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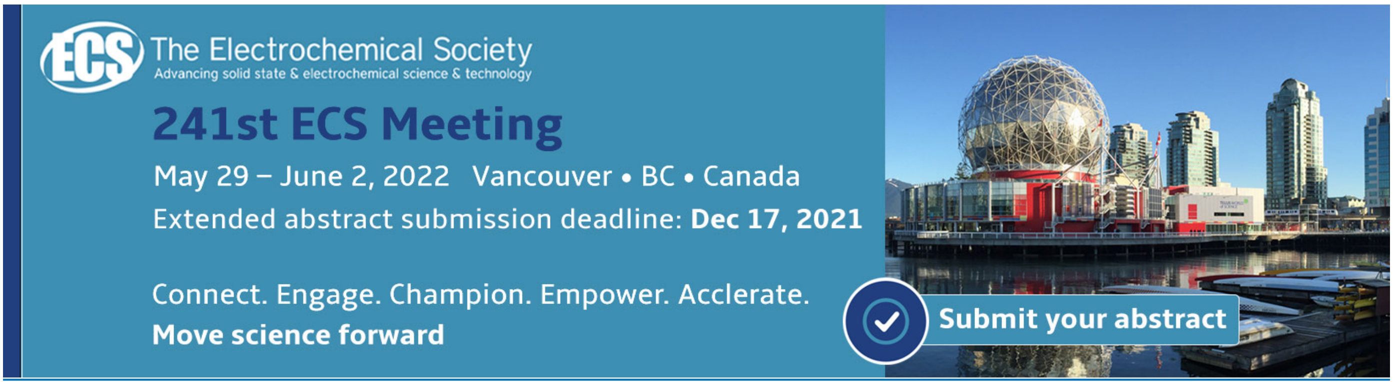

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Digital Twins of Building Physics Experimental Laboratory Setups for Effective E-learning

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Abstract. Hands-on experiments in laboratories are fundamental educational tools for technical sciences. However, laboratories are expensive and not always accessible to students: lockdown and in-person meeting restrictions due to the ongoing Covid-19 pandemic, distant location of teachers and students, facilities used for higher-priority purposes. Moreover, creating specific experimental setups for teaching only can be costly. In that context, digitalizing laboratory setups provides an attractive teaching alternative for remote e-learning. Digital twins are not meant to replace real-world experiments but should enable flexible teaching and effective learning at a lower cost. They complement physical setups and can be virtual extensions, allowing for larger and more complex study cases. e-learning is now popular and many educational institutions provide open-access videos of entire courses. However, the digitalization of practical exercises for engineering is yet limited. The e-learning effort presented in this paper aims to establish a series of digital twins of experimental setups for teaching building physics, energy in buildings and indoor environment. The development of the two first digital twins is detailed here. They are designed for teaching operation and balancing hydronic heating systems. Their numerical models and graphical user interfaces are created with the LabVIEW programming environment.

1. Introduction

Hands-on experimental workshops in laboratories are a fundamental and effective educational tool to teach technical sciences, building physics and building thermodynamics in particular. However, laboratories are expensive resources that are not always available to students. Moreover, creating specific experimental setups for teaching purposes only can be very time and resource consuming. Besides, various limitations, such as limited laboratory access and restrictions imposed by the ongoing Covid-19 pandemic make it difficult to gather students in face-to-face laboratory workshops. In that context, digitalizing experimental setups (or parts thereof) provides an attractive teaching alternative.

In terms of digitalization, the advancements in computational power and digital technologies have had a tremendous impact on all aspects of Architecture and Civil Engineering. Building Information Modelling [1] has changed the way building data is created and used. The use of various digital building representations, simulation models, common data environments and collaborative platforms has caused a paradigm shift both in design and engineering research and practice, but also in related educations.

The above-mentioned concepts have further evolved throughout the past decade, thereby contributing to the introduction of the "digital twin" concept in the built environment [2]. Generally, the digital twin relies on the notion of data-centric management of a physical system and has originally emerged in the domains of aeronautics, operations, production and manufacturing [3]. They are viewed as up-to-date digital representations of the functional and physical properties of a system, which can be a physical system (e.g., an aircraft engine), a social construct (e.g., the stock market), a biological system (e.g., a medical patient) or a complex composite system (e.g., a construction project) [2]. In the built environment, several research efforts aim at the implementation of digital twins for predictive maintenance of building systems, efficient and automated asset monitoring, increasing occupant comfort, automated site progress monitoring, etc. [4][5][6].
The digital twin concept presents tremendous potential for implementation in engineering education, thereby enabling the creation of digital twins of physical laboratory facilities and experiments. Digital experimental setups can be used for remote e-learning activities, or when the laboratories are used for higher-priority purposes, but also in case of a lockdown restricting access to facilities. Digitalisation of teaching activities have recently gained massive popularity in research, but many educational institutions also provide open access to live course lectures and educational videos. Several e-learning tools have also been created to introduce building performance topics to civil engineering students. The video game-based learning tool GEENIE [7] is a dynamic building simulation in which the players accumulate points by adjusting the different Heating Ventilation and Air Conditioning (HVAC) systems to maintain an optimum indoor environmental quality while minimizing energy use (Figure 1; right). The players can compete against each other and against automated controllers. This game was found very effective for engaging students with a new teaching topic that is usually perceived as complicated. Another e-learning tool has been created to introduce students to the impact of some key building design parameters on the daylight glare probability (Figure 1; left). This simple Graphical User Interface (GUI) to a surrogate daylight model (pre-calculated simulations) enables users to intuitively and rapidly explore a range of design scenarios without using any advanced simulation tool (online demonstration video available at https://youtu.be/4YAs3R3vcUE). Such a GUI can also be very beneficial to introduce specific topics or problematics to professionals, practitioners and various stakeholders inside a *Design Charrette* workshop (an intensive, hands-on workshop that gathers various stakeholders from different backgrounds to explore design options).

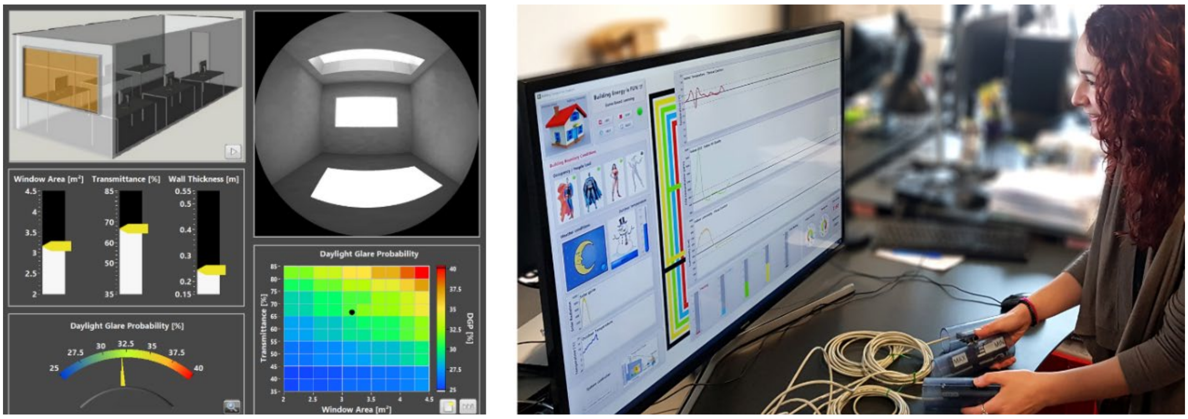

Figure 1. Examples of e-learning platforms for teaching building thermodynamics, building automation and indoor environmental engineering [7].

The exploration of the potential for the implementation of digital twins in learning has also been initiated in research [8]. In training practice, the concept of the digital twin has been implemented in flight simulators, complex system repair and maintenance, etc. However, despite its potential, the digitalization of practical exercises for engineering studies has not been explored in detail. Therefore, the study presented in this paper aims to establish a series of digital twins of various experimental setups for university teaching on topics such as building physics, building design, energy in buildings, indoor environment quality, and operation of HVAC systems. This article presents the development of the two first digital twins of this series. These digitalized experimental setups are specifically designed for teaching the operation and balancing of a hydronic heating system in a building.

2. Pedagogical implications and objectives

A significant body of research has explored the benefits and limitations of e-learning and experiential learning through digital simulations. Alanne [9] states that from the viewpoint of learning, it is essential that engineering students become familiar with various complex systems and their compatibility and interoperability. And while fundamentals of mechanics and thermodynamics remain the same, information technology and building codes experience rapid and continuous development, and the learning processes must be able to accommodate and respond to those changes. Moreover, learning is increasingly taking place outside of the lecture rooms, where the students' own responsibility for reaching their learning objectives combined with their familiarity with technology propagate.

Rajan et al. [10] stipulate that experiential learning in the form of simulations and games has proven to be effective in engineering education due to its reach, effective learning paradigms and improved learning outcomes. Traditionally, engineering courses often require students to work on oversimplified theoretical representations of real-world problems, which may give a deep understanding of the core theoretical principles, but students are rarely trained to link the theories to solving practical problems in real life. Carvalho [11] also states that simulations and games can be instantiated for learning as they aid mental and physical stimulation, develop practical skills, allow transfer learning and are inherently experiential. Furthermore, it has been suggested that in the context of Problem Based Learning, virtual learning environments enhance the experience and the effectiveness of the learning [12].

David et al. [8] investigate particularly how digital twins fits in the context of learning. The authors state that digital twins can assist as rich educational tools to deliver quality learning experiences by combining these experiences with pedagogically sound learning theories. The authors propose a framework for a digital twin of a manufacturing system with pedagogical extensions to educate students in production-based engineering courses in universities. The results suggest that a pedagogical digital twin can be valuable for teaching complex engineering courses that require hands-on training.

In the context of civil engineering education, when introducing complex new topics to students, it can be hard for them to relate to dynamics and correlations of building systems such as hydraulic and hydronic systems. Making them manipulate such systems with hand-on exercises early in the course increases their interest and their perception and understanding of non-linear effects, dynamics, correlation and relationship between the different components of a system. One should note that digital twins are not meant to replace real-world physical experiments but should enable flexible teaching at a lower cost. They complement traditional experimental setups and can serve as virtual extensions of these, allowing for larger and more complex study cases for students. However, digital twins can provide an opportunity for participation in realistic, dynamic and complex situations before interacting with the real system, or instead of, when such a system is not available.

3. Graphical user interface of the digital twins

The dynamic numerical model and the GUI of these digital twins have been developed with the LabVIEW programming environment (*National Instruments*). The first digital twin consists of a single-loop hydronic heating system (see Figure 2). A boiler supplies inlet fluid at a constant temperature of 60 °C. A hydraulic variable-speed pump circulates this fluid in the single-loop hydronic circuit. The fluid is then circulated through a radiator that provides heat to a single room. A valve is placed on the radiator's inlet to regulate its fluid flow. The flow in the hydronic loop is affected by the speed of the pump and the opening of the radiator valve. The heat supplied by the hydronic radiator into the simulated room and the return fluid temperature are calculated according to the fluid flow rate and the temperature difference between the fluid and the indoor environment. The indoor temperature is affected by the space heating gain, the outdoor temperature and the thermal energy stored in the building thermal mass. The simulation of the dynamic system is computed continuously with a simulation time running faster than that of a real building so that the user can rapidly observe the dynamic response of the system.

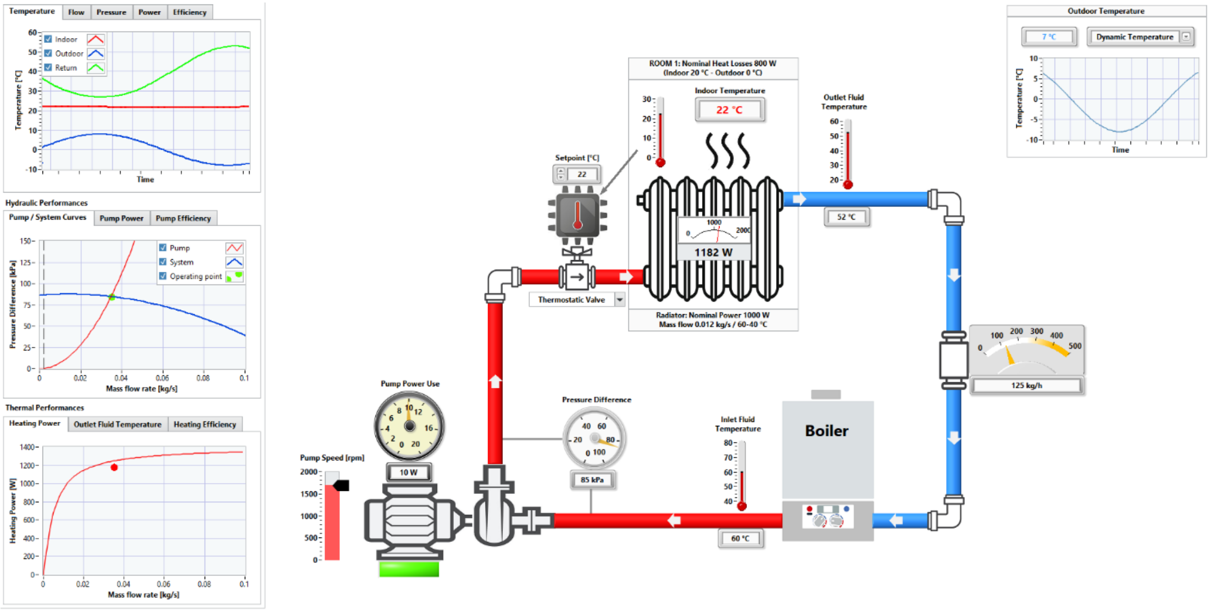

Figure 2. Digital twin of building hydronic heating system with a single loop.

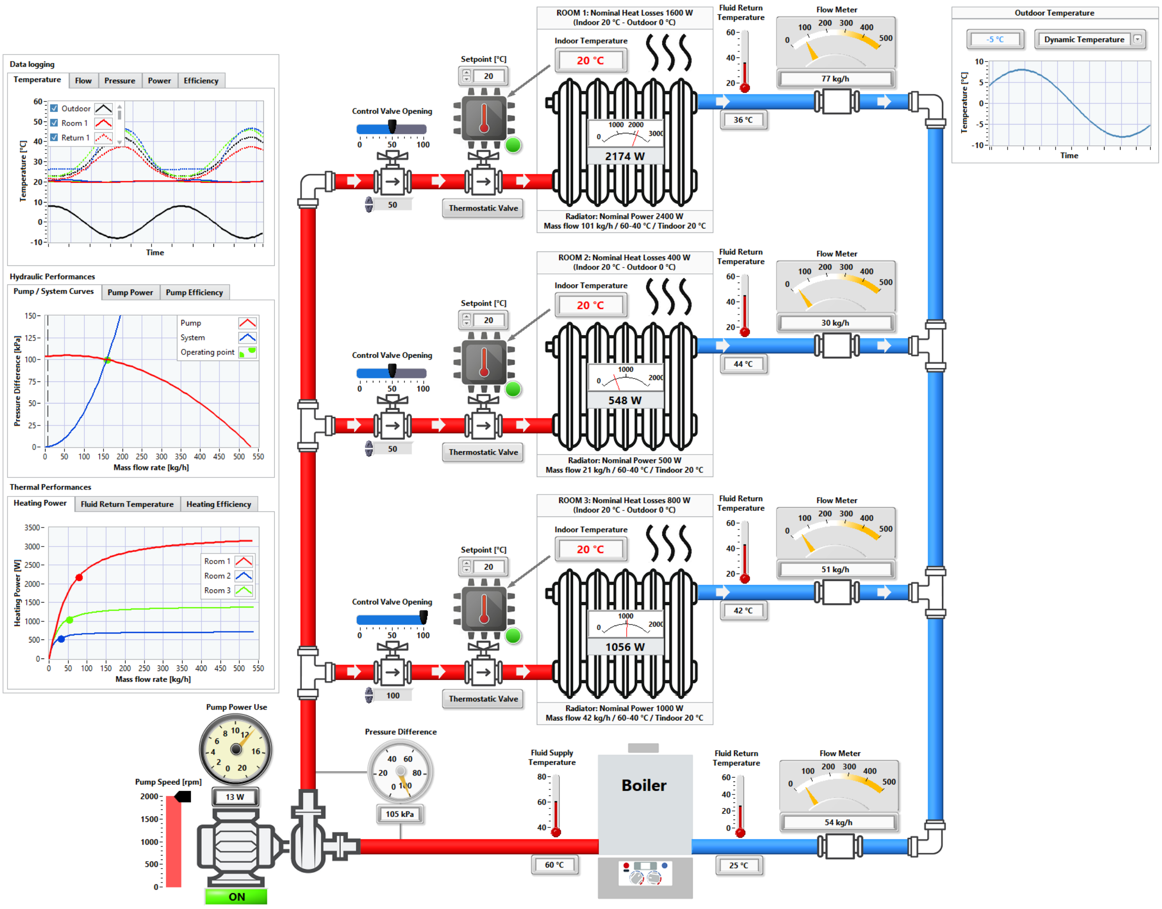

Figure 3. Digital twin of building hydronic heating system with parallel loops.

The user can interact with the system by changing the speed of the pump and the type of the radiator valve shut-off valve (very nonlinear behaviour that only allows for opening and closing completely the circuit); control valve (linear behaviour that enables precise regulation of the fluid flow in the circuit); thermostatic valve (regulation of the flow according to the room temperature). When the thermostatic valve is selected, the user can choose a temperature setpoint for the simulated room. The outdoor temperature can be changed from constant to dynamic (sinusoidal variations).

The user can observe the current state variables of the system via a number of indicators: gauges for the pump pressure difference and the pump energy usage; thermometers for the supply and return fluid temperature and the room temperature; flowmeters for the fluid mass flow rate in the circuit; wattmeter for the heating power delivered by the radiator. Besides, the recordings of the aforementioned variables are displayed on a data logging chart together with the outdoor temperature and the pump efficiency. Six additional graphs indicate the hydraulic performance curves (pump/system curves, pump power usage, pump efficiency) and the thermal performance curves (heating power, return fluid temperature, heating efficiency) as a function of the fluid mass flow rate (over the full range of operation). The current operating point corresponding to the actual fluid mass flow rate is also displayed.

The second digital twin of this series is a direct extension of the first one. It consists of a hydronic heating system with three parallel loops providing heat to three different rooms (see Figure 3). Each radiator is equipped with a control valve (for manual regulation) and a thermostatic valve. The fluid flow in each sub-circuit depends on the flow in the other loop and the rotational speed of the circulation pump. Demonstration videos of these two digital twins can be found online:

- Building hydronic heating system with a single loop: https://youtu.be/F4ZU_8z5c18
- Building hydronic heating system with parallel loops: https://youtu.be/TQzcENwBtWk

4. Numerical model of the digital twins

The hydraulic components of the systems are assumed to be in a quasi-steady state: no fluid storage or delay inside the circuit. The heat transfer fluid (pure water) is assumed to have constant thermophysical properties (stated at 50 °C): Density of 987.7 kg/m^3, thermal conductivity of 0.6435 W/m.K, specific heat capacity of 4180.6 J/kg.K, dynamic viscosity of 0.000547 N.s/m^2, and Prandtl number of 3.5537.

Pressure losses in the circuit are calculated with the Darcy-Weisbach equation. For the linear pressure losses in the pipes and the radiators, the friction factor is calculated with Churchill's approximation of the Colebrook-White equation (valid for all flow regimes) [15] for a pipe's roughness of 0.000025 m. The singular pressure loss coefficient k of the different valves is computed as a function of the valve's opening x with the simple Equation 1 for the shut-off valve and Equation 2 for the control valve. The functions are fitted with manufacturer's data for typical ball valves and linear valves:

$$k(x) = \left(a/(x+b)\right) - \left(a/(100+b)\right) \tag{1}$$

$$k(x) = \exp\left((100-x)/c\right) - 1 \tag{2}$$

For a given valve's position, the total pressure loss of the circuit is calculated from the linear and singular pressure loss coefficients for 100 different fluid flow rates (covering the full range of the system's operation). These data points are then used to fit the system curve quadratic polynomial function (Equation 3) with R, Δp and $\dot{m}$ as the linearized pressure loss coefficient, the pressure drop and the fluid mass flow rate of the hydraulic circuit, respectively:

$$\Delta p = R \times \dot{m}^2 \tag{3}$$

Similarly to the system curve, operation points of the pump curve are generated from a 2D linear interpolation on manufacturer's data: table of pump's rotational speed with corresponding fluid mass flow rate and pumping pressure. A pump curve quadratic polynomial function is then fitted with this data. For the single-loop system, the calculation of the hydraulic operating point is then straightforward. The roots of the quadratic polynomial formed by subtracting the system curve polynomial from the pump curve polynomial are determined. The operating point (fluid mass flow rate) is the only positive real root that is within the range of the pump's operation data. However, for hydraulic systems with multiple parallel loops, the pressure losses and fluid flow distributions in each branch have to be performed before the evaluation of the overall hydraulic operating point. This fluid flow distribution is performed according to an analogy with electrical circuits and Kirchhoff's current law (conservation of mass flow for hydraulic circuit) and Kirchhoff's voltage law. As described above, for a given valve's position, the linearized pressure loss coefficient R_i is calculated from the curve fitting of a quadratic polynomial on the system curve data of each loop i. The equivalent linearized pressure loss coefficient R_{eq} of the entire hydraulic circuit is then calculated from the R_i of each loop as follows:

$$R_{eq} = 1 \Big/ \left(\sum_i 1 \big/ \sqrt{R_i} \right)^2 \tag{4}$$

The system curve of the entire circuit can thus be approximated by the following quadratic polynomial:

$$\Delta p_{tot} = R_{eq} \times \dot{m}_{tot}{}^2 \tag{5}$$

As described before, the operating point of the system can then be determined as the root of the polynomial formed with the system curve and the pump curve. Finally, the fluid mass flow rate m_i in each branch i is calculated with Equation 6 which respects the conservation of mass flow:

$$\dot{m}_i = \dot{m}_{tot} \times \sqrt{R_{eq} / R_i} \tag{6}$$

The pipes are considered adiabatic (no heat losses). There is no heat generation or dissipation from the circulation pump. The only heat exchange between the heat-transfer fluid and the environment (simulated rooms) occurs via the hydronic radiator. The latter is modelled with the ε-NTU method [14]. The heat carrier fluid is considered to have a heat capacity rate that is much lower than that of the radiator and the indoor environment thermal mass. The thermodynamic model of the simulated rooms is a simple *1R1C* thermal network with constant thermal resistance and thermal capacitance. All the thermal inertia from the radiator and the indoor environment is lumped into this single thermal capacitance. The thermal resistance represents the only construction element of the building. It is connected to the outdoor temperature boundary conditions (either kept constant at 0 °C or varying as a sinusoidal function). The rooms have no additional internal heat gains or losses.

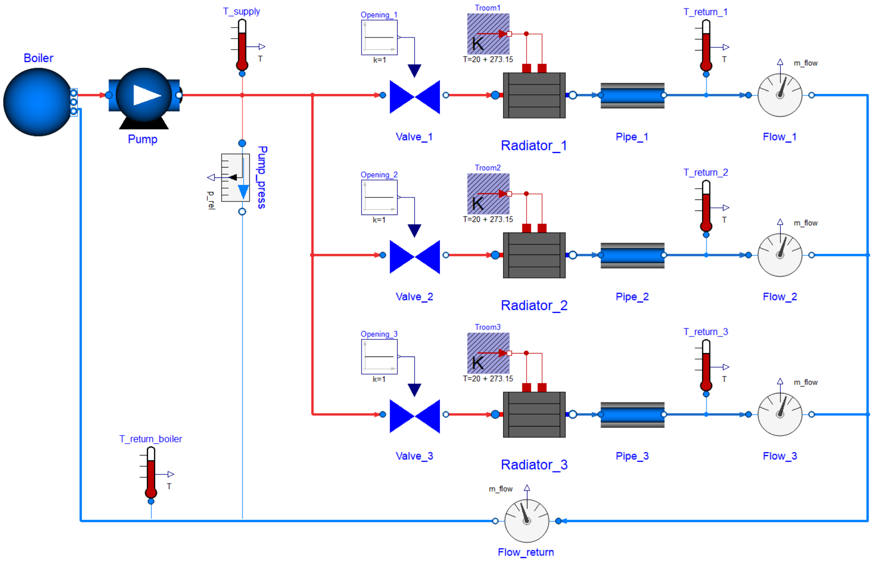

Figure 4. Reference *Modelica* model of the hydronic heating system (*AixLib* library [15]).

The LabVIEW-based model of the hydronic heating system with parallel loops is validated against a reference *Modelica* model of the same system (see Figure 4). This reference model is created with basic components from the validated *Modelica* library *AixLib* [15]. In both the digital twin model and the reference *Modelica* model, the 1R1C model of the rooms is replaced by a constant temperature boundary condition at 20 °C. The numerical models are computed for different values of pump speed and valve opening. These values cover the full operation span of the system. Four key simulated variables (heating power delivered to the rooms, return fluid temperature, fluid mass flow rate, pump pressure difference) are evaluated in each parallel loop and in the main loop at steady state. The simulation results of the digital twin are compared to that of the reference *Modelica* model with three common comparison metrics or key performance indicators (KPIs): Normalized Mean Bias Error (NMBE), Coefficient of Variation of Root Mean Square Error (CVRMSE), coefficient of determination (R^2). One can see in Table 1 the comparison results for the four simulated variables of interest. The NMBE and the CVRMSE are very close to 0, and the R^2 are very close to 1. This indicates that the digital twin is in very good agreement with the reference *Modelica* model. It can thus be concluded that the LabVIEW-based hydraulic and hydronic models of the digital twins are valid and accurate.

Table 1. Comparison of the digital twin model against the *Modelica* reference model.

KPI	Heating Power	Return fluid temperature	Fluid mass flow rate	Pump pressure difference
R^2	0.9974	0.9995	0.9999	0.9999
NMBE	-2.3%	0.6%	-0.6%	0.1%
CVRMSE	5.4%	1.7%	0.8%	0.3%

5. Results and discussions

In September 2020, these digital twins were used for a university course titled “Building Heating and Cooling Systems” (design, sizing, implementation, and commissioning of HVAC systems) that was held online because of pandemic restrictions. After the lecture concerning hydronic heating systems, the students were asked to download and run the first digital twin on their own computer. This first digital system is intended to be explored freely (*sandbox* mode) to test the influence of the different parameters on the overall behaviour of the system. Students were asked to describe their observations, but no specific objectives were set. A few days later, after the lecture concerning the balancing of hydronic heating systems, the students were asked to run the second digital twin. Similarly to the first digital twin, students were firstly let free to explore and test the influence of each parameter on the overall system and observe the impact that one parallel loop can have on the other parallel branches of the circuit. After this initial exploration phase, the students were given the task to adjust the speed of the circulation pump and the opening of the control valves in each parallel hydronic loop to balance the system and achieve optimum performance: providing enough heat to each room so that indoor temperature could be maintained at 20 °C while the outdoor temperature conditions change dynamically.

Having these digital twins allowed us to rapidly switch from the lecture to the practical exercise on a realistic system. Bringing a computer with pre-installed digital twins or distributing them prior to the lecture is much easier than transitioning from a lecture room to the laboratories, or bringing a small-scale or full-scale experimental setup in the classroom. Each student can have their own realistic dynamic system to explore and put new knowledge of the lecture into practice immediately. Providing a real physical test setup for each student would have been very costly and would have required much more supervision time. In addition, it is much easier to emphasize or hide certain complexities of the system and adapt the former to the focus of the lecture. It can also be an excellent introduction before diving into the topic of the lecture or before transitioning to hand-on experiments on a real-world system. The feedback from the students was very positive. They could easily download and run the software. The students expressed a very high curiosity for these digital twins. They really appreciated the ability to freely change many system parameters. Many have asked if it was possible to get a new version of the software in which more components could be added, changed and operated. This indicates a clear and strong engagement of the students with the digital twins. They also pointed out the importance of the GUI graphical quality and a good balance between details and the readability of the overall system.

6. Conclusions and suggestions for future work

Hands-on experiments in laboratories are fundamental for teaching technical sciences. In the context of e-learning intensified by lockdowns and physical distancing, the digitalization of experimental setups provides an attractive teaching alternative. Digital twins of laboratory setups are not meant to replace real-world physical ones but should enable flexible teaching at a lower cost. They complement traditional experiments and can extend them virtually into larger and more complex cases. The project introduced in this paper aims to establish a series of digital twins of experimental setups for university teaching of building physics, energy in buildings, indoor environmental quality and building automation. The two digital twins presented in this article are intended to introduce students to the operation of hydronic heating systems in buildings and comprehend valve balancing to ensure optimum operation in a multi-parallel loop configuration. Having students to manipulate such virtual but realistic systems early on in the course increases their interest, engagement, perception and understanding of non-linear effects, dynamics and relationship between the different system's components. This pilot project received very positive feedback from the students, and many asked if it was possible to get more complex digital twins like those. This indicates a clear interest from the students. However, it is difficult to objectively assess the improvement of teaching with those two particular e-learning tools, and more in-depth studies are needed. The next steps of this digitalization project are as follows: expand the number of virtual experiments; develop web-based digital twins; replace LabVIEW-based numerical models by direct coupling (co-simulation) of commercial building models such as *Modelica*, *IDA ICE* or *EnergyPlus*; utilize surrogate models for computationally-intensive numerical models; create semi-digital twins that include a real physical system monitored remotely (hardware-in-the-loop).

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