

PERFORMANCE ASSESSMENT OF RESIDENTIAL HEAT PUMP SYSTEMS WITH AND WITHOUT BUFFER TANK INTEGRATION: A SIMULATION-BASED STUDY

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ABSTRACT

This paper proposes an analysis of the performance associated to heating technologies. In particular, heat pumps are considered together with different configurations characterized by the presence or not of a buffer and by various heating systems, i.e., radiators and underfloor heating. In addition, different sizing of the various elements is considered. The inclusion of a buffer in the design of a heating plant represents a critical choice due to its purchase and installation costs and to the space required for its installation. A focus on defrost cycles of the heat pump is presented in terms of observed failures. Different scenarios are taken into account in order to provide a thorough analysis in terms of significant key performance indicators, e.g., the number of defrost failures. A tailored simulator based on a mathematical model is used to perform the simulations in the different scenarios designed and to analyse the data obtained; Dymola and MATLAB/Simulink environments are exploited.

Keywords: heat pump, defrost cycle, buffer, valve control logic, performance analysis.

1 INTRODUCTION

Emissions, costs and sustainability in buildings represent crucial themes to be tackled [1]. In this context, retrofit, design, maintenance and operation of cooling/heating, indoor air quality (IAQ) and lighting technologies cover a crucial role [2]–[4]. The specifications to be fulfilled are thermal and lighting comfort together with IAQ parameters monitoring and control [5]–[8].

Heating, ventilation and air conditioning (HVAC) and domestic hot water (DHW) systems represent significant case studies where multi-domain features and the peculiarities of each component (e.g., buffers and heat pumps) must be taken into account to optimize performance in terms of significant key performance indicators (KPIs) [9], [10].

Heat pumps are an alternative technology to traditional systems for heating/cooling purposes. Heat pumps can provide a reduction in carbon emissions and energy consumption if they are properly designed, operated and maintained. For example, defrost cycles represent a typical operation associated to heat pumps and they must be correctly managed [11], [12]. In temperate and continental zones, heat pumps are becoming significantly popular, e.g., in residential applications, due to their cost-effectiveness and environmental advantages.

In this paper, an analysis of the performance associated to heating technologies is proposed, considering heat pumps and different configurations characterized by the presence or not of a buffer and by various heating systems.

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The paper is organized as reported in the following: the case study is presented in Section 2, while Section 3 reports the valve control logic. Results and discussion are reported in Section 4, while conclusions are summarized in Section 5.

2 CASE STUDY

This section provides a detailed description of the simulation scenarios and the various parameters chosen for the case study.

The adopted apartment model consists of two floors, and a multi-zone setup was chosen to evaluate the performance of the heat pump system. The apartment layout and zone configurations are shown in Fig. 1. The heat distribution is partitioned in three zones: two at the ground floor (Zone 1 and Zone 2) and a single one at the first floor (Zone 3). The ground floor bedroom is separated from the other rooms and forms Zone 2. The temperature control of this single zone plays a crucial role due to its size and location.

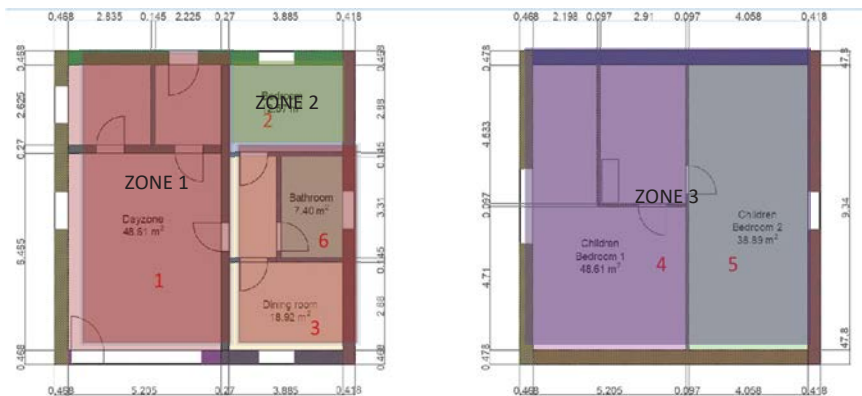


Figure 1: Apartment layout with zone distribution.

In the simulation, both radiator and underfloor heating were considered. The total water volume in the radiator circuit for the entire apartment is 100 litres, with 20 litres allocated to the Zone 2 circuit alone. When underfloor heating (UFH) is considered, the total water volume in the heating circuit increased to 381 litres, with Zone 2 water volume rising to 35 litres.

This apartment model is assumed to be a newly constructed building. In the simulations no occupants, furniture, or other sources of heat generation are taken into account. The apartment model together with the heat pump was initially created in the Dymola environment and then exported to MATLAB/Simulink using the Functional Mock-up Unit (FMU) standard for simulation.

The heat pump considered in this work has a nominal heating capacity of 12 kW. Simulations were run under different (winter) weather conditions and hourly programming of the temperature setpoints. In addition, the simulations evaluated the performance with and without a buffer tank, considering various tank sizes.

The first scenario simulates idealized weather conditions, with a constant outdoor temperature of 0°C and 95% humidity. This controlled environment allowed for a more focused examination of the heat pump's performance under challenging conditions. The second weather scenario utilized real meteorological data from Milan (Italy), representing typical winter conditions in January.



Different hourly programming temperature setpoints can be assigned to the three distinct zones within the apartment. Zone 1 and Zone 3 were scheduled with the same hourly program, while Zone 2 was scheduled with a fixed temperature setpoint throughout the day and night. This setup ensured continuous operation of the heat pump. Fig. 2 shows the hourly temperature setpoints for each zone: the grey line represents the constant setpoint for Zone 2, while the orange line indicates the setpoints for the other zones. The initial temperature of the apartment was set to 15°C for all simulations.

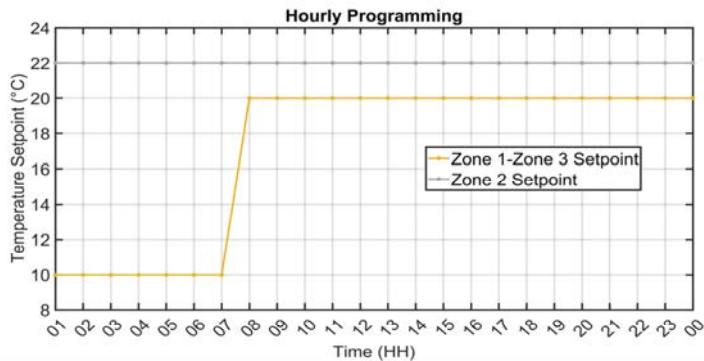


Figure 2: Hourly programming of the thermostat: Zone 2 constant set point (grey line) and all the other zones hourly programming (orange line).

2.1 Buffer tank and heating emitter specifications

The integration of a buffer tank into heat pump systems is a common industry practice, often aimed at enhancing performance. However, this addition introduces significant drawbacks. A primary concern is the large space required for installation, posing a major constraint in many applications. Additionally, the capital investment for the installation of a buffer tank can be considerable, thereby increasing the overall system cost. In addition to the above considerations, it was proven that the presence of buffer while it can improve defrost performance, it also increases the heat pump's on/off cycles, potentially leading to increased wear and tear on mechanical components [13]. Furthermore, the presence of buffer requires the heating of additional water, consequently increasing energy consumption and operational costs.

In this paper, to assess how the presence and size of the buffer tank influence system performance, several configurations with different tank capacities were first evaluated, alongside a baseline scenario without any buffer tank. Successively, two different valve control logics are proposed and analysed to optimize defrost performance and potentially eliminate the need for buffer tanks altogether.

Fig. 3(a) illustrates the hydraulic arrangement for the buffer tank setup. The heating system is here integrated with a buffer tank installed in the return path of the thermal circuit; in the considered configuration, the buffer tank has only two connections serving as input and output. In this setup, the return water from the apartment first flows into the buffer tank before being routed back to the heat pump. In Fig. 3, 'LW' indicates the leaving (supply) water from the heat pump, while 'EW' refers to the entering (return) water. Fig. 3(b) depicts the hydraulic scheme without the buffer tank. This configuration is particularly attractive given the lower installation costs and the reduced space requirement.

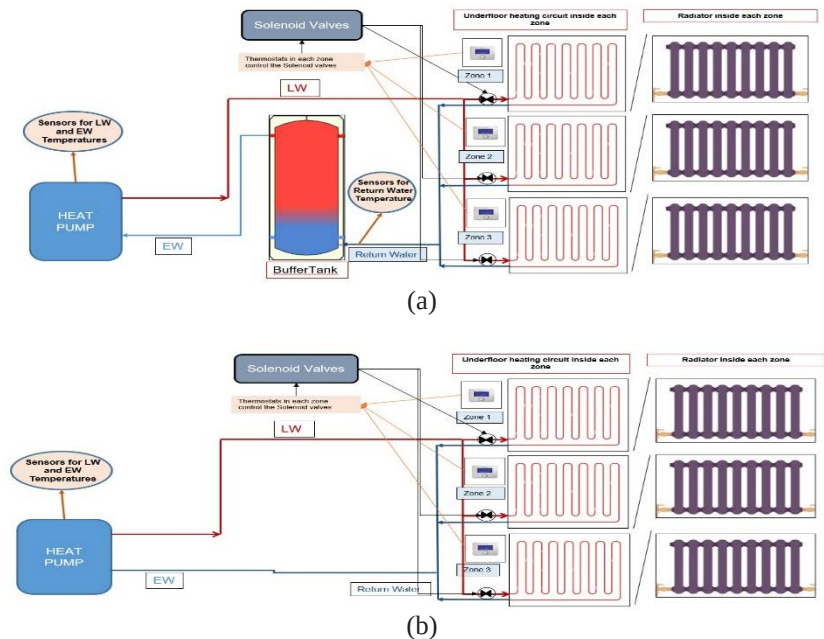


Figure 3: Scheme of the thermal network. (a) Hydraulic scheme with buffer installed in the return line; and (b) Hydraulic scheme without the buffer tank.

3 VALVE CONTROL LOGIC

During winter period, the control system of the heat pumps periodically requires the activation of defrost cycles. This is to prevent a severe formation of ice in the external unit that would drastically lower the unit performances.

Simulations tests were performed taking into consideration that during the night only one zone was in request. The smaller zone, Zone 2, was chosen since this configuration was the most challenging for the heat pump.

With the buffer tank in place, it was observed that the defrost cycles were successful, even when it was only the smaller zone requesting heat. This is because the buffer tank, by increasing the overall amount of water in the thermal circuit, ensures adequate thermal power as required by defrost activity. Conversely, when the buffer was not present, several defrost cycles did not end successfully as shown in Fig. 4 that refers to the case with radiators.

In order to eliminate the presence of a buffer tank while ensuring successful defrost cycles in all situations, i.e., even when the zones that are in thermal request are the ones related to the circuit with a small amount of water, a valve control logic was developed. The main objective of the proposed logic is to guarantee the necessary thermal power required for melting all the ice during the defrost cycles by forcing the thermal request of other zones of the apartment. The proposed valve control logic regulates the valves of the zones: when, at new request for a defrost cycle, the smaller zone is the only one demanding heat, other zones are opened during the entire defrost cycle to ensure the required water amount in the thermal circuit (see Fig. 5). In particular, two possible strategies for defrost cycles are considered. In the first, if defrost is requested and only the small Zone 2 is active, the larger Zone 1 is additionally activated. Alternatively, the second strategy activates all the heating zones.

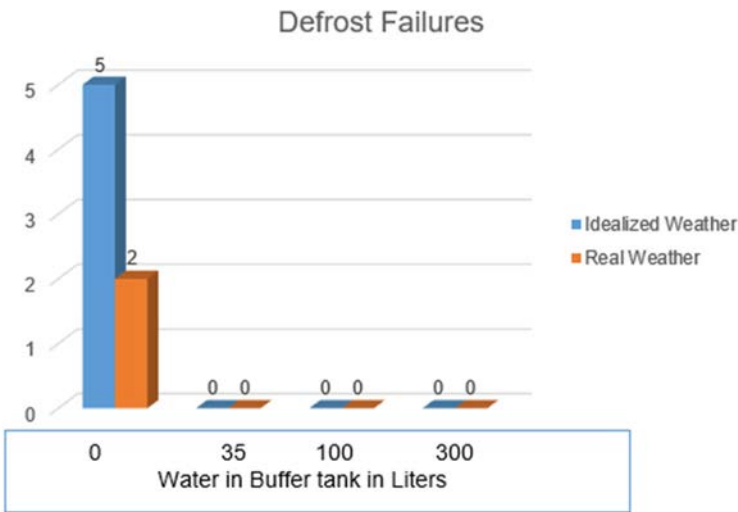


Figure 4: Statistical analysis of heat pump defrost failures.

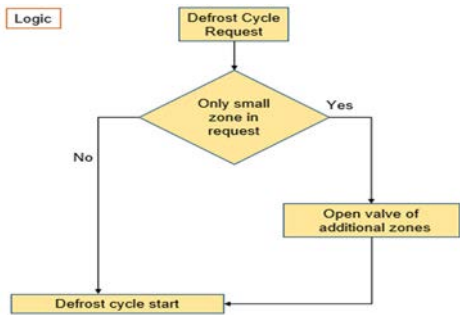


Figure 5: Valve controlling logic working principle.

The hydraulic scheme used to test the valve control logic is shown in Fig. 3(b). In this setup, the buffer tank is not present to assess the performance of the valve control logic when the smaller zone is in demand and the defrost cycle is triggered.

3.1 Process simulation configuration

The two-floor apartment with three distinct thermal circuits was simulated in the Dymola environment together with heat pump system. To test the proposed logic in the different environments, a 12-kW heat pump was chosen.

Many simulation sets were performed, each based on unique combinations of external weather conditions, heating emitter types, and the presence/absence of the proposed control logic. A 10-day simulation period was chosen. The simulation parameters were set in a MATLAB script, which included the Leaving Water Temperature (LWT) setpoint, buffer tank capacity, user-defined hourly temperature setpoints for each zone (as shown in Fig. 2),

and either simulated or historical weather data corresponding to the winter season in Milan. The simulation scenarios discussed in this paper are summarized in Tables 1 and 2. In idealized weather conditions, it is assumed a constant external temperature of 0°C and humidity at 95%. Scenario #1 was further divided into four sub-scenarios, each testing a different buffer tank size: 35, 100 and 300 litres. A scenario with no buffer tank was also included, indicated with zero litres in Table 1. The other scenarios do not include the buffer tank, and the proposed valve control logic is applied. Table 2 specifies the heating emitter types, weather conditions, and the chosen control logic strategy: active zones during the day and night for each sub-scenario. In all the simulations reported in this work, all zones are active during the day, and only Zone 2 remains active at night, as illustrated in Fig. 2.

Table 1: Simulation scenarios (Part 1).

ID #	Apartment size (m ²)	Buffer size (litres)	Heat pump power (kW)	Weather
1-0; 1-35; 1-100; 1-300	175	[0 35 100 300]	12	Idealized
2	175	[0]	12	Idealized
3	175	[0]	12	Idealized
4	175	[0]	12	Idealized
5	175	[0]	12	Real data

Table 2: Simulation scenarios (Part 2).

ID #	Emitter	Location	Year period	Control logic	Control logic setting: additional valves/zones opened
1-0; 1-35; 1-100; 1-300	Radiator	Simulated	Winter	Not active	–
2	UFH	Simulated	Winter	Active	+1 (Zone 1)
3	Radiator	Simulated	Winter	Active	+2 (Zone1 and Zone 3)
4	Radiator	Simulated	Winter	Active	+1 (Zone 1)
5	UFH	Milan	January	Active	+1 (Zone 1)

4 RESULTS AND DISCUSSION

This section presents the key results from the most important simulated scenarios to provide a clear understanding of the performance of the heat pump when the proposed valve control logic is activated.

Fig. 6 illustrates the simulation results for Scenario #1-300, focusing on the behaviour of the heat pump when integrated with a buffer tank of 300 litres, specifically during the defrost cycle. Fig. 6(a) depicts the activation of the defrost cycle and eventually the presence of a defrost failure; Fig. 6(b) illustrates the water temperatures within the circuit in the same time period. In Fig. 6(b), the Leaving Water Temperature (LWT), shown by the blue line, clearly demonstrates a temperature drop during the defrost cycle. This occurs because, during



defrost, the water flow direction is reversed to supply heat to the exchanger, facilitating the removal of ice. The green line indicates the temperature of the water returning from the apartment to the buffer tank (Return Water Temperature, T_{RW}), as schematically illustrated in Fig. 2. The integration of the buffer tank helps maintain a high entering water temperature (red line, Fig. 6(b)), especially noticeable during the defrost cycle leading to a successful completion of the defrost cycle.

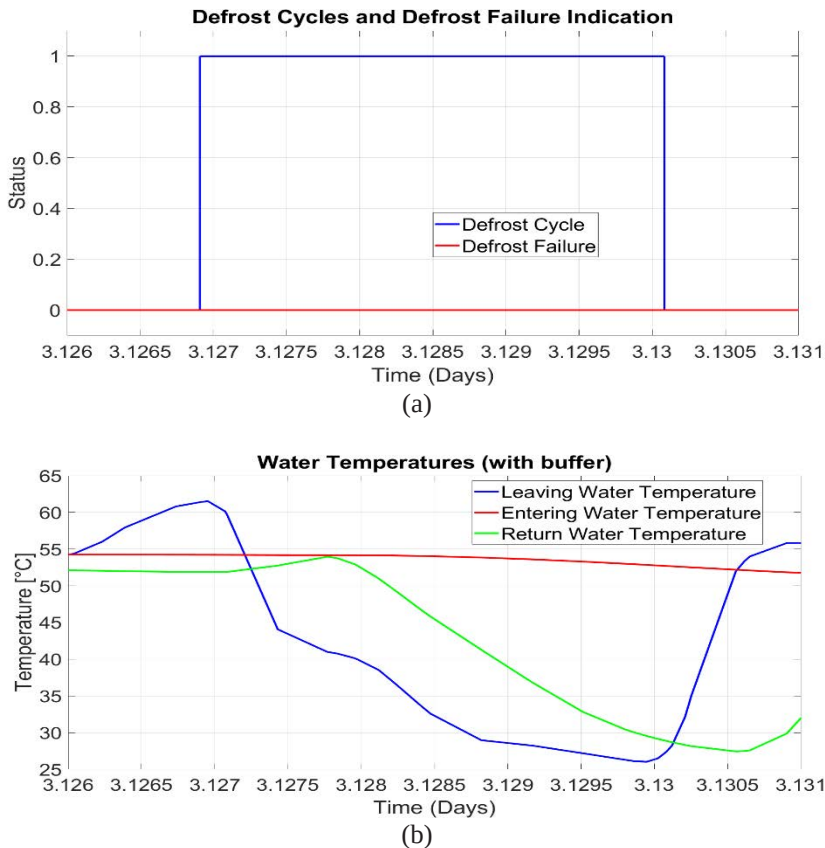


Figure 6: Results of the Scenario #1-300 with buffer (300 litres). (a) Defrost cycle and defrost failure; and (b) Water temperatures.

In the simulations, the heat pump's control system terminates the defrost cycle under two possible conditions: either when the ice is completely melted or when the LWT drops below a defined minimum threshold before the ice on the outdoor coil is fully removed. In the latter case, where de-icing is incomplete, the cycle is classified as a failure.

The occurrence of a defrost cycle failure is illustrated in Fig. 7; this scenario (Scenario #1-0) simulates heat pump performance without buffer tank integration. In Fig. 7(a), the red line clearly indicates a defrost cycle that has ended unsuccessfully. Fig. 7(b) presents the corresponding water temperatures, where the blue line represents the leaving water temperature (LWT). During the defrost cycle, the LWT reaches its minimum threshold. The

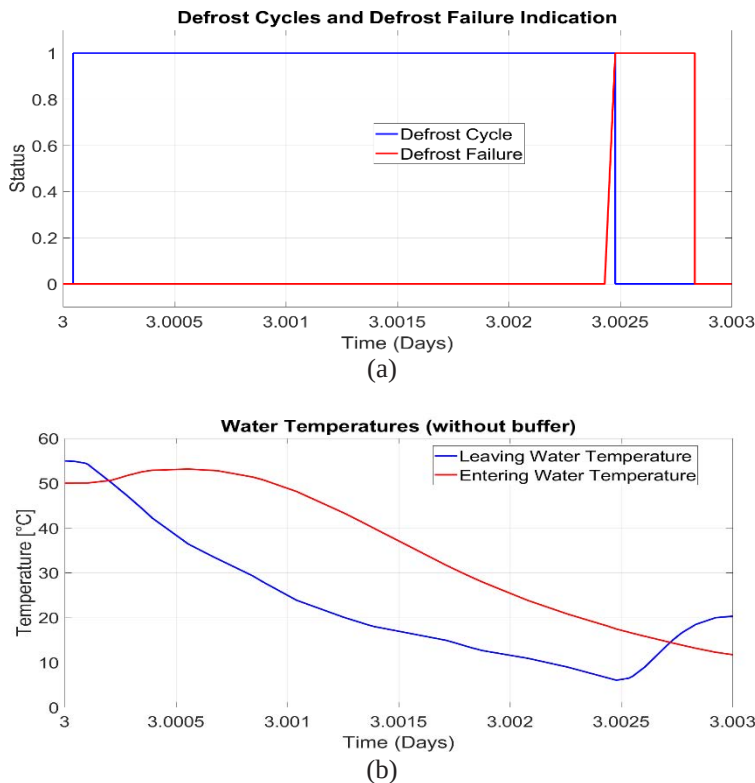


Figure 7: Results of the Scenario #1-0 without buffer. (a) Defrost cycle duration and defrost cycle failure; and (b) Water temperatures.

failure of the defrost cycle occurs during a period when only the smaller zone is requesting heat, and it is due to insufficient water quantity in the circuit.

Fig. 8 refers to the case underfloor heating (UFH) configuration and the control logic is activated. In this scenario (Scenario #2), the chosen valve control logic activates only an extra zone (Zone 1) when, at the request of activation of the defrost cycle, only Zone 2 is demanding heat (see blue line in Fig. 8(c)). In this setup, the total water content in the apartment is approximately 370 litres. The simulation shows that opening just this single larger zone, in addition to the smaller zone already in demand, is sufficient to complete the defrost cycle successfully. This behaviour contrasts with Scenario #4, where radiators were present instead of underfloor heating and the same valve control logic as in Scenario #2 was applied.

As shown in Fig. 9(c), the valve control logic triggers the opening of a larger zone's valve when the defrost cycle is initiated. The red line represents the valve status of Zone 2, which is already open prior to defrost start. In contrast, the green and blue lines are at zero, indicating that the other zones are initially closed. As soon as the defrost cycle begins, the blue line switches from 0 to 1, indicating that the corresponding zone's valve has been opened to increase water amount in the circuit. Despite this action, a defrost failure is still observed in this scenario (see red line in Fig. 9(a)). However, the duration of the failure is significantly



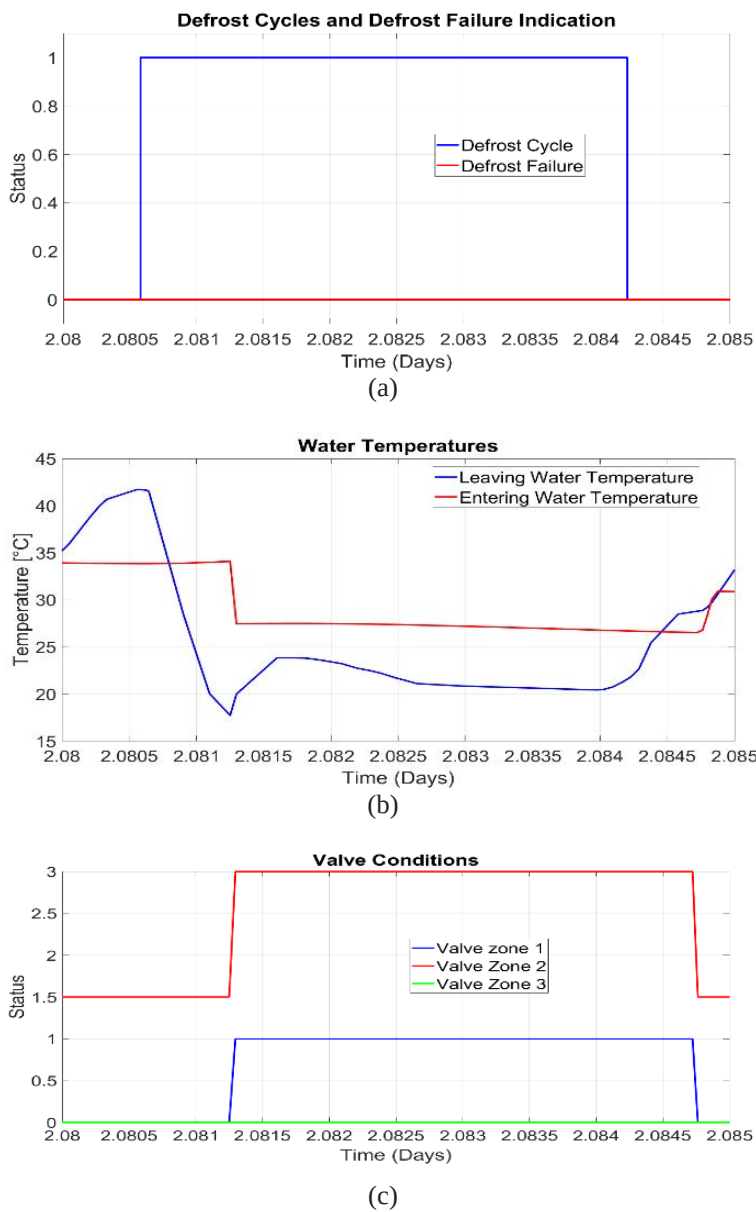


Figure 8: Results of the Scenario #2 UFH. (a) Defrost cycle and defrost failure; (b) Water temperatures; and (c) Valve condition.

reduced compared to Scenario #1-0. The cause of failure is attributed to the LWT dropping below the critical threshold of 8°C given the limited amount of water flowing in the circuit.

A different valve control logic was applied in Scenario #3: here all three zone valves are opened when, at the request of activation of the defrost cycle, only Zone 2 is demanding heat.

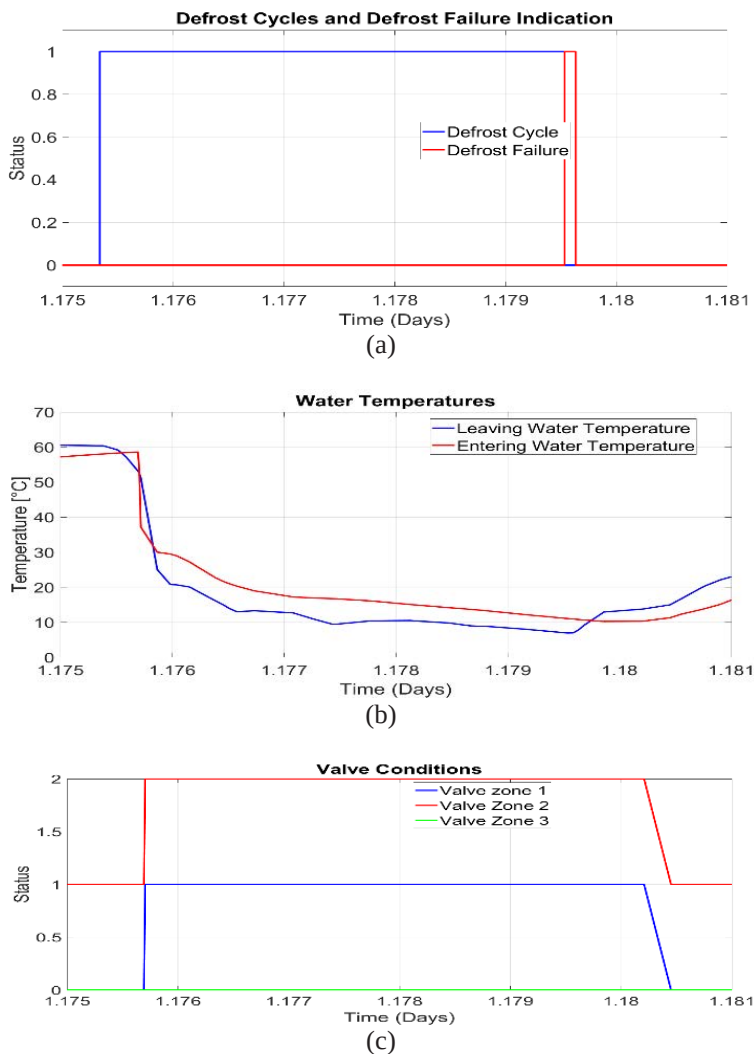


Figure 9: Results of the Scenario #4. (a) Defrost cycle and defrost failure; (b) Water temperatures; and (c) Zone valve conditions.

This configuration ensures that the entire volume of water in the thermal circuit – 100 litres in the case of radiator-based heating – is actively circulating.

From Fig. 10(b), it is evident that the LWT stays above 20°C, well above the critical point, throughout the defrost cycle; this ensures that sufficient thermal energy is available to complete the defrost process effectively with no failure (see Fig. 10(a)). Finally, Fig. 10(c) displays the valve status of all zones during this period, confirming that all zones contribute to the water flow.

Figs 11 and 12 present the statistical analysis of defrost cycle performance, with particular focus on defrost cycle failures in the case radiators are applied as heat emitters. As shown in

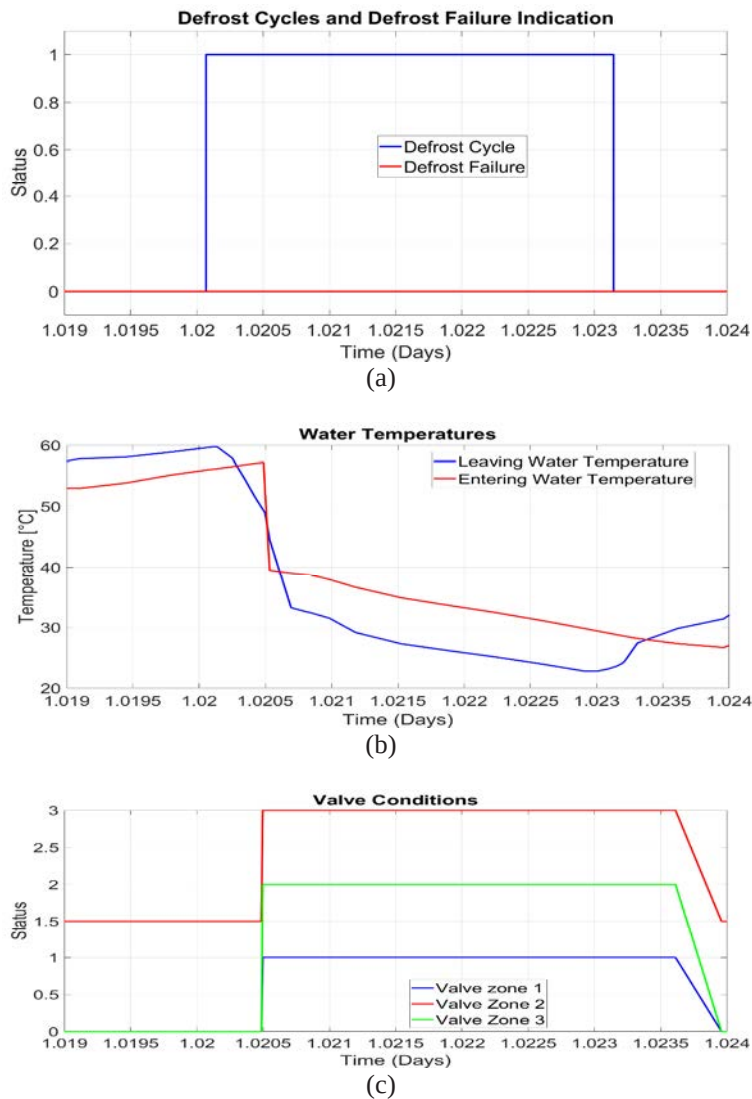


Figure 10: Result of the Scenario #3. (a) Defrost cycle and defrost failure; (b) Water temperatures; and (c) Valve conditions.

Fig. 11, defrost failures are not present when a buffer tank is integrated. The positive effects of the introduction of the valve control logic can be observed in Fig. 12 that refers to scenarios where the buffer tank is not integrated. With the application of the first control strategy, i.e., when one larger zone is opened alongside the smaller zone during the defrost cycle, the number of failures is noticeably reduced though not entirely eliminated. Notably, when all zones are opened during the defrost cycle, that is, the second control strategy is applied, all defrost cycles are completed successfully.

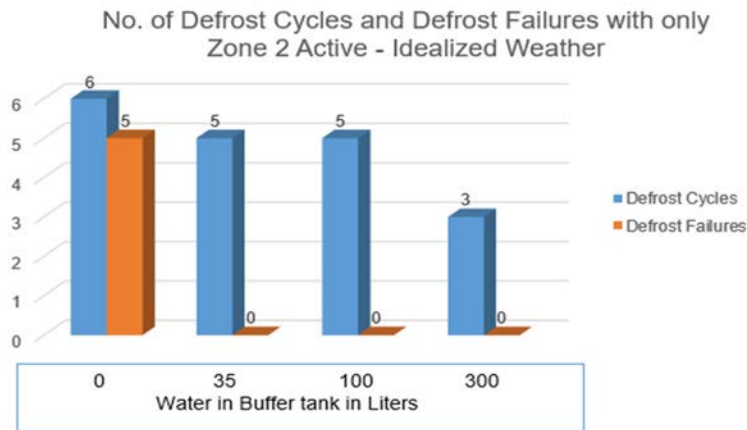


Figure 11: Heat pump defrost cycles and defrost failures with integration of buffer.

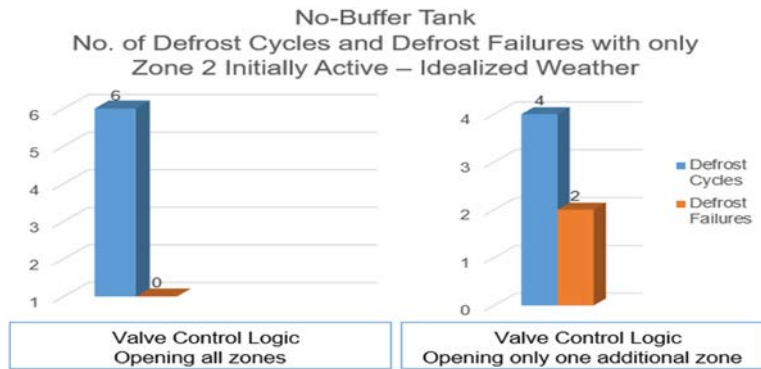


Figure 12: Heat pump defrost cycles when all zones are opened and when only two zones are opened during defrost cycle.

5 CONCLUSIONS

This study primarily focused on evaluating the effectiveness of a valve control logic strategy designed to improve defrost cycle reliability in residential heat pump systems, without the need of the integration of a buffer tank, achieving a more compact and cost-efficient system design.

The apartment and heat pump models were developed in the Dymola environment at Ariston Group and imported into the MATLAB/Simulink platform using the Functional Mock-up Unit (FMU) standard. Simulations were carried out under various configurations involving different heating emitter types and outdoor weather conditions, with result analysis performed in both MATLAB and Dymola environments.

The proposed logic dynamically opens additional heating zones during defrost events particularly when only the smaller zone is in demand in order to maintain adequate water amount and thermal support. The simulation results proved that the implementation of this control strategy significantly reduced the occurrence of defrost cycle failures.

These findings indicate that intelligent valve control can serve as an effective alternative to buffer tanks, enabling more space-efficient and energy-conscious system designs without sacrificing performances.

As future work, simulations will be extended to include more severe outdoor weather conditions and cold start scenarios, especially for radiator-based systems, to better evaluate heat pump behaviour under demanding operating conditions.

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REFERENCES

- [1] International Energy Agency & United Nations Environment Programme, 2018 global status report: Towards a zero-emission, efficient and resilient buildings and construction sector. 2018. <https://www.unep.org/resources/report/global-status-report-2018>. Accessed on: 25 Jun. 2025.
- [2] Krajčík, M., Arıcı, M. & Ma, Z., Trends in research of heating, ventilation and air conditioning and hot water systems in building retrofits: Integration of review studies. *Journal of Building Engineering*, **76**, 107426, 2023.
- [3] Hafez, F.S. et al., Energy efficiency in sustainable buildings: A systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research. *Energy Strategy Reviews*, **45**, 101013, 2023.
- [4] Annaswamy, A.M., Johansson, K.H. & Pappas, G.J. (eds), *Control for Societal-Scale Challenges: Road Map 2030*. IEEE Control Systems Society Publication, 2023. <https://ieeecss.org/control-societal-scale-challenges-road-map-2030>. Accessed on: 25 Jun. 2025.
- [5] Pepe, C., Ali, M.F. & Zanolli, S.M., Heat pump management for building's indoor temperature control. *Proceedings of the 2024 25th International Carpathian Control Conference*, pp. 1–6, 2024.
- [6] Pepe, C., Ali, M.F. & Zanolli, S.M., Impact of wind speed look-ahead mismatch on carbon dioxide-based IAQ nonlinear MPC. *Proceedings of the 2025 26th International Carpathian Control Conference*, pp. 1–6, 2025.
- [7] Zanolli, S.M. & Pepe, C., Design of nonlinear MPC techniques for indoor air quality control. *Proceedings of the 2023 24th International Carpathian Control Conference*, pp. 478–482, 2023.
- [8] Pepe, C., Ali, M.F. & Zanolli, S.M., Impact of occupancy previewing mismatch on nonlinear model predictive control for indoor air quality management. *Proceedings of the 2024 1st International Conference on Innovative Engineering Sciences and Technological Research*, pp. 1–5, 2024.
- [9] Kou, X., Wang, R., Du, S., Xu, Z. & Zhu, X., Heat pump assists in energy transition: Challenges and approaches. *DeCarbon*, **3**, 100033, 2024.
- [10] Serale, G., Fiorentini, M., Capozzoli, A., Bernardini, D. & Bemporad, A., Model predictive control (MPC) for enhancing building and HVAC system energy efficiency: Problem formulation, applications and opportunities. *Energies*, **11**, p. 631, 2018.



- [11] Milev, G., Al-Habaibeh, A., Fanshawe, A. & Siena, F.L., Investigating the effect of the defrost cycles of air-source heat pumps on their electricity demand in residential buildings. *Energy and Buildings*, **300**, 113656, 2023.
- [12] Klingebiel, J. et al., Optimal defrost initiation for air-source heat pumps: Evaluating the improvement potential of common defrosting controllers. *Energy*, **324**, 135871, 2025.
- [13] Ali, M.F., Perticaroli, F., Marra, L., Pepe, C. & Zanolì, S.M., Impact of buffer sizing on heat pump performances for residential applications. *Proceedings of the 2025 26th International Carpathian Control Conference*, pp. 1–6, 2025.

