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INDOOR SWIMMING POOLS: A DYNAMIC SIMULATION MODEL FOR ENERGY ANALYSES

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Abstract

Swimming facilities[1] require high amounts of energy to provide thermal comfort for occupants. To identify energy-saving measures, we developed a novel dynamic simulation model of a swimming pool and the connected water treatment circuit. The integration into a building enables to capture interdependencies between water evaporation and thermal demand of the building. The model is applicable for various changing boundary conditions and specifications (e.g. air and pool conditioning and occupancy levels) and thus allows the investigation of multiple measures at a facility. Within a parameter study, we identified energy-saving potentials of 21 % through improved pool operation and equipment.

Introduction

Tempering water and providing comfortable indoor air in swimming facilities[1] require significant energy consumption. The annual energy consumption for an average German swimming facility is 3,400 kWh/(m^2 water area) for sport- and 5,900 kWh/(m^2 water area) for leisure-oriented facilities (DGfdB 2020). As a result, the energy demand accounts for a high proportion of swimming facilities' total operating costs (Yuan et al. 2021). Reducing the energy demand can therefore combine economic benefits with climate protection goals. In Germany, the public sector operates more than 75 % of all public swimming facilities (LfU 2012). As many of the public operators face budget constraints, reducing energy demand is also a way to preserve a high amount of swimming facilities. The aim of a climate-neutral building stock in Germany by 2045 will further increase the pressure on operators to save energy. Especially because public authorities have the aspiration to lead the way in energy efficiency and resource conservation.

As publications on swimming facilities are limited (Smedegård et al. 2021) and mainly focus other topics, such as disinfection optimisation (Abbasnia et. al 2019; Carter and Joll 2017; Yang et al. 2016), we collaborate with the *Deutsche Gesellschaft für das Badewesen e.V. (German Society for Bathing)*, an overarching organisation that covers, among others, experienced operators and engineering consultants who are specialized on energy efficiency in swimming facilities, to close the knowledge gap.

Together, we developed a simulation tool to analyse the effect of different measures on the energy demand and the emissions of swimming facilities. The measures include single or combined improvements on the building shell and HVAC (heat, ventilation and air conditioning) system. We focus on sport-oriented, indoor swimming facilities, which are the most typical municipal swimming facility. And we concentrate on the provision of energy for the pool and the air conditioning, because together they are responsible for the majority of indoor facilities' energy demand (Yuan et al. 2021).

Dynamic simulations consider thermal and moisture-related interdependencies between pool water and air as well as the storage capacity and the inertia of the water. Therefore, dynamic simualtions are advantageous over static calculations to identify and compare energy-related measures within swimming halls. In this context, many contributions on outdoor swimming pools, especially on solar heated ones, exists (Nouanegue et al. 2011; Ruiz and Martínez 2010). In contrast, indoor swimming facilities are only rarely addressed in literature (Smedegård et al. 2021).

Since evaporation causes high humidity rates within the swimming hall, evaporation itself or the operation of air-handling-units (AHUs) to handle humidity is of particular interest in research regarding indoor facilities. Thereby, most studies focus on the control of the AHU and consider a fixed setup of equipment (Ciuman and Kaczmarczyk 2021; Ribeiro et al. 2010).

[1] We differentiate between swimming pools (the baisin with water), swimming halls (rooms including pools) and swimming facilities (the whole building).

In our study, however, we developed a model, which is easily applicable for different swimming facilities and provides the opportunity to simultaneously consider different energy-saving measures and variable setup scenarios. To this end, we contribute with the following aspects:

- Novel dynamic simulation model of an indoor swimming facility within the modeling language Modelica.
- Toolchain and specifications for automatic parametrization and model generation.
- Comparison of different energy-saving measures and their interdependencies.

The flexibility of the model allows a wide range of changing boundary conditions, such as pool numbers, dimensions of pools, occupancy levels and different specifications of pool operation, equipment and air conditioning.

Simulation Model

The purpose of the model is to determine the energy demand of different types of public swimming facilities and to identify the influence of energy-saving measures. Due to the implementation of default parameters according to standards and typical building equipment, the parameterization effort is kept low. However, the model offers the flexibility for detailed parameterization at the level of individual buildings.

Building Model

TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit), a tool for automatic generation of building models of different archetypes, serves as basis for the modeling approach (Remmen et al. 2018). We extent it by the archetype *indoor swimming pool*, which compromises the following six energetic relevant thermal zones:

- Swimming hall (SH),
- Entrance hall (EH),
- Changing area (CA),
- Showers and other sanitary areas (SA),
- Utility areas for staff and supervision (UA),
- Technical areas (TA).

The principle of TEASER is that it generates a complete building model with few input parameters and standardized databases. In the case of the swimming pool, these are the water area, the floor height and the year of construction. Specifications from standard (KOK 2013) combined with standardized data for non-residential buildings deliver all necessary information for the archetype approach. Further building data can be added for more detailed representations of individual objects. On that basis, TEASER automatically translates the building information into a dynamic model consisting of components from the Modelica library AixLib (Müller et al. 2016). The generated building model depicts transmission, radiation, infiltration and internal gains from people, lighting and other devices. Additionally, a connected AHU maintains air humidity at a predefined level to protect the building's structure and ensures comfortable conditions for occupants.

Swimming Pool Model

Figure 1 shows all system components as well as energy and mass flows of the swimming pool model and the connected water treatment circuit. The model utilizes components from the AixLib library for media volumes, heat exchangers, heat transfers, and pumps. Fluid connections allow mass flows between the various elements, establishing corresponding mass balances. The pool filter and disinfection unit are not depicted as own components in the model. Instead, the resistances of both systems are considered in the pump delivery head and the filter type is taken into account in the determination of volume flows and storage capacities.

For easy usability, we implement specifications from standards on the characteristics of the swimming pool and the water treatment circuit, such as the pool dimensions, pool water temperature, pool and filter type, into our tool-chain for automated model

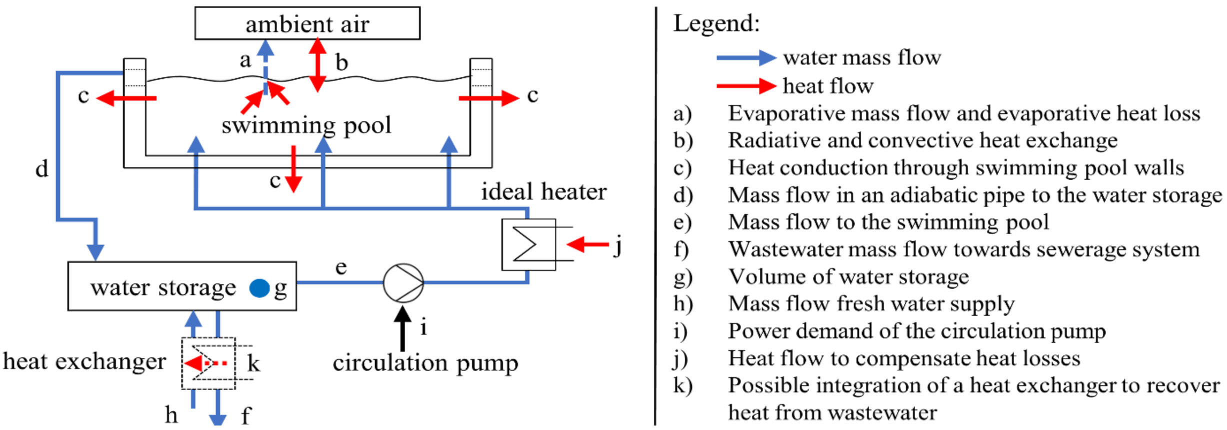

Figure 1:Components, related energy and mass flows within the building model

parameterization. The following section points out the most important predetermined parameters - the circulation volume flow, the water storage volume and wastewater mass flow, defined by DIN 19643 (DIN 2012). Afterwards the dynamic equations for heat and mass flows are presented.

Predetermined Parameters

The pool water constantly circulates in the system. It flows over the edge of the pool into the water treatment circuit and back through inlets at the bottom. In this context, the model parameterization includes equations from DIN 19643, which indicate a circulating volume flow that ensures hygienic and damage-free operation of the hydraulic system (DIN 2012). Depending on the pool size and type as well as the filter type the standard provides different specifications. Further, it allows water treatment volume flow reduction during non-operating hours to a hydraulic minimum.

In addition, Equation 1 states the minimum storage size according to the standard, which is set as default value. It consists of the water volume displaced by swimmers (V_D), discharged by waves (V_{Wave}) and used for filter flush (V_{FF}) depending on the filter type.

$$V_{storage} = V_D + V_{Wave} + V_{FF} \quad \textbf{(1)}$$

The wastewater mass flow rate $\dot{m}_{WW}$, which describes the continous water discharge from the water storage tank into the sewer system, depends on two processes: filter flushing ($\dot{m}_{WWF}$) and the exchange of water due to pollution by swimmers ($\dot{m}_{WWS}$)(Equ. 2).

$$\dot{m}_{WW} = \max(\dot{m}_{WWS}, \dot{m}_{WWF}) \quad \textbf{(2)}$$

The number of filter flushes per week n_{FF} multiplied by the required water volume V_{FF} and its density ρ_W defines the amount of filter flushing water m_{WWF}, (Equ. 3). Equation 4 determines water exchange due to occupants from the number of swimmers per day n_S and opening days per week t_{oh} multiplied by a factor of 0.03 m^3.

$$m_{WWF} = \rho_W * V_{FF} * n_{FF} \quad \textbf{(3)}$$

$$m_{WWS} = n_S * t_{oh} * 0.03\, m^3 \quad \textbf{(4)}$$

Energy and Mass Flow Equations

For the calculation of evaporation in swimming halls many different approaches exist. In their study, Ciuman & Lipska (2018) experimentally evaluate different correlations and demonstrate that the description from VDI 2089 in Equation 5 is the most accurate (VDI 2010).

$$\dot{m}_{D,B,u/b} = \frac{\beta_{u/b} \cdot A_B}{R_D \cdot \bar{T}} \cdot (p_{D,W} - P_{D,L}) \cdot Z_o \quad \textbf{(5)}$$

According to Equation 5 the evaporation mass flow $\boldsymbol{\dot{m}_{D,B,u/b}}$ differs for used (b) and unused (u) pools, which is realized by the water transfer coefficent $\boldsymbol{\beta_{u/b}}$. Table 1 shows the relevant values of the coefficient for this study. Further, the pool surface area $\boldsymbol{A_B}$, the specific gas constant $\boldsymbol{R_D}$, the arithmetic mean of current water and air temperature $\boldsymbol{\bar{T}}$ as well as saturated vapor pressure at water temperature $\boldsymbol{p_{D,W}}$ and the vapor pressure of ambient air $\boldsymbol{p_{D,L}}$ influence water evaporation from the pool's surface. The factor Z_o considers the occupancy level.

Table 1 Water transfer coefficient excerpt from VDI 2089 Part 1

POOL	$\beta_u \left[\frac{m}{h}\right]$	$\beta_b \left[\frac{m}{h}\right]$
covered	0.7	-
Depth > 1.35 m	7	28
Depth < 1.35 m	7	40

The sum of water losses due to evaporation and waste water removal determines the mass flow of fresh water supply ($\dot{m}_{FW}$) to compensate it (Equ. 6).

$$\dot{m}_{FW} = \dot{m}_{WW} + \dot{m}_{evap,u/b} \quad \textbf{(6)}$$

Evaporation and compensation of water losses with fresh water from tap, which has an estimated mean temperature of 10 °C (Saunus 2005) cause heat losses. To calculate these, VDI 2089 provides Equation 7 for the evaporative heat loss $\dot{Q}_{evap}$, determined with the specific enthalpy of evaporation h_{evap}, and Equation 8 for the heat losses due to fresh water supply $\dot{Q}_{FW}$ (VDI 2010). The latter mainly depends on the temperature difference between fresh T_{FW} and existing storage water T_{SW}, multiplied by mass flow and heat capacity of water c_p.

$$\dot{Q}_{evap} = \dot{m}_{evap,u/b} * h_{evap} \quad \textbf{(7)}$$

$$\dot{Q}_{FW} = \dot{m}_{FW} * c_p * (T_{SW} - T_{FW}) \quad \textbf{(8)}$$

A built in heat exchanger model from AixLib reduces heat losses by recovering heat $\dot{Q}_{HR}$ from the waste to fresh water dependent on an efficiency ε_{HR} according to Equation 9. As heat recovery is not always realized in swimming facilities, the model is conditional and can be deactivated.

$$\dot{Q}_{HR} = \dot{m}_{FW} * c_p * \varepsilon_{HR} * (T_{SW} - T_{FW}) \quad \textbf{(9)}$$

The radiative heat exchange $\dot{Q}_{rad}$ between the water surface and the surrounding swimming hall walls is approximated in Equation 10 with the Boltzmann-Equation (Recknagel et al. 2017) under the assumption that the emissivity of the water ε_W and the zone-enclosing enveloping surface ε_Z are constant. The calculation includes the Boltzman constant σ and the temperature of water T_W and the zone-enclosing enveloping surface T_Z, consiting of all sorounding walls and windows weigthed by their area.

$$\dot{Q}_{rad} = A_B * \varepsilon_W * \varepsilon_Z * \sigma * (T_W^4 - T_Z^4) \quad \textbf{(10)}$$

In the swimming hall, forced convection occurs in addition to free convection due to the air circulation. Since the expected air movement near the water surface with a maximum of 0.2 m/s (Li and Heiselberg 2005) is very low, the heat transfer coefficient of forced convection is similar to that of free convection. The resulting heat transfer coefficient at the water surface is therefore the sum of both effects. Estimations yield to a value of α_{WS} = 3.5 W/(m²K). Consequently, the convective heat exchange $\dot{Q}_{conv}$ is calculated according to Equation 11, taking into account the difference between T_W and the ambient air temperature T_A (Recknagel et al. 2017).

$$\dot{Q}_{conv} = \alpha_{WS} * A_B * (T_W - T_A) \quad \textbf{(11)}$$

Equation 12 presents the formula for the transmission loss through the pool wall $\dot{Q}_{cond}$ corresponding to the heat flow through a multi-layer plane wall (Recknagel et al. 2017). More precisely, it corresponds to the ratio of temperature difference between ground or basement T_G and walls to the combined resistance of the pool wall R_{PW} and convective transmission between pool wall and water $R_{\alpha PW}$.

$$\dot{Q}_{cond} = \frac{(T_W - T_G)}{R_{PW} + R_{\alpha PW}} \quad \textbf{(12)}$$

In order to represent the three different cases: (I) vertical pool wall with contact to the ground, (II) pool floor with contact to the ground and (III) wall sections adjacent to indoor spaces, the heat conduction submodel is depicted with the help of three multi-layer plane models. If the pool does not border the ground and only basement spaces the model components for heat transfer to the ground are deactivated and vice versa.

An estimation for the heat transfer coefficient based on equations for forced and natural convection from the VDI Wärmeatlas (Stephan et al. 2019) results in heat transfer coefficents for the convective heat exchange between the water and vertical pool wall to α_{WPW} = 5,200 W/(m²K) and water and horizontal pool floor to α_{WPF}= 50 W/(m²K).

In summary, the heating demand $\dot{Q}_{HD}$ of the indoor swimming pool composes of the sum of the heat losses presented above minus the potential heat recovery from the waste water (Equ. 13).

$$\dot{Q}_{HD} = \dot{Q}_{evap} + \dot{Q}_{rad} + \dot{Q}_{conv} + \dot{Q}_{cond} + \dot{Q}_{FW} - \dot{Q}_{HR} \quad \textbf{(13)}$$

The pump power depends on the volume flow of the water treatment. The number of pumps, the types of pumps and the positions in the treatment circuit are different for each pool system. To keep the number of input parameters small and simplify the system, the pumps are approximated by a large circulation pump. The head can be estimated to 1.7 bar for the complete treatment circuits (Saunus 2005). On this basis, the pump model calculates the pump performance according to a standard pump characteristics curve.

Both, the pool and the building model can be connected to a hydraulic circuit and supplied by different heating plants. However, within our study we focus on the demand of swimming facilities and therefore realize the heat supply ideally within the following simulation study. Further, conductive and other heat losses in the pipes are neglected. All pipes are assumed to be watertight and adiabatic.

Simulation study

In order to show the wide range of applicability of the model and to identify the impact of energy-saving measures we perform a simulation study. An existing sport-oriented swimming facility in West Germany serves as use-case. Via TEASER we automatically create the building and the pool model with the water treatment circuit. Detailed building information of the use-case enrich the standardized data. Table 2 gives an overview on the dimensions and conditions of the swimming facility, as well as Table 3 on the swimming pools within the swimming hall.

Table 2: Properties of thermal zones (A: area, V: volume, T: temperature)

ZONE	A [m²]	V [m³]	T [°C]
SH	1,325	8,215	32
EH	247	1,528	21
CA	268	964	24
SA	252	819	28
UA	21	65	24
TA	370	1,250	24

Table 3: Properties of pools for swimmer (SP) and non-swimmer (NSP) (D: depth, T: temperature)

POOLS	A [m²]	D[m²]	T [°C]
SP	416	2.2	28
NSP	125	1.0	30

The focus of the parameter study is particular on the operation and equipment of the indoor swimming pool. We first compare annual heat and electricity demands of the following energy saving-measures separately and subsequently analyse their combined effect: (1) Use of a pool cover during non-operating hours to reduce evaporation, (2) Integration of heat recovery for wastewater to decrease heat losses, (3) Reduction of the pool circulating flow to the hydraulic minimum to minimize pump power.

However, as the operation of the AHU strongly influences the thermal and electric demand of swimming facilities we take a demand driven control of the AHU as reference (R). This indicates that the controller does not inject a constant air flow, but rather maintains the indoor air conditions below specified limits. We use 14.3 g_{Water}/kg_{Air} as limit, which is the rate for occupants of feeling sultriness (VDI 2010).

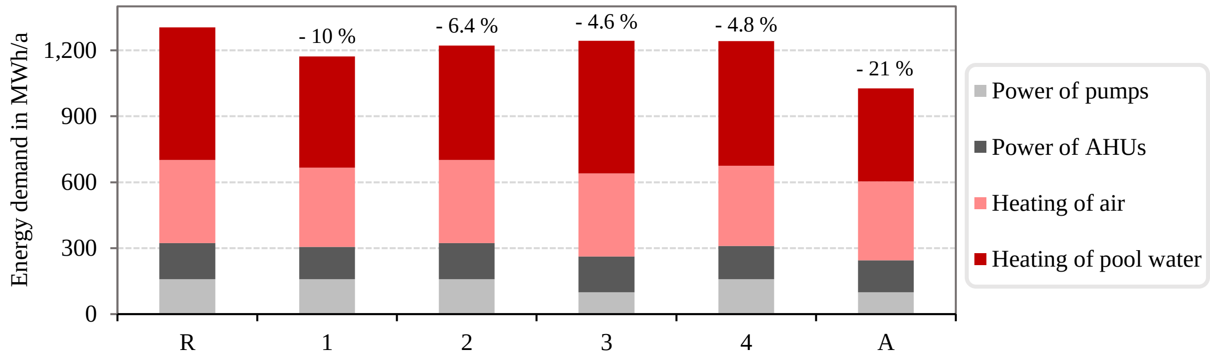

Figure 2: Annual heat and power of the use-case: (R) Reference, (1) Pool cover, (2) Heat recovery, (3) Circulation flow reduction, (4) Increase of humidity, (A) all combined

Generally, increasing indoor air humidity leads to energy-savings, as it decreases evaporation and the effort for dehumidification (Yuan et al. 2021). Hence, we increase the set limit during non-opening hours within a fourth energy-saving scenario (4). For the preventive protection of the building structure, relative humidity should be below 64 %, which corresponds to an upper limit of 18.9 g_{Water}/kg_{Air} for an air temperature of 32 °C within the swimming hall.

Figure 2 shows the results of a one-year simulation for the different measures. It includes heat demand (air and pool water) and power demand (AHU and circulating pumps) directly related to pool and air-conditions, and neglects others, such as lightning and domestic hot water. Comparing the single energy-saving measures, the use of a pool cover (1) results in the highest energy-savings compared to the reference case of 10 %. Integration of heat recovery (2) comes second with reductions of 6.4 %, followed by the other two measures of pool flow reduction (3) and the night operation limit for the humidity control (4), which deliver comparable results. Overall, the combined integration of all measures obviously shows the best results, with a reduction of the energy demand by 21 %.

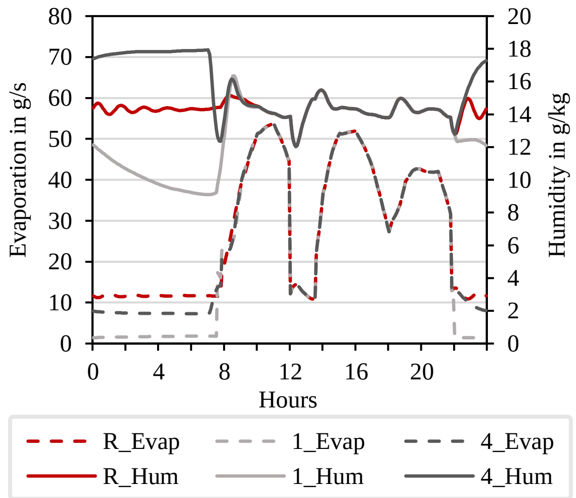

Figure 3: Evaporation of pools and humidity rate in the swimming hall for an examplary day in May.

Since some of the measures correlate with each other, the results of the combined application of all do not reach the sum of individual measures. This is especially the case when considering the integration of a pool cover (1) and the increased humidity set point (4) during non-operating hours. Figure 3 demonstrates that both measures result in decreased evaporation during non-operating hours compared to the reference case and thus reduce the effort for dehumidification. As air humidity even decreases due to a higher effect of infiltration during covered hours, the combination with an increased set point for air humidity is almost without any influence when combining both measures.

Discussion

Evaporation in general, is one of the most important factors when analysing energy-saving measures for swimming facilities. However, in our model evaporation is independent of the realization of the AHU and stratification within the swimming hall, which is only valid for mixed ventilation. Yet, this concept is the most common in practice. For more innovative stratified ventilations, the model should be extend in the future by corresponding correlations. For this purpose, extensive measurements within swimming halls should be executed to derive the influence of stratification to model more detailed fluid dynamics. In addition, the level of occupancy has great impact on the evaporation and therefore on the energy demand. Hence, further scenarios with different number of visitors and opening hours should be considered in following studies.

Conclusion

In this study, we developed a dynamic simulation model for a swimming facility. The model includes the building itself, representing impacts related to transmission, radiation, infiltration and internal gains from machines, light and persons. Further, the interaction of swimming pools and the swimming hall results in evaporation effects. With help of an automated pre-parametrization the model can easily be applied for many use-cases. For the specific use-case of one swimming facility in West-Germany we compared the impact of four different energy-saving measures. As single measure a pool cover during non-operating hours results in the highest savings of 10 % compared to a reference scenario. The combination of all measures show a reduction potential of 21 %.

For future research, the model can be coupled with an hydraulic heating circuit instead of an ideal heat supply. This enables analysis of a heat generation system and the actual heat consumption. Furthermore, the flexibility of the model allows to perform other investigations to verify the results within changing boundary conditions, such as different air conditions, pool water temperatures and occupancy levels.

Acknowledgement

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