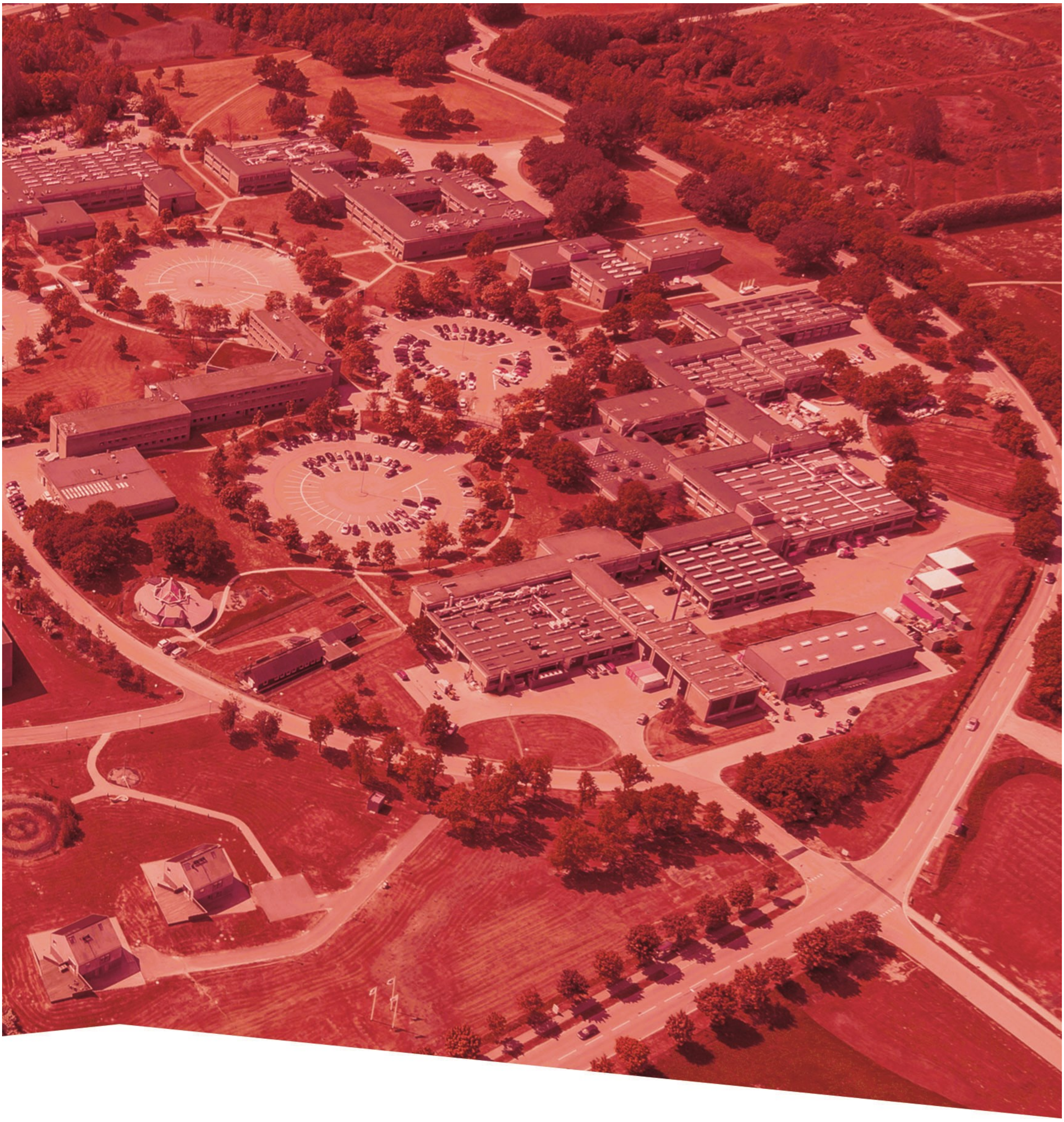

Deliverable 6.1

Demonstration of digital twins for supermarket refrigeration systems

Digital twins for large-scale heat pumps and refrigeration systems

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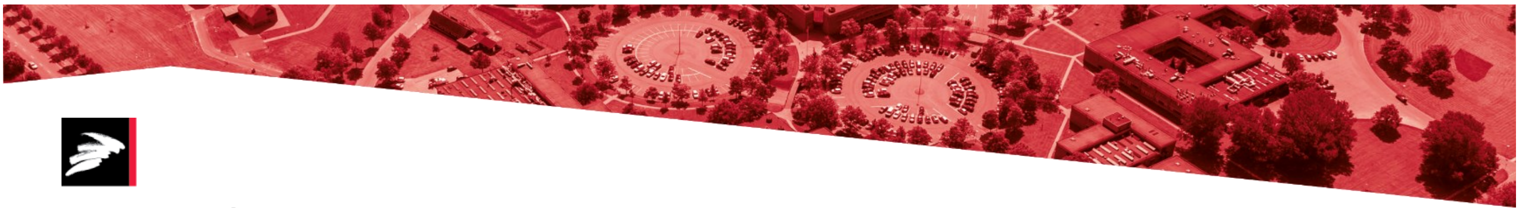

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Demonstration of digital twins for supermarket refrigeration systems

Digital twins for large-scale heat pumps and refrigeration systems

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Contents

1. Introduction

Supermarkets play a pivotal role in our societies, providing essential goods and services. On average, they are responsible for about 3-4% of the electricity consumption of industrialised countries [1]. Up to 50% of this consumption is due to the refrigeration systems used for cooling the display cases and cold rooms where food is stored [2]. Heating, ventilation, and air conditioning (HVAC), together with lighting, account for the remainder. Moreover, supermarkets are responsible for both direct and indirect carbon dioxide (CO_2) emissions. The former stem from leakages from the HVAC and refrigeration systems, while the latter are related to the supermarket electricity consumption. It is thus clear that enhancing energy efficiency of supermarkets is crucial not only for mitigating their carbon footprint and environmental impact, thus aligning with the growing emphasis on sustainable and environmentally conscious business practices, but also for reducing their high operational costs.

Supermarket owners often rely on service providers to cost-optimally run their refrigeration systems while ensuring the highest quality of food preservation. However, despite increasing levels of digitisation and automation, and increasing volumes of data available for decision-making, monitoring, set-point adjustment and alarm management still rely heavily on manual operations, leaving the full potential of the digital transformation untapped.

In this framework, the project "Digital Twin for large-scale heat pumps and refrigeration systems" funded by EUDP - Energy Technology Development and Demonstration Program, aims to leverage the power of data and digitization to develop adaptable, modular, and reusable digital tools that enhance the supermarket refrigeration business by offering advanced monitoring capabilities, efficient fault detection and diagnosis, and optimized operational performance.

The rest of this report is structured as follows: Section 2 provides an overview of the digital-twin technology, together with the services it can enable with a special focus on the retail sector. Then, Section 3 introduces the case studies analysed during the project and provides a description of a typical CO_2 refrigeration systems. The modelling framework used to develop the digital twin of a CO_2 refrigeration system is described in detail in the last part of the section. Next, Section 4 summarises the main results achieved during the project in terms of both simulations and subsequent field trials. Finally, Section 5 summarises the main conclusion obtained by the project.

2. Digital-twin based services for supermarkets

Over the past decades, we assisted at the exponential growth in the volume of data available to businesses, catalysed by the fast-paced development of digitalisation and technical advancement in Information and Communication Technologies (ICT). The ability of companies to harness this growing volume of data by converting it into valuable information is key to creating value, business innovation and increasing competitiveness. Despite that, only about 30% of this data is used for decision-making, while the remaining part goes unleveraged [3].

Within this framework, digital twins have emerged as a powerful technology, capable of transforming data into insightful information that supports business decision-making and improves business performance, improving efficiency and reducing costs.

As their name suggests, digital twins are virtual representations (counterparts) of physical objects, systems, or processes. The virtual model is developed using advance numerical models, which include physics-based (or first-principles) models, statistical (or data-driven) models, and a combination of both with the so-called grey-box models [4]. The choice of the modelling approach depends on the intended scope of use of the digital twin and can also result in a combination of two or more approaches. The virtual model is designed to accurately reproduce the behaviour of the physical system it mirrors and therefore it serves as a simulation platform for product design, simulation, system integration, and operational optimisation. But a digital twin is much more than a simulation tool. Indeed, the integration of the virtual model with real-time operational data enables further services, such as: advanced system monitoring, fault detection and diagnosis, and predictive analysis. Figure 1 shows the closed loop through which digital twins can bring value into a business.

As for supermarkets, where energy consumption is a major operational concern, digital twins can play a key role in increasing energy efficiency and reducing costs. More specifically, digital twin-based services for supermarkets can include:

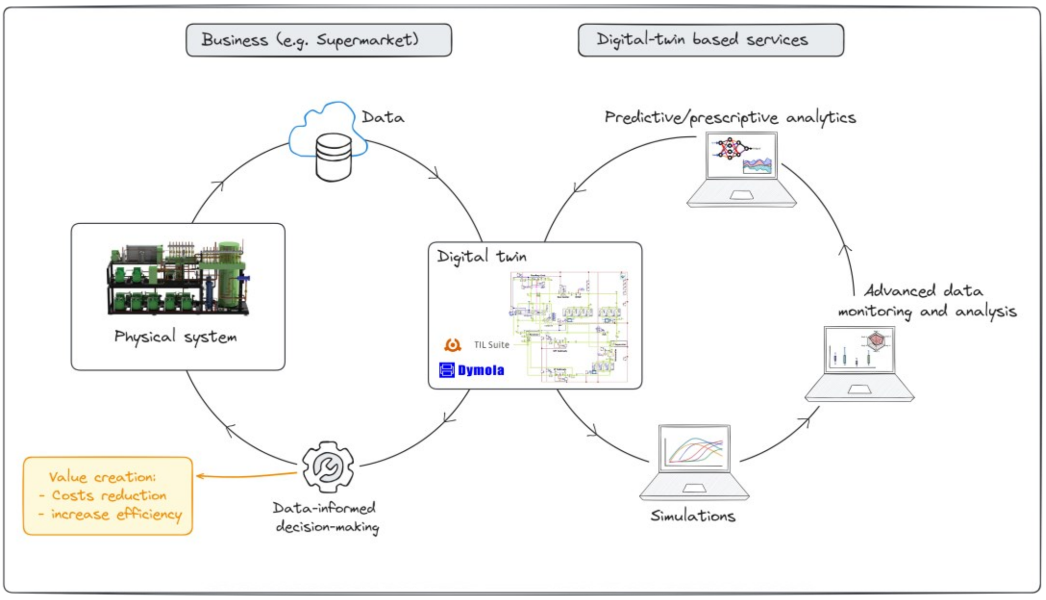


Figure 1: Digital-twin value creation loop.

1. **Real-time monitoring and analysis:** continuous collection and analysis of data from temperature sensors, energy meters, and control systems. This enables the identification of potential inefficiencies, such as anomalous consumption patterns, and offers the possibility to implement corrective measures, thus enhancing the overall system performance.

2. **Operational (set-points) optimisation:** use of simulations and scenario testing to analyse and fine-tune operational parameters, e.g. controllers' set-points, to enhance efficiency, minimize energy consumption, and optimize overall performance.

3. **Predictive analytics:** by closely mirroring the dynamics of their physical counterparts, digital twins enable the deployment of predictive control methods, such as model predictive control (MPC). These methods determine the optimal control action by not only considering the current state of the system but also taking into consideration future boundary conditions, such as varying electricity prices, weather forecasts, and load forecasts. This enables the refinement of set-point optimisation strategies over time.

4. **Condition monitoring:** digital twins can improve fault detection and diagnosis (FDD) by integrating real-time monitoring with simulation and predictive analysis. This allows to detect and diagnose fault mechanisms before or at an early stage of their occurrence, helps reduce unexpected failures and equipment downtime and extend the overall life of systems and components.

During the project, activities on supermarket refrigeration mainly focused on operational optimisation. In this respect, a digital twin of a supermarket refrigeration system has been developed with the aim of:

- investigating the dynamic relations among subsystems, with a focus on the interaction between display cabinets and compressor rack, and their impact on the energy consumption of the refrigeration system.
- Assessing with the aid of simulations the energy saving potential of different control strategies for both the compressor rack and the display cabinets (building on the knowledge gained from the previous point).
- testing the improved control measures/settings in real applications.

Alongside these activities, it has also been carried out research on fault-detection algorithms and heat recovery. A detailed description of the developed fault-detection algorithms can be found in Green et al. [5].

3. Case studies

To develop the digital twin of a supermarket refrigeration system and demonstrate its potential in real-life applications, five supermarkets were initially considered. These are all equipped with CO_2 refrigeration systems and, despite some differences in their layout, present the same general structure. A more detailed description of the main components of a CO_2 refrigeration system is provided in the following sections.

Table 1: Description of the supermarkets involved in the project.

Store name	Location	Country	Size	System type
Fakta	Otterup	Denmark	Small	Air cooled booster, no heat recovery
SuperBrugsen	Otterup	Denmark	Medium	Air cooled booster, prepared for heat recovery
SuperBrugsen	Kerteminde	Denmark	Large	Air cooled booster with heat recovery

However, only in Fakta Otterup and SuperBrugsen Otterup was it possible to demonstrate the results of the project due to technical problems which arose during project execution in the other supermarkets. More specifically, SB Kerteminde experienced a leak in the heat recovery heat exchanger that was not possible to be fixed before the conclusion of the project.

3.1. CO_2 refrigeration system with heat recovery

The use of CO_2 as a refrigerant is not something new. Its first applications date back to the end of the nineteenth century, when CO_2 was extensively used in marine refrigeration due to its safety (i.e. nontoxicity and non-flammability) compared to other refrigerants. In the middle of the twentieth century, CO_2 faced a period of progressive abandonment mainly due to the introduction of halocarbons and unsolved technical challenges, such as high-pressure containment problems and capacity and efficiency loss at high ambient temperature [6]. Nowadays, the increasing attention to environmental concerns, such as global warming and ozone depletion, stringent environmental policies, and advancements in CO_2 refrigeration technology, have dusted off the interest in CO_2 as a refrigerant, as confirmed by the market share that CO_2 systems have taken over the last years. Among other things, CO_2 offers a very good possibility of reclaiming waste heat to be used to satisfy the local heat demand or to be sold to a district heating network, thus generating an additional cash flow, and reducing the system operational costs.

Figure 2 shows the layout of a CO_2 refrigeration system with heat recovery used in supermarket refrigeration.

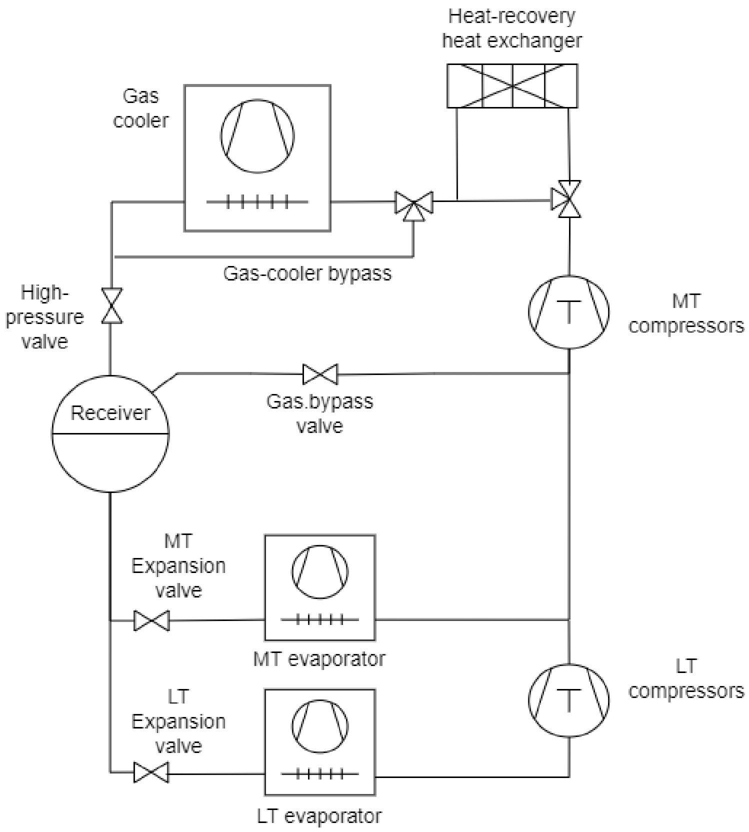


Figure 2: Simplified schematic of a CO_2 refrigeration system with heat recovery.

This system, called "booster", is the most adopted solution for supermarkets and consists of various subsystems, namely: two groups of evaporators, one for the freezing demand at low evaporating temperatures (LT), and one for the cooling demand at medium evaporating temperature (MT), two compression groups, a condenser/gas cooler, a high-pressure valve (HPV), a flash gas bypass valve (FGBP), and a liquid receiver. The compression group consists of two or more compressors operating in parallel on the two stages connected with the LT and MT cabinets. The compressors of the LT stage operate under subcritical conditions, while those of the MT stage can operate under both subcritical and transcritical conditions depending on the external temperature conditions. Moreover, in each compression group the first compressor is often speed controlled while all the others run at constant speed and are on/off controlled. The LT and MT evaporators are located inside the refrigerated display cases and cold rooms in the supermarket sales area, while all the other components are located in a dedicated technical room.

As for the control of the system, it is possible to distinguish between two main types of controllers:

- Pack controller: it controls the suction (evaporation) pressure, the receiver pressure, and the gas cooler pressure and outlet temperature. The suction pressure is controlled by varying the engaged compressor capacity, so that it can adapt to the different load conditions, while ensuring the desired evaporation temperature. This is usually done by coupling an inverter-driven, or variable speed, compressor with one or more fixed-speed compressors. This ensures a continuous capacity modulation within the whole operational range, if the capacity of the variable speed compressor covers the full gap among the capacity steps of the fixed-speed compressors. The receiver pressure is controlled through the flash gas-bypass valve. Lastly, the gas cooler pressure and outlet temperature are controlled through the high-pressure valve and the gas cooler fans, respectively. More details about the pack controller can be found in [7].
- Cabinets' controller: each display cabinet is equipped with a controller that meters the flow of refrigerant into the evaporator to maintain the air temperature in the display cabinet and ensure a safe superheat at the evaporator outlet. This is done by controlling the opening time of the solenoid valve or, alternatively, the electronic expansion valve, that feeds liquid refrigerant into the cabinet evaporator. For additional details, the reader can refer to [8].

3.2. Digital twin model of supermarket refrigeration systems

The basic configuration (almost standard in Denmark) of a CO_2 booster system consists of the components shown in Figure 2. All the supermarkets involved in the project (see Table 1) share this layout. Therefore, to define a general and scalable model to be used in each specific application/case study, these main components constituted the basic structure from which the development of the digital twin began.

Following this structure, an analytical/numerical model, i.e. digital twin, of a CO_2 booster system was developed in Modelica [9] using TIL Suite [10], an external library of TLK-Thermo which contains a wide range of models for modelling thermodynamic systems. These models are fully based on the physical laws governing the system/process being modelled, i.e. continuity, momentum, and energy equations. Therefore, their parameters are fully interpretable and can be identified from expert knowledge and manufacturer datasheets. However, in practice the model parametrisation can be complicated by outdated documentation of the system and its components, undocumented changes, or missing information. In this cases, data-driven models represent an effective way to solve this problem by estimating unknown parameters directly from the data.

This is usually the case for the display cabinets of supermarkets for which key parameters like the infiltration rate, heat conduction through the cabinet, and evaporators' overall heat transfer coefficients are not initially known. Instead, they can be estimated from historical data utilizing statistical methods. In the project, the so-called grey-box modelling approach has been used.

These models integrate both physical understanding and statistical methods, and have demonstrated their effectiveness in modelling dynamic systems like supermarket refrigeration plants [11]. They estimate the unknown parameters of a defined model structure (derived from prior physical knowledge) from data using statistical parameter estimation techniques. Unlike physics-based models, grey-box models can also include uncertainty effect into the model, e.g. the stochastic behaviour of customers which influences the frequency of door opening in closed display cabinets, hence the estimation of the air infiltration rate. In particular, a lumped-parameter description of the cabinets' dynamics was derived from heat and mass balance equations, and their parameters estimated from historical data using the maximum likelihood estimation method. A detailed description of the cabinet models used in the project can be found in Schulte et al. [12] and Leerbeck et al. [13,14,15]. The individual compressors of the compressor rack, the receiver and the condenser/gas cooler were instead modelled using physics-based models from the TIL library.

Finally, the overall model was exported as a Functional Mock-up Unit and integrated in MATLAB, where it was coupled with a Simulink model of the Danfoss pack controlled used to control the actual supermarket refrigeration systems.

Establishing a closed-loop connection between two systems, this setup facilitated the analysis of the dynamic interaction between the control algorithm and the controlled system through co-simulations, which led to the optimisation of the overall system performance.

Figure 3 shows a schematic of the developed digital twin modelling and co-simulation framework.

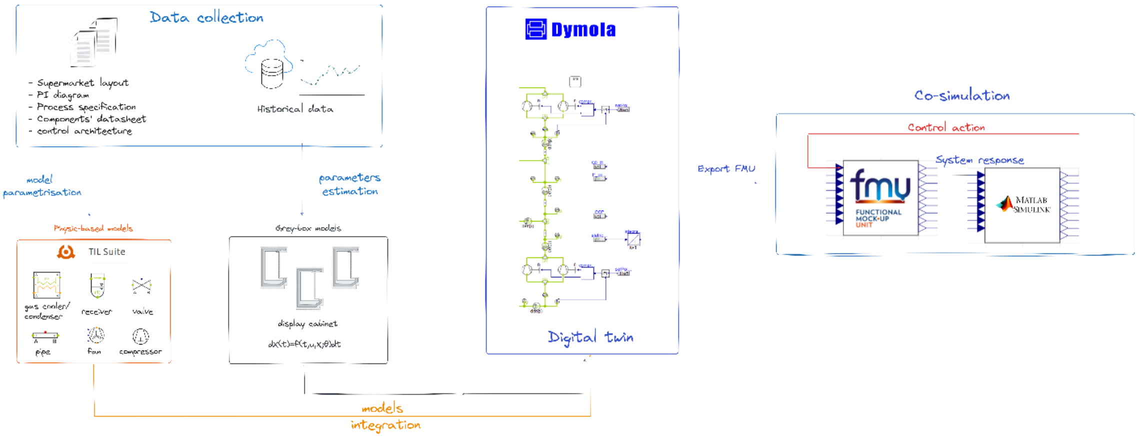


Figure 3: Schematic of the adopted digital twin modelling framework.

Before being used for the intended investigation, the digital model was validated by comparing the evaporation pressures, cooling loads, and compressors power and capacity profiles with actual operational data fetched from the supermarket monitoring systems. Details about the validation procedure can be found in [12].

Digital twin of the supermarket Fakta Otterup

The modelling framework described above has been used to model the supermarket Fakta in Otterup (DK). This choice stemmed from the large amount of data available in that supermarket for model development and validation. Indeed, unlike other supermarkets, the Fakta store was equipped with additional measurement points due to its participation in the previous research project ESO-2 [16].

The layout of the refrigeration system is analogous to the one shown in Figure 1, but without heat recovery. The MT group consists of one variable-speed and one fixed-speed compressor. The maximum capacity of the variable speed compressor is approximately 80% of the capacity of the fixed speed compressor, which ensures an almost continuous capacity modulation. Conversely, the LT suction group consists of two fixed speed compressors and can therefore provide stepped capacity control. However, despite the possibility of a smoother regulation, the MT group suffers from efficiency losses during part load operation and start/stop of the first compressor.
As for the display cabinets, the MT and LT groups consists of seven and four evaporators, respectively, which are operated day and night at a fixed evaporation temperature reference of, respectively, -8 °C and -30°C.

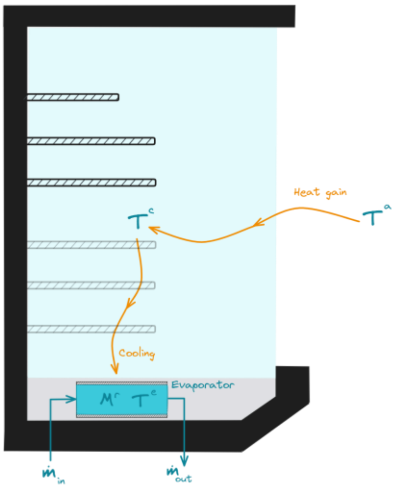
Once developed, the model has been used to investigate through dynamic simulations the dynamic interactions between the different components of the refrigeration system, in particular between the compressor pack and display cabinets and their related controllers, and their impact on the overall power consumption. Afterwards, the model has been used to assess the energy and cost-saving potential of different control strategies developed based on the initial investigation. Finally, the main findings of the simulation results have been tested in the actual supermarket and in the supermarket SuperBrugsen also located in Otterup (DK) for further validation.

4. Boosting energy efficiency through digital twins

The present section introduces the main results of the project in the field of supermarket refrigeration achieved using the co-simulation framework described above.

4.1. Grey-box modelling of supermarket display cabinets

As mentioned above, display cabinets were modelled using the so-called grey-box modelling approach. The model consisted of a lumped-parameter description of the cabinets' dynamics derived from heat and mass balance equations, whose parameters were estimated directly from data using statistical techniques.
By way of example, equations 1 and 2 shows one of the state-space models developed during the project to model a single display cabinet.



$$dT^c = \frac{1}{C_c} \cdot [UA_{load}(T^a - T^c) + M^r UA_m(T^e - T^c)]dt + \sigma_c d\omega_c \quad (1)$$

$$dM^r = (\dot{m}_{in} - \dot{m}_{out})dt + \sigma_r d\omega_r \quad (2)$$

$$\dot{m}_{out} = \frac{UA_m M^r}{\Delta h_e} \quad (3)$$

Figure 4: Schematic of the display cabinet and the simplified heat and mass balance described by Equations 1 and 2. In blue the model parameters.

UA_{load}, UA_m, C_c, σ_r and σ_c are the parameter to be estimated. UA_{load} and UA_m are the overall heat transfer coefficients of the envelope and evaporator of the cabinet, respectively. Cc is the heat capacity of the air inside the cabinet, while σ_r and σ_c are the incremental standard deviation of the process. T^c and M^r are the variables of which we wanted to model the dynamic, i.e. the cabinet temperature and the mass of refrigerant inside the evaporator of the cabinet. In this respect, it is worth mentioning that the state representing the cabinet air temperatures also take into accounts the goods stored in the cabinet. More details about this modelling choice can be found in [14]. T^a, T^e, $\dot{m}_{in}$, and $\dot{m}_{out}$ are the ambient temperature, evaporation temperature, and mass flow of refrigerant entering and leaving the evaporator, respectively, and are inputs to the model. Δh_e is the enthalpy variation across the evaporator, and, as the previous parameters, is an input to the model. The last terms in Equations 1 and 2 are diffusion terms used to take into account the stochasticity of the dynamic process.

The model parameters were estimated using the maximum likelihood estimation method with the CTSM-R package in R. For a rigorous mathematical description of the estimation process the reader can refer to [17,18].

In [14], a similar model was developed with the aim of estimating the size of the expansion valves feeding the evaporators of the display cabinets with liquid refrigerant. This allowed the calculation of the mass flow through the valve, hence the cooling load on the cabinet.

In both works, results showed how the estimated parameters represent reliable estimates of the actual physical properties of the system, e.g. overall heat transfer coefficient or size of the expansion valve. Moreover, the models have proven to be robust in the prediction of the cabinet temperatures. However, the need of recursively estimate the model parameters to constantly adapt to the different load conditions has also been pointed out, especially when the model is intended to use for temperature prediction in a controller. It has been shown that grey box models can be used also for more informative applications, such as the classification of the cabinets' type. Last but not least, it is worth mentioning that the developed grey box models also enable the detection of faults in the system through the analysis of the model residuals and the tracking of the parameter estimates.

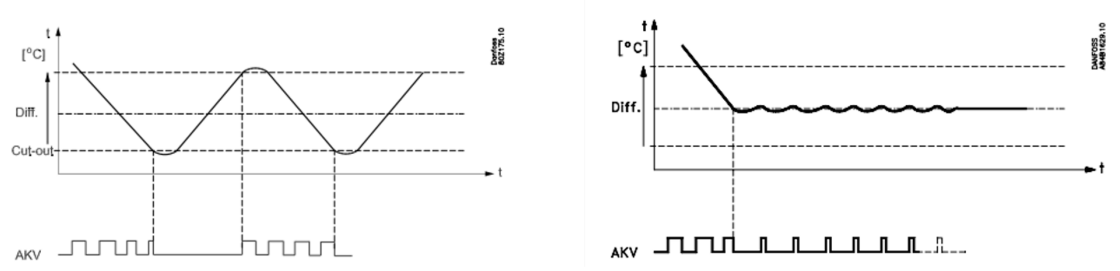
4.2. Influence of evaporation pressure dynamics on supermarket energy consumption

The power consumption of the compressor rack is one of the main drivers of supermarket energy consumption, and accounts for about 25% of the total electric energy usage. It is strongly influenced by the compression ratio, i.e. the ratio between discharge and suction pressures, which in a simple refrigeration cycle coincide, apart from pressure drops, with evaporation and condensation pressures. Larsen et al. [19], shown that rising the evaporation pressure is the most effective way to reduce the compressor lift, and hence the power consumption.

Moreover, operational data shows that in each display cabinet the evaporation pressure constantly fluctuates around its setpoint due to the action of the thermostats used to keep the cabinet's air temperature within the desired range and the control action of the pack controller. These fluctuations are reflected on the degree of superheat with which the refrigerant leaves the evaporators and which, together with the cabinet temperature, drives the opening and closing of the expansion valves feeding the evaporators. This gives rise to decreasing and increasing pressures in the suction line, which, in turn, trigger the pack controller that consequently decreases or increases the engaged compressor capacity

to match the cabinet loads and keep the suction pressure close to its setpoint. This dynamic interaction between the cabinets and pack controller which is behind the fluctuation of the evaporation pressure is suspected to lead to higher energy consumption levels on the compressor rack.
In view of this, and to improve the energy and cost efficiency, the digital twin of the supermarket refrigeration system was used to evaluate the impact of these fluctuations on the compressors' energy consumption. To do so, the original cabinets and pack control strategies, which represents our baseline, were compared against an improved strategy aimed at maintaining a higher and more stable evaporation pressure. The latter consisted of the following main changes:

- Switch of the cabinet's thermostat mode from **"ON/OFF"** to **"Modulating"**: In the baseline case, the cabinet's temperature was controlled through an ON/OFF strategy that open and close the expansion valve at the upper and lower bounds, respectively, of the defined temperature range (Figure 4a). Conversely, under the modulating temperature regulation the opening time of the expansion valve was controlled in such a way to restrict the flow of refrigerant to precisely the amount that is required to maintain the temperature at the required setpoint, while ensuring a minimum degree of superheat at the evaporator outlet (see Figure b). This favours a more constant evaporation temperature and better compressors' operating conditions.



(a) (b)

Figure 5: Thermostat control mode: ON/OFF (a); Modulating (b). Figures from Danfoss [7].

- Allow a **continuous compressors' modulation capacity**: In the baseline scenario, the LT compressors are fixed speed and therefore cannot smoothly adapt to continuous load variations. As a results, the mismatch between the compressors' capacity and the actual load causes fluctuations in the suction pressure, which, as mentioned above, are suspected to lead to non-optimal operating conditions. In view of this, to reduce the number of compressors' switching and shutdown of the last running compressor, the proposed control strategy allows compressors to continuously adapt their capacity to any load condition.

Simulation results

Simulation results are shown in Figures 6 and 7.

It can be noted that the proposed control strategy reduces the fluctuations of the evaporation pressure significantly. This is particularly evident for the LT suction line, while the pressure in the MT suction line still presents relatively high fluctuations, probably due to the impact of the mass flows coming from both the LT compressor and the flash gas-bypass valve. Similar results can be noted for the LT and MT compressor capacities for which the mean values remain unchanged, but the magnitude of their fluctuations reduces significantly. Lastly, it is worth noting that besides the reduction in the magnitude of the fluctuations of the evaporation pressure, it can be observed an increase in its mean value compared to the baseline case, especially at low load conditions. This suggests a reduction in the number of pump-downs and the consequent shut-down of the last running compressor.
As a result of the higher and more stable evaporation pressure, the LT and MT compressors show a lower power consumption compared to the baseline case. This confirms the initial assumption that a more stable evaporation pressure ensures better compressor performance, hence a lower energy consumption. Moreover, a more stable pressure allows the use of higher evaporation temperature's set-points, which, in turn, could lead to additional energy savings.

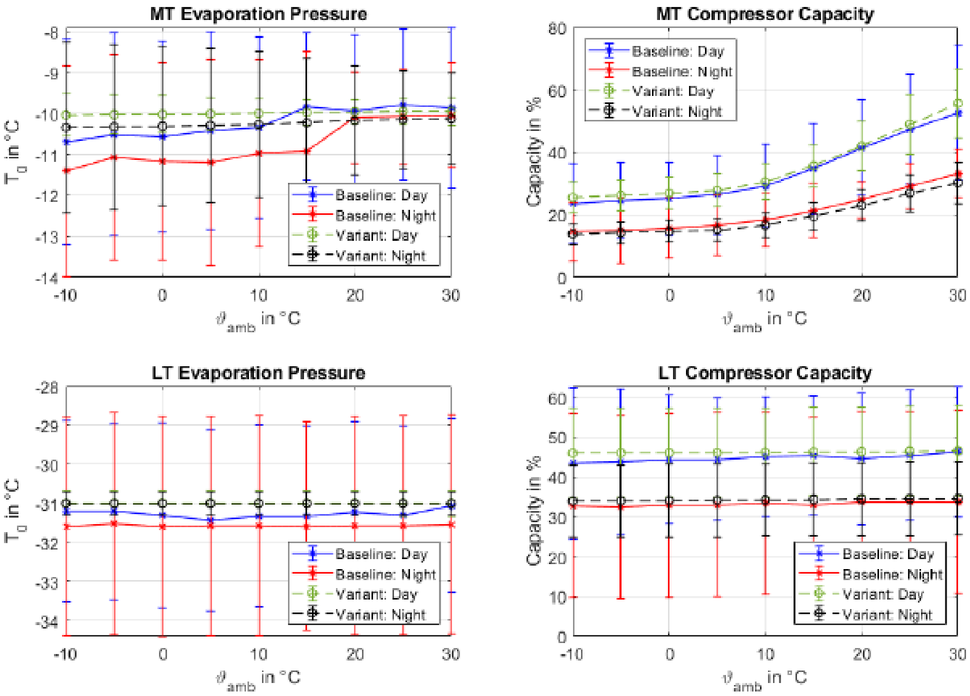


Figure 6: Comparison between the average evaporation pressure and compressor capacity in the baseline and improved control scenarios. Magnitude of fluctuations are also shown (Source: Schulte et al. [20]).

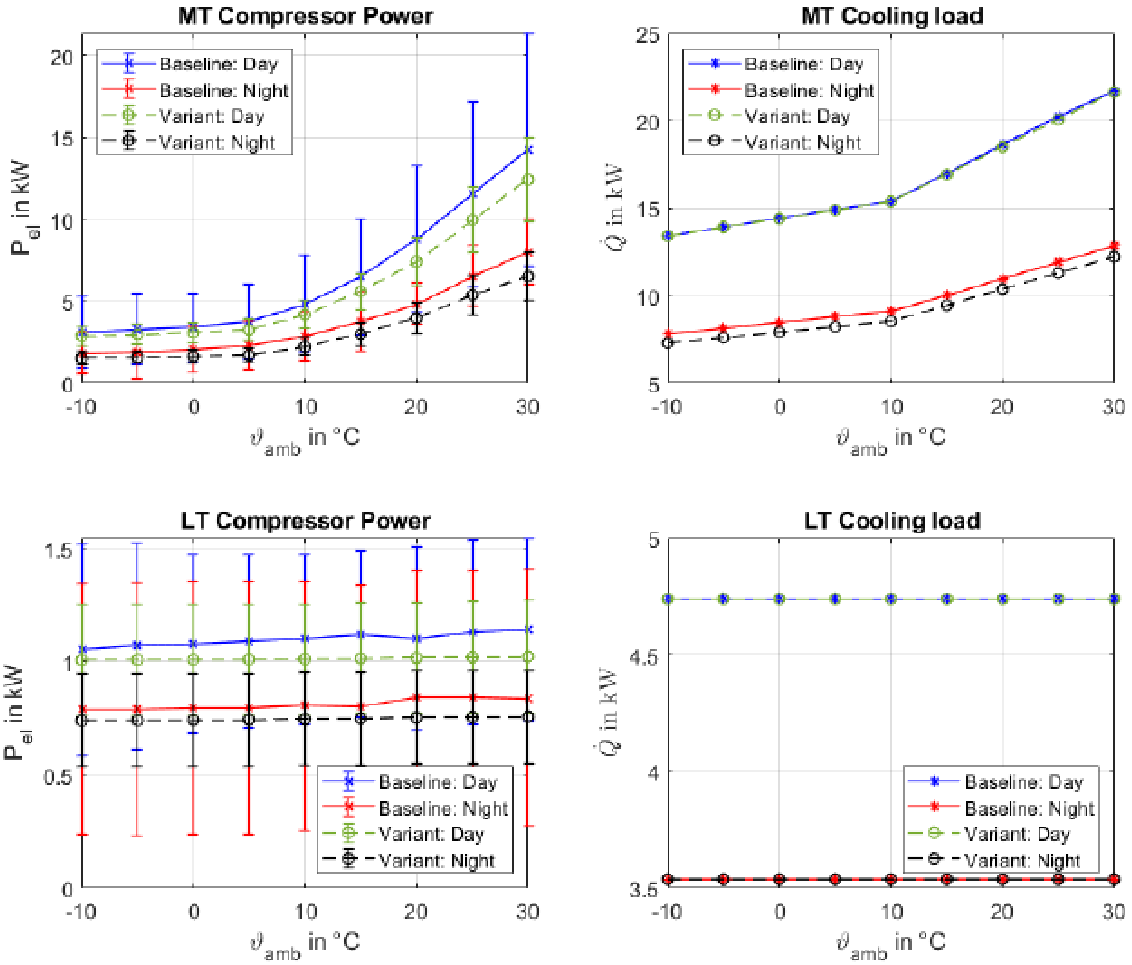


Figure 7: Comparison between the average compressor power and cooling load in the baseline and improved control scenarios. Magnitude of fluctuations are also shown (Source: Schulte et al. [20]).

4.3. Energy efficient control strategies in supermarket refrigeration systems

Once the model's capability to represent the dynamics of the display cabinets and the compressor rack together with their mutual interactions, was proven, the model was further used to investigate different control strategies for both the compressor rack and the display cabinets. The investigated control strategies are summarised in Tables 2 and 3.

Table 2: control modes for the LT cabinets and compressors.

		LT cabinet control mode	
		Thermostatic ON/OFF	Modulating
LT compressor control	Ideal variable speed	IdVar+Ther	IdVar+MTR
	Only Fixed speed	Stp+Ther	Stp+MTR

Table 3: control modes for the MT cabinets and compressors.

		MT cabinet control mode	
		Thermostatic ON/OFF	Modulating
MT compressor control	Ideal variable speed	IdVar+Ther	IdVar+MTR
	1 variable speed + fixed speed	VarStp+Ther	VarStp+MTR

Their performances were assessed in terms of annual power consumption of the compressor pack, COP and number of compressor start/stops.
Simulations were conducted considering the ambient temperature distribution of a typical Danish climate with values in the range -10/+35°C. For each temperature bin, a daily simulation run where performed at constant ambient temperature. Results have been finally weighted based on the frequency of the temperature bin within the distribution.

Simulation results

Figures 8 and 9 show the annual coefficient of performance versus the daily-average start/stop of the first compressor for the LT and MT suction group, respectively. The performances under ideal compressor modulation capacity, which represent the maximum achievable gains, are also represented for comparison purposes.

Starting with the LT group, it can be noted that, as previously shown, switching from thermostatic to modulating control leads to an improvement in the annual performance of about 2−2.5%. It can also be noted that the adoption of fixed speed compressors reduces the annual performance significantly, regardless of the control mode used for the display cabinets. This is mainly due to the part-load conditions occurring during the night, which force the first compressor to frequent start/stop, as confirmed by the high average of daily start/stop (see Figure 8). Moreover, it must be considered that, to avoid frequent cycling, the first compressor stops only after a minimum suction pressure has been reached. But this phase, also known as pump-down, has the effect of further lowering the evaporation pressure, thereby increasing the compressor energy consumption.

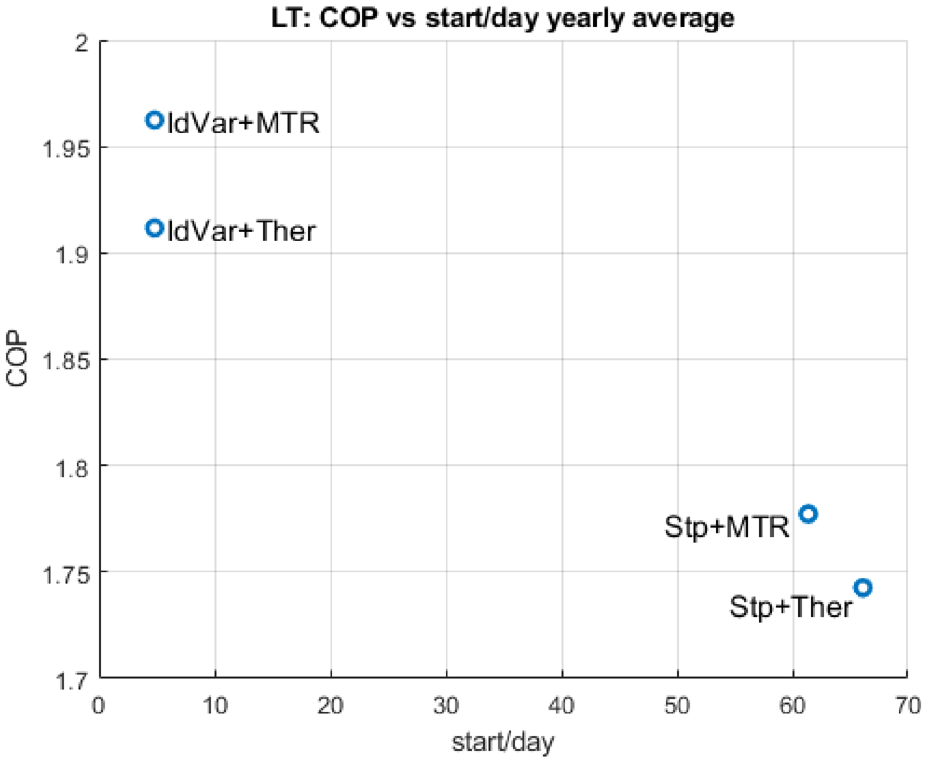


Figure 8: Low temperature compressors COP vs starts per day (Source: Schulte et al. [21]).

As for the MT suction group, the change from thermostatic to modulating mode benefits both the annual coefficient of performance and start/stop frequence. This is because the average cooling load at the most frequent ambient conditions enables the variable speed compressor to run close to its rated operational conditions, while minimizing part-load conditions. Lastly, it is worth noting that the gain of efficiency which follows the change from thermostatic to MTR is about 7%, i.e. ~3,5 times higher than the one observed for the LT group. Also in this case, the reasons behind the lower performance of the thermostatic control mode lie in the part-load operation which force frequent compressor's shut-downs and pump down periods.

We can therefore conclude that the most cost- and energy- efficient operations of a supermarket refrigeration system can be achieved by equipping the suction group with a variable speed compressor and adopting a modulating regulation of the temperature of the display cabinets. This is because it would ensure a more stable load and, hence, a more stable and efficient operation of the compression group. However, it is worth underlining that this must be accompanied by a proper dimensioning of the suction group, so that the variable speed compressor can run close to its rated speed most of the time. On the contrary, if only fixed-speed compressors are available, the operating mode of the thermostat of the display cabinets does not have a significant impact on the system performance.

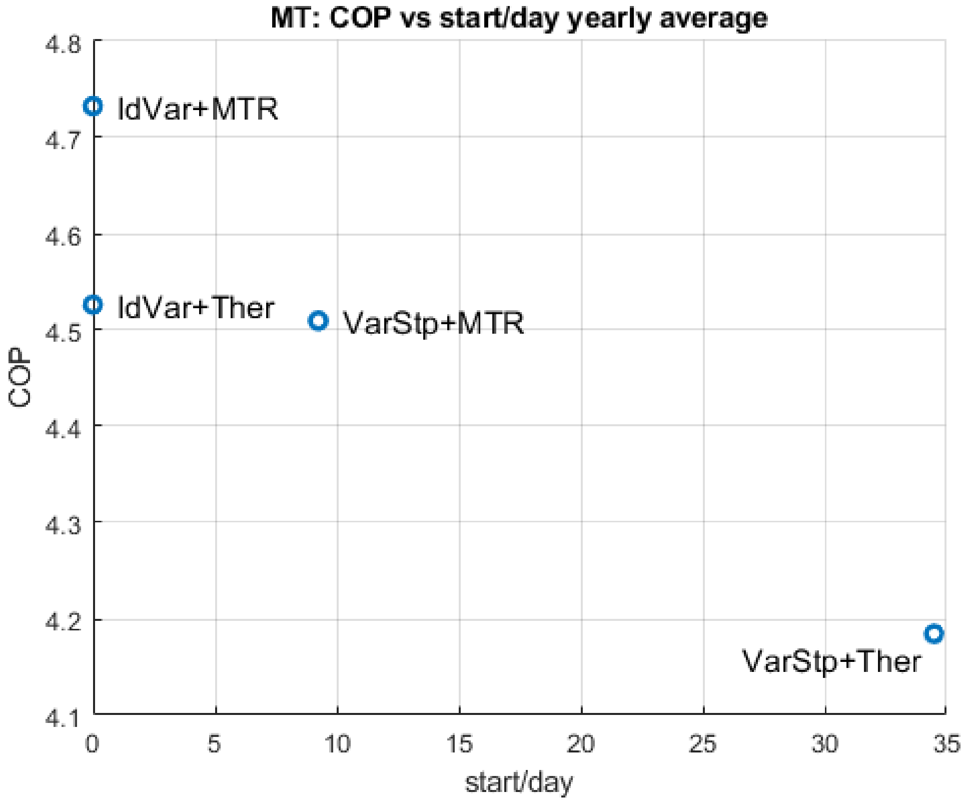


Figure 9: Medium temperature compressors COP vs starts per day (Source: Schulte et al. [21]).

4.4. Field trials

Field trials have been carried out in two different supermarkets to further validate the main findings of the simulation activities discussed in the previous sections. The two supermarkets were the Fakta store in Otterup, which was also used for model development, and the SuperBrugsen store also located in Otterup. The latter has the same characteristics as Fakta but is larger in size.

It is worth mentioning that the Fakta supermarket underwent renovation during the execution of the project, so it was no possible to carry out the tests under the same framework used in the simulations. In particular, cabinets were added, and the compressor pack was changed to a larger size where the LT suction group was equipped with a variable speed drive and the MT lead compressor was equipped with modulating unloaders enabling a more precise capacity control. However, despite these changes, the store can be considered comparable in its characteristics to its previous version. The control of the evaporation pressure was upgraded with a functionality that dynamically optimise the reference for the evaporation pressure based on the most-loaded cabinet, instead of keeping it constant. This was the experimental proof of the findings from the digital twin as described in the following section.

Fakta Otterup

The changes in the original control settings implemented during the field trials are summarized as follows:

- Before 8 August 2023: all cabinets in Thermostatic mode
- 8 August 2023: all cabinets switched from Thermostatic to MTR mode.
- 29 November 2023: Maximum limit for Po-optimization changed from -5 ºC till -2 ºC.

Experimental results confirmed the results from the simulation model discussed above.

Figures 10 and 11 show the distribution of the evaporation pressure during day and night operations for the MT and LT group, respectively, before and after the changes in the control settings.

It can be clearly observed that under MTR mode the evaporation pressure shows a more stable behavior, with fluctuations of half the amplitude of the thermostatic mode during both day and night. Residual fluctuations are most likely due to the neutral zone of the compressor controller, which aims to avoid too frequent control actions. It can also be noticed how the changes from Thermostatic to MTR affected positively also the average evaporation pressure, which for the MT group increased from -7.3 ºC to -3.9 ºC during the day, and from -11.3 to -2.9 during the night. A similar behavior can be noted for the LT group, although the increase in the average suction pressure was less pronounced changing from –30.9 ºC to -20.1 ºC during the day, and from -29.4 ºC to -27.4 ºC during the night.

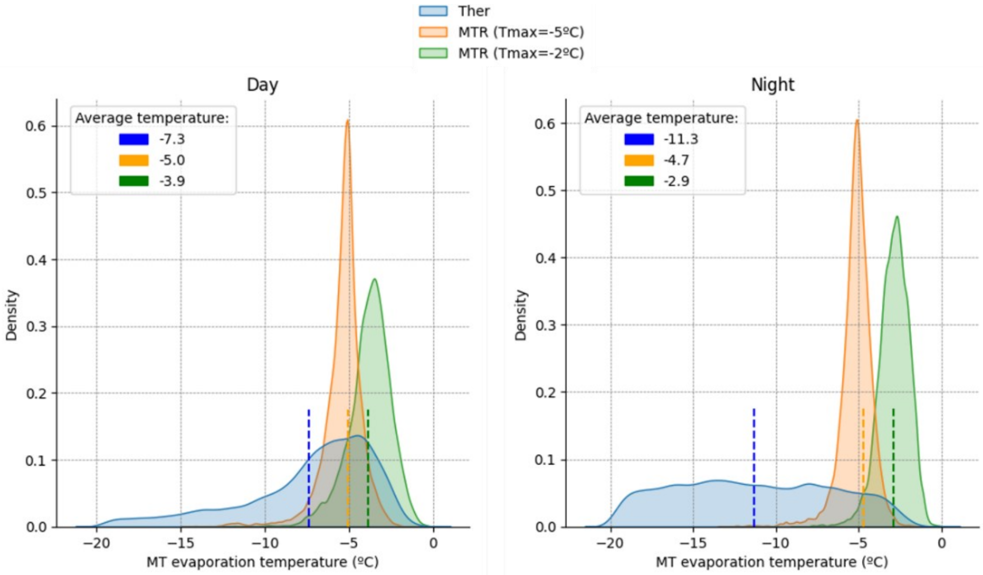


Figure 10: Medium temperature (MT) evaporation pressure fluctuation for thermostatic (THER) and modulating (MTR) mode.

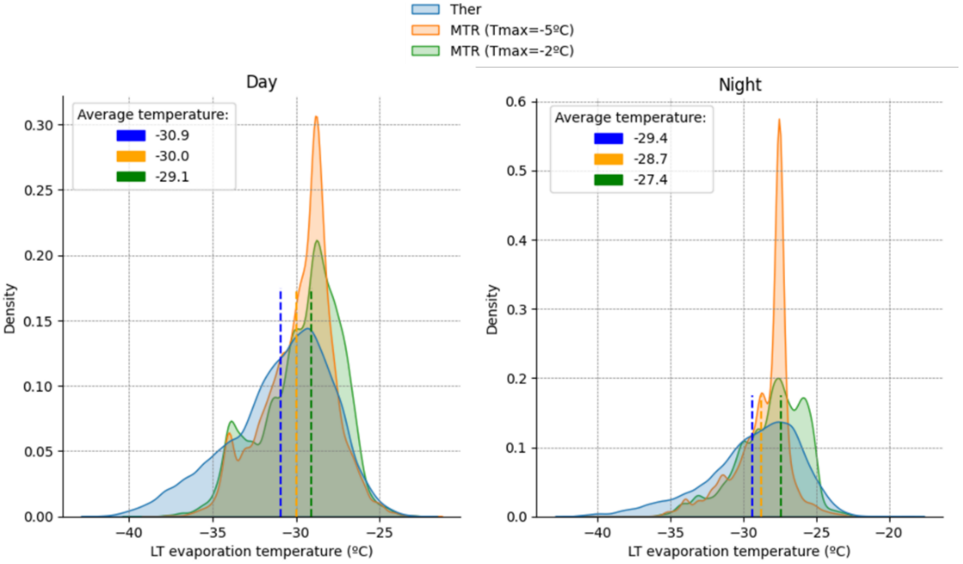


Figure 11: Low temperature (LT) evaporation pressure fluctuation for thermostatic (THER) and modulating (MTR) mode.

Figure 12 shows the power consumption of the compressor rack against the ambient temperature for the two tested control modes during day and night. As further proof of our initial hypothesis and simulation results, the compressor power in MTR mode is on average 2% lower than that required by thermostatic control across the whole operational range. Therefore, it can be argued that the annual energy consumption might be reduced by the same percentage.

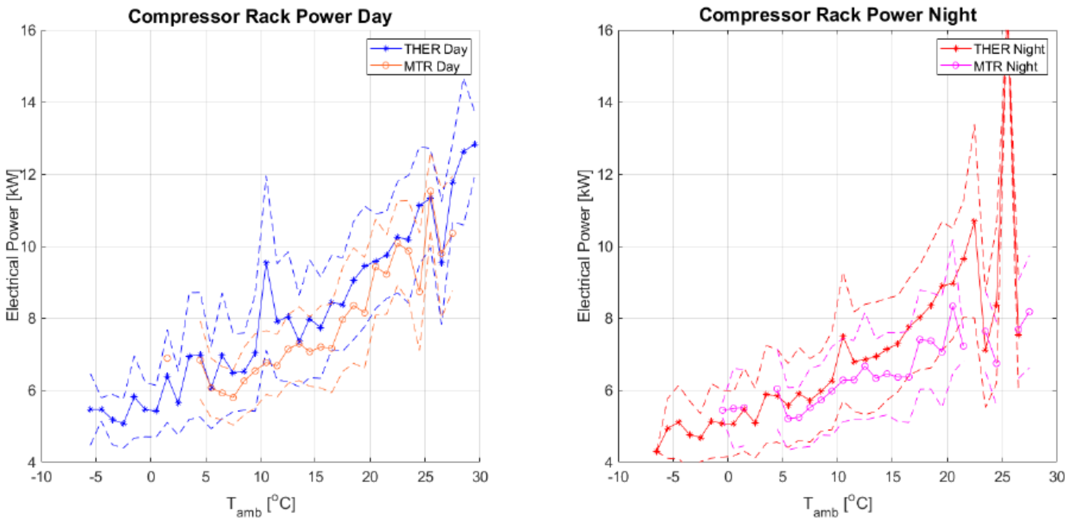


Figure 12: Comparison of compressor rack power for thermostatic (THER) and modulating (MTR) mode. Solid lines show the mean values and dashed lines show the standard deviation (Source: Schulte et al. [20]).

Lastly, Figures 13-14 and 15- 16 show the daily profiles, together with the average profile, of the evaporation temperature and the engaged compressor capacity of the MT and LT groups, respectively.

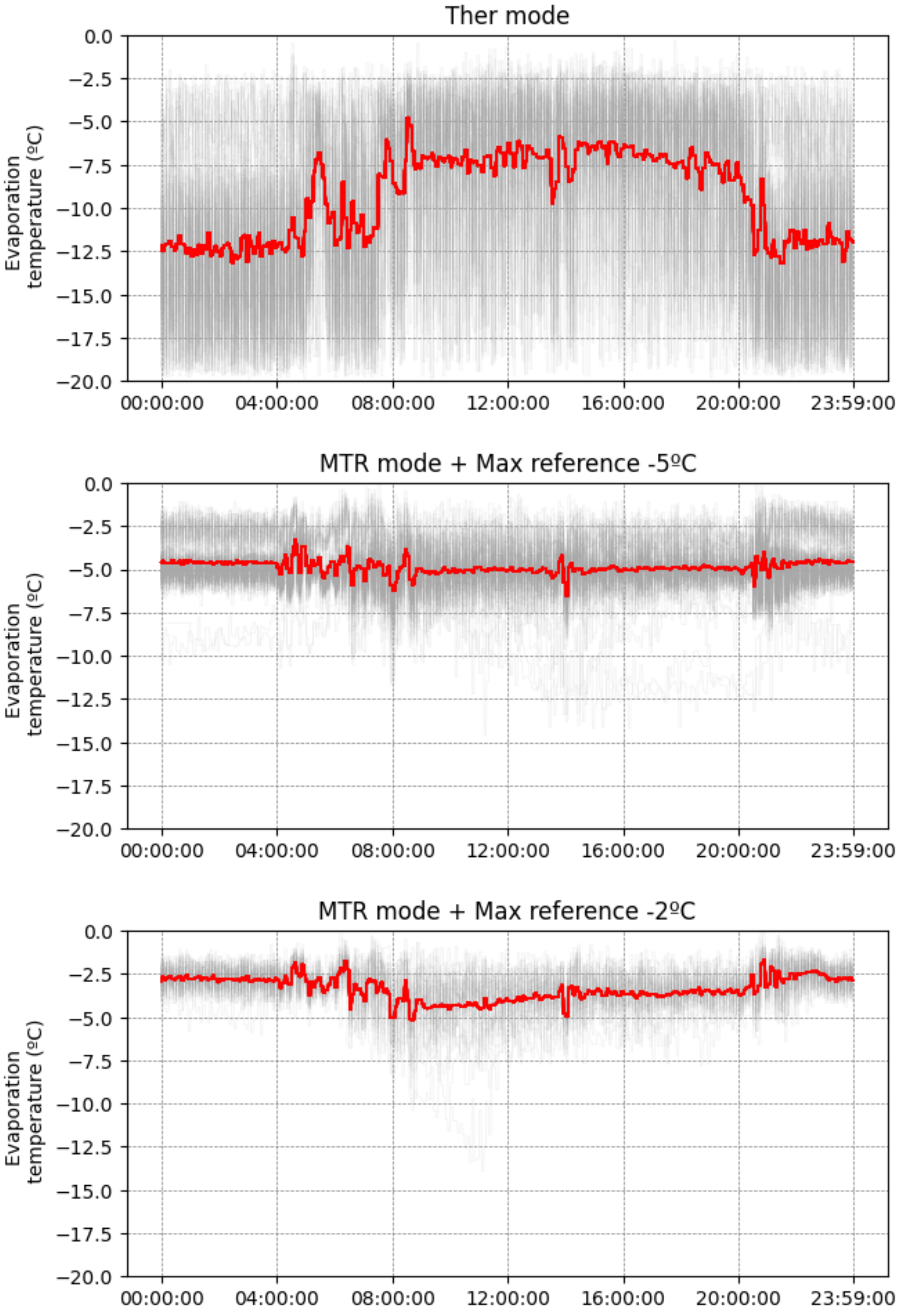


Figure 13: Average daily profiles of the evaporation temperature of the MT group.

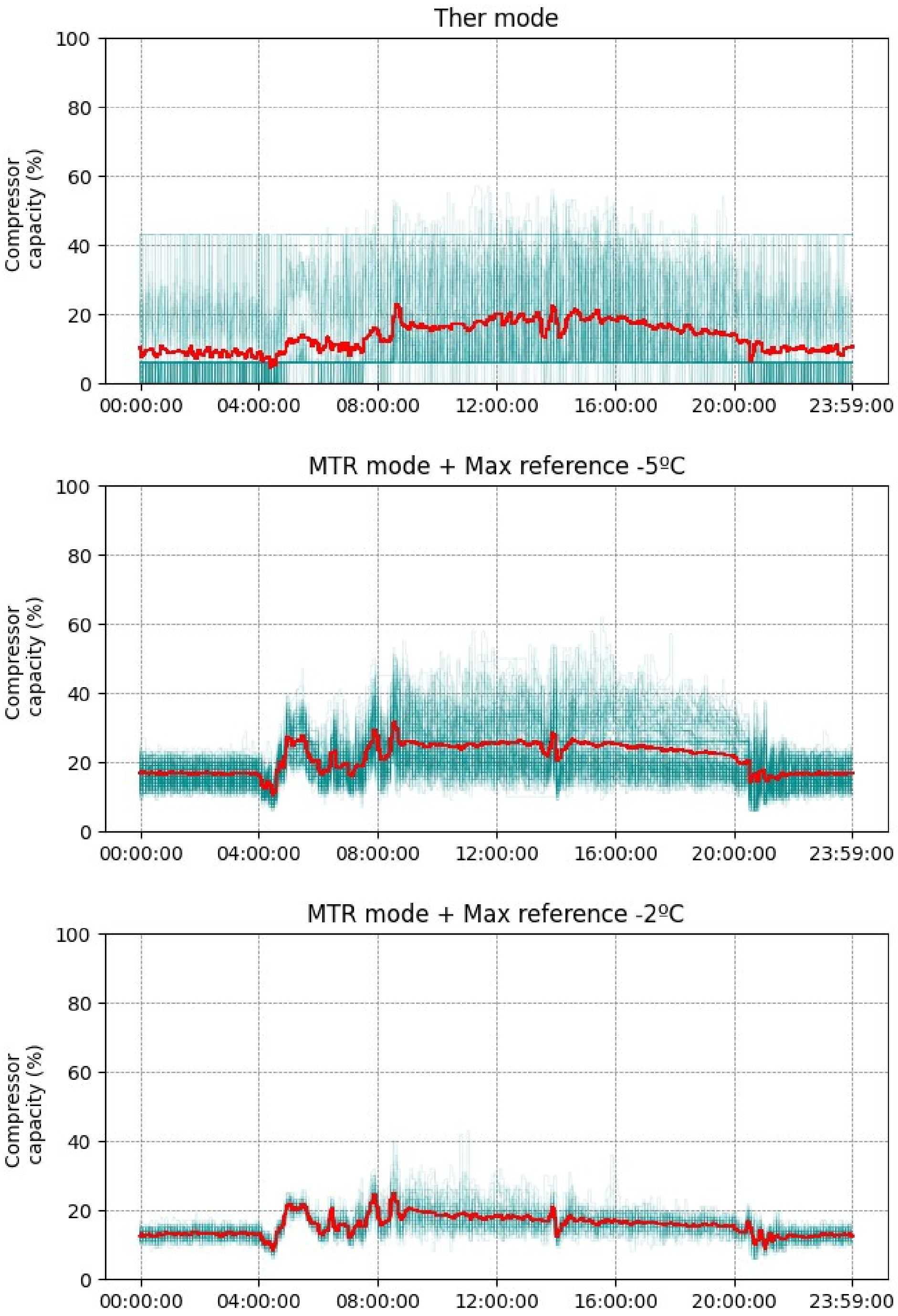


Figure 14: Average daily profiles of the engaged compressor capacity of the MT group.

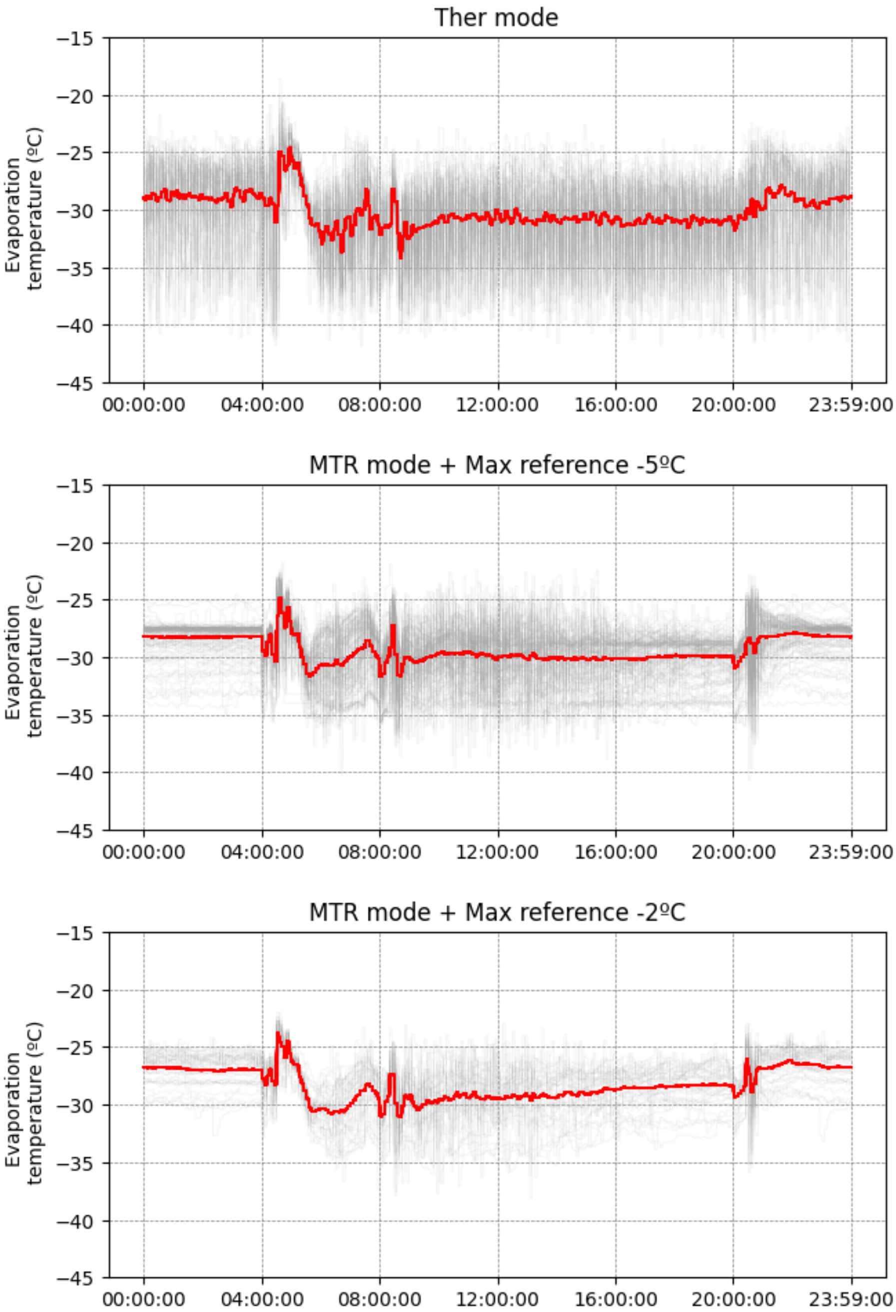


Figure 15: Average daily profiles of the evaporation temperature of the LT group.

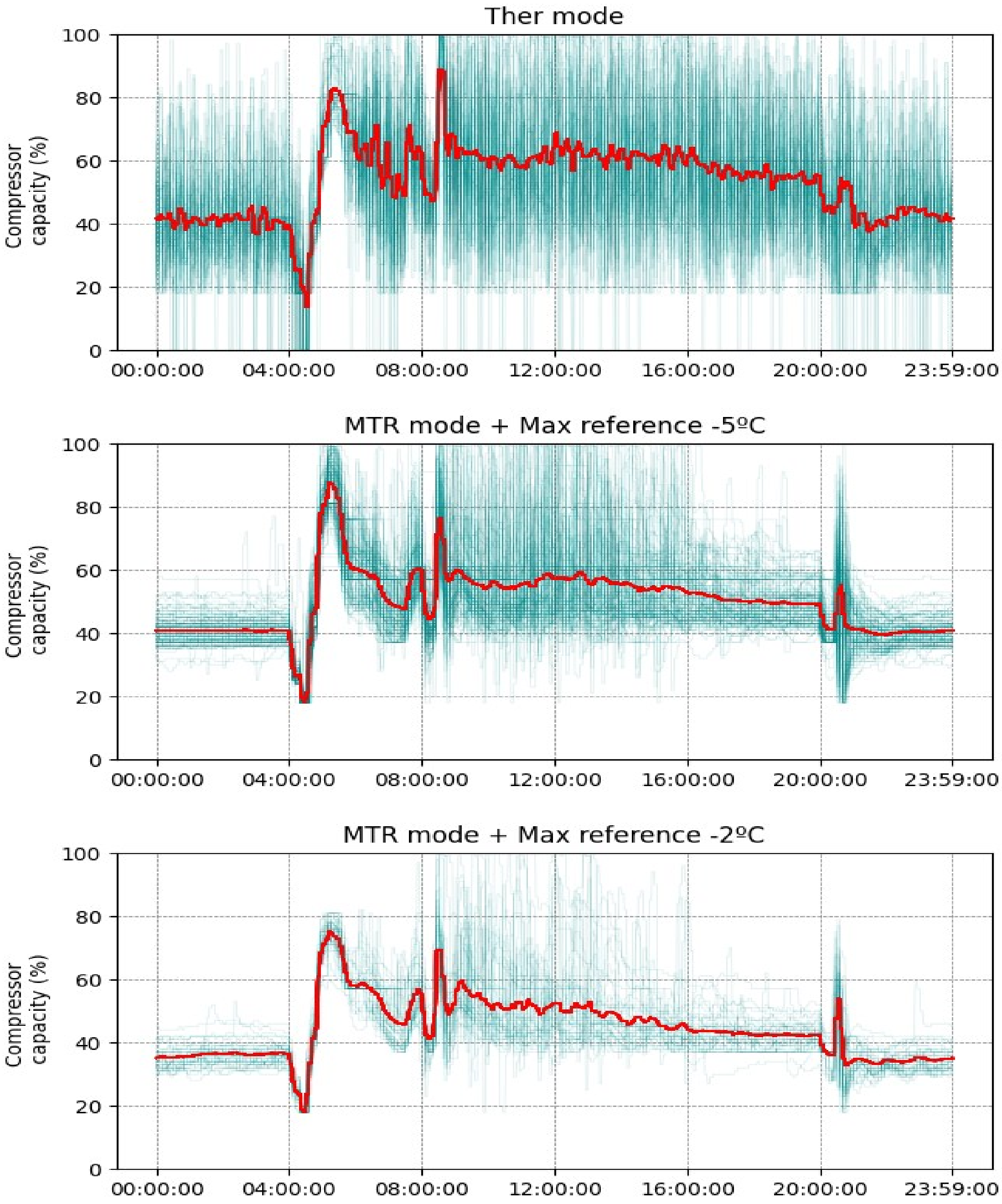


Figure 16: Average daily profiles of the engaged compressor capacity of the LT group.

SuperBrugsen Otterup

In SuperBrugsen we tested changes in control settings like those applied to the Fakta store. In particular, the following changes have been applied:

- Before 3 November 2023: all cabinets in Thermostatic mode.
- 3 November 2023: all cabinets changed from Thermostatic to MTR mode.
- 12 December 2023: Maximum limit for Po-optimization changed from -5 till -2.

Figures 17 and 18 show the distribution of the MT and LT evaporation pressure over the period between 1 September 2023 and 18 December 2023. It can be clearly seen the positive effect of the MTR control on the average value of the MT evaporation pressure, which increased from -11.1 ºC to -8.8 ºC during daily operation and from -10.2 ºC to -7.7 ºC during nighttime. The increase in the maximum reference limit of the evaporation temperature further contributed to lifting its average value by an additional degree in both daily and night operations. However, unlike the Fakta store, there is no significant variation in the fluctuation of the evaporation pressure. Furthermore, the LT group seems not to be affected by the changes in the control settings.

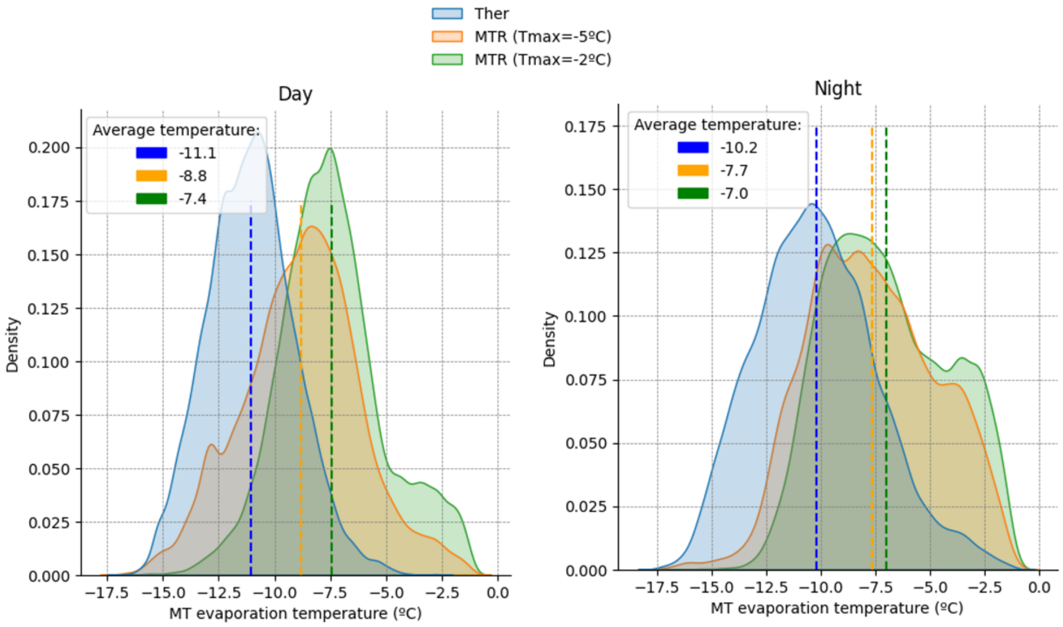


Figure 17: Distribution of the MT (a) and LT (b) evaporation pressure before and after the changes in the control settings.

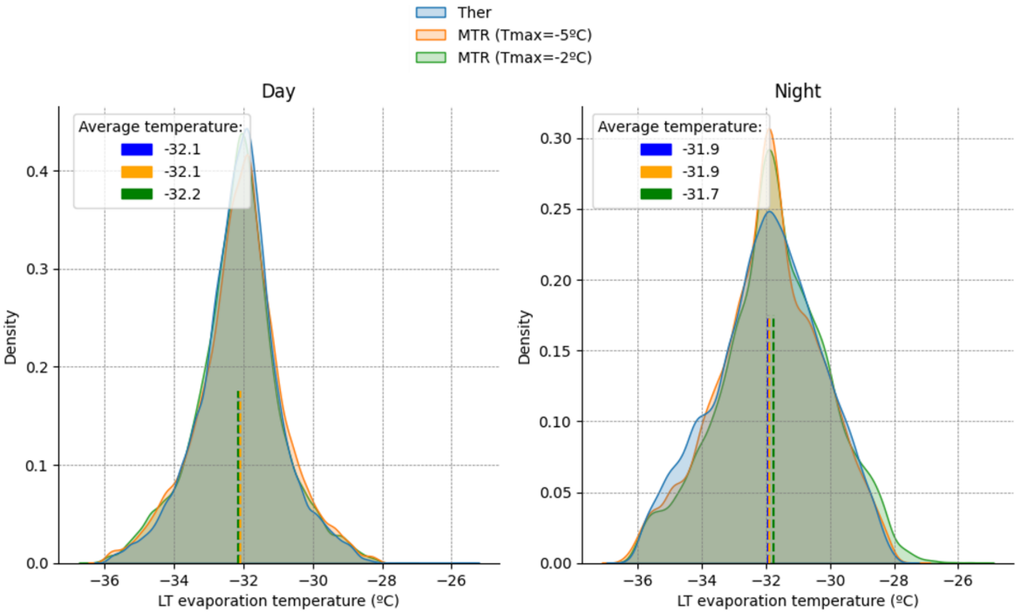
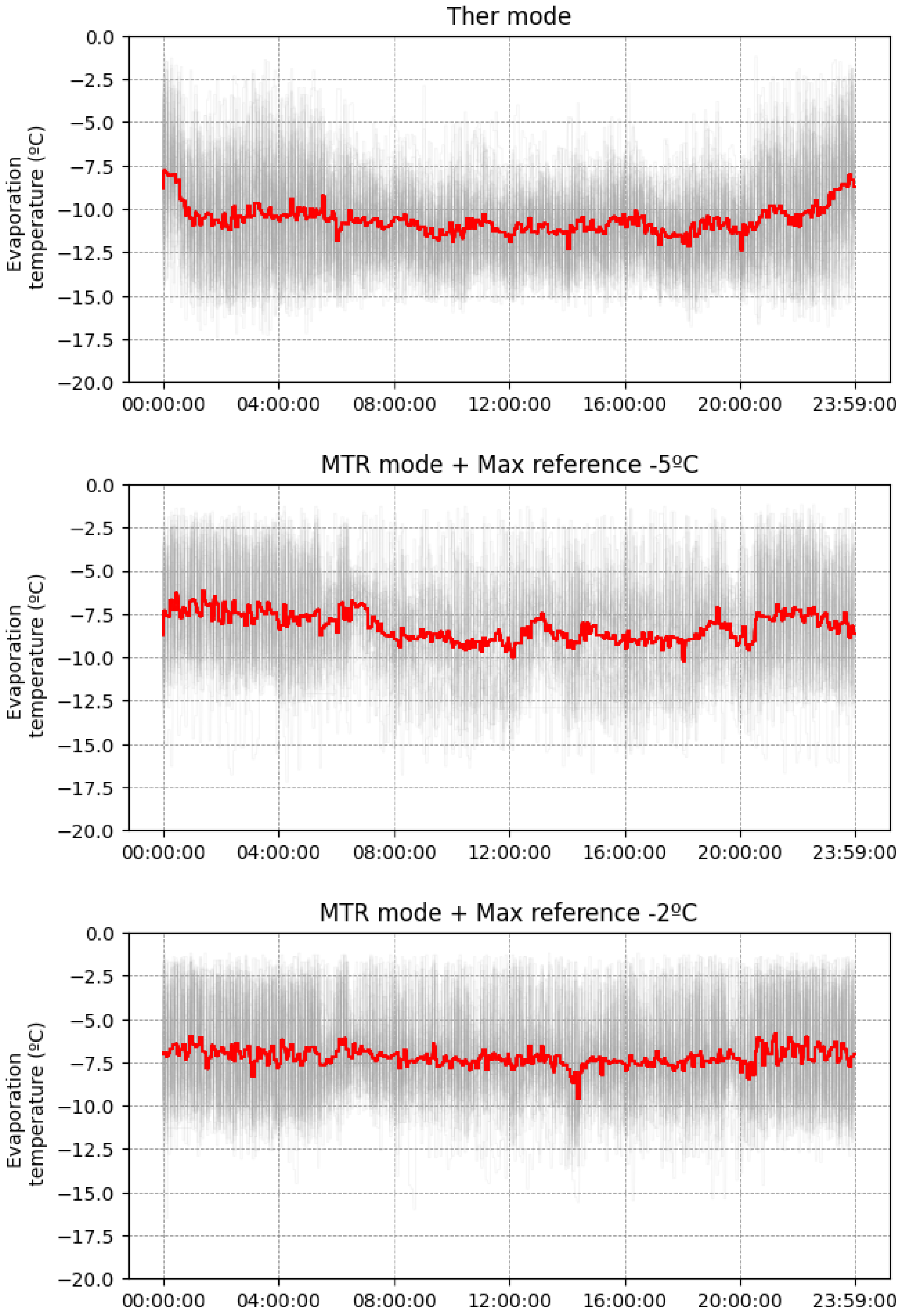


Figure 18: Low temperature (LT) evaporation pressure fluctuation for thermostatic (THER) and modulating (MTR) mode.

Also for these field trials, the daily profiles of the evaporation temperature and the engaged compressor capacity of the MT and LT groups are reported in Figures 19-20 and 21-22, respectively.


Ther mode

MTR mode + Max reference -5ºC

MTR mode + Max reference -2ºC

Figure 19: Average daily profiles of the evaporation temperature of the MT group.

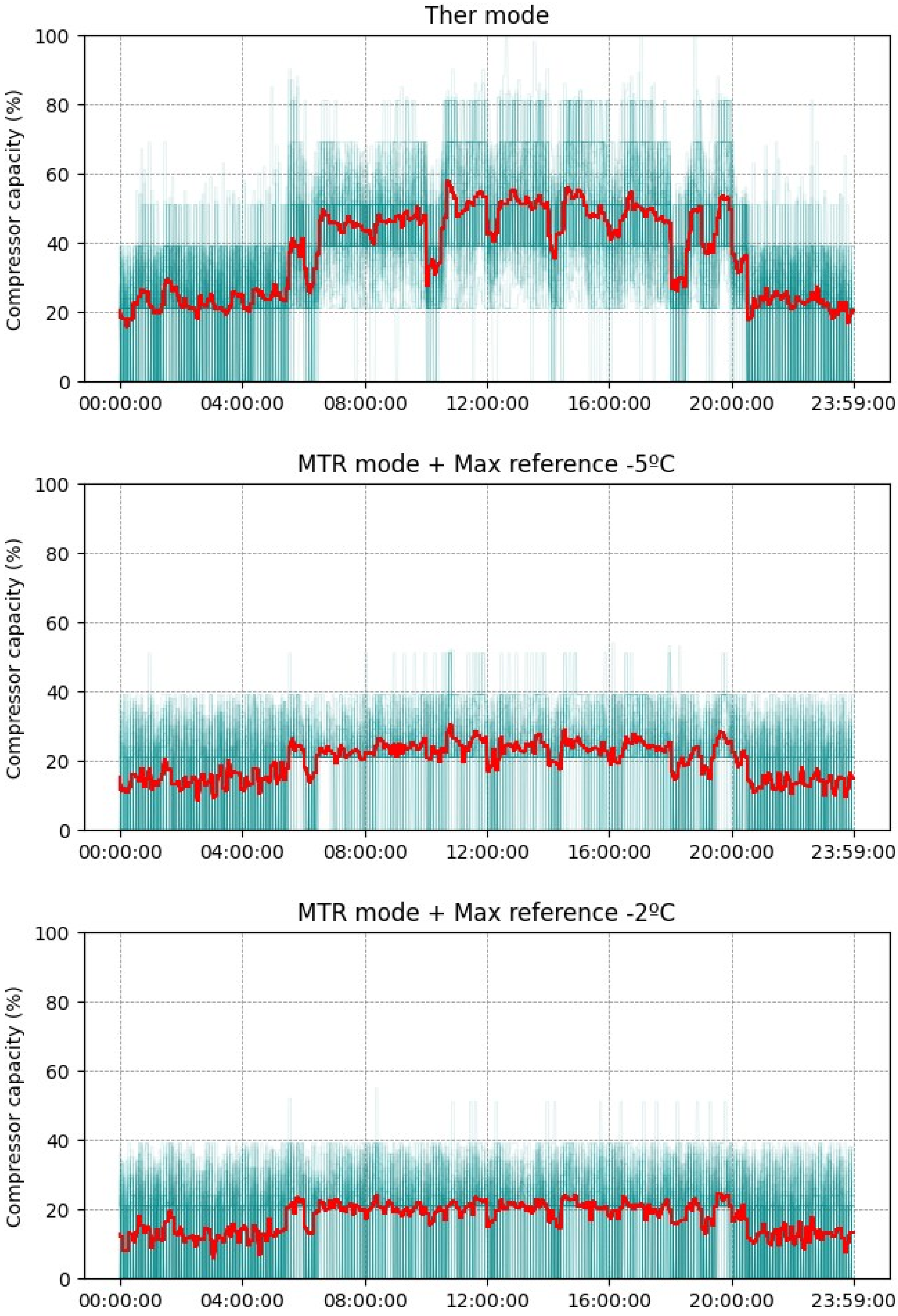


Figure 20: Average daily profiles of the engaged compressor capacity of the MT group.

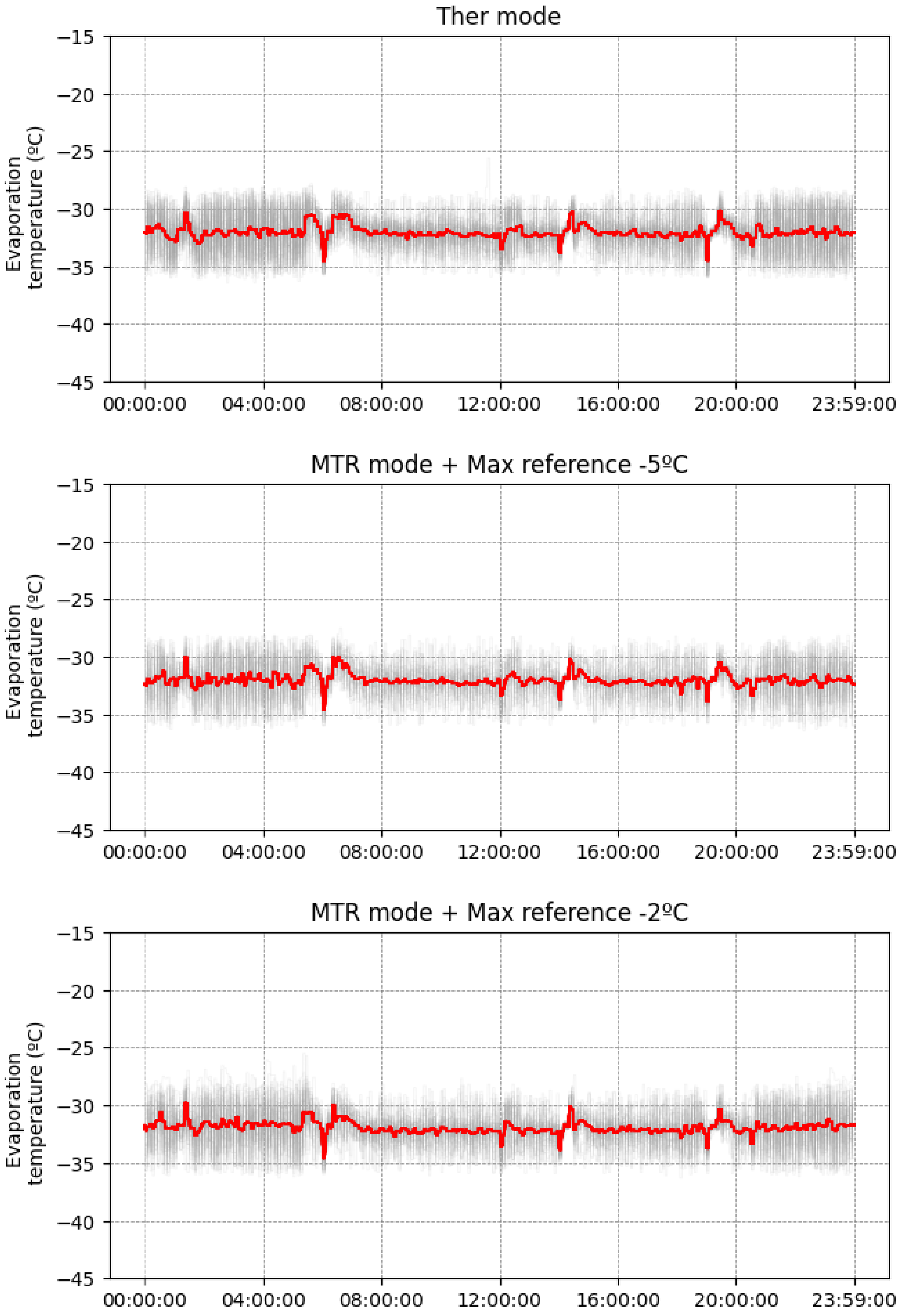


Figure 21: Average daily profiles of the evaporation temperature of the LT group.

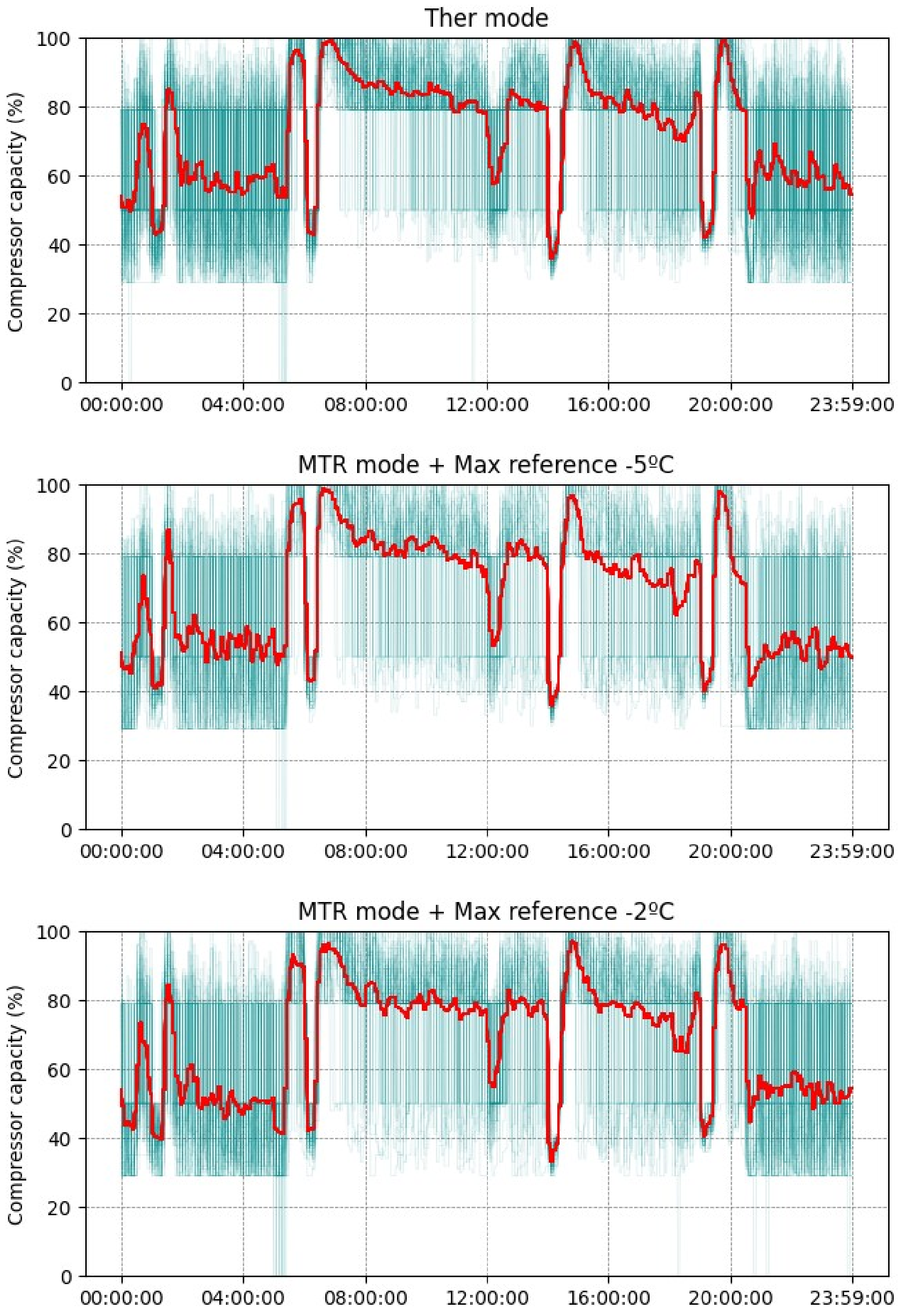


Figure 22: Average daily profiles of the engaged compressor capacity of the LT group.

5. Conclusions

The research and demonstration activities conducted during the project have successfully proven the potential of digital twin in enhancing the performance of supermarket refrigeration systems.

The use of digital twins enabled improvement in terms of cost-effectiveness and energy efficiency. It has been shown that the most cost- and energy- efficient operations of a supermarket refrigeration system can be achieved by equipping the suction group with a variable speed compressor and adopting a modulating regulation of the temperature of the display cabinets. This is because it would ensure a more stable load and, hence, a more stable and efficient operation of the compression group.

The use of digital twins also enabled a better understanding of the operating conditions of supermarket refrigeration systems, and of the dynamic interconnections among their components. This empowers supermarket operators with valuable insights into system behaviour, as well as system designer and component manufacturers. During the project, a special focus has been given on the mutual interaction between the display cabinets and the compressor pack, which has been studied through dynamic simulations based on the developed digital twins. This enabled the identification of optimised control settings which resulted into more stable operations of evaporation pressure, and hence into more smooth and efficient operation of the compressor pack which, in turn, led to lower energy usage and lower costs. These results were confirmed by the field trials conducted in the last phase of the project.

The project also contributed to the development of general and scalable data-driven and grey-box models for refrigerated display cabinets. Unlike models already available in the literature, the developed model proven their ability to infer the actual physical parameters of the modelled system, which can thus be used as inputs in physic-based modelling approaches, classification problems, and fault detection applications. Indeed, when integrated with real-time data streams, digital twins enable proactive monitoring and informed decision-making that not only minimizes downtime and maintenance costs but also ensures optimal performance and energy utilization.

In conclusion, we can state that the adoption of digital twin technology represents a paradigm shift in the management and optimization of supermarket refrigeration systems and that, together with advanced analytics, machine learning algorithms, and IoT sensors pave the way for autonomous, self-regulating refrigeration systems capable of adapting to dynamic boundary conditions and environmental factors, thereby enabling supermarkets to achieve higher efficiency, lower operating costs, and greater sustainability. However, there are still challenges preventing the adoption of advanced digital twins, mainly related to automated model generation, scalability and interoperability.

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