Balancing Energy Consumption and Food Quality Loss in Supermarket Refrigeration System

J. Cai and J.B. Jensen and S. Skogestad and J. Stoustrup

Abstract— **This paper presents an optimal strategy with balanced energy consumption and food quality loss, at varying ambient condition, in a supermarket refrigeration system. Compared with traditional operation with pressure control, the method shows a large potential for energy savings without extra loss of food quality. 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.**

I. INTRODUCTION

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

Many efforts on optimization of cooling systems have focused on optimizing objective functions such as overall energy consumption, system efficiency, capacity, or wear of the individual components [4], [5], [8], [9], [10]. They have proved significant improvement of system performance under disturbance, while there has been little emphasis on the quality aspect of food inside the display cabinet.

This paper will discuss a strategy of dynamic optimization of commercial refrigeration system, featuring balanced system energy consumption and food quality loss. A former developed thermal model [1] and quality model of food [2] provide a tool for monitoring and controlling quality loss during the whole process. The model and parameters for the refrigeration system are from [7].

The paper is organized as follows: Operation and modelling of refrigeration systems is presented in Section II. In Section III we introduce the problem formulation used for optimization. Different optimization schemes are presented in Section IV. Finally some discussion follows in Section V.

II. PROCESS DESCRIPTION

A simplified sketch of the process is shown in Fig.1. In the evaporator there is heat exchange between the air inside

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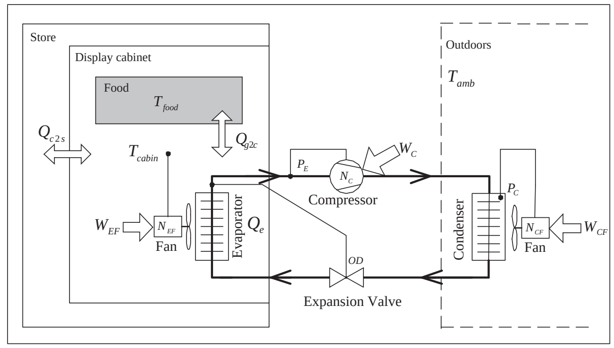

Fig. 1. Sketch of a simplified supermarket refrigeration system studied in this paper.

the display cabinet and the cold refrigerant, giving a slightly super-heated 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.

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 the condenser fan is located at the roof of the shop. Condensation is achieved by heat exchange with ambient air.

A. Degree of freedom analysis

There are 5 degrees of freedom (input) in a general simple refrigeration system [6]. 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 [6].

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

- 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 [6] for details).

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})

TABLE I
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
$\dot{Q}_{c2f} = UA_{c2f} \cdot (T_{cabin} - T_{food})$
$\dot{Q}_{s2c} = UA_{s2c} \cdot (T_{store} - T_{cabin})$
$\frac{dT_{food}}{dt} = (\dot{m}_{food} \cdot Cp_{food})^{-1} \cdot \dot{Q}_{c2f}$
$\frac{dT_{cabin}}{dt} = (\dot{m}_{cabin} \cdot Cp_{cabin})^{-1} \cdot (-\dot{Q}_{c2f} - \dot{Q}_E + \dot{Q}_{s2c})$
$Q_{food,loss} = \int_{t_0}^{t_f} 100 \cdot D_{T,ref} \exp(\frac{T_{food} - T_{ref}}{z}) dt$

TABLE II
SOME DATA USED IN THE SIMULATION

Display cabinet[a]
heat transfer area $UA_{\mathrm{s2c}} = 160\,\mathrm{W\,K^{-1}}$
heat capacity: $(mcp)_{\mathrm{air}} = 10\,\mathrm{kJ\,K^{-1}}$
Food
heat transfer area: $UA_{\mathrm{c2f}} = 20.0\,\mathrm{W}\,K^{-1}$
heat capacity: $(mcp)_{\mathrm{food}} = 756\,\mathrm{kJ\,K^{-1}}$
quality parameter: $D_{T,ref} = 0.2\,\mathrm{day}^{-1}$;
quality parameter: $T_{ref} = 0\,^{\circ}\mathrm{C}$
quality parameter: $Z = 10\,^{\circ}\mathrm{C}$

[a]Combined values for the air inside the cabinet, walls etc.

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.

B. Mathematical model

The model equations are given in Table I. 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 air 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 II, please see [7] for further data.

C. 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 cabinet temperature T_{cabin2}. T_{cabin1} is lower than T_{cabin2}, so the energy consumption is higher in point A than in point B.

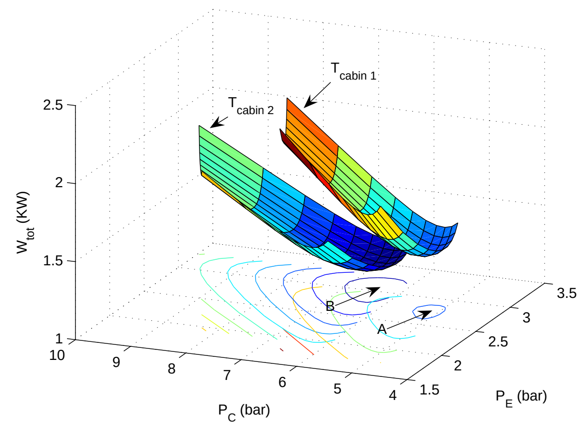

Fig. 2. Energy consumption under different setpoints.

D. Influence of setpoint on food quality

Food quality decay is determined by the food composition and many environmental factors, such as temperature, relative humidity, light and mechanical stress. Of all the environmental factors, temperature is the most important, since it not only strongly affects reaction rates, but is also directly dependent on external conditions, the other factors being at least to some extent controlled by food packaging.

Here we focus on the influence of temperature on the food quality, Q_{food}. The only setpoint directly influencing food temperature (and thus food quality) is the cabinet temperature T_{cabin}. Fig. 3 shows the quality loss for chilled cod during one day for 4 different cases; T_{food} of 0, 1, 2 °C and T_{sin}. T_{sin} is a sinusoidal function with mean value of 1 °C, amplitude of 1 °C and period of 24 h. Note that the quality loss is larger with higher temperature, but there seems to be only minor extra degrading of food quality over the 24 h period by using the sinusoidal temperature function.

III. PROBLEM FORMULATION

We here consider at a time horizon of three days, in which the ambient air temperature (T_{amb}) is assumed to follow a sinusoidal function with a mean value of 20 °C, period of 24 hours and an amplitude of 6 °C. This is a normal temperature profile in Denmark during summer.

The objective is to minimize the energy consumption, subject to maintaining an acceptable food quality, by using

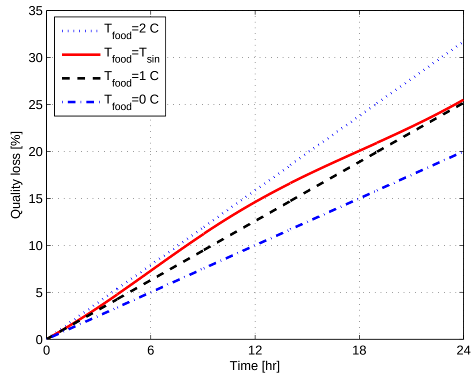

Fig. 3. Fresh fish quality loss when stored at different temperatures. The dashed line show that sinusoidal variations have little effect on the end quality.

the three unconstrained degrees of freedom. This can be formulated mathematically as:

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

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

The quality of the food could be included in the objective function directly, but we choose to limit the quality loss 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 respectively.

In this paper, the food is fresh cod. Danish food authorities require one to keep the fresh fish 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 ($T_{cabin} = T_{food} =$ 1 °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 operate at 1°C, we will illustrate our optimal strategy 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 $\overline{T_{food}} = \int T_{food}\, \mathrm{d}t$ constant at 1 °C.
Three remaining unconstrained degrees of freedom as functions of time are used for minimizing the energy consumption in 1.

Case 4 $Q_{food,\,loss}(t_f) \leq 75.5\%$.
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.

In Case 2, the constraint (T_{cabin}) is given at all times, so this consumes one degree of freedom. In the last two cases, the constraint is given as an average and at the end time respectively so there are still three degrees of freedom left at any given time. Case 3 will obviously give larger quality loss than cases 1, 2 and 4, because of variations in the food temperature.

IV. Optimization

A. 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 discretization 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. Since we are considering a fixed time horizon, the optimization can for some cases produce results with strange behavior near the end. This will not be optimal if one consider that the display cabinet will also operate the next day.

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

B. Results

Table III compares the four cases in terms of the overall cost J, end quality loss, maximum total power ($W_{tot,max}$) and maximum compressor power ($W_{C,max}$). 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.4 through Fig.7.

TABLE III
TRADITIONAL OPERATION AND OPTIMAL OPERATION FOR THREE DIFFERENT CONSTRAINTS

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

[a] Traditional operation; $T_{cabin} = 1$ °C, $P_E = 2.4$ bar and $P_C = 8.0$ bar
[b] $T_{cabin} = 1.0$ °C
[c] $\overline{T_{food}} = 1.0$ °C
[d] $Q_{food,loss}(t_f) \leq 75.5\%$

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 $T_{\text{cabin}} = T_{food}$ 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. 5 shows that the evaporator temperature is constant, because we still control the cabinet temperature, while the condenser temperature varies sinusoidally following the ambient air temperature. The quality is the same as in traditional operation (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 $\overline{T}_{\text{food}} = 1.0^\circ$C (Case 3). This reduces the total energy consumption with another 0.9%, while the food quality loss is slightly worse. Note from Fig.6 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%). However, we obtain the same end quality of the food. Note from Fig.7 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 very 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 period.

V. 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 [11], and little evidence of any reduction in final quality due to fluctuations was reported at temperatures colder than -18 $^\circ$C. Gormley [3] tested samples of frozen raw salmon, smoked mackerel, stewed pork pieces, ice cream, etc., by subjecting them to temperature fluctuations below the freezing point. The results shows that the temperature variations had a minimal effect on texture, color, water-holding capacity and drip loss on thawing for most of the products.

In our case, food temperature is only slowly varying, and with an amplitude of less than 1°C. This will not pose any negative influence on food quality.

VI. 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 total power consumption is reduced with additional 14% for the same food quality loss.

Note that the optimal policy with respect to energy is to increase the cooling when the ambient temperature is low (Cases 3 and 4). This is opposite of the traditional operation with constant cabinet temperature (Case 1). In all the current cases, we found the phase shift of inputs is very small, but some extreme case might need a larger phase shift, such as an extremely hot second day, when the system foreseen this situation, in order to meet the constraint on food quality, it may need to cool much more down during the night.

Practical implementation, in terms of selecting controlled variables for the 3 manipulated inputs (N_{C}, N_{CF} and N_{EF}) we have optimized will be the theme of future research.

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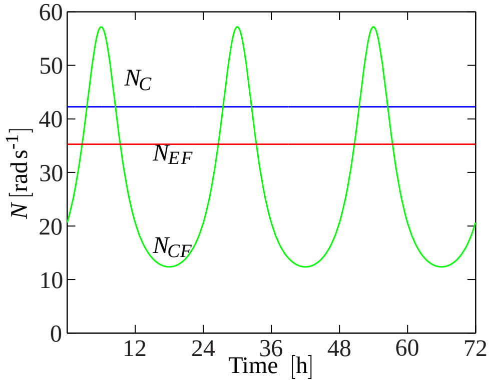
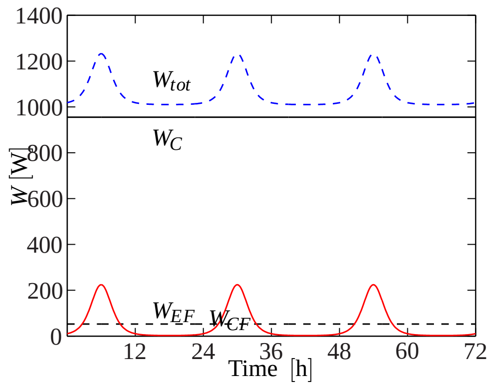
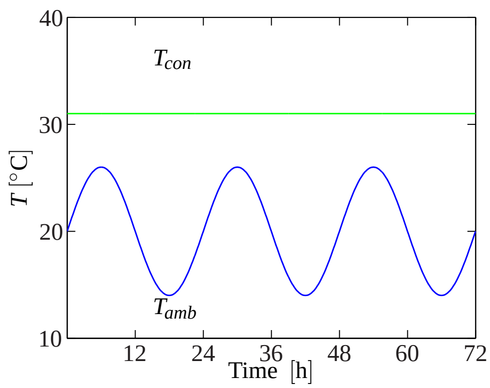


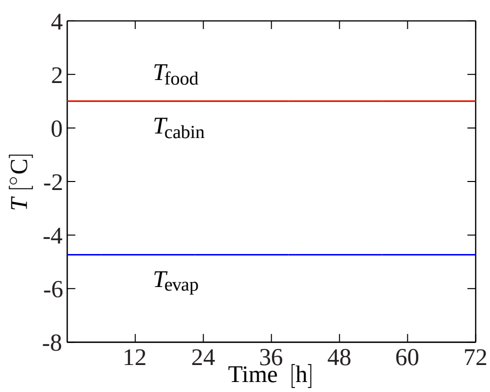
(a) Speed



(b) Power

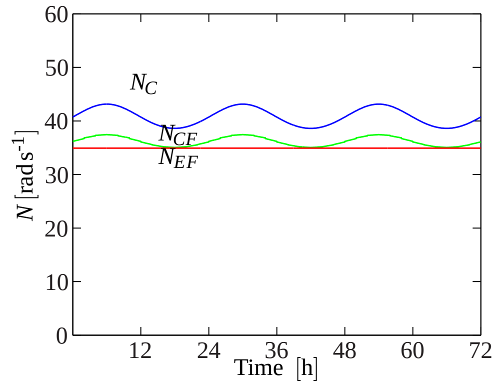


(c) High temperatures

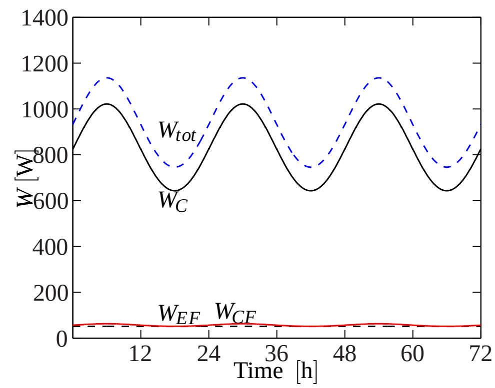


(d) Low temperatures

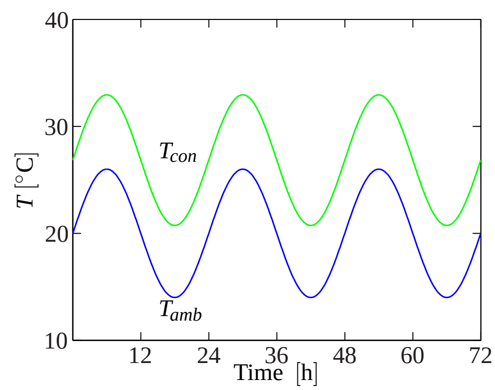
Fig. 4. Traditional operation with $T_{\text{cabin}} = 1\,^{\circ}\mathrm{C}$, $P_E = 2.4\,\mathrm{bar}$ and $P_C = 8.0\,\mathrm{bar}$ (Case 1)



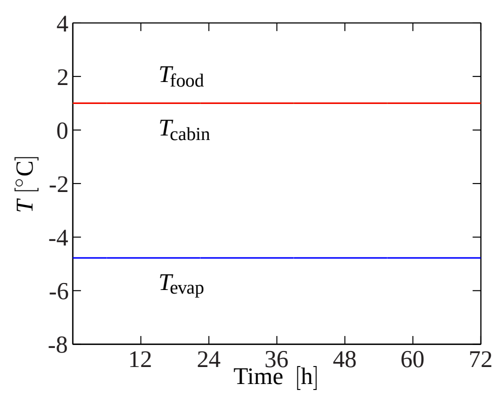
(a) Inputs



(b) Power

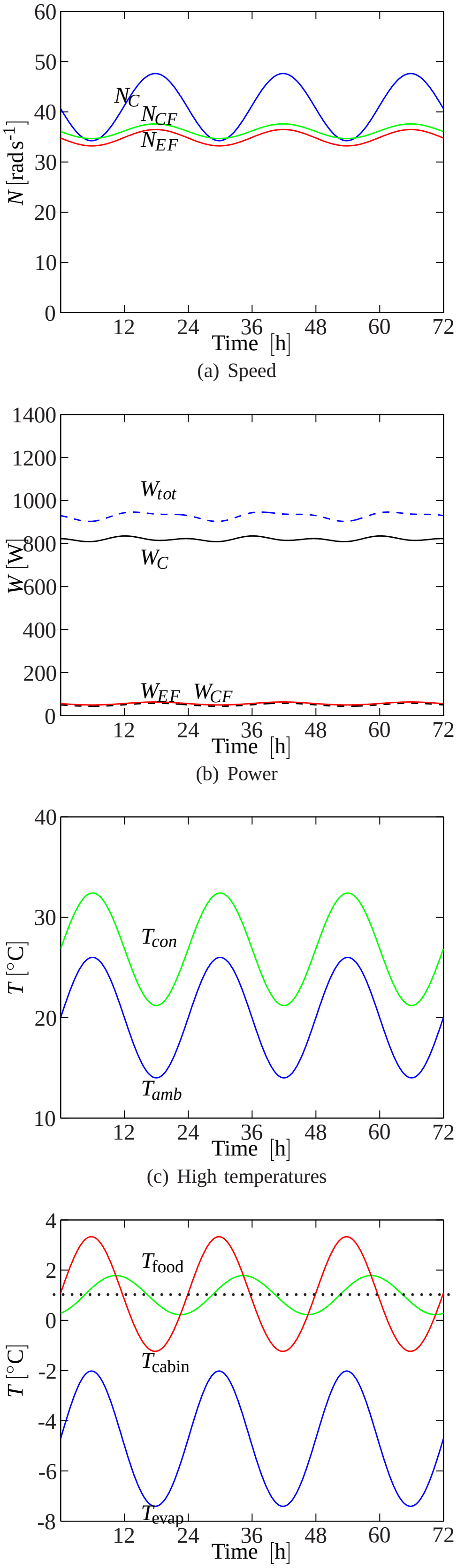


(c) High temperatures



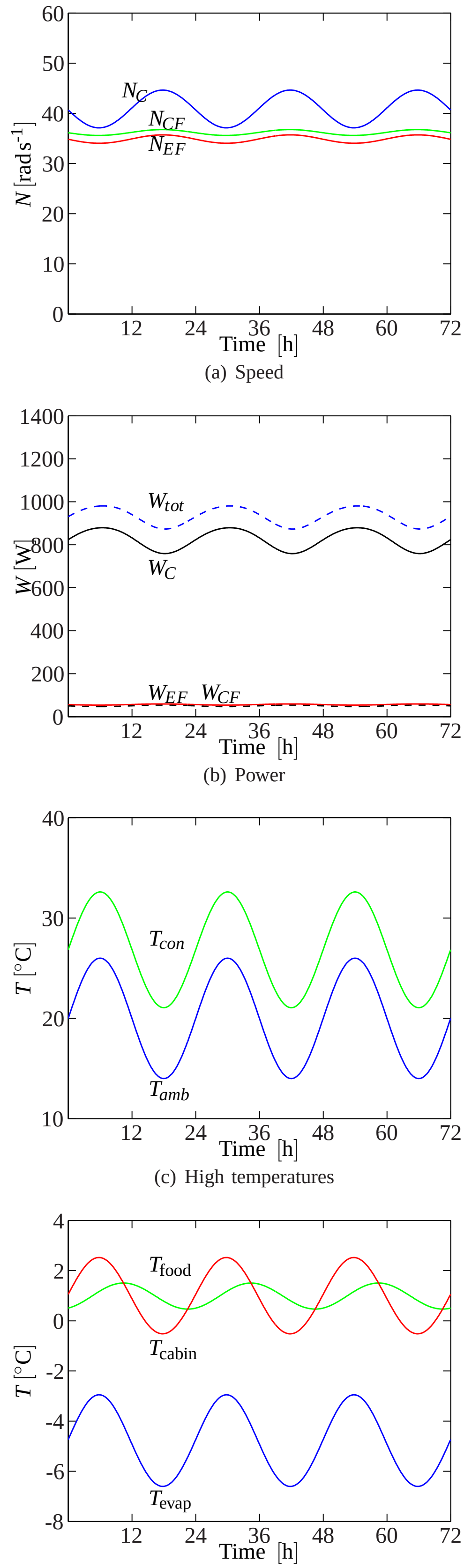
(d) Low temperatures

Fig. 5. Optimal operation for $T_{\text{cabin}} = 1\,^{\circ}\mathrm{C}$ (Case 2)



(a) Speed (b) Power (c) High temperatures (d) Low temperatures

Fig. 6. Optimal operation for $\overline{T}_{\text{food}} = 1\,^{\circ}\text{C}$ (Case 3)



(a) Speed (b) Power (c) High temperatures (d) Low temperatures

Fig. 7. Optimal operation for $Q_{\text{food}} \leq 75.5\%$ (Case 4)