Romanian Journal of Civil Engineering, Volume 16 (2025), Number 4

Development of a Digital Twin for a thermal manikin used in the evaluation of indoor environmental quality

Dezvoltarea unui geamăn digital pentru un manechin termic utilizat în evaluarea calității mediului interior

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DOI: 10.37789/rjce.2025.16.4.9

Abstract-This paper presents an innovative digital twin solution for thermal manikins used to evaluate indoor environmental quality in buildings. While digital twin technology is gaining traction across industrial sectors, its adoption in building sector remains limited due to the industry's slow integration of innovative technologies. The research addresses the need for more accessible tools to analyze thermal comfort, which is often treated superficially in building design phases despite its fundamental importance for occupant well-being and energy efficiency. Traditional approaches rely on costly physical testing or simplified models that fail to capture complex human-building thermal interactions, leading to suboptimal designs and post-occupancy comfort issues. The proposed solution consists of a MATLAB application that provides an intuitive interface for monitoring thermal comfort parameters and real-time visualization of thermophysiological models applied to thermal manikins. A key innovation is the bidirectional data integration with ANSYS Fluent solver, enabling real-time simulations using data extracted from physical thermal manikin and vice versa. This work contributes to understanding and implementing digital twin concepts in thermal comfort evaluation, offering an innovative technological platform that balances occupant comfort with energy efficiency while providing a foundation for future research in this evolving field.

Index Terms-Energy efficiency, Indoor environmental quality, Manikin Digital Twin, Thermal comfort.

I. INTRODUCTION

In 2023, the construction sector was responsible for nearly 34% of total carbon dioxide (CO_2) emissions and 32% of total energy demand, suggesting that solutions are needed to improve these numbers in order to achieve our 2050 climate targets [1]. Approximately one-third of a building's energy consumption is due to heating, ventilation and air conditioning (HVAC) systems, therefore, one impactful way to reduce a building's CO_2 emissions and associated energy consumption is to improve the energy

The article was received on 24.10.2025, accepted on 27.10.2025 and published on 27.11.2025

consumption of the HVAC system by adopting efficient operating and design methods, while ensuring indoor thermal comfort and a satisfactory level of indoor air quality [2].

Indoor environmental quality (IEQ) refers to thermal comfort, indoor air quality (IAQ), visual comfort, lighting quality and acoustics and they have an impact on occupant health and productivity [3]. While only thermal comfort and IAQ have been extensively studied, standards like EN 16798-1 and ASHRAE guidelines, alongside net zero energy building (NZEB) initiatives, aim to minimize environmental impact while prioritizing occupant wellbeing [4]. Building energy dynamics are directly influenced by occupants' thermal comfort needs, especially in non-automated HVAC systems where users control thermostats and windows. Unmet thermal preferences lead to occupant discomfort and complaints, making it essential to balance energy efficiency with thermal comfort satisfaction. In addition to the thermal environment, we must also address IAQ, which is not as widely discussed as thermal comfort due to its low direct impact on occupants and the fact that thermal comfort is better understood in terms of parameters of interest and their ranges that define comfort conditions [5]. Regarding methods of improving the energy efficiency of buildings from a thermal perspective, modifications are made to the building envelope, which could result in lower ventilation rates to maintain thermal comfort, but this could lead to higher concentrations of pollutants in the indoor environment, causing discomfort and even health problems for occupants [6].

To evaluate the indoor thermal comfort of a building, it is necessary to measure physical parameters such as temperature and air velocity, which are used to evaluate the thermal sensation of the occupants which represents the heat exchange between the occupant and the environment, as well as the thermoregulatory mechanisms implemented by the body to maintain a stable internal temperature [7]. The evaluation of indoor thermal comfort is provided by thermal comfort models who fall into two categories: thermal equilibrium models (developed from climate chamber experiments) and adaptation models (based on field study data) [2]. Fanger's 1970 model remains foundational, calculating PMV (Predictive Mean Vote) and PPD (Percentage of People Dissatisfied) from air temperature, radiant temperature, air velocity, and relative humidity [8]. Unlike these measurable thermal parameters, IAQ evaluation presents significant complexity due to the ambiguous nature of air contaminants. Pollutants vary widely in type, concentration, source, and health impact, making comprehensive assessment challenging. Experts in the field recognize that new indices should consider the latest findings in human thermal physiology and biophysics in order to evaluate the IEQ [9].

A recent growing demand for robust computer models predicting human thermophysiological responses spans military, automotive, aerospace, meteorology, clinical research, textiles, and medical engineering sectors, addressing performance, tolerance limits, and thermal comfort [10]. Since heat transfer, temperature regulation, and occupant comfort are crucial for buildings and IEQ analyses, thermoregulation models now incorporate skin temperature variations, regulatory responses, clothing properties, and environmental conditions including humidity, temperature, and air contaminants [9].

With the evolution of research, the building sector has begun to adopt emergent technologies such as machine learning or artificial intelligence and in consequence it has opened up new avenues of research in this field. Although new methods of assessing IEQ have emerged over time, one method that has always stood out and yielded results as close as possible to actual or experimental results has been the use of a thermal manikin. Initially used only to assess thermal comfort, recent studies show their complexity and ability to represent not only heat transfer and thermoregulation in the human body, but also respiration and perspiration, in order to represent reality more accurately [11].

Thermal manikins have evolved over 80 years, adapting to new technologies through increased controlled surfaces, improved skin-mimicking materials, and advanced automation systems to create the most "human-like" models possible [12]. Their recent popularity in IEQ analysis, textiles, automotive, and aerospace industries stems from being more cost-effective and practical than human subjects [13].

An analysis of the history of thermal manikin reveals three main categories [14]: **traditional thermal manikins** (measure environmental impacts on the human body, including thermal radiation and surface heat transfer), **thermoregulatory thermal manikins** (use physiological thermal regulation models to simulate complex human responses like shivering, vasomotor control, and sweating in response to temperature changes), **digital thermal manikins** (represent virtual copies of physical manikins based on numerical simulations such as computational fluid dynamics (CFD).

The category of digital thermal manikins has sparked exponential growth in research in this field due to the simplicity and efficiency they bring to the study of heat transfer and physiological responses in different environmental conditions and for a better understanding these phenomena the manikins are often coupled with CFD and thermoregulations models. Control equations model thermoregulation by managing blood flow, metabolic rates, and perspiration to maintain homeostasis [15]. When coupled with CFD models, these equations enable detailed analysis of heat transfer and physiological responses at local body levels, allowing experiments under extreme conditions unsafe for human subjects [16].

With the transition to Industry 5.0, the symbiotic relationship between humans and emerging technologies such as deep learning techniques, brain-computer interfaces, multisensory and multimedia reality, or geospatial Digital Twin (DT) via building information modeling (BIM) and real-time building operation with the Internet of Things (IoT) is becoming increasingly crucial [17], [18]. A DT comprises a virtual model faithfully replicating its physical counterpart, connected through real-time data transfer [19]. Unlike static digital models or predetermined co-simulation scenarios, DTs maintain continuous bidirectional data exchange with physical systems, enabling real-time adaptation and predictive capabilities that evolve based on actual sensor feedback. In this paper, the thermal manikin represents the physical model, CFD simulation the virtual model, and sensor-acquired data the real-time link.

Unlike Human Digital Models or Computer-Simulated Persons found in literature, DTs are distinguished by real-time data exchange [17]. These digital thermal manikin models aim to develop customized HVAC control algorithms for improved building energy efficiency [20].

Regarding DT integration prospects in construction and energy efficiency, a thermal manikin DT for evaluating thermal comfort and indoor air quality can deliver precise, realistic results. By faithfully simulating real-world phenomena and continuously exchanging data, it enables real-time comparison between model and actual conditions while facilitating emerging technology integration for continuous digital model improvement. This dynamic enhancement involves parameter adjustments to better reflect reality. Such DTs also enable development of personalized HVAC systems, self-adaptive algorithms that respond to environmental changes, and intuitive interfaces that simplify data control and streamline experimental analysis processes.

II. METHODS

A. *Thermal manikin*

The thermal manikin used in this study is one the simplified prototypes developed at UTCB described in [21]. It represents an average adult male, and it can control its surface temperature using PID controller with an Arduino microcontroller. The surface of the manikin can only be heated, and the surface is heated by means of nickel-plated wires placed on the surface of a polyurethane medical manikin. The manikin comprises 6 individual segments that can be independently heated, with each segment equipped with its own temperature sensor. A layer of Kapton foil was used to electrically insulate the nickel wires, and guides were used to eliminate any air pockets that might form. A layer of Kapton was added on top to electrically insulate the aluminum layer that will be added later used to better distribute the heat on the manikin surface. A schematic representation of the manikin's physical composition is presented in Fig. 1.

B. *CFD model*

The geometry of the manikin used for the CFD simulation comes from the open-source geometry platform GrabCAD. The geometry was chosen to be as close as possible to that of the existing thermal manikin. This geometry was selected to ensure a balance between complexity and simplicity: detailed enough to capture the relevant aspects of the human anatomy in numerical simulations but simplified enough not to significantly affect computation time. Details about the geometry can be seen in Fig. 2.

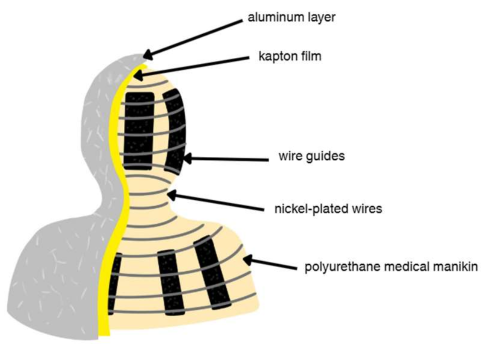


Figure 1. Physical composition of the thermal manikin

Within the CFD simulation the geometry of the virtual manikin is positioned as seated in a 3 x 3 x 2.5 m room to simulate the microclimate around it. We considered the geometry to be a simple parallelepiped in order to simplify subsequent numerical calculations. The chair was also omitted for the same reasons, to avoid detailed geometries that could interfere with the numerical calculation and because it does not show the object of the work. Fig. 3 shows the location of the mannequin in the center of the room; this geometry will be used for the following calculations.

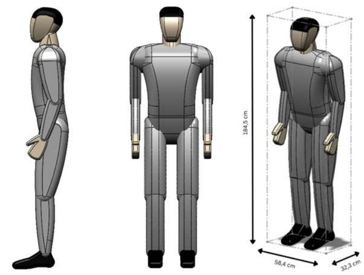


Figure 2. 3D geometry of the virtual manikin and boundary dimensions in standing position

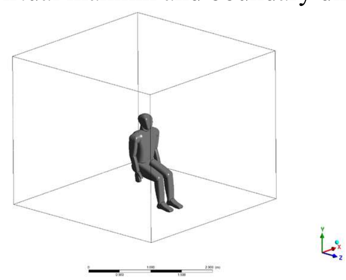


Figure 3. The geometry of the microclimate studied and the seated position of the thermal mannequin

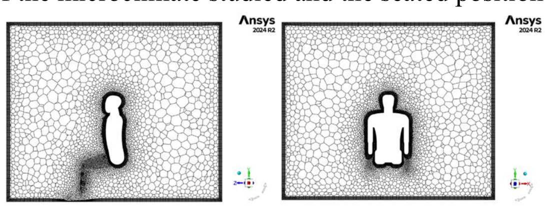


Figure 4. Grid used for CFD calculation using ANSYS Fluent

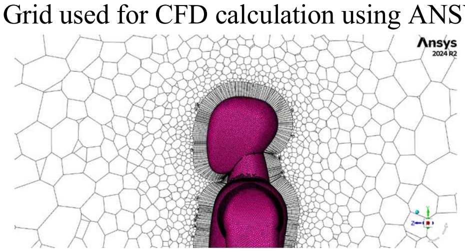


Figure 5. Inflation of the grid around the mannequin

The CFD numerical simulations were performed using the ANSYS Fluent 2024 R2 program, running on a system equipped with an AMD Ryzen processor, 32 cores, and Windows 11 operating system. Sixteen cores were used in the solver calculation, without double precision enabled. The solver used is a pressure-type, steady-state solver with gravity enabled active energy transfer and an SST k-omega turbulence model. The material considered for the numerical simulation domain is air. The calculation scheme used is a coupled type, for faster convergence and better numerical stability.

The numerical grid for the selected geometry was constructed in light of previous findings that identify the region above the head as critical for heat-transfer and microclimate analysis. Because a convective (buoyancy-driven) plume forms close to the body in this area, leading to higher velocities and turbulence, we applied local mesh refinement there. We therefore created the numerical grid shown in Fig. 4, which comprises 2 million elements and 4.8 million nodes, after transforming the elements into polyhedrons in order to obtain a more accurate calculation. Similarly, Fig. 5 shows the inflation of the elements around the manikin in order to better capture the results in this area, which is important from the point of view of air velocities.

C. Thermophisiological model

The surface temperature of the manikin can be controlled in two ways: using fixed temperature setpoints which allow for a constant surface temperature, and using Gagge's thermophysiological model to achieve a surface temperature adapted to changes in the environment.

The best-known model is Gagge's 'Pierce two-node model', used to study thermal comfort in uniform environments. It accounts for core and skin temperature variations, weighted by proportion. For moderate activity in constant environments, it describes thermoregulation (sweating, blood flow, shivering) based on thermal signals from core, skin and body [22]. The model applies to sedentary people in normal clothing and ventilation.

Gagge's model is suited to uniform, active and moderate environmental conditions for the individual, which corresponds to our experimental case [23]. The thermophysiological model is of the type with one segment and two nodes representing the core and skin. The code for Gagge's thermophysiological model has been taken from Fortran and converted to MATLAB. The model was created for a man weighing 81.7 kg, measuring 1.77 m height and with a DuBois body surface area of 2 m². The mass of the core is estimated at 78.3 kg and the mass of the skin at 3.4 kg.

D. Digital Twin

For the Digital Twin approach, we created a user interface using MATLAB's App Designer for the thermal manikin DT. The interface created is used for operating and visualizing data for the thermal manikin. This interface is needed for the DT because it represents the connection between the physical model and the digital model. In Fig. 6, we have highlighted the data flow between the user, the digital copy and the physical copy to show that the DT created fulfils the necessary conditions to be called a 'digital twin', thus the presence of a two-way data flow between the digital model and the physical model.

Fig. 7 shows the interface created for the thermal mannequin. It has five main blocks, each with different functionalities described in detail below.

Input data block - Located top left, allows manual entry of air temperature, radiant temperature, air velocity, and humidity (real-time sensors may be added later). It also enables exploration of metabolic rate, activity level, and clothing insulation to assess thermal comfort variations.

Temperature display block - Central intuitive display showing the thermal manikin with color-coded temperatures for each of 6 individually controlled segments, viewable in real-time Celsius readings.

Temperature control block - Bottom left block offering two temperature control methods via selectable tabs. Each tab has an activation button with current mode indication. Segment colors match the central manikin display for easy monitoring.

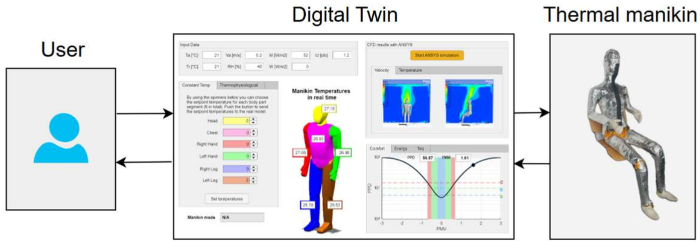


Figure 6. Data flow between user, Digital Twin and thermal manikin

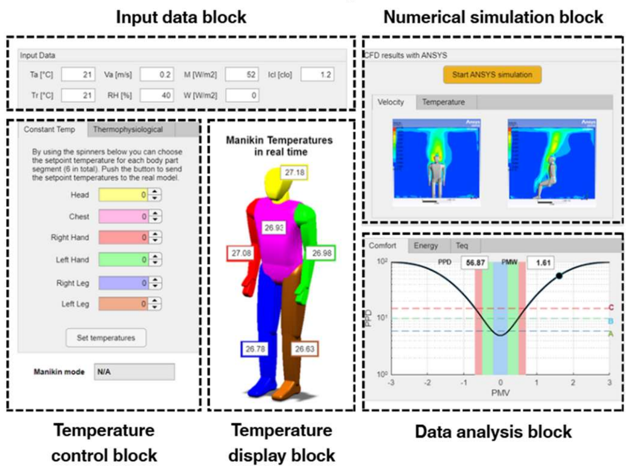


Figure 7. The user interface created in MATLAB AppDesigner for the thermal mannequin and its functional blocks

In Fig. 8 -it can be seen the experimental setup representing the thermal manikin, Digital Twin accessed from a computer and the user.

Numerical simulation block - Top right block with button to initialize CFD calculations in ANSYS Fluent. Uses weak MATLAB-ANSYS coupling to extract manikin surface temperatures and generate velocity/temperature profiles in sagittal and coronal planes.

Data analysis block - Bottom right module organizing numerical model data into user-friendly displays. Shows thermal comfort via PMV/PPD indicators, energy consumption, equivalent temperature, and seasonal comfort representations.

III. RESULTS AND DISCUSSIONS

A. Model validation

To validate the thermophysiological model, we compared the results obtained by our model with those obtained by Gagge [37]. In order to compare them, we entered the input data used in the article [37] and we calculated the exposure for one hour for the temperature range 10-40°C and for different relative humidity values. The mean error obtained was 8.6%. The errors are due to the method used by Gagge to extract the values, as he used a program that extracts data from figures, and we estimate that the poor quality of the graphs due to their age may have introduced certain errors.

To validate the numerical model, we decided to compare the results with those obtained by Danca et al. [21], in which the same thermal plume created by the manikin was used and validated. The validation was performed by acquiring data using temperature sensors and 2D PIV velocity measurements.

For the validation in terms of velocity field, we introduced the same boundary conditions, and we extracted the velocity and temperature values above the head of the thermal manikin where the thermal plume is formed. Fig. 9 shows a comparison of the velocity results in the sagittal plane for the experimental results and the numerical CFD results obtained by them with the model used for DT in this article. We can conclude that the values are similar and that the model is validated in terms of velocities. We can observe that the same maximum values of approximately 0.25 m/s are obtained and that the velocity airflow is similar.

We also compared the results obtained by Danca et al. [21] for the temperature profiles above the manikin, where temperature variations are most pronounced. In Fig. 10, we can see the comparison between the temperature profiles obtained from the numerical model of Danca et al. and the results of the numerical model of the DT manikin. We can conclude that the model is validated in terms of the temperatures obtained, as the values are similar. Differences exist due to the shape of the head, which is different in the two models.

Due to high element counts and long simulation times in DT applications, we chose a model with fewer elements and iterations, accepting some calculation errors for faster processing within technical limitations. Validation used 3,500 iterations. In Fig. 11, velocity comparisons across 500, 2,000, and 3,500 iterations showed minimal differences between 2,000 and 3,500 iterations, but 500 iterations introduced ~0.2 m/s velocity differences. This accuracy compromise achieves lower simulation times while maintaining overall consistency rather than high precision.

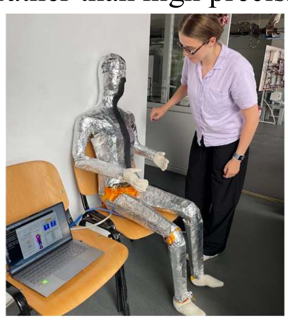
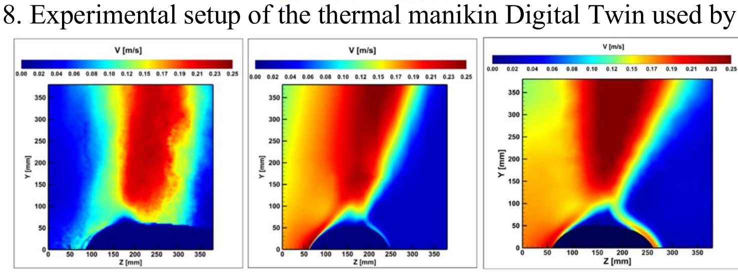


Figure 8. Experimental setup of the thermal manikin Digital Twin used by a person



a) b) c)

Figure 9. Comparison of velocities values in the sagittal plane for results obtained by Danca et al. [26] a) using PIV measurements, b) numerical CFD results and c) CFD results from manikin Digital Twin

In Fig. 12, temperature profile comparisons showed even smaller differences, a maximum of 0.2°C between 500 and 2,000 iterations. The goal remains capturing realistic temperature variations without prioritizing accuracy over computation time.

We also reduced computing time by decreasing grid elements. Our simplified grid (Fig. 13) removed element inflation around the mannequin (Fig. 14), resulting in 181,245 elements and 1,029,691 nodes while maintaining adequate sophistication.

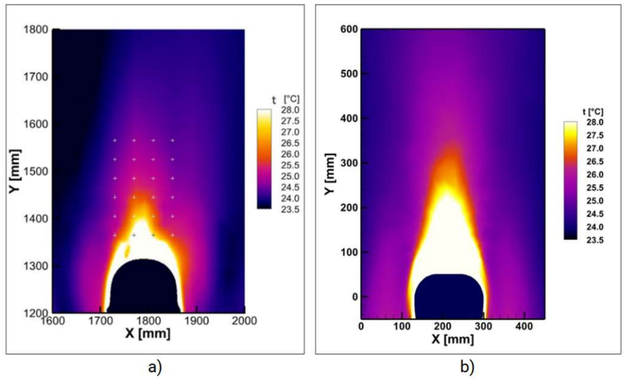


Figure 10. Comparison of temperature profiles for a) CFD results obtained by Danca et al. [26] and b) CFD results obtained from the mannikin Digital Twin

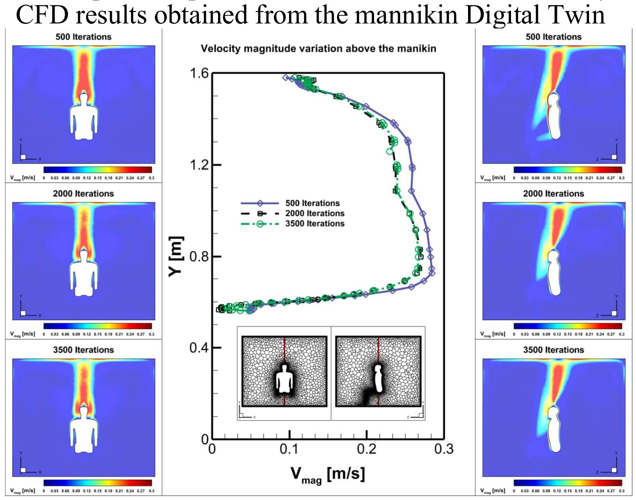


Figure 11. Comparison of velocity profiles obtained by CFD numerical simulation for different numbers of iterations

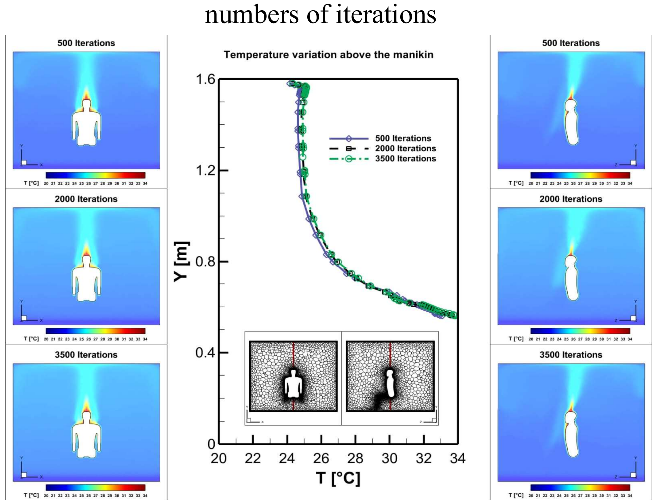


Figure 12. Comparison of temperature profile results obtained by CFD numerical simulation for different numbers of iterations

B. Data assimilation and integration

The DT created for the thermal mannequin using the MATLAB App Designer application is capable of reading, processing, and sending various values. There is a constant exchange of data between the different components of the DT, some in real time and others entered manually. The data to be entered manually includes air temperature, radiant temperature, air velocity, and relative humidity. In the future, this data may be extracted automatically using various sensors.

Adjusting manikin surface temperatures is a key DT application with two available methods within temperature control block. The first method is simple and intuitive, using user-entered data to impose specific temperatures, useful for obtaining desired conditions or scenarios. The second method employs Gagge's thermophysiological model, which automatically estimates skin surface temperature based on environmental conditions and human thermal response. This approach enables real-time monitoring of the thermal manikin's thermophysiological reactions correlated with ambient parameter changes.

To calculate the PMV and PPD comfort parameters, certain data must be provided by the user, as the sensors required to acquire this data were not available at the time the DT was developed. To facilitate the process, this data can be added by the user, which also allows different scenarios to be explored and visualized, as seen in Fig. 15 that shows the interface displaying PMV and PPD parameters along with comfort classes A, B, and C. It is also possible, using the application created, to view the thermal mannequin's energy consumption in real time. Fig. 16 shows a graph of the evolution of consumption during DT operation. Energy consumption is calculated from the PWM values and the power installed in the nickel wires.

Another parameter that users can monitor is the equivalent temperature (Teq) specific to the thermal manikin to assess thermal comfort. The DT can display the comfort level according to the season, summer or winter, as shown in Fig. 17. The temperature and power are calculated using a moving average over a predefined period.

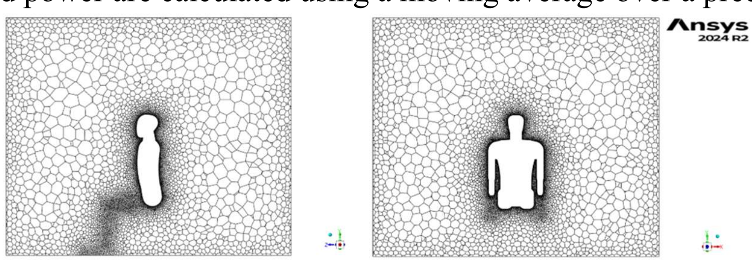


Figure 13. Simplified numerical grid used for the thermal manikin Digital Twin

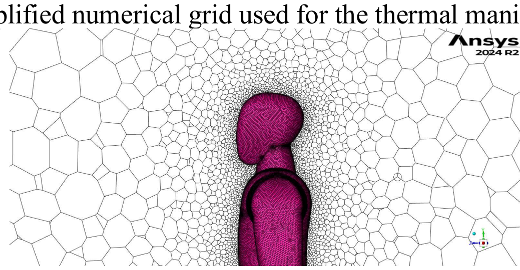


Figure 14. Simplified numerical grid around the manikin for the manikin Digital Twin

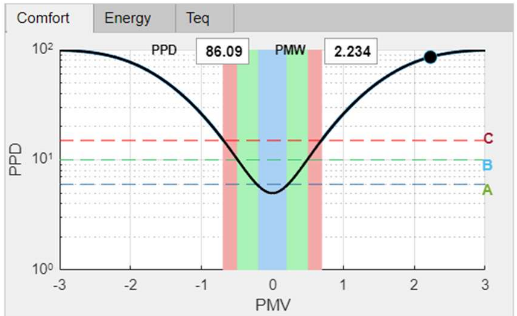


Figure 15. The DT visual interface for displaying PMV and PPD parameters

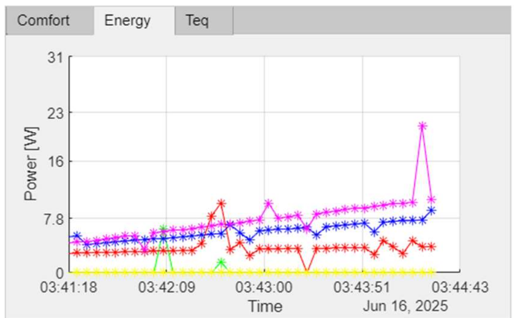


Figure 16. The DT visual interface displaying the power consumed by the thermal manikin

All of the data we have discussed can be extracted and saved in Excel files for post-processing or storage. The application is versatile and can be adapted to the user's needs. It is also possible to add different sensors or actuators to improve the DT's operation or give it new applications.

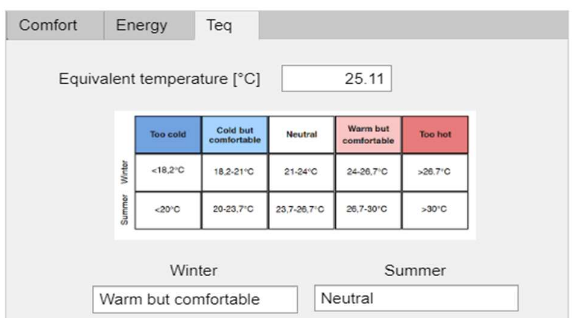


Figure 17. The DT visual interface displaying the equivalent temperature of the thermal manikin

IV. CONCLUSIONS

This work successfully created a Digital Twin for a thermal manikin used in built indoor environment quality analysis. The main achievement was developing a MATLAB application that communicates in real-time with the thermal manikin, featuring an interactive interface for analyzing thermal comfort parameters, real-time CFD simulations of indoor environments, and temperature control using both user-defined values and Gagge's thermophysiological model. The CFD model was validated against literature data and optimized to balance accuracy with computational efficiency for real-time applications. Key contributions include the simplified CFD model, dual temperature control methods, and the visual interface integrating all functionalities.

While technological limitations affected simulation complexity and coupling processes, this work establishes a foundation for intelligent indoor climate control systems and opens perspectives for applications in smart buildings, vehicles, and medical environments through integration of artificial intelligence and more sophisticated physiological models.

This work represents a promising contribution to the field that will be further developed and improved in future research endeavors. The digital twin framework established here provides a solid state-of-the-art foundation and serves as an excellent starting point for future research directions. The integration of real-time thermal manikin control with CFD simulations and thermophysiological modeling demonstrates significant potential for advancing indoor environmental quality assessment. As computational capabilities continue to evolve and new sensing technologies emerge, this foundational work will enable more sophisticated implementations, paving the way for next-generation intelligent building systems and occupant-centered environmental control strategies.

ACKNOWLEDGEMENT

This work was supported by the grant of CCCDI - UEFISCDI, project number 60PHE din 01/04/2024 2024-2026.

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