Report on the study of improving the advanced control algorithm for supermarket cabinets

AKO

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Author:
Dr. Gabriel Zsembinszki

Reviewed by:
Dr. Luisa F. Cabeza

1. Introduction

This report is related with the CICARON subproject, which focuses on an advanced ("self-drive") algorithm for panel and DIN-rail electronic controllers for supermarket display cabinets. It is worth noting that the activities carried out in the CICARON subproject are based on a previous collaboration between the research group GREiA at UdL and AKO, in which a self-drive algorithm was developed to improve evaporator fan control and the optimal defrost timing in cold storage units.

A first exhaustive experimental study was conducted during 2024 with two of the five supermarket display cabinets available at AKO facilities: one cabinet at positive temperature (refrigeration) and another one at negative temperature (freezing), both having doors to separate the indoor air from the outside. Several experiments were carried out to study the influence of the control strategy and of the product load and set-point temperature on the overall power consumption and air and product temperature. In all cases, the standard (serial) control of the cabinets was also used as a reference to which the different strategies could be compared.

As a result of the experimental campaign carried out during 2024, a report was submitted by GREiA to AKO in December 2024, where the main findings were presented along with a few proposals for modifying the control algorithm and future studies to be carried out. The main findings of the report will be briefly explained in the next section, for each of the two display cabinets evaluated.

2. Summary of main findings from previous report and objectives of this report

2.1 Refrigeration display cabinet

One of the most important conclusions drawn in this case was the fact that the evaporator fan must operate continuously (mode 2) to ensure a better temperature level and distribution inside the cabinet. Otherwise, the product might be affected by undesired temperature fluctuations and incorrect temperature level, which might deteriorate the quality of the product. As a result, it was decided that in the next experimental campaign, the evaporator fan strategy should be the same as for the standard control, i.e., fan always on.

Another key point was related with the defrost strategy. During the AKO strategy tests, the final temperature at the end of the defrost cycle was lowered from 5 ºC to 2 ºC, which lead to evaporator blockage because of incomplete defrosts, especially when considerable amounts of ice were allowed to be accumulated on the evaporator coil due to AKO strategy. Therefore, it was decided that the temperature at the end of each defrost cycle should also be 5 ºC, as in the case of the standard control strategy. Moreover, the AKO strategy should not be too aggressive to avoid accumulation of great amounts of ice that could block the evaporator. Nevertheless, the AKO strategy should be able to reduce the frequency of defrost cycles, to avoid that the cabinet temperature increases above the set-point range too often. For the standard control, the defrost frequency was set to one defrost every 6 hours, with a maximum duration of one defrost cycle of 45 minutes or until the evaporator surface reaches 5 ºC, whichever occurs first. For the AKO strategy, the defrost frequency was regulated by the level of ice accumulated on the evaporator, with relatively low levels of ice being allowed, with a maximum temperature of 5 ºC at the evaporator surface at the end of the defrost cycle, and with no limitations in the maximum duration of the defrost cycle.

With these changes, the additional experimental tests presented in this report should assess the effect of the control strategy on the quality of the product, and not on the energy consumption of the cabinet. Therefore, the proposed AKO strategy can be considered successful if it is able to improve the indoor temperature conditions and, consequently, also the quality of the product. In addition, no savings in the energy consumption were foreseen, although the energy consumption was expected to be similar to that of the standard control, since in this case the defrost cycle is not performed using an electric heater, which is an energy-intensive component.

2.2 Freezing display cabinet

In this case, the main findings of the previous experimental campaign are very different compared to the case of the refrigeration cabinet, leading to totally different modifications in the testing plan of the second experimental campaign. In this case, ice accumulation of the evaporator surface was not a critical issue, because the defrost is performed using an electric heater that completely melts the ice in a relatively short period of time. Consequently, the defrost strategy of AKO, which considerably reduces the defrost frequency, was considered as the most adequate. For the standard control, the defrost frequency was set to every 12 hours, with the same value of the evaporator temperature at the end of the defrost cycle for both standard and AKO strategies. Therefore, in this case, the objective was to reduce the energy consumption of the cabinet by reducing the frequency of defrost cycles, and check if the quality of the product was not affected by this strategy, especially during the defrost cycles, which are expected to be longer because of a higher amount of ice accumulated on the evaporator.

To further reduce the energy consumption without significantly affecting the quality of the product, two different strategies for evaporator fan operation were proposed and tested (Figure 1). They are variants of the mode 3 used in the original AKO strategy that was commercially implemented in walk-in freezers. These two variants, called mode 3_1 and mode 3_2, follow a similar concept of using the cold stored in the ice accumulated on the evaporator coil when the compressor is off. However, in the case of mode 3_1, the fan is kept on when the control temperature increases above the small intermediate deadband to discharge at maximum the amount of cold stored in the ice. In the case of mode 3_2, the fan is not turned off when the compressor turns off, so the cold is discharged from the ice when the ice is at its minimum temperature. Once the ice temperature increases above the small intermediate deadband, the fan is turned off to save some energy considering that it is not worth using the fan to discharge the cold from the ice at a higher temperature.

Another important difference with respect to the previous AKO strategy is that the system operated in mode 3_1 or mode 3_2 all the time, regardless the level of ice on the evaporator. The reason for this is the fact that, as presented in the first report, when operating in mode 1 at low levels of ice, the temperature inside the cabinet was higher, which negatively affects the quality of the product.

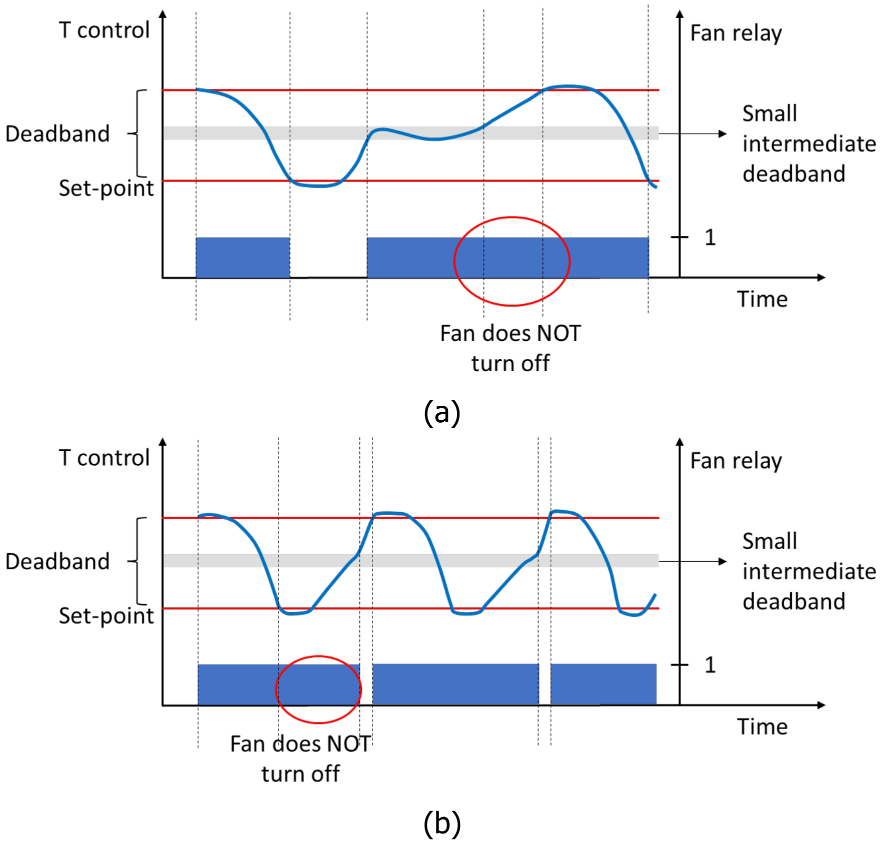

Figure 1. Proposed options to modify current mode 3: (a) mode 3_1 and (b) mode 3_2.

3. Experimental methodology

For the second experimental campaign, only those tests with control strategies for which potential improvements in product quality or energy savings were identified were carried out. For both refrigeration and freezing cabinets, the experiments with the standard control were also carried out to have a good reference for comparing the new AKO control strategies. All tests lasted for at least 1 week to ensure sufficient data for a more reliable and confident comparison, although for the standard control tests this was not critical given the repetitive nature of those tests. Therefore, the tests using the standard control lasted around 5-6 days. Moreover, all tests were performed with a product load of 50% and only for one set-point, 0 ºC and -26 ºC, for the refrigeration and freezing cabinets, respectively. All tests carried out are summarized in Table 1 below.

Table 1. List of experimental tests carried out.

Test	Display cabinet	Control	Load	Set-point	Fan mode
20a	Refrigeration	Standard	50%	0 ºC	2
21a	Refrigeration	AKO v2.0 + fan always on	50%	0 ºC	2
20b	Freezing	Standard	50%	-26 ºC	2
21b	Freezing	AKO v2.0 + mode 3_1	50%	-26 ºC	3_1
22b	Freezing	AKO v2.0 + mode 3_2	50%	-26 ºC	3_2

4. Variables analysed

The same variables that were assessed and presented in Section 4 of the first report were also analysed in this second experimental campaign. A summary of the variables analysed is given below:

- Average air and product temperature: considering all sensors as well as one relevant for each case ($T_{control}$ for air and S17 or S18 for product temperature).
- Maximum air and product temperature: considering all sensors as well as one relevant for each case ($T_{control}$ for air and S17 or S18 for product temperature).
- Percentage of time outside the set-point range: only $T_{control}$ was considered for air temperature and S17 or S18 for product temperature. A margin of 0.3 °C for the refrigeration cabinet and 0.6 ºC for the freezing cabinet were allowed to eliminate possible sensor measurement errors or random temperature variations during periods of normal system operation.
- Maximum time outside the set-point range: only $T_{control}$ was considered for air temperature and S17 or S18 for product temperature.
- Average deviation from the set-point: considering all sensors as well as one relevant for each case ($T_{control}$ for air and S17 or S18 for product temperature). The use of $T_{control}$ and S17 or S18 is new in this case, since it can give a more accurate picture of the influence of the control strategy on the indoor temperature.
- Maximum deviation from the set-point: only $T_{control}$ was considered for air temperature and S17 or S18 for product temperature.
- Average energy consumption (power): it is the average power consumed by the cabinets during the whole testing period for each test.

5. Results and discussion

This section highlights the key results of the experimental tests and discusses the most significant findings.

5.1 Refrigeration cabinet

The average air and product temperatures inside the refrigeration cabinet are shown in Table 2.

Table 2. Average air and product temperatures in the refrigeration cabinet.

Control strategy	Average temperature (ºC)			
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S17)
Standard	2.3	2.1	0.9	1.1
AKO v2.0 + fan always on	2.0	1.7	0.6	0.8

For both air and product temperatures, AKO control strategy achieves an improvement of 0.3-0.4 ºC with respect to the standard control in all cases.

Similarly, Table 3 shows the maximum temperature reached at different points in the refrigeration cabinet, both in the air and in the product.

Table 3. Maximum air and product temperatures in the refrigeration cabinet.

Control strategy	**Maximum temperature (ºC)**			
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S17)
Standard	5.1	4.2	4.5	2.4
AKO v2.0 + fan always on	4.9	4.2	4.6	3.0

In this case, AKO control strategy cannot generally reduce the maximum temperature, with a slight decrease in the air temperature when considering all temperature sensors. However, product temperature when considering all sensors remain unaffected, while an increase of 0.6 ºC is observed in the case of one reference sensor (S17), probably because the defrost cycles took longer and the heat could penetrate in more depth and affected the coldest zones of the cabinet (where S17 was located).

The time the refrigeration cabinet was out of the set-point range is shown in Table 4.

Table 4. Time the refrigeration cabinet was out of the set-point range.

Control strategy	**Time out of range (%)**		**Maximum time out of range (h)**	
	Air ($T_{control}$)	Product (S17)	Air ($T_{control}$)	Product (S17)
Standard	12.7	19.8	0.73	1.08
AKO v2.0 + fan always on	1.1	3.3	1.30	2.20

AKO control strategy can significantly reduce the time when the air and product temperatures are out of the set-point range, demonstrating that the reduction in frequency of defrost cycles is beneficial for maintaining the cabinet temperature within the set-point range for much longer periods. As a negative effect, AKO control strategy leads to an increase in the maximum time when the cabinet is out of range. However, the impact of this negative effect is negligible, since the maximum air and product temperatures do not increase with respect to the standard control, as can be seen in Table 3, except for one particular location of the product.

The average and maximum deviations from the set-point, considering all sensors as well as one relevant sensor for air and product temperatures, are shown in Table 5.

Same trends are observed as in the case of the time out of set-point range. In general, the deviations from the set-point range are lower for the AKO control strategy, especially in the case of $T_{control}$ and S17 sensors, where the reduction is considerably high. The maximum deviation from the set-point range increases in the case of AKO control, which is directly related to the increase in the maximum time out of range (which proved to be harmless in general).

Table 5. Temperature deviation from the set-point for the refrigeration cabinet.

Control strategy	**Average deviation from set-point (K·h)**		**Deviation from set-point (K·h)**		**Maximum deviation from set-point (K·h)**	
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S17)	Air ($T_{control}$)	Product (S17)
Standard	25.1	19.9	6.2	1.9	1.53	0.48
AKO v2.0 + fan always on	16.8	14.1	0.6	0.4	2.98	1.47

Finally, the average electricity consumption of the refrigeration cabinet in the different cases is shown in Table 6. The defrost frequency is also shown in the table to make it easier to observe the possible relation between the defrost frequency and average electricity consumption (average power).

Table 6. Average electricity consumption of the refrigeration cabinet.

Control strategy	**Defrost frequency (day^{-1})**	**Outdoor temperature (ºC)**	**Indoor temperature (all sensors) (ºC)**	**Average power (W)**	**Corrected average power (W)**
Standard	4.4	22.8	2.3	240.0	234.2
AKO v2.0 + fan always on	0.2	22.0	2.0	228.5	229.0

As a reminder, the corrected average power is the value expected for the average electricity consumption if the difference between the indoor and outdoor temperatures is constant and equal to 20 K. The equation used to perform this correction is the same that the one used in the first report. The results show that the average electricity consumption remains practically the same, demonstrating that, although the defrost frequency is considerably reduced using the AKO strategy, the electricity consumption of the compressor is not affected (one might expect an increase in the compressor consumption, since the higher the defrost frequency, the longer the compressor is off). Surprisingly, the compressor-on time was 38% for the standard control and only 28% for the AKO control, which means that, despite the longer time the compressor is off at the first part of the defrost cycle, it finally requires more time to take the cabinet back to the set-point temperature.

Based on the previous finding, the frequency of compressor switching on/off was also calculated, showing a reduction from 216.8 day^{-1} for the standard control strategy to 157.6 day^{-1} for the AKO control strategy, which means a reduction of 27%.

5.2 Freezing cabinet

The average air and product temperatures inside the freezing cabinet are shown in Table 7.

Table 7. Average air and product temperatures in the freezing cabinet.

Control strategy	Average temperature (ºC)			
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S18)
Standard	-23.9	-24.4	-24.9	-25.3
AKO v2.0 + fan mode 3_1	-23.9	-24.4	-25.3	-25.4
AKO v2.0 + fan mode 3_2	-24.2	-24.7	-25.3	-25.6

All three control strategies produce very similar effects on air and product temperatures. AKO v2.0 + fan mode 3_2 strategy shows slightly better performance, with temperature levels around 0.3-0.4 ºC lower than the standard control.

Similarly, Table 8 shows the maximum temperature reached at different locations in the freezing cabinet, both for the air and for the product.

Table 8. Maximum air and product temperatures in the freezing cabinet.

Control strategy	Maximum temperature (ºC)			
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S18)
Standard	-10.3	-16.1	-1.9	-19.9
AKO v2.0 + fan mode 3_1	-14.7	-17.9	-3.2	-22.5
AKO v2.0 + fan mode 3_2	-22.3	-22.8	-24.3	-25.3

Regarding the maximum temperature achieved in the freezing cabinet, AKO v2.0 + fan mode 3_1 clearly shows better performance than the standard strategy. AKO v2.0 + fan mode 3_2 shows even better performance, but this is because in this case no defrost was carried out during the whole period. However, even if a defrost was carried out, values similar to AKO v2.0 + fan mode 3_1 would be expected.

The time the freezing cabinet was out of the set-point range is shown in Table 9.

Table 9. Time the freezing cabinet was out of the set-point range.

Control strategy	Time out of range (%)		Maximum time out of range (h)	
	Air ($T_{control}$)	Product (S18)	Air ($T_{control}$)	Product (S18)
Standard	5.0	11.2	0.72	1.91
AKO v2.0 + fan mode 3_1	0.6	1.7	0.54	1.32
AKO v2.0 + fan mode 3_2	0.0	0.0	0.00	0.00

The time that the freezing cabinet temperature was out of range was considerably reduced by the AKO v2.0 + fan mode 3_1 strategy, due to a drastic reduction in defrost frequency. Surprisingly, the maximum time out of range, corresponding to one defrost cycle, was also reduced by the AKO v2.0 + fan mode 3_1 strategy. Like the previous table, the results for the AKO v2.0 + fan mode 3_2 are not conclusive because of the lack of defrost, but similar results to AKO v2.0 + fan mode 3_1 strategy are expected.

The average and maximum deviations from the set-point, considering all sensors as well as one relevant sensor for air and product temperatures, are shown in Table 10.

Table 10. Temperature deviation from the set-point for the freezing cabinet.

Control strategy	**Average deviation from set-point (K·h)**		**Deviation from set-point (K·h)**		**Maximum deviation from set-point (K·h)**	
	Air (all sensors)	Product (all sensors)	Air ($T_{control}$)	Product (S18)	Air ($T_{control}$)	Product (S18)
Standard	17.6	10.3	9.0	4.0	6.2	4.1
AKO v2.0 + fan mode 3_1	15.5	8.9	1.0	0.3	4.1	1.3
AKO v2.0 + fan mode 3_2	10.5	5.0	0.0	0.0	0.0	0.0

Both AKO v2.0 control strategies perform better than the standard control strategy also from the point of view of the deviations from the set-point. This is especially relevant if $T_{control}$ and S18 sensors are considered.

Finally, the average electricity consumption of the freezing cabinet in the different cases is shown in Table 11.

Table 11. Average electricity consumption of the freezing cabinet.

Control strategy	**Defrost frequency (day^{-1})**	**Outdoor temperature (ºC)**	**Indoor temperature (all sensors) (ºC)**	**Average power (W)**	**Corrected average power (W)**
Standard	2.1	22.6	-23.9	1208.6	1192.5
AKO v2.0 + fan mode 3_1	0.3	22.0	-23.9	1135.9	1138.6
AKO v2.0 + fan mode 3_2	0.0	22.5	-24.2	1069.7	1049.6

A reduction of 5% and 12% in the average electricity consumption was achieved by the AKO v2.0 + fan mode 3_1 and AKO v2.0 + fan mode 3_2 strategies, respectively. This can be explained by a reduction in the electricity consumption associated with the defrost cycles, and probably also by a reduction in the electricity consumption of the evaporator fan. To assess this aspect, the average electricity consumption of the freezing cabinet was calculated for the normal regulation periods (no defrost cycles included) and showed in the next subsection.

As in the case of the refrigeration cabinet, the compressor-on time as well as the frequency of compressor switching on/off was also calculated. The compressor-on time reduced from 72% for the standard control to 69% and 67% for the AKO v2.0 + fan mode 3_1 and AKO v2.0 + fan mode 3_2 strategies, respectively. A reduction in the frequency of compressor switching on/off from 473.9 day^{-1} for the standard control to to 442.9 day^{-1} and 389.7 day^{-1} was observed for AKO v2.0 + fan mode 3_1 and AKO v2.0 + fan mode 3_2 strategies, respectively. For the latest strategy, this reduction is equivalent to almost 18%, which is quite relevant. In this case, both ambient temperatures were very similar (22.6 ºC vs. 22.5 ºC), confirming that the reduction in both compressor-on time and frequency of compressor switching on/off is a direct result of the implementation of fan mode 3_2 strategy.

5.3 Influence of the fan operating mode

The comparison between the different fan operating modes can only be done for the freezing cabinet, since in the case of the refrigeration cabinet, mode 2 was used in both standard and AKO control strategies. As mentioned above, mode 2 was used for the standard control, and mode 3_1 and mode 3_2 were used for the two variants of the AKO control strategy.

The average and maximum air and product temperatures in the freezing cabinet for the different fan operating modes are shown in Table 12.

Table 12. Average and maximum air and product temperatures in the freezing cabinet.

Fan mode	**Average temperature (ºC)**		**Maximum temperature (ºC)**	
	Air (all sensors)	Product (all sensors)	Air (all sensors)	Product (all sensors)
2	-24.1	-24.5	-19.8	-19.6
3_1	-23.9	-24.4	-20.0	-20.4
3_2	-24.2	-24.7	-22.3	-22.8

No significant difference is observed between the different control strategies, except for the maximum product temperature, which is clearly lower in the case of AKO strategies. The much better results for fan mode 3_2 could be explained by the lack of defrost cycles, which can affect the maximum air and product temperature especially right after the end of a defrost cycle.

Table 13 shows the average electricity consumption of the freezing cabinet associated with the different operating modes of the fans.

Table 13. Average electricity consumption of the freezing cabinet.

Fan mode	**Outdoor temperature (ºC)**	**Indoor temperature (all sensors) (ºC)**	**Average power (W)**	**Corrected average power (W)**
2	22.6	-24.1	1174.9	1152.2
3_1	22.0	-23.9	1131.5	1133.5
3_2	22.5	-24.2	1069.7	1049.6

The results confirm that part of the total savings in electricity consumption is due to the fan operation mode, especially in the case of mode 3_2, which achieves a reduction in the energy consumption of 9% with respect to the standard control strategy (fan mode 2).

6. Conclusions

6.1 Refrigeration cabinet

In general, AKO control strategy investigated here proved to perform better than the standard control strategy. The most significant improvement consisted of a significant reduction in the time the refrigeration cabinet was out of the set-point range. This led to an improvement in the average deviation from set-point, which means that the product was kept closer to the set-point temperature along the whole day. This could be seen from the fact that both air and product average temperatures were around 0.3 ºC lower than the corresponding temperatures in the standard control case. Another positive effect observed was a reduction of 27% in the frequency of compressor switching on/off. Although this reduction might be attributed to a different ambient temperature, its magnitude is still considerably high to be considered in further research where the same ambient temperature could be used to demonstrate the real magnitude of this effect. Despite of this, no significant changes in the total daily electricity consumption were observed. On the negative side, AKO control strategy produced longer defrost cycles, which led to slightly higher maximum product temperature achieved in the coldest parts of the cabinet. However, this negative effect was not observed in maximum average product temperature.

6.2 Freezing cabinet

Both AKO control strategies proved to clearly perform better than the standard control strategy in all aspects. From the point of view of product quality, both AKO strategies achieve improvements in the average and especially in the maximum air and product temperatures, as well as considerable reductions in the time out of the set-point range and deviations from the set-point. From the electricity consumption perspective, some savings are also achieved, especially in the case of AKO v2.0 + fan mode 3_2 strategy, which achieves energy savings due to a reduction in defrost frequency as well as in the evaporator fan and/or compressor consumption. Therefore, no negative effect was observed related to AKO v2.0 + fan mode 3_2 strategy, which is worth further research to confirm its benefits under different boundary conditions.