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Model predictive control for load shifting in supermarket refrigeration

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Abstract. Load shifting has an important potential for the integration of renewable energies in future electricity grids. This study presents a supervisory control approach for load shifting in supermarket refrigeration systems using model predictive control. Rather than directly controlling the chillers, the proposed method adjusts cabinet temperature setpoints within safe bounds to maintain cold chain integrity while optimizing energy costs. Based on a white-box model validated with real measurement data from a German pilot supermarket, the control implementation leverages the thermal inertia of refrigerated products to shift cooling loads to periods of lower electricity prices. Annual simulations across different price scenarios show cost savings ranging from 5.4 % to 12.3 %, with energy demand increases of approximately 2.3 %. Temperature band variations demonstrate that wider operational ranges enhance cost savings, but reveal diminishing returns beyond 3 K of precooling flexibility. In summary, the control successfully balances economic benefits with product quality preservation while effectively utilizing renewable energy during price valleys. This approach does not require additional storage installations and offers a scalable solution for supermarkets to contribute to grid flexibility and integration of renewable energies.

1. Introduction

To meet climate protection targets, renewable energy sources must be used efficiently [1]. As an alternative to the costly expansion of power generation and distribution, existing energy systems can be used to shift their demand to a surplus of renewable energy through load shifting [2]. Load shifting can also be financially incentivized through dynamic electricity pricing [3].

Supermarkets are a promising and scalable example for implementing predictive control for load shifting [4; 5]. A study by the EHI Retail Institute, covering 40,500 stores in Germany, Austria, and Switzerland reported that refrigeration in supermarkets consumed 4.35 TWh of electricity in 2022 [6], corresponding to 1.88 million metric tons of CO_2 emissions [7]. Their energy systems are standardised, equipped with measurement technology, and highly automated. Supermarkets have load shifting potential due to the flexibility of refrigeration, especially with controllable consumers such as cabinets. Currently, energy systems in supermarkets operate on a demand-driven basis, leaving the available flexibility unused. To exploit this flexibility, previous work has already focused on the development of supervisory controls for load shifting in supermarkets [8–10]. However, the wide-scale potential of such strategies is still unknown, especially under the consideration of different electricity price scenarios and operation limits.

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Therefore, in this work, a supervisory control concept for load shifting is developed (section 2) and quantitatively evaluated in different scenarios. The cold chain integrity is a non-negotiable requirement. Therefore, the supervisory control does not directly control the chillers, but instead controls the cooling demand through adjustment of the cabinet temperature setpoints within specified temperature bands, relying on established local controllers. The supervisory control is implemented in the form of a model predictive control (MPC), as its predictive properties are ideal for load shifting. As a main contribution, the potential of the control is quantified with a simulation model of a real pilot supermarket in Germany (section 3). Special focus is placed on the influence of different electricity prices and the allowed temperature bands.

2. Methods

In this study, a load shifting strategy is developed for a pilot supermarket in Germany. The modelling of the supermarket is explained in section 2.1. The supervisory control is described in section 2.2. The control is implemented as a MPC, which is detailed in section 2.3.

2.1. Modelling of the supermarket

The modelling of the supermarket is based on hourly measurement data collected during normal operation from June 2022 to May 2023. Additionally, a dynamic identification test is conducted over one week with minute-resolution data, during which the cabinet setpoints are deliberately varied to capture dynamic behaviour. The refrigeration system under investigation represents a typical CO_2-based refrigeration plant with a normal refrigeration circuit (NT) and a booster configuration for deep freezing (LT).

The cabinet modelling approach is inspired by the work of Shafiei et al. [9]. In our work, all cabinets operating at the same temperature level, i.e. NT and LT, are aggregated into a single node to reduce model complexity. Each aggregated node incorporates two thermal capacities: one representing the air volume and another representing the stored products. The thermal losses are modelled with both a static and dynamic component, where the dynamic component accounts for customer interactions, such as opening cabinet doors. The model parameters for the cabinets are calibrated using the measurements and subsequently validated against values reported in the literature [9; 11]. All calibrated parameters fall within realistic ranges. While the cabinets in the pilot supermarket operate with on/off control, this discrete behaviour was approximated by a PID controller in the simulation model due to the aggregation of multiple units into a single node. The chiller itself is modelled using a performance map, with compressor speed, evaporator temperature, and condenser temperature as input variables. Both the normal cooling refrigeration machine and the booster configuration are equipped with PID controllers.

2.2. Supervisory control concept

The supervisory control system that enables load shifting prioritizes three hierarchical requirements. The cold chain integrity serves as a non-negotiable requirement, ensuring product temperatures remain within legally prescribed limits. Secondly, economic operation is crucial for supermarket operators. The goal is to minimize operational costs while requiring no additional investment for storage installations. The tertiary requirement focuses on the integration of renewable energy sources. When looking at dynamic electricity pricing, the second and third goals align, as the dynamic price typically correlates with the availability of renewable energy.

Direct control of the chillers is considered unsafe by the supermarket operators due to risks of compliance with the cold chain in case of controller failure. Therefore, in this work, the supervisory control adjusts the setpoints of the cabinet air temperatures, with local controllers ensuring the cold chain through established safety protocols. Although product temperatures are the critical parameters, comprehensive product monitoring is not available in the pilot supermarket. Therefore, cabinet air temperatures serve as proxy measurements and are maintained within the legally prescribed limits to guarantee compliance with the cold chain. This approach adopts more conservative constraints as air temperatures may briefly fluctuate without compromising product integrity [11]. The temperature limits are given in table 1.

Table 1. Product temperature constraints

Temperature group	$T_{\min}$ (Precooling)	$T_{\max}$ (Normal operation)
Refrigeration (NT)	3 °C	6 °C
Deep Freezing (LT)	−23 °C	−20 °C

2.3. Model predictive control

The supervisory control is implemented through a white-box MPC approach using the AgentLib framework. AgentLib [12] is a modular Python framework designed to facilitate the development, testing, and deployment of advanced control systems for energy applications. This framework and its plug-ins provide extensible modules for optimization and simulation.

The MPC model is largely based on the system model (section 2.1), with several modifications to ensure numerical stability. A significant difference lies in the representation of the performance maps of the chillers. Direct optimization over these maps leads to numerical instabilities due to their discontinuities. Therefore, a quadratic surrogate function is employed to maintain differentiability. Another simplification concerns the representation of the non-differentiable behaviour of the anti-wind-up mechanism of the local PID controllers. This is approximated in the MPC model using a differentiable surrogate function. Due to these approximations, the MPC model does not constitute a perfect prediction model. The MPC requires a state estimation of the product temperature [11]. For this potential analysis, a perfect state estimation is assumed.

The optimization model is formulated in CasADi [13] and solved using the IPOPT solver [14], enabling efficient solution of the non-linear differential equations. The objective function minimizes energy costs for both refrigeration and deep freezing. The optimization operates with a receding horizon, a step size of 15 minutes and a prediction horizon of 24 hours. The optimization receives a perfect forecast of disturbance variables, where the historical measurement data used for modelling is used as a forecast for the ambient temperature and customer presence.

3. Results

The evaluation of the developed supervisory control is conducted in 3 steps. First, MPC control results are analysed in Section 3.1 for the base scenario in Germany from June 2022 to May 2023. This scenario is chosen as the benchmark because it matches the validation period of the simulation model. Secondly, the cost savings and increase in energy demand are analysed in section 3.2, with a special focus on the influence of the price scenario. Both the location (Germany and Sweden) and the period (June 2022 to May 2023 and the year 2024) are varied. Sweden is selected because its electricity prices are more dynamic compared to Germany. In the third step, the influence of the temperature bounds is analysed in section 3.3. Wider permitted temperature bounds expand the operational flexibility of the MPC and thus increase the load shifting potential. However, product suitability for specific temperature ranges must be assessed for each cabinet. For example, certain products may not tolerate freezing conditions, while others might deteriorate with rapid or frequent temperature fluctuations.

3.1. Evaluation of MPC control results

Figure 1 illustrates the MPC results over three days for the refrigeration (NT), with comparable results for deep freezing (LT). The first subplot displays the cabinet air and product temperatures alongside the supervisory control setpoint. Throughout the three days, three distinct precooling events occur, each lasting several hours. The cabinet air temperature responds rapidly to the setpoint due to its low thermal inertia, while the products respond more gradually. Therefore, the MPC schedules extended precooling events to maximize load shifting potential through the products' thermal mass. The second subplot presents the electrical power consumption of the chiller supplying the refrigeration system (NT). Power consumption increases substantially during precooling events as the chiller delivers the additional cooling power. Following precooling, power consumption decreases markedly for brief periods, demonstrating how cabinets effectively function as thermal storages. Beyond the three power increases attributable to precooling, three additional power spikes are evident. These additional spikes are explained in the third subplot, which displays the dynamic electricity price on the left y-axis and ambient temperature on the right y-axis. The three power spikes correlate with elevated ambient temperatures, which is expected as chiller efficiency decreases at higher ambient temperatures. Additionally, these performance increases coincide with store opening hours, when cooling demand rises due to frequent cabinet access. The dynamic electricity price exhibits six price valleys, yet the MPC initiates precooling only during three of these opportunities. This selective approach demonstrates that precooling during every price valley is not necessarily cost-optimal. During the non-utilized price valleys, reduced chiller efficiency and increased thermal losses due to customer presence would result in excessive additional energy demand that the price advantage cannot offset. This complexity highlights the limitations of simple rule-based control strategies for effective load shifting and underscores the advantages of the developed MPC approach.

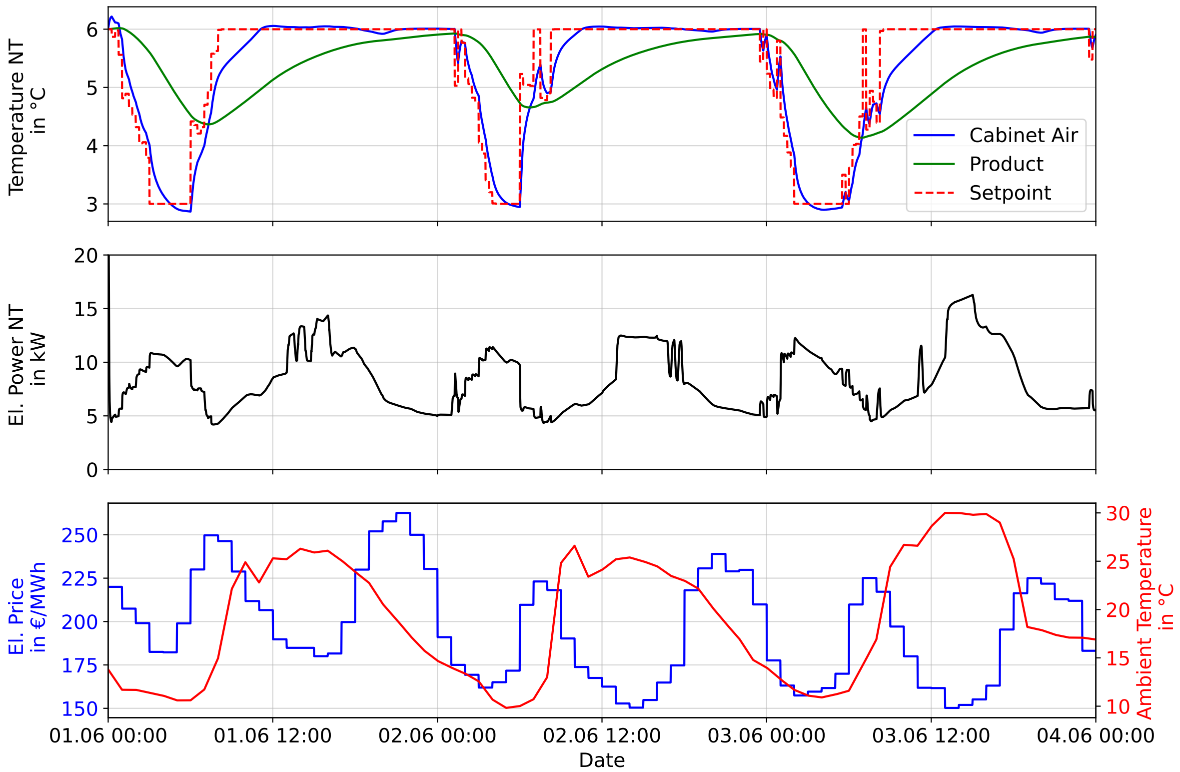

Figure 1. MPC control results of 3 days for the refrigeration

3.2. Variation of the price scenario

Table 2 presents the costs and energy demand across various price scenarios in the one-year simulation. Starting with the base scenario (Germany 22/23), the MPC achieves cost savings of 5.38 %. The operator of the pilot supermarket has targeted a minimum cost saving of 5 % to consider the introduction of a load shifting strategy. Therefore, in the base scenario, the MPC marginally exceeds the minimum threshold. Concurrently, the MPC increases cooling energy demand by 2.28 %. This increase is expected, as the reference system operates in an energy-efficient mode, and the MPC must necessarily deviate from this optimal energy efficiency to enable load shifting. However, it is worth noting that due to the correlation between dynamic electricity pricing and renewable energy production, the additional energy demand is predominantly met by renewable energy sources.

Table 2. Comparison of costs and energy demand for different price scenarios

Scenario	Cost	Cost savings	Energy demand	Increase energy demand
Reference Germany 22/23	18120.71 €	-	81470 kWh	-
MPC Germany 22/23	17145.73 €	-5.38 %	83328 kWh	2.28 %
Reference Sweden 22/23	11988.96 €	-	81470 kWh	-
MPC Sweden 22/23	10514.77 €	-12.30 %	83338 kWh	2.29 %
Reference Germany 24	6357.65 €	-	81470 kWh	-
MPC Germany 24	5805.48 €	-8.69 %	83345 kWh	2.30 %
Reference Sweden 24	4266.92 €	-	81471 kWh	-
MPC Sweden 24	3785.15 €	-11.29 %	83203 kWh	2.13 %

When examining the Swedish electricity price during the same period, the MPC achieves substantially higher cost savings of 12.3 %. This significant improvement demonstrates that load shifting potential is heavily dependent on electricity price dynamics. In this case, Sweden's more volatile electricity prices create greater saving opportunities for the MPC. Given the comparable energy consumption between the German and Swedish scenarios, it can be inferred that a similar amount of energy was shifted in both cases, but with markedly different economic outcomes.

Following the onset of the Ukraine conflict, energy costs in 2022/2023 are substantially higher than in 2024. In Germany, MPC cost savings demonstrate significant improvement in 2024. It can be assumed that the MPC potential is likely to continue to increase in the coming years as renewable energy integration accelerates within the grid. The comparable increase in energy demand across both periods indicates similar quantities of shifted energy. Conversely, in Sweden, both cost savings and energy demand increases are slightly lower in 2024 compared to 2022/2023, suggesting a reduction in the amount of energy shifted. Nevertheless, Sweden's potential for MPC optimization remains considerably higher than Germany's. In summary, these analyses demonstrate that MPC potential is strongly influenced by electricity price dynamics. However, it is noteworthy that all scenarios examined satisfied the minimum cost saving requirements of the supermarket owner while shifting comparable amounts of energy. The literature reports cost saving potentials of load shifting for various applications such as heat pumps or electric vehicles ranging from 1 % to 48 % [3]. Therefore, overall, supermarkets have a moderate potential.

3.3. Variation of the temperature bounds

Table 3 illustrates the impact of temperature bounds on MPC performance for the benchmark scenario. In this evaluation, $T_{\max}$ remains constant while the precooling temperature difference varies between 1 K and 5 K. As indicated in Table 1, all previous results are simulated with a temperature difference of 3 K. The findings align with expectations: wider temperature bands provide the MPC with greater operational flexibility, thus enhancing potential savings. The corresponding increase in energy demand indicates that larger amounts of energy are shifted when temperature bands are expanded. However, the data reveals a diminishing marginal benefit as temperature bands widen further. Following discussions with the supermarket operator, a temperature difference of 3 K represents an optimal compromise between cost savings, energy consumption, and the risk of product deterioration that could result from excessive or frequent temperature fluctuations.

Table 3. MPC performance for different precooling setpoints (Germany 22/23)

Scenario	Cost	Cost savings	Energy demand	Increase energy demand
Reference	18120.71 €	-	81470 kWh	-
MPC (1 K)	17600.90 €	-2.87 %	81689 kWh	0.27 %
MPC (2 K)	17301.96 €	-4.52 %	82559 kWh	1.34 %
MPC (3 K)	17145.73 €	-5.38 %	83328 kWh	2.28 %
MPC (4 K)	17122.79 €	-5.51 %	83880 kWh	2.96 %
MPC (5 K)	17092.21 €	-5.68 %	84057 kWh	3.18 %

4. Conclusion and Outlook

This paper introduces a supervisory control approach using model predictive control for load shifting in supermarket refrigeration systems. The developed control adjusts the temperature setpoints of the cabinets rather than directly controlling the chillers, thus eliminating the risk of compromising the cold chain. The model predictive control schedules precooling events during periods of low electricity prices, thus, effectively shifting energy consumption to optimize operational costs. The approach relies on a white-box model with non-linear differential equations.

The year-long simulation results demonstrate that the proposed control successfully enables load shifting across various electricity price scenarios. In all tested cases, the control strategy exceeded the minimum required cost savings of the supermarket owner, although the potential was found to be mostly dependent on the electricity price. Investigation of different temperature bands revealed an important trade-off: while wider temperature bands increase load shifting potential, they also elevate the risk of product quality degradation due to frequent or extreme temperature fluctuations. Based on the analysis, a maximum precooling of 3 K is identified as an optimal compromise between cost savings, energy demand and product quality preservation.

Future work will focus on implementing and validating the control in the real pilot supermarket. Additionally, further research is needed to determine which specific characteristics of electricity price profiles most significantly enhance the potential of load shifting. In addition, one supermarket alone cannot make a major contribution to grid stability. For this reason, in the future, it should also be investigated how the developed approach can be used to combine several supermarkets into a virtual power plant [15].

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References

[1] Fetting C 2020 The european green deal Vienna

[2] Fallahi Z and Henze G 2019 *Sustainability* **11** 3988

[3] Li H, Wang Z, Hong T and Piette M A 2021 *Advances in Applied Energy* **3** 100054

[4] James S J and James C 2010 *Food Research International* **43** 1944–1956

[5] Goli S, McKane A T and Olsen D Demand response opportunities in industrial refrigerated warehouses in california *2011 ACEEE Summer Study on Energy Efficiency in Industry*

[6] EHI Retail Institute 2023 Studie: Energiemanagement im Einzelhandel URL `https://www.ehi.org/presse/handel-verbraucht-weniger-energie/`

[7] Icha P and Lauf T 2025 Entwicklung der spezifischen treibhausgas-emissionen des deutschen strommix in den jahren 1990 - 2024

[8] Hovgaard T G, Larsen L F, Edlund K and Jørgensen J B 2012 *Energy* **44** 105–116

[9] Shafiei S E, Stoustrup J and Rasmussen H 2013 A supervisory control approach in economic mpc design for refrigeration systems *2013 European Control Conference (ECC)* (IEEE) pp 1565–1570 ISBN 978-3-033-03962-9

[10] Beghi A, Rampazzo M and Zorzi S 2017 *IFAC-PapersOnLine* **50** 13754–13759

[11] Pedersen R, Schwensen J, Biegel B, Green T and Stoustrup J 2017 *IEEE Transactions on Control Systems Technology* **25** 855–863

[12] Eser S, Storek T, Wüllhorst F, Dähling S, Gall J, Stoffel P and Müller D 2025 *Applied Energy* **385** 125496

[13] Andersson J A E, Gillis J, Horn G, Rawlings J B and Diehl M 2019 *Mathematical Programming Computation* **11** 1–36

[14] Wächter A and Biegler L T 2006 *Mathematical Programming* **106** 25–57

[15] Kaiss M, Wan Y, Gebbran D, Vila C U and Dragičević T 2025 *Renewable and Sustainable Energy Reviews* **211** 115242