On the Trade-off between Energy Consumption and Food Quality Loss in Supermarket Refrigeration Systems

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Abstract: This paper studies the trade-off between energy consumption and food quality loss, at varying ambient conditions, in supermarket refrigeration systems. Compared with the traditional operation with pressure control, a large potential for energy savings without extra loss of food quality is demonstrated. We also show that by utilizing the relatively slow dynamics of the food temperature, compared with the air temperature, we are able to further lower both the energy consumption and the peak value of power requirement. The Pareto optimal curve is found by off-line optimization.

1. INTRODUCTION

Increasing energy costs and consumer awareness on food products safety and quality aspects impose a big challenge to food industries, and especially to supermarkets, which have a direct contact with consumers. A well-designed optimal control scheme, continuously maintaining a commercial refrigeration system at its optimum operation condition, despite changing environmental conditions, will achieve an important performance improvement, both on energy efficiency and food quality reliability.

Many efforts on optimization of cooling systems have been focused on optimizing objective functions such as overall energy consumption, system efficiency, capacity, or wear of the individual components, see Jakobsen and Rasmussen (1998), Jakobsen et al. (2001), Larsen and Thybo (2004), Leducqa et al. (2006), Swensson (1994). They have proved significant improvements of system performance under disturbances, while there has been little emphasis on the quality aspect of food inside display cabinets.

This paper discusses a dynamic optimization of commercial refrigeration systems, featuring balanced system energy consumption and food quality loss. A former developed quality model of food provide a tool for monitoring and controlling quality loss during the whole process, see Cai et al. (2006).

The paper is organized as follows: Operation and modelling of refrigeration systems is presented in Section 2. In Section 3 we introduce the problem formulation used for optimization. Different optimization schemes and results are presented in Section 4. Finally some discussions and conclusions follow in Section 5 and Section 6.

2. PROCESS DESCRIPTION

A simplified sketch of the process is shown in Fig.1. In the evaporator there is heat exchange between the air inside the display cabinet and the cold refrigerant, giving a slightly superheated vapor to the compressor. After compression the hot vapor is cooled, condensed and slightly sub-cooled in the condenser. This slightly sub-cooled liquid is then expanded through the expansion valve giving a cold two-phase mixture.

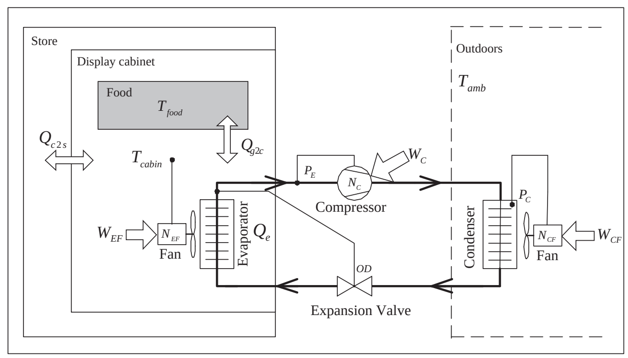


Fig. 1. Sketch of a simplified supermarket refrigeration system studied in this paper.

The display cabinet is located inside the store and we assume that the store has a constant temperature. This is true for stores with air-conditioning. The condenser and fan are located at the roof of the shop. Condensation is achieved by heat exchange with ambient air.

2.1 Degree of freedom analysis

There are 5 degrees of freedom (input) in a general simple refrigeration system, see Jensen and Skogestad (2007). Four of these can be recognized in Fig.1 as the compressor speed (N_C), condenser fan speed (N_{CF}), evaporator fan speed (N_{EF}) and opening degree of the expansion valve (OD). The fifth one is related to the active charge in the system.

Two of the inputs are already used for control or are otherwise constrained:

Table 1. Model equations

Compressor
$\dot{W}_C = \frac{\dot{m}_{ref} \cdot (h_{is}(P_e,P_c) - h_{oe}(P_e))}{\eta_{is}}$
$h_{ic} = \frac{1-f_q}{\eta_{is}} \cdot (h_{is}(P_e,P_c) - h_{oe}(P_e)) + h_{oe}(P_e)$
$\dot{m}_{ref} = N_C \cdot V_d \cdot \eta_{vol} \cdot \rho_{ref}(P_e)$
Condenser
$\dot{W}_{CF} = K_{1,CF} \cdot (N_{CF})^3$
$\dot{m}_{air,C} = K_{2,CF} \cdot N_{CF}$
$T_{aoc} = T_c + (T_{amb} - T_c) \cdot \exp\left(-(\alpha_C \cdot \dot{m}_{air,C}^{m_C})/(\dot{m}_{air,C} \cdot Cp_{air})\right)$
$0 = \dot{m}_{ref} \cdot (h_{ic}(P_e,P_c) - h_{oc}(P_c)) - \dot{m}_{air,C} \cdot Cp_{air} \cdot (T_{aoc} - T_{amb})$
Evaporator
$\dot{W}_{EF} = K_{1,EF} \cdot (N_{EF})^3$
$\dot{m}_{air,E} = K_{2,EF} \cdot N_{EF}$
$T_{aoe} = T_e + (T_{cabin} - T_e) \cdot \exp\left(-(\alpha_E \cdot \dot{m}_{air,E}^{m_E})/(\dot{m}_{air,E} \cdot Cp_{air})\right)$
$0 = \dot{Q}_e - \dot{m}_{air,E} \cdot Cp_{air} \cdot (T_{cabin} - T_{aoe})$
Display cabinet
$\dot{Q}_{c2f} = UA_{c2f} \cdot (T_{cabin} - T_{food})$
$\dot{Q}_{s2c} = UA_{s2c} \cdot (T_{store} - T_{cabin})$
$\frac{dT_{food}}{dt} = (mCp_{food})^{-1} \cdot \dot{Q}_{c2f}$
$\frac{dT_{cabin}}{dt} = (mCp_{cabin})^{-1} \cdot (-\dot{Q}_{c2f} - \dot{Q}_E + \dot{Q}_{s2c})$
$Q_{food,loss} = \int_{t_0}^{t_f} 100 \cdot D_{T,ref} \exp(\frac{T_{food} - T_{ref}}{z}) dt$

- Constant super-heating ($\Delta T_{sup} = 3\,^\circ$C): This is controlled by adjusting the opening degree (OD) of the expansion valve.
- Constant sub-cooling ($\Delta T_{sub} = 2\,^\circ$C): We assume that the condenser is designed to give a constant degree of sub-cooling, which by design consumes the degree of freedom related to active charge, see Jensen and Skogestad (2007).

So we are left with three unconstrained degrees of freedom that should be used to optimize the operation. These are:

(1) Compressor speed N_C
(2) Condenser fan speed N_{CF}
(3) Evaporator fan speed N_{EF}

These inputs are controlling three variables:

(1) Evaporating pressure P_E
(2) Condensing pressure P_C
(3) Cabinet temperature T_{cabin}

However, the setpoints for these three variables may be used as manipulated inputs in our study so the number of degrees of freedom is still three.

2.2 Mathematical model

The model equations are given in Table 1; please see Larsen (2005) for the modelling of refrigeration systems. We assume that the refrigerator has fast dynamics compared with the display cabinet and food, so for the condenser, evaporator, valve and compressor we have assumed steady-state. For the display cabinet and food we use a dynamic model, as this is where the slow and important (for economics) dynamics will be. The food is lumped into one mass, and the airs in the cabinet together with walls are lumped into one mass. The main point is that there are two heat capacities in series. For the case with constant display cabinet temperature we will also have constant food temperature. There are then no dynamics and we may use steady-state optimization.

Some data for the simulations are given in Table 2; please see Larsen (2005) for further data.

Table 2. Some data used in the simulation

Display cabinet *
heat transfer area $UA_{\text{s2c}} = 160\,\text{W K}^{-1}$
heat capacity: $mCp_{\text{cabin}} = 10\,\text{kJ K}^{-1}$
Food
heat transfer area: $UA_{\text{c2f}} = 20.0\,\text{W}\,K^{-1}$
heat capacity: $mCp_{\text{food}} = 756\,\text{kJ K}^{-1}$
quality parameter: $D_{T,ref} = 0.2\,\text{day}^{-1}$;
quality parameter: $T_{ref} = 0\,^\circ$C
quality parameter: $Z = 10\,^\circ$C

* Combined values for the air inside the cabinet, walls etc.

2.3 Influence of setpoints on energy consumption

As stated above, this system has three setpoints that may be manipulated: P_C, P_E and T_{cabin}. In Fig.2, surface shows that under 2 different cabinet temperatures, the variation of energy consumption with varying P_C and P_E. Point A is the optimum for cabinet temperature T_{cabin1} and point B is the optimum for T_{cabin2}. T_{cabin1} is lower than T_{cabin2}, so the energy consumption is higher in point A than in point B.

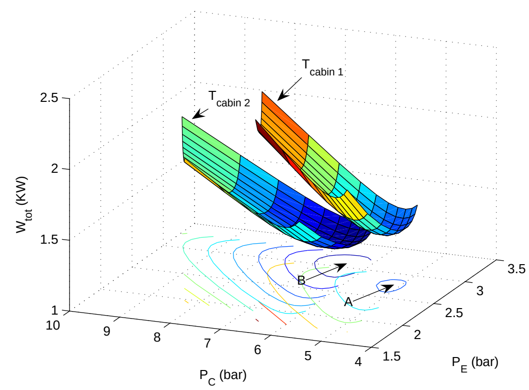


Fig. 2. Energy consumption under different setpoints.

2.4 Influence of setpoint on food quality

Food quality decay is determined by its composition factors and many environmental factors, such as temperature, relative humidity, light etc. Of all the environmental factors, temperature is the most important, since it not only strongly affects reaction rates but is also directly imposed to the food externally. The other factors are at least to some extent controlled by food packaging.

Here we focus on the temperature influence to food quality Q_{food}. The only setpoint directly influencing food temperature (and thus food quality) is T_{cabin}. Fig. 3 shows the daily quality loss for chilled cod product under 4 cases: T_{food} of 2, $1\,^\circ$C and T_{sin}. $T_{\text{sin,1}}$ and $T_{\text{sin,2}}$ are the sinusoidal function with mean value of $1\,^\circ$C, amplitude of $1\,^\circ$C and $3\,^\circ$C respectively, period is 24h. Note that the quality loss is higher with higher temperature, but there is only minor extra loss over 24h by using a sinusoidal temperature with small amplitude. A sinusoidal with large amplitude has a larger influence to quality due to the non-linearity of the quality function; it will not be considered here.

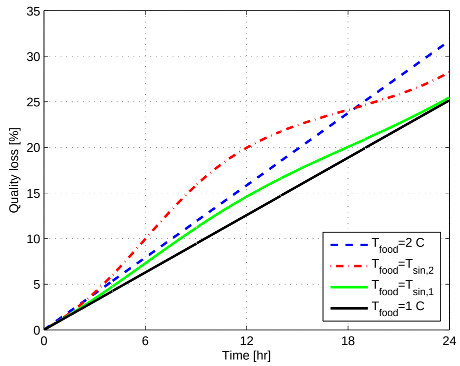


Fig. 3. Fresh fish quality loss when stored at different temperatures.

3. PROBLEM FORMULATION

We here consider at a time horizon of three days, ambient temperature (T_{amb}) follows a sinusoidal function with a mean value of 20 °C, period of 24 hours and amplitude of 6 °C. This is a normal temperature profile in Denmark during summer, see DMI (2007).

The objective is to minimize the energy consumption, subject to maintaining a fixed quality loss, by using those 3 DOF. This can be formulated mathematically as:

$$\min_{(N_C(t),N_{CF}(t),N_{EF}(t))} J \tag{1}$$

$$\text{where} \qquad J = \int_{t_0}^{t_f} \underbrace{(W_C(t) + W_{CF}(t) + W_{EF}(t))}_{W_{tot}(t)} \, \mathrm{d}t \tag{2}$$

The quality loss of the food could be included in the objective function directly, but we choose to limit it by using constraints. The optimization is also subjected to other constraints, such as maximum speed of fans and compressor, minimum and maximum value of evaporator and condenser pressure etc.

In this paper, the food is a fresh cod product. Danish food authorities require it to be kept at a maximum of 2°C. The control engineer will normally set the temperature setpoint a little lower, for example at 1°C.

Case 1 Traditional operation with constant pressures (P_{E}), (P_{C}) and constant temperatures ($T_{\mathrm{cabin}} = T_{\mathrm{food}} = 1\,°\mathrm{C}$)

There are usually large variations in the ambient temperature during the year so in traditional operation it is necessary to be conservative when choosing the setpoint for condenser pressure. To reduce this conservativeness it is common to use one value for summer and one for winter. We will here assume that the summer setting is used.

To get a fair comparison with traditional control, which operates at 1°C, we will illustrate our optimization by considering the following cases:

Case 2 T_{cabin} and T_{food} constant at 1 °C.
Two remaining unconstrained degrees of freedom as functions of time are used for minimizing the energy consumption in 1.
Case 3 $\overline{T_{\mathrm{food}}} = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} T_{\mathrm{food}}(t)\,\mathrm{d}t$ = 1 °C.
Three remaining unconstrained degrees of freedom as functions of time are used for minimizing the energy consumption in 1.
Case 4 $Q_{\mathrm{food,\,loss}}(t_f) \le 75.5\,\%$.
Three remaining unconstrained degrees of freedom as functions of time are used for minimizing the energy consumption in 1. 75.5% is the quality loss at constant temperature of 1 °C obtained in cases 1 and 2.

4. OPTIMIZATION

4.1 Optimization

The model is implemented in *gPROMS*® and the optimization is done by dynamic optimization (except for Case 1). For the Case 2, we have used piecewise linear manipulated variables with a discretisation every hour. For the cases with varying cabinet temperature (Case 3 and 4), we have used sinusoidal functions $u = u_0 + A \cdot \sin(\pi \cdot t/24 + \phi)$, where u_0 is the nominal input, A is the amplitude of the input, t is the time and ϕ is the phase shift of the input.

Using a sinusoidal function has several advantages:

- There are much fewer variables to optimize on, only 3 for each input, compared with 3 parameters for each time interval for discrete dynamic optimization
- There are no end-effects.

In all cases we find that the phase shift is very small.

4.2 Optimization results

Table 3 compares the four cases in terms of the overall cost J, end quality loss, maximum total power ($W_{\mathrm{tot,max}}$) and maximum compressor power ($W_{C,\mathrm{max}}$). The two latter variables might be important if there are restrictions on the maximum compressor power or on the total electric power consumption.

Some key variables, including speed and energy consumption for compressor and fans as well as temperatures, are plotted for each case in Fig.5 through Fig.8.

Table 3. Traditional operation and optimal operation for three different constraints

	Case 1 *	Case 2 **	Case 3 ***	Case 4 ****
J [MJ]	273.7	242.8	240.7	241.4
$Q_{food,loss}(t_f)$ [%]	75.5	75.5	76.1	75.5
$W_{C,\mathrm{max}}$ [W]	955	1022	836	879
$W_{\mathrm{tot,max}}$ [W]	1233	1136	946	981

* Traditional operation; $T_{\mathrm{cabin}} = 1\,°\mathrm{C}$, $P_E = 2.4\,\mathrm{bar}$ and $P_C = 8.0\,\mathrm{bar}$
** $T_{\mathrm{cabin}} = 1.0\,°\mathrm{C}$
*** $\overline{T_{\mathrm{food}}} = 1.0\,°\mathrm{C}$
**** $Q_{\mathrm{food,loss}}(t_f) \le 75.5\,\%$

For Case 1 (traditional operation) the total energy consumption over three days is 273.7 MJ. Note that the condenser temperature (and pressure) is not changing with time.

If we keep $T_{\mathrm{cabin}} = T_{\mathrm{food}}$ constant at 1 °C, but allow the pressures (and temperatures) in the condenser and evaporator to change with time (Case 2), we may reduce the total energy consumption by 11.3% to 242.8 MJ. Fig. 6 shows that the evaporator temperature is constant, because we still control the cabinet temperature, while the condenser temperature varies with ambient temperature. The quality is the same as in Case 1 because of the constant cabinet temperature. The power variations are larger, but nevertheless, the maximum total power ($W_{\text{tot,max}}$) is reduced by 7.9% to 1136 W.

Next, we also allow the cabinet temperature to vary, but add a constraint on the average food temperatures $\overline{T}_{\text{food}} = 1.0\,^{\circ}\text{C}$ (Case 3). This reduces the total energy consumption with another 0.9%, while the food quality loss is slightly higher. Note from Fig.7 that the evaporator, cabinet and food temperature is varying a lot.

Finally, in Case 4 we do not care about the average food temperature, but instead restrict the quality loss. With $Q_{\text{food,loss}}(t_f) \leq 75.5\%$, which is the same end quality we obtained for Case 1, we save 11.8% energy compared with Case 1, but use slightly more than for Case 3 (0.29%). Note from Fig.8 that the amplitude for food, cabinet and evaporator temperature are slightly reduced compared to Case 3.

An important conclusion is that most of the benefit in terms of energy savings is obtained by letting the setpoint for P_E and P_C vary (Case 2). The extra savings by changing also the cabinet temperature T_{cabin} (Case 3 and 4) are small. However, the peak value for compressor power and total system power is significantly decreased for Case 3 and 4. This is also very important, because a lower compressor capacity means a lower investment cost, and a lower peak value of total power consumption will further reduce the bill for supermarket owner, according to the following formula:

$$C_{op} = \int_{month}^{year} (P_{el}(t) \cdot E_{el}(t) + \max(P_{el}(t)) \cdot E_{el,dem}(t))\, \mathrm{d}t \quad (3)$$

where C_{op} is the operating cost, E_{el} is the electricity rate, P_{el} is the electric power, $E_{el,dem}$ is the electricity demand charge, $\max(P_{el}(t))$ is the maximum electric power during one month.

4.3 Trade-off between energy consumption and food quality loss

Fig. 4 plots the Pareto optimal curve between food quality loss and energy consumption. It shows that reducing quality loss and saving energy is a conflicting objective to systems. An acceptable tradeoff between the two goals can be selected by picking a point somewhere along the line. It also shows that Case 1 is far away from optimization; Case 4 is one optimal point, while Case 2 and 3 are near optimal solutions.

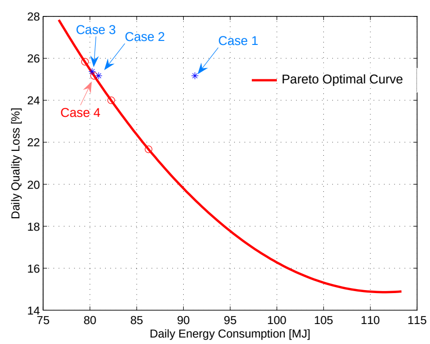


Fig. 4. Optimization between food quality loss and energy consumption

5. DISCUSSION

Having oscillations in the pressures will impose stress and cause wear on the equipment. This might not be desirable in many cases, but in this study the oscillations are with a period of one day, so this should not be an issue.

Experiments on the influence of fluctuating temperatures on food quality were reviewed by Ulrich (1981), where marginal reduction in final quality due to fluctuations was reported. In our case, food temperature is only slowly varying, and with an amplitude of less than 1 °C. Thus, this will not pose any negative influence on food quality.

6. CONCLUSION

We have shown that traditional operation where the pressures are constant gives excessive energy consumption. Allowing for varying pressure in the evaporator and condenser reduce the total energy consumption by about 11%. Varying food temperature gives only minor extra improvements in terms of energy consumption, but the peak value of the total power consumption is reduced with an additional 14% for the same food quality loss.

Reducing quality loss and saving energy is a conflicting objective. Our optimization result will help the engineer to select an acceptable tradeoff between the two goals by picking a point somewhere along the Pareto front line.

This paper investigates the potential of finding a balancing point between quality and energy consumption, by open-loop dynamic optimizations. It uses the sinusoid ambience temperature as one example. In real life, weather patterns are not exactly sinusoidal functions, but real weather conditions can be easily obtained in advance from forecast. Practical implementation, including selecting controlled variables and using closed-loop feedback control, will be the theme of future research.

REFERENCES

J. Cai, J. Risum, and C. Thybo. Quality model of foodstuff in a refrigerated display cabinet. Purdue, USA, 2006. In proc.: 11th International Refrigeration and Air Condition Conference.

DMI. Weather in denmark, www.dmi.dk. 2007.

A. Jakobsen and B. Rasmussen. Energy-optimal speed control of fans and compressors in a refrigeration system. pages 317–323., Nancy, France, July 1998. Eurotherm 62.

A. Jakobsen, B. Rasmussen, M. J. Skovrup, and J. Fredsted. Developement of energy optimal capacity control in refrigeration systems. Purdue, USA, 2001. In proc.: International refrigeration conference.

J. B. Jensen and S. Skogestad. Optimal operation of simple refrigeration cycles. Part I: Degrees of freedom and optimality of sub-cooling. *Comput. Chem. Eng.*, 2007.

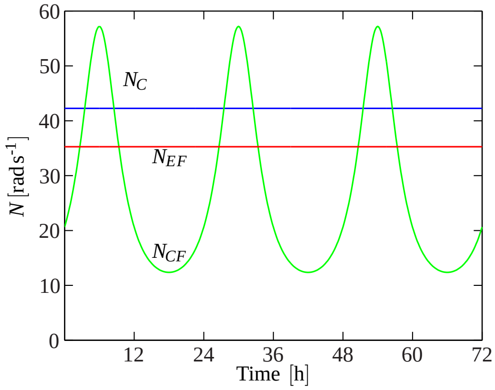
L. F. S. Larsen. *Model based control of refrigeration system*. PhD thesis, Department of Control Engineering, Aalborg University, Denmark, 2005.

L. F. S. Larsen and C. Thybo. Potential energy saving in refrigeration system using optimal setpoint. Taipei, Taiwan, 2004. In proc.: Conference on control applications.

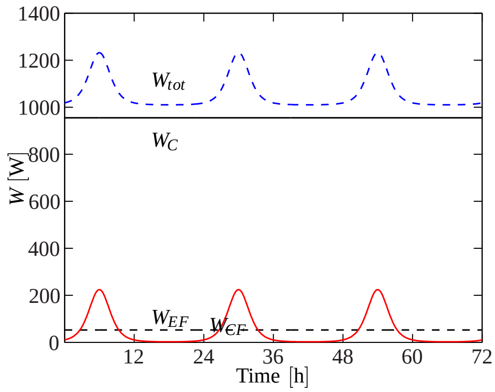
D. Leducqa, J. Guilparta, and G. Trystramb. Non-linear predictive control of a vapour compression cycle. *International Journal of Refrigeration*, 29:761– 772, 2006.

M. C. Swensson. *Studies on on-line optimizing control, with application to a heat pump*. PhD thesis, Department of Refrigeration Engineering, NTNU, Norway, 1994.

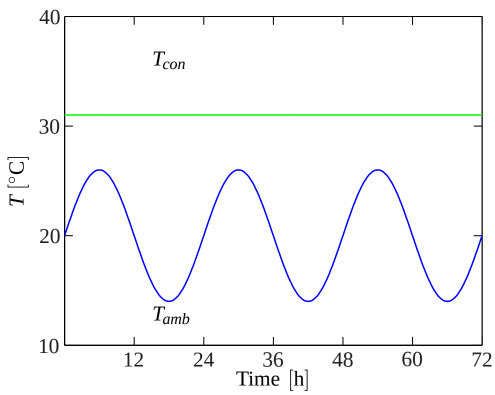
R. Ulrich. Variations de temperature et qualite des produits surgeles. *Review Generale due Froid*, 71:371–389, 1981.



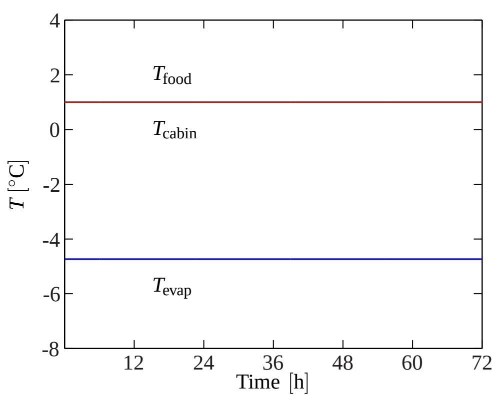
(a) Speed



(b) Power

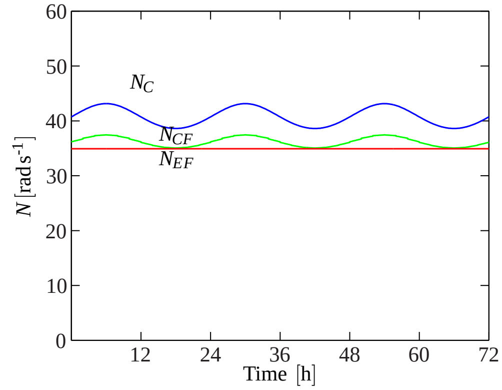


(c) High temperatures

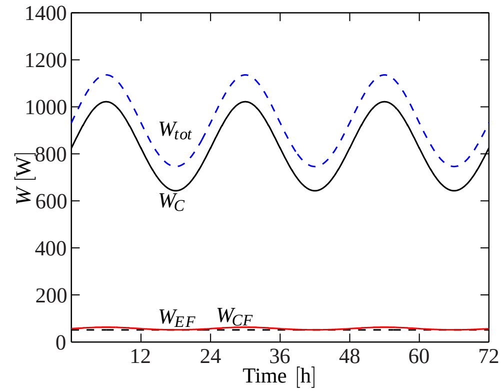


(d) Low temperatures

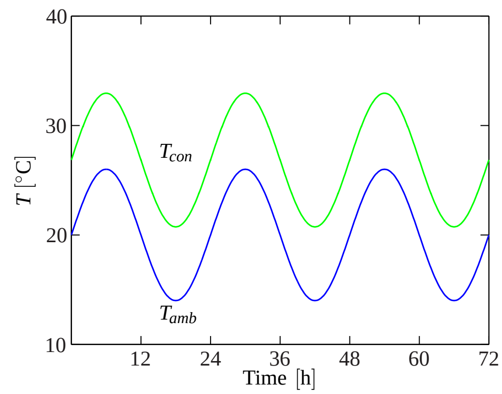
Fig. 5. Traditional operation with $T_{\text{cabin}} = 1\,°\text{C}$, $P_E = 2.4\,\text{bar}$ and $P_C = 8.0\,\text{bar}$ (Case 1)



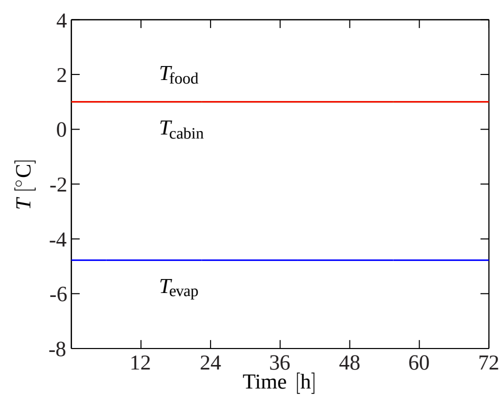
(a) Inputs



(b) Power



(c) High temperatures



(d) Low temperatures

Fig. 6. Optimal operation for $T_{\text{cabin}} = 1\,°\text{C}$ (Case 2)

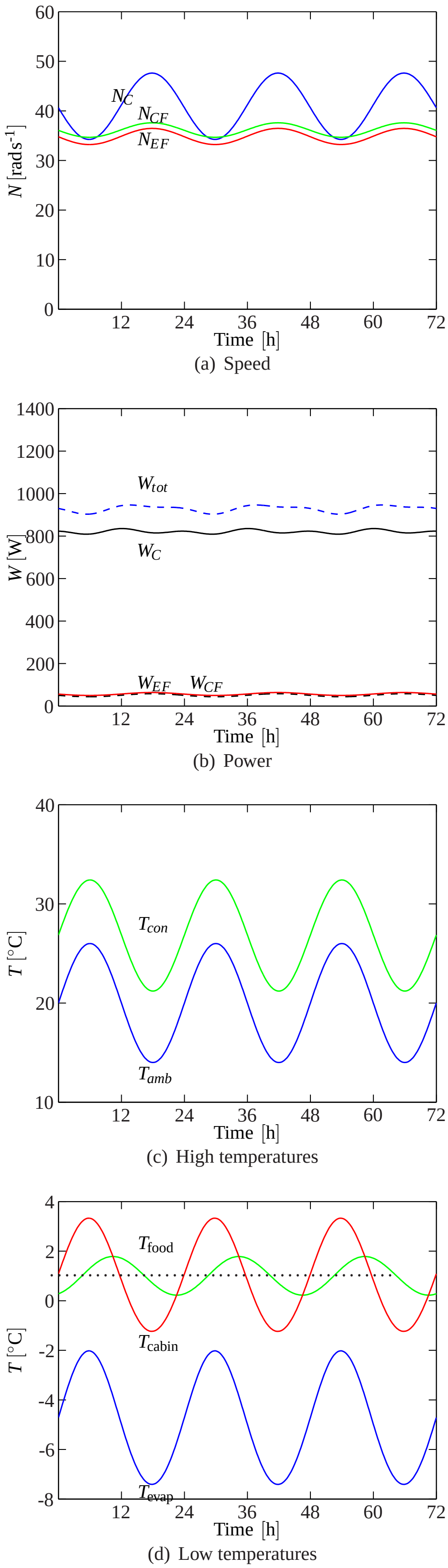


Fig. 7. Optimal operation for $\overline{T}_{\text{food}} = 1\,^\circ\text{C}$ (Case 3)

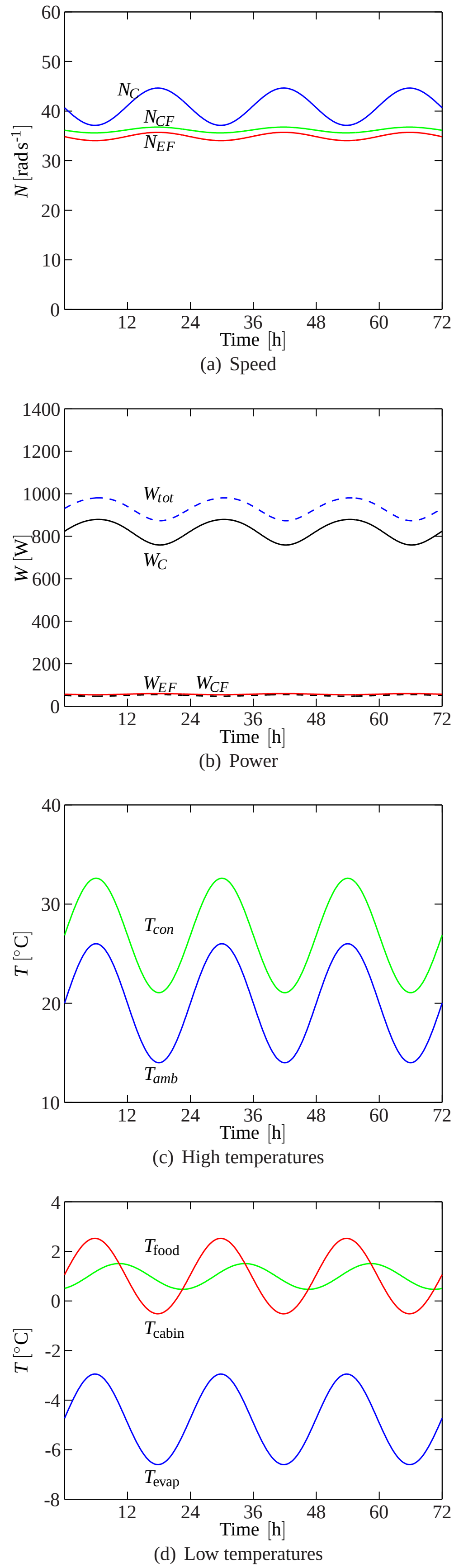


Fig. 8. Optimal operation for $Q_{\text{food}} \leq 75.5\,\%$ (Case 4)