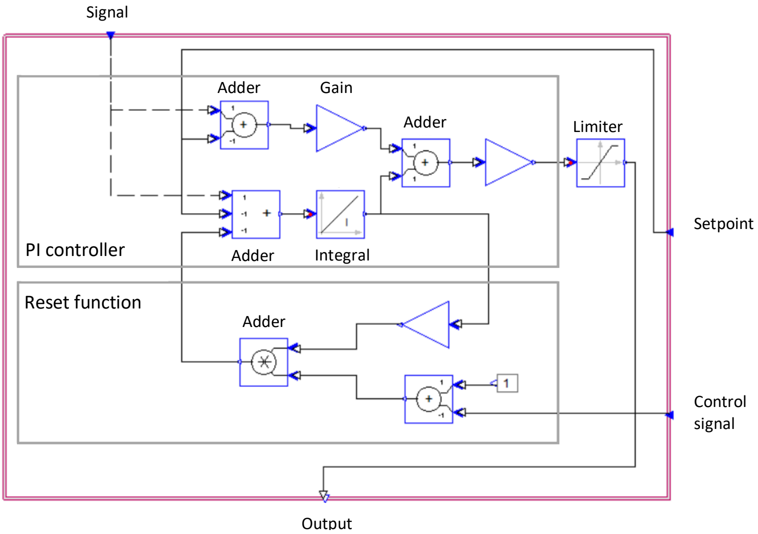

Figure 5 Schematic presentation of the applied PI controller with an on/off switch (32).

2.3 The Control Algorithms

The control algorithms direct signals to the actuators based on the input signals distributed by the controller(s). Figure 4 illustrates this level in the control system.

The humidity control is dedicated with two algorithms, one for each operating mode. In "idle mode", the humidity algorithm has three stages: (1) Increase heat pump capacity, (2) Switch to fresh air operation and increase fresh air share, (3) Increase total circulated air flow rate. If stages 2 and 3 are executed, the heat pump is operated in "heat recovery mode", which means that the heat pump capacity is controlled by the evaporation pressure in the heat pump circuit.

The "bathing mode" control algorithm works in a similar way as the "idle mode", except for stage 1, because the AHU is already operating in fresh air mode with a minimum share of fresh air. Due to this, the heat pump capacity is operated in accordance with the minimum evaporator pressure setpoint.

The temperature control algorithm is also in two parts, a heating and a cooling algorithm. The heating algorithm simply controls the two-way valve in the heating coil which increases the water flow rate through the heating coil and consequently the heat supply to the air flow.

As for the humidity control algorithm, the cooling algorithm is divided into three stages with serial connection. These are represented as: (1) Reducing the heat supply to the airflow from the heat pump, (2) Increasing the share of fresh air and (3) Increasing the total airflow rate. Since the cooling controller group is represented by several controllers, where the minimum allowed supply air temperature controller reduces the output of the cooling controller, the swimming facility may in extraordinary cases operate with an indoor temperature above setpoint and a cooling control signal below maximum, even with the integral term active.

2.4 The Simplified AHU Using Optimal Control

In optimal control, an objective function is minimized by numerical optimization. This objective function is here defined as the sum of the heat supplied by the heating coil (P_{coil}), the electricity consumption of the supply and extract fans (P_{fan}) and the electricity consumption of the heat pump compressor (P_{comp}) while the waste heat (P_{waste}) is subtracted from the objective function.

$$min\left(P_{coil} + P_{fan} + P_{comp} - P_{waste}\right) \tag{1}$$

The waste heat is defined as the difference between the total heat supply from the condenser ($P_{cond,max}$) and the condenser heat rejected to the supply air (P_{cond}). As the waste heat can cover other heating demands in the swimming pool facility such as the pool heating, it is therefore subtracted from the objective function. In the decoupled approach, the heating or cooling demand (Q_h) of the swimming pool and the dehumidification demand (W) are pre-computed by the pool model without the AHU. These demands are related to the specific enthalpy (h) and absolute humidity (ω) of the supply and exhaust air. The last constraint is the maximum electric power input for the heat pump ($P_{comp,max}$), see Equation (4). The four decision variables of the optimal control are the enthalpy of the supply air ($h_{sup,in}$), the outlet air temperature from the evaporator (T_{cool}), the fresh air fraction (k_{si}) and the inverse of the supply mass flow rate (m_{sup}). The inverse of m_{sup} has been considered as it makes the constraints on the heating or cooling demands linear. The other states of the AHU, like the state of the exhaust air, are computed using a simplified AHU model where each component is modeled in steady-state using the conservation of energy and humidity. The system of equations for the AHU model is given in the Appendix and is solved by successive substitution.

$$P_{comp} = \left[0, P_{comp,MAX}\right] \tag{2}$$

3 Case study

3.1 General description

The constraints of this study are defined by the swimming facility in the multipurpose sports center located at Jøa, an island in the municipality of Namsos in Norway, Figure 6. It is located at 64.6°N, 11.2°E, 65 meters above mean average sea level, and the climate is defined as the Marine West Coast climate zone according to the climate zones definition in the Köppen and Geiger climate system (34). The sports center was built in 2015 and commissioned during 2016.The swimming hall has a usable area of 266 m² (13.7 x 19.4 meters) including the 8.5 x 12.5 meters swimming pool. This paper only considers this part of the building. Typical meteorological conditions for Trondheim, Værnes, Norway, were used.

Figure 6 The multipurpose sports center of Jøa.

The swimming facility at Jøa is a state-of-the-art swimming facility which complies with the Norwegian passive house standard (35). It includes a conventional water treatment train, which research has found to be the most effective solution (36), and a ventilation heat recovery system equipped with a heat pump, as recommended in the literature (15, 22). The latter is interconnected with the pool basin water circuit and indirectly to the thermal heating system in the building as shown in Figure 1. The facility was selected due to its availability and properties, which fulfill the requirements for this study.

3.2 Input parameters

Several key processes have been carefully investigated, including calculation of the evaporation rate for the pool, the thermal loads and the heat recovery. Regarding the indoor thermal climate, long-term measurements have been investigated with the purpose of having a representative model for fulfilling the purpose of the study. Key variables and assumptions are summarized in **Error! Reference source not found.**.

Table 1 Key variables and assumptions applied in the study for the simplified and the detailed BPS models.

	Simplified model	Detailed model	Description
T_{room}	31.5°C		Indoor dry-bulb temperature.
T_{pool}	31°C		Pool water temperature.
$RH_{bathing}$	55 %		Indoor relative humidity in "bathing mode"
RH_{idle}	**If** (T_{out} < 10°C) 55 % **else if** (T_{out} > 25°C) 70 % **else** (55 + (T_{out} − 10)		Indoor relative humidity in "idle mode"
$T_{sup,max}$	NA	41.5°C	Upper limit for the supply air temperature
$\dot{V}_{nominal}$	11 000 m^3/h		Nominal airflow rate from AHU technical documentation
$\dot{V}_{extract}$	$\dot{V}_{nominal}$ x O$_f$		Extract airflow rate
$\dot{V}_{supply}$	$\dot{V}_{extract}$	$\dot{V}_{extract}$ x 0,98	Supply airflow rate
O$_{f\text{ - Bathing}}$	0.75		Min. share of air flow in "bathing mode"
O$_{f\text{ - Idle}}$	0.6		Min. share of air flow in "idle mode"

$\dot{V}_{FA,bathing}$	0.05 x $V_{nominal}$		Min. share of fresh air (in "bathing mode", or in fresh air operation at night)
$\dot{V}_{FA,idle}$	0		Min. share of fresh air at night
T_{evap}	0°C		Setpoint evaporation temperature, heat pump. Substitute for evaporator pressure in real device.
Infiltration	Fixed = 0	Dynamic, sub pressure	
Heat sink, pool	Unlimited		

Other important variables in the model are the setpoints for the water and air temperature, and the difference between them. Figure 7 shows the range for the variables measured during the period summer 2018 to summer 2019 for the swimming facility at Jøa (see Section 3.1). The levels of these variables are within the recommended levels in the literature (37-39), and are found to be relatively constant over the operating year. These are added to the model as constraints in the steady-state calculations and as setpoints in the detailed model.

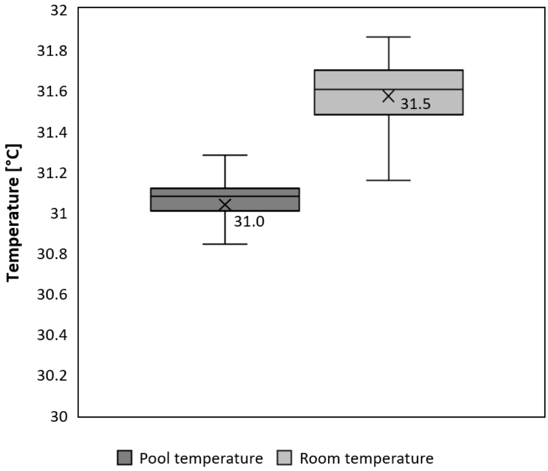

Figure 7 *Box plot – Measurements of the pool water temperature and the indoor dry-bulb temperature at Jøa for the operating year of 2018-2019.*

3.3 Simulation scenarios

The investigation of the complexity of a swimming facility BPS model was carried out by comparing both steady-state calculations and whole year simulations. The models are represented by (1) A decoupled approach with the AHU using optimal control (simplified model), and (2) A closed-loop system with an AHU using a detailed heuristic (rule-based) control system adapted from the technical documentation (detailed model).

Regarding the steady-state comparison, four characteristic operating conditions were identified. The outdoor conditions of interest were found analytically by investigating the calculation results from a whole year simulation of the detailed model in IDA ICE. The outdoor conditions of special interest are given in Table 2. These operating conditions are marked in Figure 8, which illustrates the outdoor conditions with respect to dry-bulb temperature (T_{out}) and relative humidity (RH).

Table 2 Description of the scenarios with operating modes (ID) and outdoor conditions (T_{out}, RH).

ID	Conditions	Comment
S.1 - Scenario 1 **“Hot dry, bathing”**	Bathing T_{out}: 29°C RH: 30 %	Choice based on cooling control signal peak in "bathing mode"
S.2 - Scenario 2 **“Hot dry, idle mode”**	Nighttime T_{out}: 25°C RH: 50 %	Choice based on cooling control signal peak in "idle mode"
S.3 - Scenario 3 **“Mild, idle mode”**	Nighttime T_{out}: 5°C RH: 60 %	Outdoor condition where humidity control algorithm switches from level 1 to level 2 (fresh air dehumidification)
S.4 - Scenario 4 **“Winter, bathing”**	Bathing T_{out}: -16°C RH: 85 %	Winter design condition.

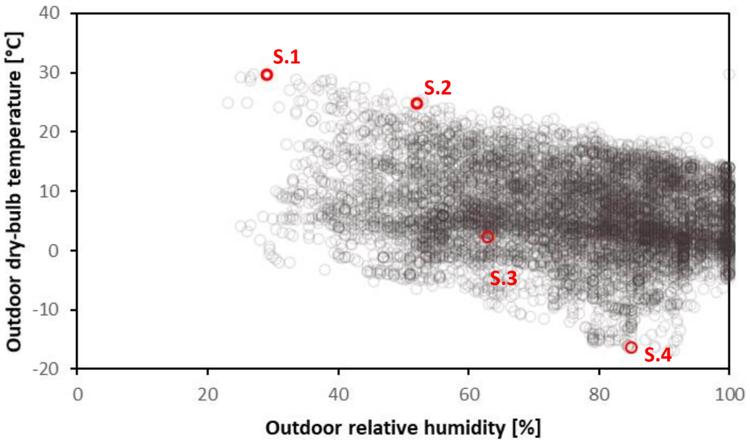

Figure 8 Outdoor dry-bulb temperature vs. outdoor relative humidity for the weather file. Each scenario is identified in red and by the ID given in Table 2.

4 Results

4.1 Experimental validation of the detailed model

The performance of the detailed model was tested with a short-term validation process. Measurements, usage registration and operation schedule were collected from the case study building where the first was used for comparison and the others were used as input parameters for the BPS model. The performance of the model was evaluated by comparing the temperature and vapor pressure (calculated by using temperature and relative humidity) for supply air and extract air and the airflow rate for extract air. The collected historic measurements were downloaded from the building automation system (BAS) and the usage information was collected by handwritten registration. The integrated temperature and humidity sensors ranged from -30°C to 70°C and RH 10 % to 95 % respectively. The accuracy of the sensors was given to ±0.4K for temperature and ±3 % for relative humidity. Taking into consideration the range of the measured variables and the purpose of the comparison it can be assumed that the accuracy of the measurements was sufficient. The measurements ranged from January 10th to 16th, 2020. The chosen period was due to the need for stable operation and the registered usage data available. However, the short-term validation was found to be a sufficient method of evaluate the model (21, 23, 24). Figure 9 presents the comparison of the measured and calculated variables.

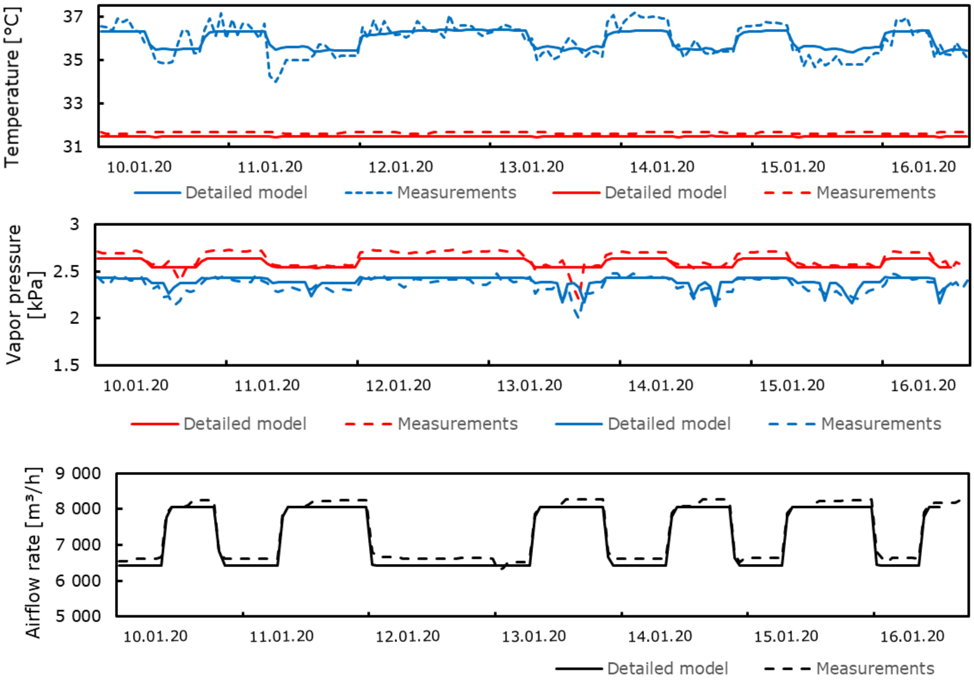

Figure 9 *Calculated and measured parameters of the air from 10.01.20 – 16.01.20. Supply air (blue), extract air (red) and extract airflow rate (black).*

4.2 Validity of the decoupling assumption

The deviation between the detailed model and the simplified model can have multiple explanations. For instance, the governing equations for the AHU in the simplified model differ slightly from the detailed modeling in IDA ICE. However, as explained in Section 2.1, a central assumption is made regarding on the influence of the airflow rate on the heating and dehumidification demands. In the simplified model, the airflow is kept constant to evaluate the need. In our case study, the air change rate was set to 70 % of nominal airflow rate, as the diurnal average (min. 75 % in "bathing mode", min. 60 % in "idle mode"). To test this assumption, the sensitivity of the heating demand on the airflow rate is shown in Figure 10, where the relative airflow rate is defined as the ratio of the actual and the nominal airflow rates. Variations in the airflow rate during operation range from 60 % to 100 % of the nominal air low rate. In this range, the influence of the airflow rate on the heating demand is low so that taking a fix value at 70 % gives a fair estimate of the need. However, this assumption slightly underpredicts the heating demand in "bathing mode" and overpredicts in "idle mode".

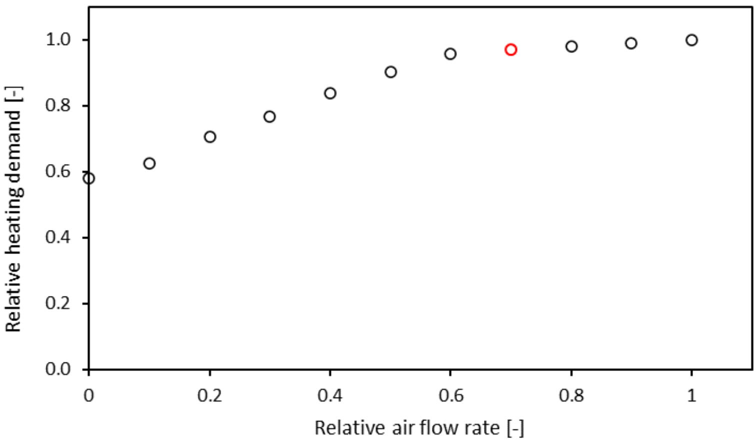

Figure 10 Relationship between the relative airflow rate and the relative heating demand defined as the ratio between the actual and highest heating demand at nominal airflow rate: the red marker represents the chosen relative airflow rate used in the decouple approach.

4.3 Analysis during steady-state operation

The ventilation system has a strong impact on proper operation of the building making its design of this system crucial. This includes the impact on the users' comfort, operating costs and the safety of the building structure where the major task is to ensure appropriate thermal-moisture conditions by removing the moisture gained from the water surface (40). For this task, the amount of fresh air has a great influence. Its calculation is reported in column “Air Flow Share Heat exchanger” in Table 3, which describes the relative airflow share of fresh air in the heat exchanger. During operation, this variable is constantly fluctuating.

The results from the steady-state calculations show that both models calculate similar fresh air supply rates when the models are operated in "bathing mode", meaning scenarios 1 and 4. The fresh air supply is represented as the combination of the calculated figures in the column "Power Load Ratio (PLR)" and the "Air Flow Share Heat Exchanger". Due to the hot and humid outdoor conditions, the largest fresh airflow rate is found in Scenario 1, calculated by both models to be approx. 30 %. In comparison to the cold conditions of Scenario 4, the fresh airflow rate share in Scenario 1 is about double that in Scenario 4. While the large fresh airflow rate in Scenario 1 is due to the required dehumidification, exclusively, Scenario 4 is more complex since the temperature controller strategy is also calling for an increased fresh airflow rate. In this case, the simplification of the precalculated steady-state demands provided by the simplified model contributes to an even larger deviation, since the dehumidification demand (i.e. moist mass flow rate from the water surface to the room node) depends on the vapor partial pressure in the swimming hall. Due to the closed loop approach, the detailed model takes this phenomenon into account, which reduces the indoor relative humidity and therefore the vapor partial pressure, thereby increasing the evaporation rate and consequently the heating demand for the pool. Figure 11 illustrates 24 hours of operation, day and night, for the AHU. This is also illustrated in Figure 13A, where the moist gain from the facility is identified by a slight increase for the detailed model. However, the difference in air state is modest. This is due to both the large air flow rate in this facility and the controllers for the detailed model. In this scenario the room air temperature is controlled by a P controller only, where the steady-state error is neutralizing the effect of the increased evaporation rate.

The dynamic infiltration loss, where exclusion is represented as one of the simplifications in the simplified model, can be found as the deviation in the calculated air flow rates. The effect of the infiltration is decreasing with decreasing outdoor temperature.

Table 3 Essential key numbers from the calculations results. SM = Simplified model; DM = Detailed model.

Scenario	Airflow share Heat exchanger		Power Load Ratio Fans		Coefficient of Performance (COP)		P_{comp}	
	SM	DM	SM	DM	SM	DM	SM	DM
1	0.30	0.32	0.75	0.72	5.20	3.72	6,200	8,086
2	0.04	0.075	0.60	0.57	4.20	3.38	2,442	3,520
3	0.11	0.14	0.60	0.58	4.15	3.31	3,951	4,898
4	0.17	0.12	0.75	0.72	4.10	3.30	4,547	4,373

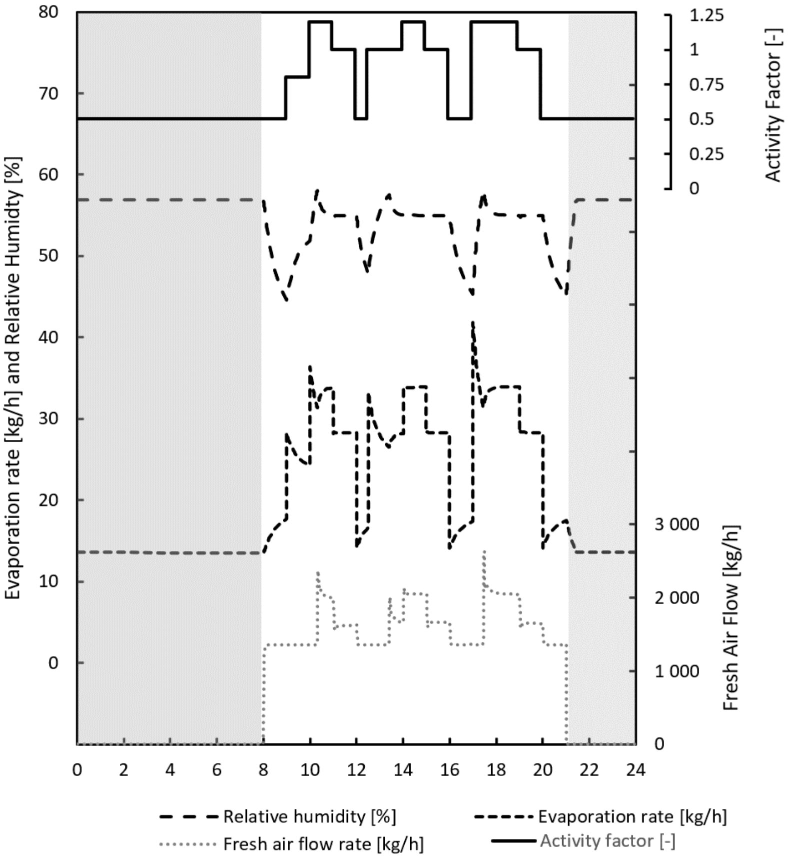

Figure 11 Simulation results from the detailed model. The gray area represents the periods when the air handling unit is operated in "idle mode" with no fresh air supply.

4.4 Power Load Ratio (PLR)

The models calculate the same power load ratio (PLR) for the fans, which also means that the models follow the same control strategy. Despite the good correlation between the calculated airflow rates, which Figure 12 confirms, there is a deviation in the calculated electricity consumption, identified as “P_{fan}” in Scenarios 1 and 4. This is due to small differences in the modeling assumption of the AHU in the IDA ICE and simplified model in MATLAB. However, the deviation is small and does not contribute to a significant discrepancy in the calculation of the air states, as shown in Figure 13 and Figure 14.

4.5 Heat Pump

The calculated performance of the heat pump is seen to deviate between the models. The heat pump model included in the simplified simulation model calculates lower values compared to the gray-box model in the detailed model in IDA ICE. This is shown as COP and P_{comp} in Figure 12. In addition to the differences in the heat pump models themselves the model layout of the heat sink side (condenser side) deviates between the models. The detailed model includes an indirect system, a hydronic loop, including control system and additional heat exchangers for both airside and waterside heat supply. Also, the performance of the heat exchangers influences the performance as well as the deviation in the previous discussed thermal demand (steady-state model assumptions). This deviation is illustrated in Figure 13 and Figure 14, where the gap between states 1 and 8 defines the latent (Q_h) and sensible heating demand (W), see Equations (2) and (3). This difference in the psychrometric charts is directly comparable between models since the calculated airflow rates are almost identical.

4.6 The Controllers

The controllers have an impact on the outcome of the steady-state calculations. The impact is illustrated in the psychrometric charts in Figure 13 and Figure 14. For Scenario 1 the effect of idealizing the controller is identified as the deviation between the setpoints and the calculated temperature and relative humidity. The indoor dry bulb temperature in the detailed model is approx. 32.5°C due to the P range of the controllers at ±1°C. This deviation is due to the steady-state error in the controllers since the integral-term in the controller is not activated. The same effect, and the impact of the steady-state error in the controllers, is illustrated in Scenarios 2 and 3. Due to the allocation of the controllers in the humidity controller group, where the humidity is controlled by a P controller in "idle mode", the deviation in humidity to setpoint is due to the steady-state error. An increased humidity level or/and temperature level influences the entire cycle of the facility, where for example the evaporation rate and the thermal losses are reduced. This also affects the electricity consumption for the heat pump, P_{comp}, and the “waste heat”, as illustrated in Figure 12. Due to the interconnection between the systems, every deviation propagates into the system.

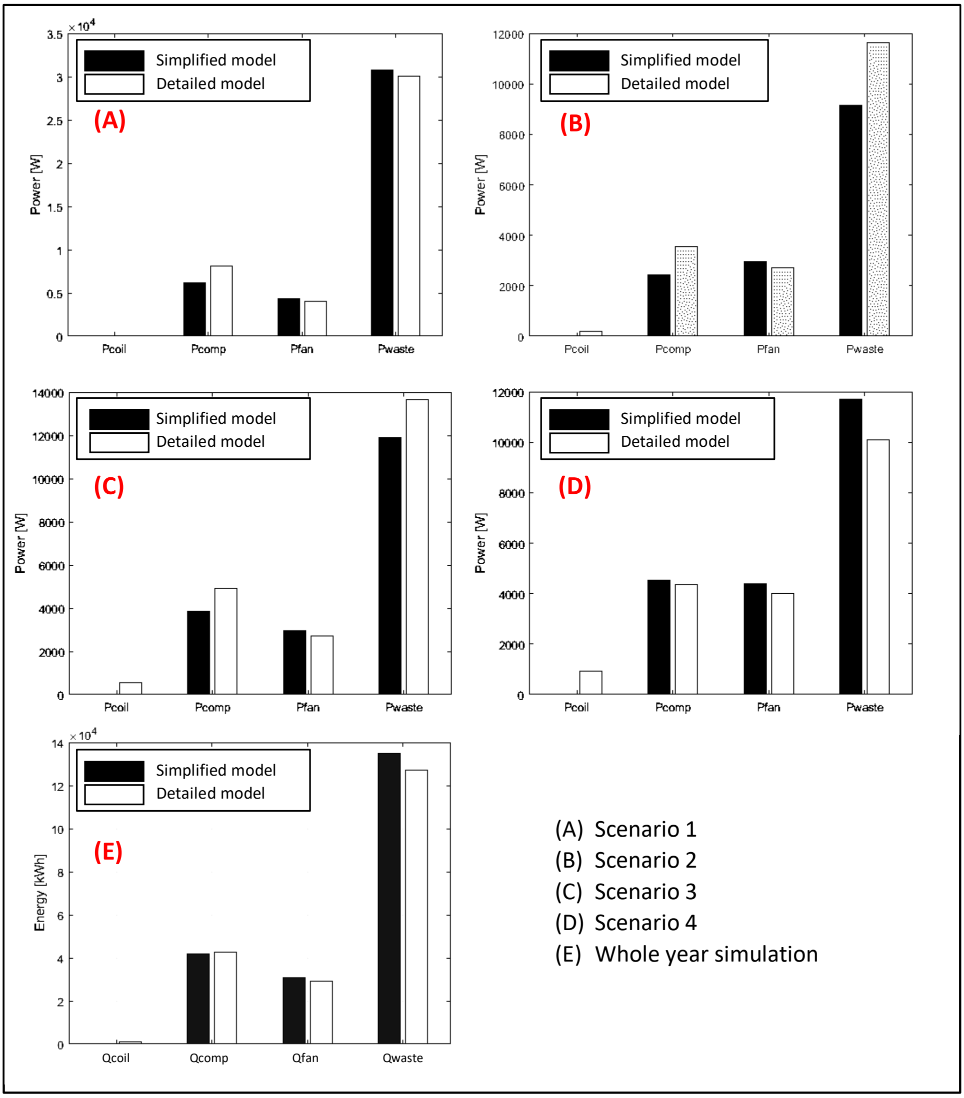

Figure 12 Power supply related to essential components in the AHU (Pcoil = heating coil, Pcomp = heat pump compressor, Pfan = AHU fan, Pwaste = pool condenser heat).

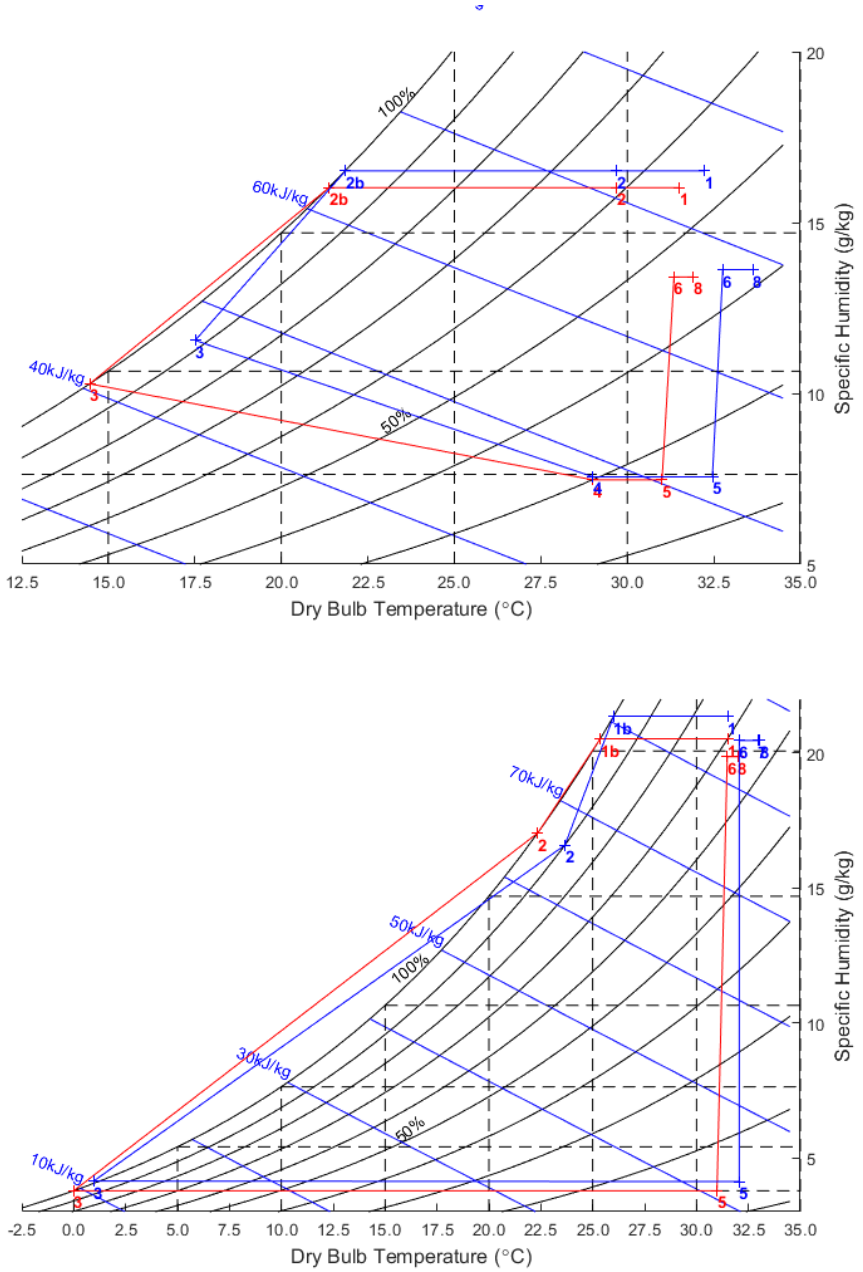

Figure 13 Psychrometric Chart – Summer season, the calculated air states for the air flow inside the AHU. Simplified model in red, detailed model in blue. The ID-numbers refer to the locations defined in Figure 3.

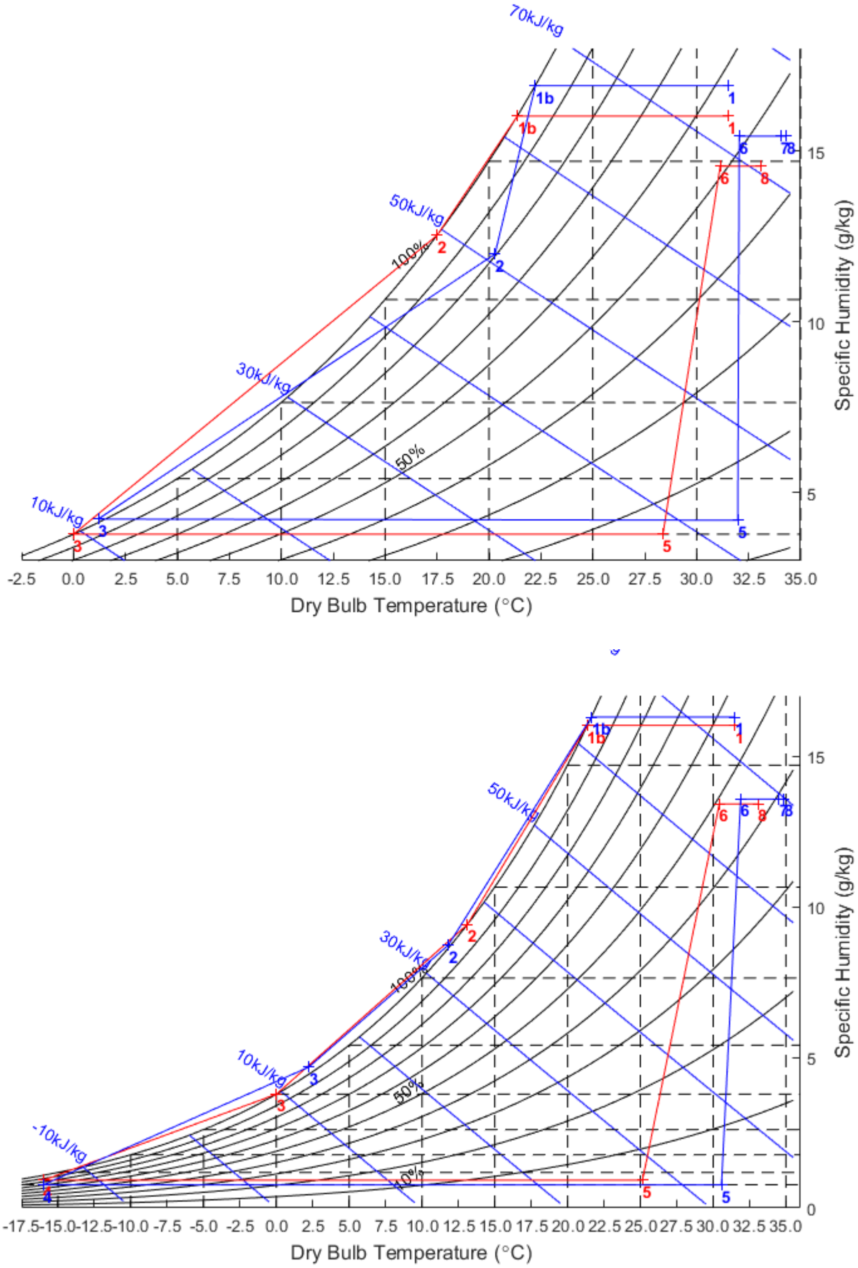

Figure 14 Psychrometric Chart – Winter season, the calculated air states for the air flow inside the AHU. Simplified model in red, detailed model in blue. The ID-numbers refer to the locations defined in Figure 4.

4.7 The Value of the Waste Heat

The detailed model is in accordance with the ideal optimized control when the alternative heat source is set to $COP_{alternative} < COP_{heat\ pump}$, which means that the detailed model does not distinguish between the heat sources. The heat pump is operated for maximizing the operation hours and for recovering as much of the energy content in the exhaust air as possible.

Figure 12 illustrates the considerable heat supply from the heat pump, referred to as P_{waste} (waste heat), regardless of the operation mode and season. The results emphasize the importance of an integrated control strategy for the AHU and the pool heater. Bearing in mind the rarity of this in traditional swimming facilities, this indicates considerable energy savings potential. Normally, these systems are neither provided with separated and dedicated control systems without any shared controller, nor a control strategy as e.g., a sequence control strategy. However, the detailed control is based on a commercial AHU which is commonly used in Norwegian swimming facilities today. This control strategy does not value the alternative heat source, which implies a prioritization and maximization of the operating time for the heat pump. However, this is the correct assumption for swimming facilities where the concurrent heat source is direct electric heating or a heat pump with a COP below the COP of the heat recovery system. In systems including e.g., district heating, a very energy efficient heat pump, solar energy, and/or the primary energy consumption is important for the facility management, this control system needs to be customized.

5 Discussion and Opportunities for Deployment

Due to the importance of the design phase when minimizing the environmental impact of swimming facilities, knowledge regarding the required complexity of building performance simulation (BPS) models has great potential for industry. Swimming facilities have a high level of complexity in the energy system, including the control system. An inappropriate and too simplified model structure will therefore cause misprediction of the energy performance of the building, and the rating conditions for the HVAC components may become incorrect which can cause excessive energy use and flaws during operation. Due to the large annual energy demand and consequent significant greenhouse gas emissions from swimming facilities, it is important to design the facilities for high energy performance. (41).

In research projects BPS models of swimming facilities are used for producing training data due to the lack of experimental data (42), for evaluation strategies for reduced energy consumption (43) and for studying various heating options (44). This study has investigated the consequences of the BPS model complexity for the AHU, which serves as the main component in the energy system of a swimming facility. The design of a well-functioning ventilation system is important for both high energy performance and satisfactory air quality (45). The analysis shows good compliance in the steady-state calculations where the models have been presented with same control strategy, but with ideal and heuristic control systems. However, some deviations stand out, and should be considered when using an idealized control system when performing calculations of the system:

- **Air flow rate** - The models calculate the fresh air ratio and volume flow rate within a deviation of 5 % for all scenarios, as illustrated in Figure 15. As Table 3 shows, the simplified model underpredicts the “air flow heat exchanger”, except for scenario 4, and overpredicts the PLR. However, the heat exchanger models differ in performance where the simplified model calculates a lower heat recovery rate for the device. This is illustrated in Figure 16, where the accumulated deviation is seen to decrease after the heat exchanger. Consequently, the heat exchanger code should be improved in the simplified model.
- **The heat pump** models calculate very different evaporator and condenser capacities (to air and pool water). For the calculation of the delivered waste heat this is illustrated in Figure 15. The operation as a heat recovery device requires a large temperature difference in the evaporator, including constant condensation of humidity (latent heat). Both evaporator

models should preferably be improved and validated for such distinct operation. This has an impact on the amount of recovered heat from the exhaust air and the power input for the heat pump.

- **Model approach** - The detailed model, which includes a closed loop approach, is a better choice than the simplified model due to the multiple indoor variable controller (temperature and humidity). For example, when the integral-term is inactive in some of the controllers a steady-state error propagates into the system, where the impact is seen on both the sensible and latent energy demand. In a swimming facility with a heat recovery loop to pool water, the level of required dehumidification influences many factors including the power input for the heat pump and fans, the thermal energy use for water heating as well as the temperature and humidity levels in the room.

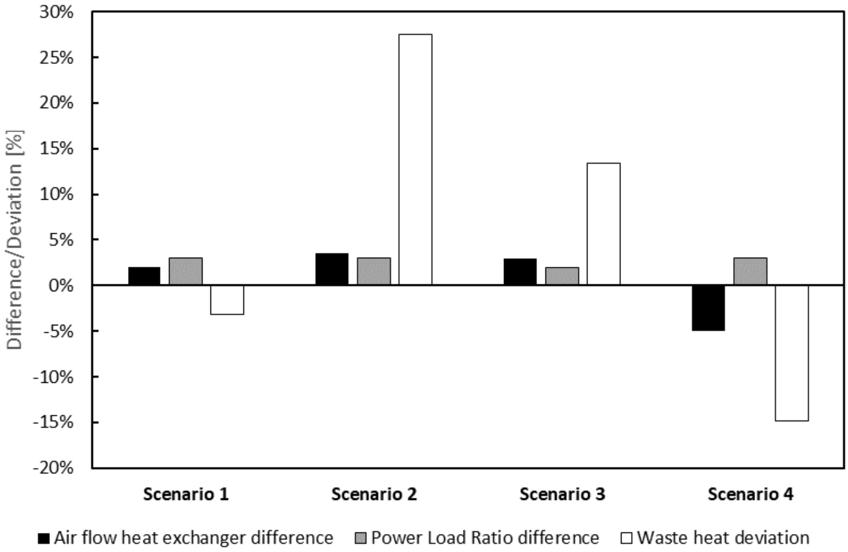

Figure 15 *Discrepancy between the calculation results for air flow rates and waste heat. Difference in air flow rates are given as the absolute difference in the calculated air flow ratio while the calculated waste heat is given as the deviation in the detailed model results, compared to the simplified model.*

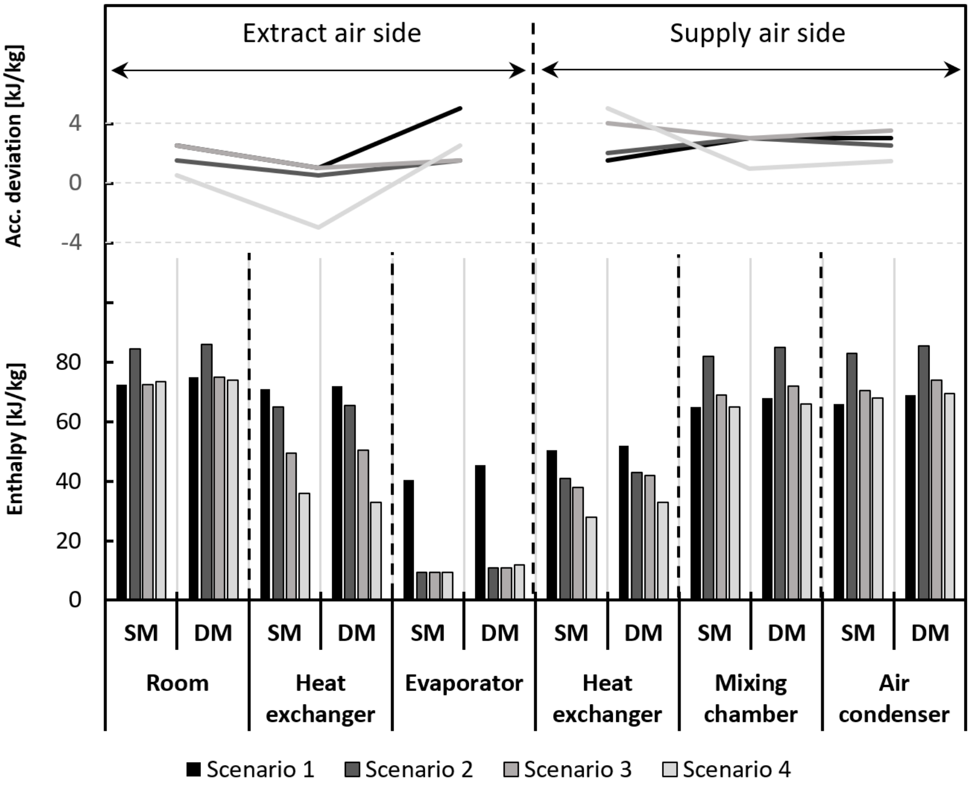

Figure 16 Summarized enthalpy levels for each stage, scenario and model. Deviation relative to the simplified model is given for the respective stage as a line plot. SM = simplified mode, DM = detailed model.

Regarding the control strategy, the heat recovery is prioritized without considering the value of the alternative heat supply. This is the optimal strategy for swimming facilities located in regions where the alternative heat supply normally is represented by a high energy cost such as electricity. For facilities with alternative heat sources with low energy costs, like natural gas, district heating, industrial waste heat or a more efficient heat pump, the control strategy should preferably be modified. However, to implement the exact control strategy from the manufacturers is shown to be impossible, due to business secrecy. This makes it impossible for the research and/or engineering community to make a digital replica of the device in the BPS tool when assessing the performance of the facility. However, this study has used the available information and compared it to a simplified model with an idealized control system. The simplified model is shown to produce calculations in compliance with the detailed model, with some required improvements of the addressed components codes. Additionally, guidelines with respect to the modeling should also be provided.

6 Conclusion

This paper treats the issue of model complexity of the control system of an air handling unit in a swimming facility. It presents a comparison of two building performance simulation models, one model with an idealized and optimized control system (simplified model), and a second model with a detailed heuristic control system (detailed model). Swimming facilities are buildings with high annual energy consumption and consequent large greenhouse gas emissions. It is therefore important to improve their energy performance and increase their energy efficiency to reduce their negative environmental impact. In order to approach this the designer should be able to make detailed predictions of the energy performance of the facility and optimize the design and operation of units such as the AHU and the heat recovery system.

The detailed description of commonly used AHUs and control systems in this study reveals that the control systems are complex with multiple controllers and control algorithms overlapping and interacting each other. The process of collecting the control strategy from the manufacturer identified the issue and obstacle that business secrecy makes when modeling swimming facilities. However, the model that was created after in-depth investigations and the outcome of the study will help future studies in the assessment of the calculations with simplified models using an ideal control system.

The detailed model of the AHU prioritized the integrated heat recovery system, represented by a heat pump, without considering the value of the alternative heat supply, with respect to either energy cost or climate impact. This is the optimal strategy for some swimming facilities in countries such as Norway, but in cases with alternative low-cost heat sources this control strategy must be modified in order to optimize the performance of the facility.

The discrepancy between the two models is shown to be below 5 % for the air flow rate calculations for all the investigated scenarios. Taking into account the modest deviation of the calculated air states as well, with a discrepancy below 5 kJ/kg (enthalpy-level), the deviation is acceptable, and the simplified model can be used for early-stage assessments of swimming facilities. This minor deviation in temperature, humidity and heating demands, compared to the detailed model, will provide the designer with the required confidence for analysis at this project stage. However, improvements regarding the waste heat calculation should be carried out, and future work should also focus on improving the evaporator models and system layouts with heat recovery from an integrated heat pump.

This study has also revealed some distinctive phenomena for swimming facilities. Due to the nature of evaporation, the detached approach applied in the simplified model, does not catch the consequences of fluctuations in the indoor variables to the full extent. The psychrometric charts also give a good illustration of the dual purpose of the ventilation system, where the air flow rate is represented with negative enthalpy difference, even when heating the facility. This is due to the supplied latent energy to the air flow. In addition, the indoor air change rate has an impact on the heating demand of the facility. This illustrates the requirement for a detailed closed-loop model when carrying out an in-depth performance analysis of the facility.

Acknowledgements

This work is a part of a doctoral project entitled “Optimizing Energy and Climate Systems in Buildings with Swimming Facilities”, which is carried out as a cooperation project between the Centre for Sport Facilities and Technology (SIAT) at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, and the engineering company COWI AS. The project is funded by COWI AS, The Research Council of Norway and COWIFonden.

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8 Appendix

8.1 Evaporation rate

The evaporation rate is the most important physical phenomenon that influences the state of the indoor air and thus closely influences the AHU control in swimming facilities (18). The mass transfer due to evaporation from a water surface can be briefly explained by two mechanisms, diffusion (molecular motion) and advection (air exchange over the water surface). Close to the water surface where the air flow speed is close to zero, diffusion is the dominant mechanism and advection is negligible. However, depending on the grade of forced convection the importance of the two mechanisms differs.

The humidity level of the room air depends on several factors: the total water surface area, water temperature, room and supply air states, air velocity at the pool surface, the ventilation air change rate and last but not least physical activity for the users. Since the evaporation rate depends on multiple variables, its calculation is not straightforward. Numerous articles have been published in the last century regarding estimation of the evaporation rate from water surfaces (46-50).

The widely known correlation introduced by Carrier in 1918 (46), was based on experimental results with an unoccupied water surface and forced convection. Even though the setup only included forced convection, the equation has also been used for natural convection by setting the input velocity to zero. The equation, which has the form of Dalton's description (51), has been widely used during the last century for different purposes. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbooks (52) recommend to use the Carrier equation for the estimation of the evaporation rate for occupied pools, and claim that the equation is valid for pools at normal activity levels, including splashing and some wetted surrounding areas.

During the 1990s, Charles C. Smith investigated the evaporation rate from indoor and outdoor swimming pools, both occupied and unoccupied (49, 53, 54). He found that the Carrier equation overpredicts the evaporation rate when applied to unoccupied pools and underpredicts the evaporation rate when the pools are in normal use (i.e. occupied).

During the last three decades, Shah published several articles regarding his work on evaporation correlations (48, 55-60). The equations are based on physical phenomena, theory and empirical data. Shah validated his formulas with all available test data and compared the accuracy with several other correlations (60). His equations and calculation algorithms predicted evaporation for unoccupied and occupied pools with a mean deviation of approx. 21 % and 16 %, respectively (58).

In the literature, several articles discuss the performance of these above-mentioned evaporation equations. For use in swimming pools, no consensus with respect to the most accurate correlation is observed. While Shah (60) stated that his own algorithm was the most accurate, he also found that the ASHRAE equation performs well with high occupancies (48). Li et al. (61) also reported the same for the ASHRAE correlation while they found Shah's correlation to give the best correlation for both unoccupied pools (56) and occupied pools (48). Ciuman et al. (40) found the German Verein Deutscher Ingenieure, VDI (37) to be the most accurate in their study when comparing the performance of Carrier (46), Smith et al. (49), Shah (60), ASHRAE (52), VDI (37) and Biasin and Krumme (62). This underlines the uncertainty the calculation of the evaporation rate adds to any evaluation of swimming facilities.

However, the engineering guidance literature provides several figures and relations. While the Norwegian guidelines provided by Ventøk (63, 64) and the SINTEF Building Research Design Guidelines (38, 65) only provide typical steady-state figures within predefined categories of swimming pools, VDI (37) and ASHRAE (52) both provide equations for estimating evaporation rates dynamically. For example, the ASHRAE handbooks provide correlations for estimating evaporation from water surfaces, mostly referred to as the ASHRAE equation (52). Among the BPS tools, IDA ICE (31) has implemented the ASHRAE's equation (52) while the TRNSYS pool add-on (66) has applied the VDI equation for occupied pools (37).

Due to the simplicity and good documentation in the literature, our study has included the ASHRAE equation. Equation (3) presents the correlation where $\dot{m}_{evap}$ is the evaporation rate [kg/s], A_{pool} is the area of pool surface [m²], p_w is the saturation vapor pressure taken at surface water temperature [kPa], p_a is the saturation pressure at room air dew point [kPa] and F_a is the activity factor/correction factor [-].

$$\dot{m}_{evap} = 4 \cdot 10^{-5} \cdot A_{pool} \cdot (p_w - p_a) \cdot F_a \qquad (3)$$

Table 4 summarizes the recommended activity factors provided by the ASHRAE handbook (52). The increased activity factor, i.e., from unoccupied to occupied pools, reflects the increased contact area between air and water due to waves and ripples and mist, which also increases with the number of occupants and the activity level. This implies an increase of the effective pool area (67).

Table 4 Recommended activity factors given in ASHRAE handbook, Heating, Ventilating and Air-Conditioning Applications (57).

Type of Pool	**Correction Factor F_a**
Baseline (pool unoccupied)	0.50
Residential pool	0.50
Condominium	0.65
Therapy	0.65
Hotel	0.80
Public, schools	1.00
Whirlpools, spas	1.00

Wave pools, water slides	1.50

For the case of unoccupied pools ASHRAE (52) recommend a correction factor of 0.5, ref. Table 4. Since our study has evaluated the performance of the BPS model, the selected activity factor is kept at 1.0, as recommended by ASHRAE (52). This represents an expected/typical use of a swimming facility which consequently leads to an expected evaporation rate.

8.2 Mathematical Expression of the Simplified Model

The model is based on a set of nonlinear equations solved numerically using successive substitution in MATLAB. Four distinct functions enable computation of the state S and its thermodynamic properties [h, ω, RH, T] based on two independent variables: S_a(T, RH), S_b(h, RH), S_c(T, ω) and S_d(h, ω). The input parameters of the model are the swimming pool air state (dry bulb temperature T_{room} and relative humidity RH_{room}), the outdoor air state (dry bulb temperature T_{out} and relative humidity RH_{out}) and airflow rate imbalance θ between supply and exhaust. The conservation equations are normalized by the exhaust mass flow rate (m_{ext}). Each state is evaluated by a function reported here below. Some clarifications can be given regarding the modeling:

- The heat exchanger is modeled using a standard NTU approach. For the sake of simplicity, it is assumed that the heat exchanger is a cross-flow heat exchanger. It is important to take the actual mass flow and the difference in mass flows at both sides of the heat exchanger. The model in IDA ICE is more elaborated and cannot be directly used in a simple model.
- The heat pump is modeled using a bilinear regression calibrated on COP given at rated conditions. To make a fair comparison with the detailed model, the rated conditions have been generated using the heat pump model in IDA ICE. This model is a quasi first-principle model where the condenser and evaporator are modeled using an NTU approach (68).
- For the same reason, the fan electric consumption as function of the volume flow is taken to be the same as in IDA ICE (69).

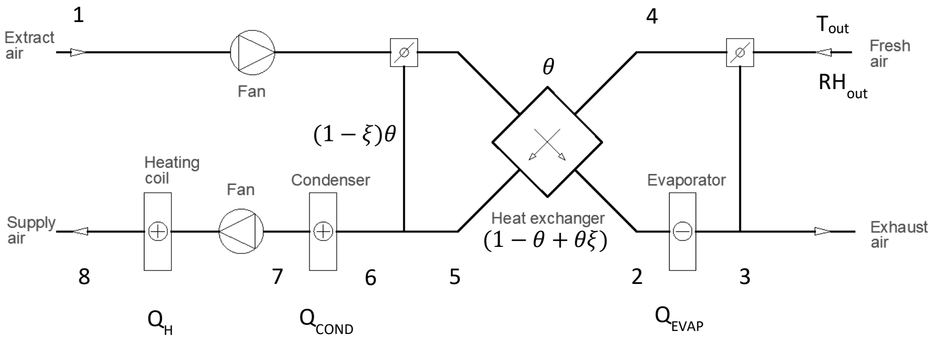

Table 5

Variables of the optimal control		
1	$T_3 = T_{cool}$	Outlet temperature evaporator
2	ξ	Mass fraction air from HX to condenser

3	$\frac{1}{\dot{M}_{EX}}$	Inverse of extraction mass flow rate
4	$T_{SUPPLY} = T_8$	Supply air temperature

Notation	
$S_a(T, RH)$	Compute state using T and RH
$S_b(h, RH)$	Compute state using h and RH
$S_c(T, \omega)$	Compute state using T and ω
$S_d(h, \omega)$	Compute state using h and ω
s in subscript	Saturated state
$S = [h, \omega, RH, T]$	State

Algorithm state 2

```
%Calculate air state 2 after heat exchanger HX at warm side
$S_1 = S_a(T_{room}, RH_{room})$
$h_2 = h_1 - Q_{HX}/(1 - \theta + \theta\xi)$
if ($h_2 < h_{1S}$) % dehumification
    $S_2 = S_b(h_2, 100)$
Else
    $S_2 = S_d(h_2, \omega_1)$
End
```

Algorithm state 3

```
%Calculate air state 3 after evaporator
if ($T_{cool} < T_2$)
  if ($T_{cool} < T_{2s}$)  % dehumidification
    $S_3 = S_a(T_{cool}, 100)$
  Else
    $S_3 = S_c(T_{cool}, \omega_2)$
  End
Else
  $S_3 = S_2$
End
  $Q_{EVAP} = (1 - \theta + \xi\theta) \cdot (h_2 - h_3)$ % evaporator power
```

Algorithm state 4

```
%Calculate air state 4 after dehumidification damper mixing
if Bathing mode
  $S_4 = S_{out}$
  Else
  $S_4 = S_3$
End
```

Algorithm state 5

```
%Calculate air state 5 at the outlet of HX modeled by cross-flow heat exchanger
$S_{5,MAX} = S_C(T_{out}, \omega_4)$ % Outlet state with highest possible temperature
$Q_{MAX} = \theta\xi(h_{5,MAX}, h_4)$ % maximum possible heat exchange
$PLR_{HX} = \theta\xi$ % part load ratio of heat exchanger
$NTU = \frac{NTU_N}{PLR_{HX}}$ % NTU number, nominal based on cross-flow heat exchanger
$\eta = \eta(C_R, NTU)$ % heat exchanger efficiency function of $C_R$ and NTU
$Q_{HX} = \eta \cdot Q_{MAX}$ % actual heat recovery
$h_5 = h_4 + \frac{Q_{HX}}{\theta\xi}$
$S_5 = S_d(h_5, \omega_4)$
```

Algorithm state 6

```
%Calculate air state 6 after the heat damper mixing
$h_6 = \xi \cdot h_5 + (1 - \xi) \cdot h_1)$
$\omega_6 = \xi \cdot \omega_5 + (1 - \xi) \cdot \omega_1)$
$S_6 = S_4(h_6, \omega_6)$
```

Algorithm state 7

```
%Calculate air state 7 after condenser and basis to evaluate waste heat $Q_{waste}$
$h_7 = MIN(h_8, h_{7,MAX})$ % maximum possible outlet enthalpy limited by state 8
$Q_{COND} = h_7 - h_6$
```

```
$COP = COP(T_{cool}, T_7)$ % COP using bilinear interpolation on manufacturer data
$Q_{COND,MAX} = Q_{EVAP} \frac{COP}{(COP-1)}$ % Total condenser power
$h_{7,MAX} = h_6 + \frac{Q_{COND,MAX}}{\theta}$ % outlet enthalpy without limitation by state 8
$S_7 = S_d(h_7, \omega_6)$
```

Algorithm state 8

```
%Calculate air state 8 after the heating coil
$Q_H = MAX(h_8 - h_7, 0)$
$S_8 = S_d(h_8, \omega_7)$
```

Final evaluation

```
$W = \dot{m}_{ext} \cdot (\omega_1 - \theta\omega_8)$ % dehumidification needs
$Q_h = \dot{m}_{ext} \cdot (\theta h_8 - h_1)$ % heating or cooling needs
$W_e = \dot{m}_{ext} \cdot \frac{Q_{EVAP}}{COP-1}$ % Heat pump compressor power
$Q_{waste} = \dot{m}_{ext} \cdot (Q_{COND,MAX} - Q_{COND})$ % waste heat
$W_{fan} = W_{fan}(\dot{m}_{ext})$ % correlation for fan consumption at part load
```

ISBN 978-82-326-7090-1 (printed ver.)
ISBN 978-82-326-7089-5 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

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