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# Digital Twins for Decentralized Infrared Heating Systems in the Industrial Metaverse

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## Abstract

In Germany, industrial buildings account for approximately 15% of heating energy, despite comprising only 2% of the total building stock. This makes this sector particularly important for achieving climate neutrality. Heat losses are not solely due to poor building insulation; they can also be attributed to other factors. A significant proportion comes from the opening of doors during material deliveries. An intelligent control system requires both predictive forecasts, such as heat simulations and performance forecasts, as well as information from external systems, including work schedules and transport arrivals. In addition, depending on the situation, there are sometimes competing target functions, such as grid-friendliness versus economic efficiency. The open-source Industrie 4.0 automation technology BaSyx (<https://eclipse.dev/basyx>) has proven effective in orchestrating such a system. It uses the concept of the asset administration shell to describe both physical and digital goods (assets) in a standardized way and make them available as so-called digital twins. Together with a semantic description of the data and services, digital twins enable interoperable data exchange. Decentralized infrared heating systems offer clear advantages in terms of energy efficiency when heating halls, as they transfer heat to the usable area almost loss-free, precisely, and quickly, without generating heat buildup under the hall roof. Additionally, the heating system can flexibly adapt to changing hall-specific usage conditions, such as door openings and shifts in crane runway positions. State-of-the-art multi-energy infrared heating systems use various energy sources, including gas and electricity, to generate infrared heat. Some of the radiant heaters considered here can switch between gas and electricity operation depending on the availability of photovoltaic power. However, there are numerous other possibilities, such as dynamic electricity prices and (short-term) weather forecasts for energy control. To fully leverage the energy-saving potential of modern multi-energy infrared heating systems, innovative software solutions must be developed and implemented for their operation that account for both the possibilities mentioned above and their interaction with other components. Digital twins are an essential building block in this direction. We developed, in close collaboration with the heater manufacturer's team, Industrie 4.0-compliant digital twins for their industrial infrared radiant heaters. We used BaSyx to model the Asset Administration Shell, incorporating several sub-models. For one of these sub-models, we developed a scoring system to evaluate the energy efficiency of industrial halls and their sections. This scoring system analyzed operating data from heating appliances at selected customers to provide heating efficiency information on a monitoring dashboard. In the future, this data could serve as the basis for enhancing the selection and placement of heaters in industrial halls. It is possible to determine whether appliances are oversized or undersized in their use, thereby achieving better planning for future projects and the associated conservation of resources. We developed a mixed-reality application for the HoloLens 2 that enables the virtual placement of heating appliances in the real world. Furthermore, we present initial concepts for accessing the sub-models and data of the digital twin in natural language, paving the way for the Industrial Metaverse.

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## 1. Introduction

Although industrial buildings account for only around 2% of the German building stock, they consume approximately 15% of the total heating energy demand [1]. This disproportionate share highlights the sector's significant role in achieving national and European climate-neutrality targets. Improving the energy performance of industrial buildings, therefore, constitutes an essential lever for reducing emissions and supporting the energy transition.

Heat losses in industrial halls cannot be explained solely by insufficient thermal insulation. A substantial portion is caused by operational factors, particularly the frequent opening of large doors during material deliveries or shifts in usage patterns [2]. These dynamic conditions make it difficult to achieve lasting energy efficiency through structural measures alone. As a result, traditional insulation strategies must be complemented by approaches that address such operationally induced losses. The first step is to be aware of insufficient thermal insulation and operationally indexed losses, and their magnitudes.

Other factors influence the economic operation of infrared heating, such as the weather, an existing photovoltaic system, electric charging stations for employees and guests, peak shaving options, and the possibility of switching infrared heating between different energy sources, such as electricity or gas (see Fig. 1). To manage these challenges effectively, intelligent control systems are required. Such systems must integrate predictive elements—such as heat simulations and performance forecasts—with contextual data from external sources, including work schedules and transport arrivals. At the same time, they must balance competing objectives, such as grid-friendly behavior versus economic efficiency. By combining predictive modeling with real-time information, these systems can enable more adaptive, efficient, and climate-friendly heating strategies in industrial buildings.

## 2. Background and Related Work

To establish a Digital Twin, several foundational elements are required. First, heterogeneous data sources (e.g., sensors, historical databases, and contextual information systems) must be integrated to capture both real-time and long-term operational data. This data feeds into a formalized digital model that represents the physical asset's structural, functional, and behavioral properties. Ensuring connectivity and interoperability is essential, and this is increasingly supported by standardized frameworks such as the Asset Administration Shell (AAS), which enable semantic data and service descriptions across system boundaries [3]. Furthermore, analytical and simulation capabilities are required to allow predictive assessments, optimization, and what-if scenario analyses. Finally, visualization and interaction layers (e.g., dashboards, 3D representations, or immersive environments) provide users with actionable insights.

The integration of energy data and the provision of responsive services are not new challenges, and there are many approaches to addressing them. One approach, for example, involves implementing a digital twin for smart grids that collects heterogeneous data via a Kafka-based messaging backbone and integrates measurements from smart meters, synthetic

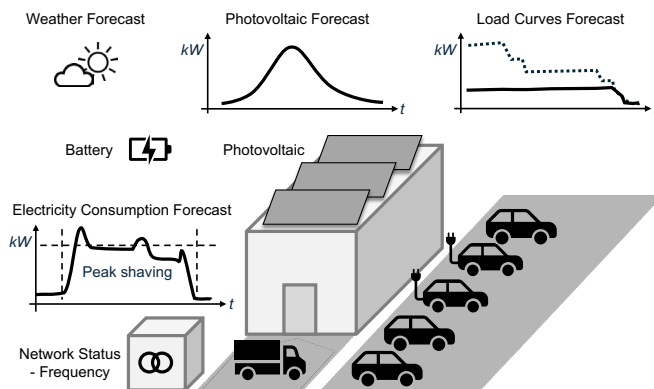


Fig. 1: Factors that influence the efficiency of industrial infrared heaters.

simulation data, and AI forecasts [4,5], coordinating them within an assistance system to visualize the grid's state [6].

The AAS implementation BaSyx natively supports event streaming via RabbitMQ or Kafka, depending on the version [7]. One application of AAS technology in the energy sector involves radiant heating systems, in which industrial buildings are monitored and evaluated based on exchanged energy data [2].

A Digital Twin must comply with the so-called FAIR principles (Findability, Accessibility, Interoperability, Reusability) if it doesn't want to remain an isolated solution [8]. To address semantic interoperability in the context of a data space, the Omega-X project, among others, proposes methods for integrating and maintaining ontologies as resource identifiers [9]. Similarly, a vocabulary hub approach focuses on the semantic integration of digital twins and energy measurement data via AAS that complies with the IDS-RAM standard [10].

In an energy system, two main objectives, grid-friendliness and economic efficiency, often conflict with each other. As grid-friendly, the system operates in a way that supports grid stability and reliability, like, e.g., avoiding peak loads, providing flexibility for frequency stabilization, or shifting consumption to times of high renewable generation [6]. As economically efficient, the system aims to minimize costs or maximize profits, like, e.g., consuming or storing electricity when prices are lowest, regardless of whether that benefits the grid. Grid-friendliness and economic efficiency are called competing target functions because it's usually not possible to optimize both simultaneously. Thus, the system must balance or trade off between these two objectives in its optimization strategy.

Warehouses and production processes can be operated in a grid-friendly manner. For instance, operations can be adjusted in response to fluctuations in grid frequency. If predefined flexibility options are available, facilities can also respond to external switching requests. In addition, production halls can be managed in line with grid requirements. For unoccupied warehouses, broader upper and lower operating limits can be applied. In contrast, in halls currently occupied by personnel or involving the use of specific equipment, narrower limits must be maintained. To remain within these limits, a simulation of heat distribution in a hall was developed and will be presented alongside the digital twin. This serves as Proof of Concept, demonstrating the physical principles. The simulation is

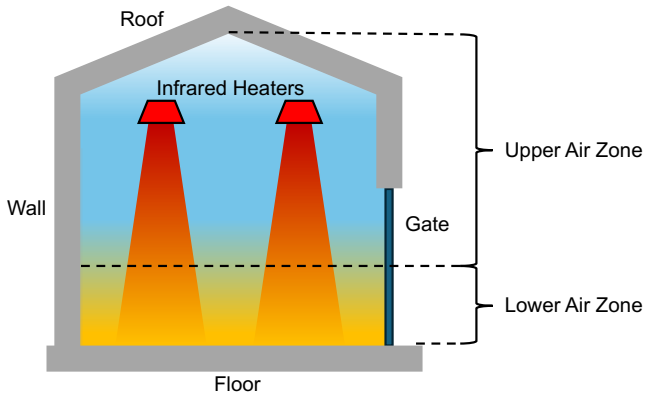


Fig. 2: Heat Distribution in an industrial hall with infrared heaters.

fundamental because both less and more complex systems are modelled and coupled through the shown differential equations.

In sum, Digital Twins emerge as cyber-physical system representations that not only mirror their physical counterparts but also advance resilience, efficiency, and sustainability in complex industrial and societal systems.

### 3. Infrared Heating in Industrial Halls

From a physical perspective, infrared radiation is an electromagnetic wave with a longer wavelength than visible light. When it hits a surface, it is absorbed and converted into heat, which is why it is often called thermal radiation. Unlike conventional air-based heating systems, infrared radiation directly warms surfaces and people, providing heat where it is needed without heating large volumes of air that rise to the ceiling [11].

Conventional hall heating systems (e.g., air-to-air heat pumps or underfloor heating) mainly heat air. This approach results in significant energy losses and long response times, as warm air accumulates under the roof before reaching the work areas. Such systems often require continuous operation in winter, leading to high energy consumption.

Decentralized infrared heating integrates heat generation and transfer into a single system, eliminating the need for auxiliary energy to power pumps or fans. It acts immediately: workers feel warmth directly, and surfaces heat up quickly. Heating can be switched on shortly before use and turned off immediately afterward, enabling substantial energy savings. Moreover, specific zones can be heated to different temperatures, allowing workspaces to remain comfortable while storage areas stay cooler.

Overall, based on the expertise of the heater manufacturer, decentralized modular infrared systems achieve 60–70% energy savings compared to conventional systems. When combined with photovoltaic electricity, CO<sub>2</sub> emissions can be reduced by up to 85% according to the heater manufacturer [12]. Their energy flexibility allows them to adapt to future renewable sources such as biogas or hydrogen, offering both cost efficiency and near-CO<sub>2</sub>-free operation. This dual benefit of efficiency and flexibility can yield heating cost reductions of up to 80%, particularly in retrofitted buildings [12].

Decentralized infrared heating thus offers fast response, localized heat distribution, and adaptability to hall-specific conditions. When combined with PV, dynamic electricity pricing, or weather forecasts, it represents a promising technology for sustainable and adaptive industrial energy systems.

### 4. Simulations for Energy Efficiency

A simulation is developed to systematically assess different operating strategies and thereby realize the full potential of energy savings. Due to the real-time temperature monitoring of a hall building based on locally distributed sensor measurements, a lumped-parameter system provides the most suitable adaptable representation for a real-world scenario [13,14]. Simulating such a system leads to a nonlinear ordinary system of differential equations that must be solved with a given control strategy  $u(t)$  for energy supply (see Eq. 1).

$$\dot{x}(t) = f(t, x(t), u(t)) \quad (1)$$

The simulation uses energy balance equations of a control volume computing the temperature  $T$  (see Eq. 2). The term  $m$  denotes the air mass in the volume. The terms  $\dot{m}_{in,j}$  and  $\dot{m}_{j,out}$  denote the incoming and outgoing mass flows. These terms model the air exchange between the adjacent zones, the Upper and Lower Air Zone, and between the Upper and Lower Air Zone and the outdoor environment; the index  $j$  stands for the Upper Air Zone, Lower Air Zone, and outdoor environment.

$$c_v m dT + c_v T dm = \dot{Q}_{convection} + \dot{Q}_{radiation} + \dot{Q}_{internal} + \sum_j \dot{m}_{in,j} c_p T_j - \sum_j \dot{m}_{j,out} c_p T \quad (2)$$

Assuming the principle of mass conservation, the system balances the mass flows determined by the parametrized orifice equation (see Eq. 3) [11,15].

$$dm = \sum_j \dot{m}_{in,j} - \sum_j \dot{m}_{j,out} \quad (3)$$

A simplified equation (see Eq. 4) models fixed structural components with no mass exchange (e.g., roof and walls) with a heat capacity  $C$  [11].

$$C dT = \dot{Q}_{convection} + \dot{Q}_{radiation} + \dot{Q}_{internal} \quad (4)$$

Equations 2 and 3 assume an ideal gas, where  $c_v$  denotes the heat capacity at constant volume. The term  $c_p$  denotes the gas capacities at constant volume and is applied to incoming and outgoing mass flows. The term  $\dot{Q}_{convection}$  refers to the heat transfer by convection and conduction terms. The term  $\dot{Q}_{radiation}$  refers to the heat transfer by radiation, and the term  $\dot{Q}_{internal}$  represents internal heat sources, such as a heater. Hence, the simulation accounts not only for the thermal dynamics of convection, conduction, and radiation, but also computes the mass balance to simulate the air flow between the zones, including infiltration and exfiltration via leakage and gate openings.

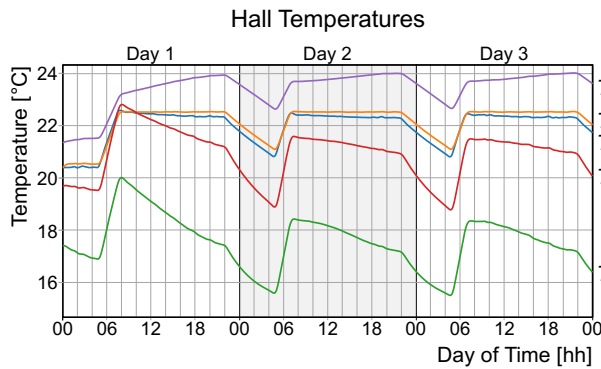


Fig. 3: Simulation of heat distribution in a basic hall measuring 15 m x 15 m x 6 m (width x length x height) over three days.

Simulating the mass flow provides the opportunity to enhance the simulation by incorporating additional external information, such as work schedules, transport arrivals, and their respective forecasts, thereby improving the accuracy and robustness of the evaluation. The simulation is encapsulated within a sub-model of the AAS, ensuring standardized integration into digital twin environments.

Fig. 3 demonstrates the outcome of a straightforward simulation of heat distribution in a basic hall measuring 15 m x 15 m x 6 m (width x length x height) over a three-day period. Notably, the simulation completed in a matter of seconds, underscoring the process's efficiency. The simulation presents the temperature curves for  $T_{\text{Floor}}$ ,  $T_{\text{lower}}$ ,  $T_{\text{upper}}$ ,  $T_{\text{Roof}}$ , and  $T_{\text{Wall}}$ , which correspond to the designations Floor, Lower Air Zone, Upper Air Zone, Roof, and Wall in Fig. 2. The simulation stabilizes during the first five hours of the first day (Day 1), with the infrared radiant heaters initiating heating at the start of the first shift. The individual temperatures gradually rise until the temperature for  $T_{\text{lower}}$  reaches the desired temperature of just over 22°C. The radiant heaters turn off and then on again at short intervals to maintain the target temperature within a desired range. The shift ends at around 11 p.m., and the infrared radiant heaters turn off. All temperatures drop. The floor has stored a lot of heat energy and releases it into the environment such that the temperatures  $T_{\text{lower}}$  and  $T_{\text{upper}}$  (the temperatures of the air in the hall) don't drop as much as the temperatures  $T_{\text{Roof}}$  and  $T_{\text{Wall}}$ . The next day, the infrared heaters turn on again at the start of the first shift. The ceiling and floor temperatures no longer rise as high as on the first day in the simulation. At around 11 p.m., the infrared heaters turn off again. The temperature curves in the simulation show a similar pattern to the first day. The results of the third-day simulation are very similar to those of the second-day simulation.

Fig. 4 showcases the result of a simple simulation of heat distribution in the same basic hall over a three-day period. The key difference is that the radiant heaters turn off when  $T_{\text{lower}}$  reaches around 22.5°C and only turn on again when  $T_{\text{lower}}$  reaches around 22.0°C. All temperature curves exhibit a corresponding jagged pattern throughout their course. The time between switching off and switching on again depends on how quickly  $T_{\text{lower}}$  cools down. In our simulation, this interval is just over two hours. Compared to the previous simulation, the radiant heaters are switched on and off much less frequently. This lower frequency could prove an advantage in terms of longer

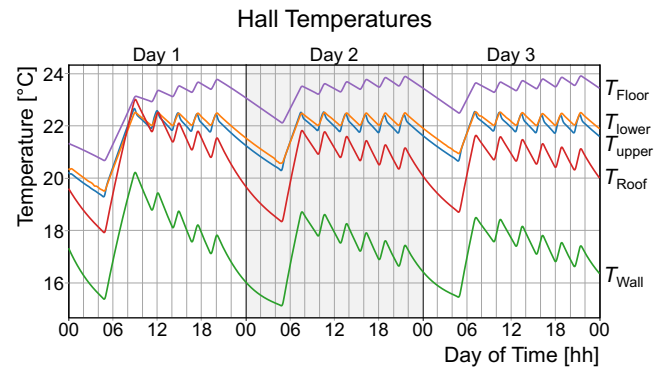


Fig. 4: Simulation of heat distribution in a basic hall measuring 15 m x 15 m x 6 m (width x length x height) over three days controlled by  $T_{\text{lower}}$ .

service life, a promising aspect for the technology's future. However, only time will tell whether this assumption is correct. A digital twin enables testing different operating modes for halls, gathering valuable experience while accounting for external influences during evaluation. The slow temperature drop enables grid-friendly heating operation.

Fig. 5 presents the results of a simple simulation of heat distribution in the same hall over three days, with the key difference being that the door is now open for goods delivery or dispatch in the evening, around 9 p.m., for approximately one hour. One can see that all temperatures drop compared to when the door is not opened (dotted lines). This temperature drop is most noticeable in the temperature curves  $T_{\text{lower}}$  and  $T_{\text{upper}}$ . However,  $T_{\text{lower}}$  and  $T_{\text{upper}}$  rise again compared to all other temperature curves when the door is closed again. This temperature rise is because the floor, walls, and ceiling reheat the air. After the door is closed, the shift is over and the radiant heaters turn off, causing the individual temperatures to drop until the infrared radiant heaters are switched on again at around 5 a.m. the next morning.

The simulations provide a practical and reliable representation of the heat distribution in a hall under different operating modes of the infrared radiant heaters. Based on the simulation results, different operating temperatures and temperature corridors can be defined and tested before being applied in real life if the simulation is satisfactory. Since the simulations themselves are also very lightweight, no AI is necessary to boost the

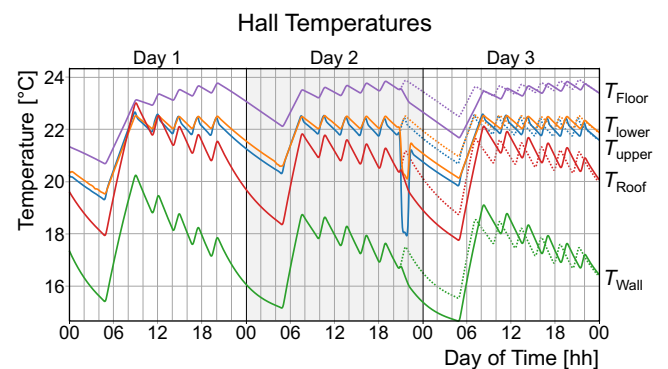


Fig. 5: Simulation of heat distribution in a basic hall measuring 15 m x 15 m x 6 m (width x length x height) over three days, controlled by  $T_{\text{lower}}$  and an open gate on the second day for delivery.

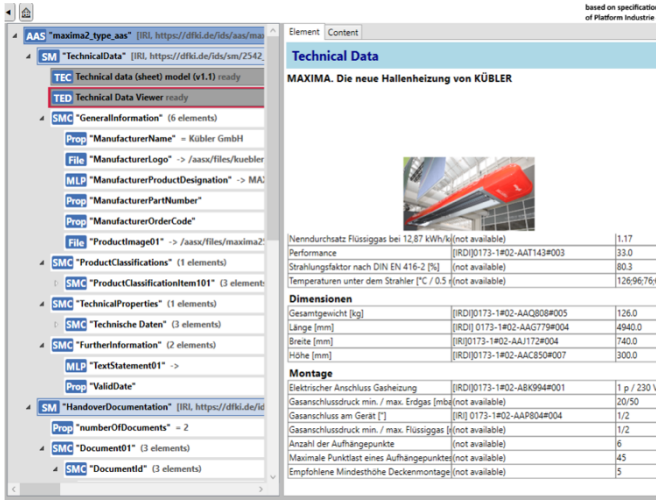


Fig. 6: Asset Administration Shell with the sub-models of the Digital Twin for an industrial infrared heater.

computation time at this stage, further enhancing their practicality and applicability. The current simulation uses the deviation of the current temperature from a setpoint to control the energy supply. However, an economic and CO<sub>2</sub>-saving control must also consider a combination of discrete cost signals  $c_i$  for the consumed Power  $P$  in the time interval  $[t_i, t_{i+1}]$   $0 \leq i \leq N$  (number of simulated intervals). This optimization problem can be described as in Eq. 5, with the total energy consumption  $E_{total}$  given by Eq. 6.

$$J = \sum_i c_i \int_{t_i}^{t_{i+1}} P(t) dt \quad (5)$$

$$E_{total} = \sum_i \int_{t_i}^{t_{i+1}} P(t) dt \quad (6)$$

The grid's supply price signal is known a day ahead. Limited energy supply, such as that from solar plants, is forecasted using digital twins. Energy capacities, such as tanks or batteries, have capacity restrictions that are utilized in the simulation. Shaving a peak, an additional external limit must be set. The strict mathematical dynamic system allows the formulation of an optimal control problem as in Eq. 7, under the system dynamics in Eq. 8 and the constraints in Eq. 9.

$$J(t, x(t), u(t)) \rightarrow \min \quad (7)$$

$$\dot{x}(t) = f(t, x(t), u(t)), \quad x(t_0) = x_0 \quad (8)$$

$$h(t, x(t), u(t)) \leq 0 \quad (9)$$

Besides the control theory, the formulation provides various possibilities for finding a sufficient control strategy [16]. Using time-discrete variables and a linearized model to approximate the system dynamics, the problem can be formulated as a linear or mixed linear integer problem, which can then be solved using a finite element method, such as the Crank-Nicolson method, or as heuristic methods, such as Q-Learning-Agents and evolutionary algorithms, if the problem is strongly nonlinear.

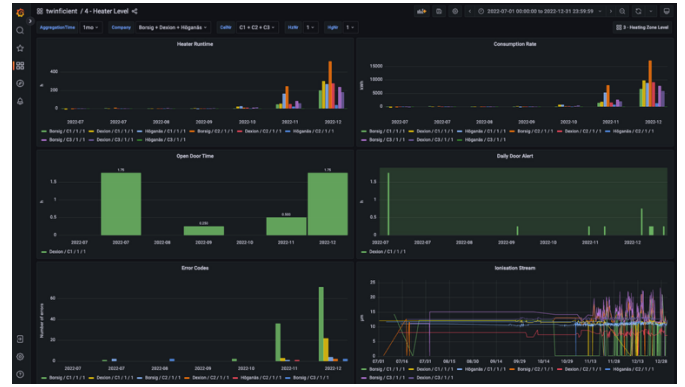


Fig. 7: Dashboard to monitor the building's heating system

### 5. Digital Twin and its Sub-models

In cooperation with the heater manufacturer, digital twins for industrial infrared heaters were developed in accordance with Industrie 4.0 [4] (see Fig. 6). Communication between the heating systems and digital twin applications is standardized via AAS models. They are managed via the BaSyx framework. The base of the automation process involves adapting and integrating the heating system into the software system.

A benefit is the dashboard, which is now directly adaptable via an AAS sub-model. This allows customers to monitor the building's heating system (see Fig. 7). An automated open gate alert system notifies users if the temperature drops below a specified threshold.

$$\text{score} = \frac{\sum_t E_t}{\alpha \sum_t \text{HDD}_t} \quad (10)$$

A score (see Eq. 10) was developed to measure the heat efficiency of a hall building independently of the weather. The score uses the sum of all energy consumptions  $E_t$  divided by the sum of all heating degree days  $\text{HDD}_t$  on a measurement interval [4]. The term  $t$  denotes the days in this interval. The term  $\alpha$  normalizes the area size gathered from the AAS model. The simulation enables forecasting the payback period for energy-efficient renovations using historical data and selecting the best solution based on the score.

A Mixed Reality application (see Fig. 8) was developed to optimize the planning and installation of heating systems. Its

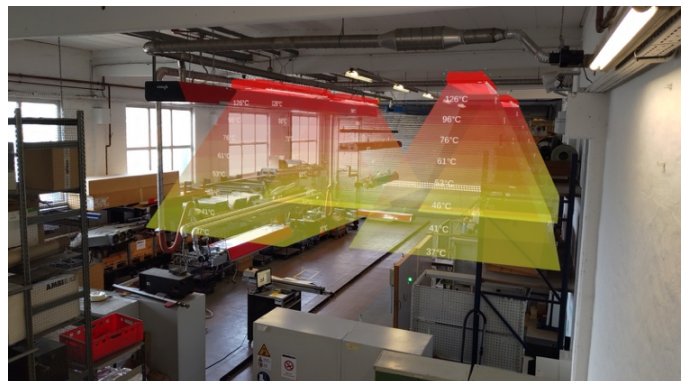


Fig. 8: Mixed Reality application for the planning of heating systems

main task is to place digital holograms in the real world, including the energy heat cone of each type. However, overlapping cones exhibit a nonlinear energy behavior due to the Stefan-Boltzmann law and the varying view factors of a reference body. In a real-world Industrial Metaverse application, the view factors must be adapted to changes in the environment or the movement of the reference body [17].

## 6. Conclusion and Outlook

The use of AI affects not only the company's resource efficiency but also that of customers who have had or are installing Kübler infrared heaters. This also applies retroactively to infrared heaters that have already been installed. For example, maintenance can be adjusted to avoid system failures, costly unscheduled repairs, wasted travel resources, or consequential damage. Improved planning and dimensioning of new halls allows usage data to be collected, enabling better planning of the size and equipment of similar halls in the future. Added to this is the development and continuous improvement of AI and the digital twin of the heating systems. In this way, the pilot project saves material, energy, and CO<sub>2</sub> in equal measure.

The integration of ontologies as a natural verbalization of the shells is a promising added value. On one hand, it serves as contextual input for a large language model, helping users to configure the heating systems and navigation in foreign industrial areas. This also includes having an interface to import AASs directly, providing hints of dangerous areas. On the other hand, it serves as a vocabulary hub for integrating digital twins into a dataspace scenario [18].

Another promising approach is the use of the simulation as a forward operator of inverse problems and in physics-informed neural networks. This provides a new foundation for extending the concept of virtual sensors.

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During the preparation of this work, the author(s) used DeepL and Grammarly to correct and improve the English language. After using these tools/services, the authors reviewed

and edited the content as needed and take full responsibility for the content of the publication.

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