Table 1
Variables of the climate dynamic model.

	Definition	Unit
C^{in}	Indoor CO_2 absolute concentration.	$\mathrm{g/m^3}$
C^{out}	Outdoor CO_2 absolute concentration.	$\mathrm{g/m^3}$
D^{dos}	CO_2 dosing rate.	g/s
D^{vent}	CO_2 changing rate due to ventilation.	g/s
D^{ass}	CO_2 assimilation rate.	g/s
F^{cool}	Humidifying rate due to cooling pads and humidifiers.	g/s
F^{deh}	Dehumidifying rate.	g/s
F^{vent}	Humidity changing rate due to venting.	g/s
F^{tran}	Humidity changing rate due to transpiration.	g/s
F^{vc}	Humidity changing rate due to vapor condensing.	g/s
g^{vc}	Vapor condensing coefficient.	m/s
g^{tran}	Transpiration conductance.	m/s
H^{in}	Indoor absolute humidity.	$\mathrm{g/m^3}$
$H^{\mathrm{in,sat}}$	Indoor saturation absolute humidity.	$\mathrm{g/m^3}$
H^{out}	Outdoor absolute humidity.	$\mathrm{g/m^3}$
H^{cano}	Absolute humidity at canopy.	$\mathrm{g/m^3}$
L	Daily light integral (resets to 0 at 00:00).	$\mathrm{mol/m^2}$
Q^{heat}	Heat-gain power due to heaters.	W
Q^{vent}	Heat-exchange power due to ventilation.	W
Q^{cool}	Heat-loss power due to cooling systems.	W
Q^{solar}	Heat-gain power due to solar radiation.	W
$Q^{\mathrm{i-o}}$	Heat-exchange power due to $T^{\mathrm{i-o}}$.	W
Q^{LED}	Heat-gain power due to LEDs.	W
Q^{tran}	Heat-loss power due to transpiration.	W
r^{s}	Canopy stomatal resistance.	s/m
$R^{\mathrm{cano-abs}}$	Canopy-absorbed radiation.	$\mathrm{W/m^2}$
$R^{\mathrm{cano-glo}}$	Global radiation at canopy.	$\mathrm{W/m^2}$
$R^{\mathrm{cano-solar}}$	Solar radiation at canopy.	$\mathrm{W/m^2}$
$R^{\mathrm{cano-LED}}$	LED radiation at canopy.	$\mathrm{W/m^2}$
R^{out}	Outdoor radiation.	$\mathrm{W/m^2}$
t	Time.	s
T^{out}	Outdoor temperature.	°C
T^{in}	Indoor temperature.	°C
T^{cover}	Covering temperature.	°C
$T^{\mathrm{i-o}}$	Indoor–outdoor temperature difference.	°C
U^{heat}	Actuation of heater power.	-
U^{fan}	Actuation of ventilation fan speed.	-
U^{nat}	Actuation of natural ventilation opening ratio.	-
U^{pad}	Actuation of cooling pad wetness level.	-
U^{dos}	Actuation of CO_2 dosing rate.	-
U^{LED}	Actuation of LED electric power.	-
U^{shad}	Actuation of shading screen closure.	-
U^{warm}	Actuation of warm-keeping screen closure.	-
U^{hum}	Actuation of humidification rate.	-
U^{deh}	Actuation of dehumidification rate.	-
V^{vent}	Total ventilation.	$\mathrm{m^3/s}$
X^{cano}	PPFD at canopy.	$\mu\mathrm{mol/(m^2 \cdot s)}$

The indoor temperature dynamics are modeled by (1).

$$\frac{\mathrm{d}T^{\mathrm{in}}}{\mathrm{d}t} = \frac{Q^{\mathrm{heat}} - Q^{\mathrm{vent}} - Q^{\mathrm{cool}} + Q^{\mathrm{solar}} - Q^{\mathrm{i-o}} + Q^{\mathrm{LED}} - Q^{\mathrm{tran}}}{\omega^{\mathrm{T}} \cdot V^{\mathrm{gh}} \cdot c^{\mathrm{vh}}} \tag{1a}$$

$$Q^{\mathrm{heat}} = \bar{Q}^{\mathrm{heat}} \cdot U^{\mathrm{heat}} \tag{1b}$$

$$Q^{\mathrm{vent}} = c^{\mathrm{vh}} \cdot T^{\mathrm{i-o}} \cdot V^{\mathrm{vent}} \tag{1c}$$

$$Q^{\mathrm{cool}} = \bar{Q}^{\mathrm{pad}} \cdot U^{\mathrm{pad}} + q^{\mathrm{evap}} \cdot \eta^{\mathrm{evap}} \cdot \bar{F}^{\mathrm{hum}} \cdot U^{\mathrm{hum}} \tag{1d}$$

$$Q^{\mathrm{solar}} = A^{\mathrm{floor}} \cdot R^{\mathrm{cano-solar}} \tag{1e}$$

$$Q^{\mathrm{i-o}} = \left[\upsilon^{\mathrm{roof}} \cdot A^{\mathrm{roof}} \cdot \left(1 - \eta^{\mathrm{warm}} \cdot U^{\mathrm{warm}}\right) + \upsilon^{\mathrm{wall}} \cdot A^{\mathrm{wall}} \right] \cdot T^{\mathrm{i-o}} \tag{1f}$$

$$Q^{\mathrm{LED}} = \bar{P}^{\mathrm{LED}} \cdot U^{\mathrm{LED}} \tag{1g}$$

$$Q^{\mathrm{tran}} = q^{\mathrm{evap}} \cdot g^{\mathrm{tran}} \cdot \left(H^{\mathrm{cano}} - H^{\mathrm{in}}\right) \cdot A^{\mathrm{floor}} \tag{1h}$$

The indoor humidity dynamics are modeled by (2).

$$\frac{\mathrm{d}H^{\mathrm{in}}}{\mathrm{d}t} = \frac{F^{\mathrm{cool}} - F^{\mathrm{deh}} - F^{\mathrm{vent}} + F^{\mathrm{tran}} - F^{\mathrm{vc}}}{\omega^{\mathrm{H}} \cdot V^{\mathrm{gh}}} \tag{2a}$$

$$F^{\mathrm{cool}} = Q^{\mathrm{cool}} / q^{\mathrm{evap}} \tag{2b}$$

$$F^{\mathrm{deh}} = \bar{F}^{\mathrm{deh}} \cdot U^{\mathrm{deh}} \tag{2c}$$

$$F^{\mathrm{vent}} = (H^{\mathrm{in}} - H^{\mathrm{out}}) \cdot V^{\mathrm{vent}} \tag{2d}$$

$$F^{\mathrm{tran}} = Q^{\mathrm{tran}} / q^{\mathrm{evap}} \tag{2e}$$

$$F^{\mathrm{vc}} = g^{\mathrm{vc}} \cdot \left[\zeta \cdot \exp\left(\delta^{\mathrm{vc}} \cdot T^{\mathrm{in}}\right) \cdot T^{\mathrm{i-o}} - (H^{\mathrm{in,sat}} - H^{\mathrm{in}}) \right] \cdot A^{\mathrm{floor}} \tag{2f}$$

Table 2
Parameters of the state-space model.

	Definition	Value	Unit
A^{floor}	Floor area.	421	$\mathrm{m^2}$
A^{roof}	Roof area.	472	$\mathrm{m^2}$
A^{wall}	Side-wall area.	628	$\mathrm{m^2}$
c^{vh}	Air volumetric heat capacity.	1230	$\mathrm{J/(m^3 \cdot °C)}$
$\hat{C}^{\mathrm{in}}$	CO_2 half-saturation constant.	0.23	$\mathrm{g/m^3}$
$\bar{D}^{\mathrm{dos}}$	Maximum CO_2 dosing rate.	1.04	g/s
$\bar{D}^{\mathrm{ass}}$	Maximum CO_2 assimilation flux.	2.2e-3	$\mathrm{g/(m^2 \cdot s)}$
$\bar{F}^{\mathrm{hum}}$	Maximum injection rate of mist water.	18	g/s
$\bar{F}^{\mathrm{deh}}$	Maximum moisture removal rate.	12	g/s
$\tilde{H}$	Empirical coefficient.	5.5638	$\mathrm{g/m^3}$
I	Leaf area index.	2.5	$\mathrm{m^2/m^2}$
ρ	PPFD response coefficient.	1.5e-3	$\mathrm{(m^2 \cdot s)}/\mu\mathrm{mol}$
$\bar{P}^{\mathrm{LED}}$	Maximum electrical power of LEDs.	4.375e4	W
q^{evap}	Latent heat of evaporation.	2430	J/g
$\bar{Q}^{\mathrm{heat}}$	Maximum power from heaters.	2.36e5	W
$\bar{Q}^{\mathrm{pad}}$	Maximum power from cooling pads.	2.95e5	W
r^{b}	Boundary layer resistance.	200	s/m
$\bar{r}^{\mathrm{s}}$	Maximum additional resistance.	570	s/m
$\underline{r}^{\mathrm{s}}$	Minimal stomatal resistance.	82	s/m
Δt	Time interval.	300	s
τ	Crop-specific coefficient.	0.4	$\mathrm{m^2/W}$
T^{sr}	Reference temperature.	24.5	°C
υ^{roof}	Heat-transfer coefficient of roofs.	6.6	$\mathrm{W/(m^2 \cdot °C)}$
υ^{wall}	Heat-transfer coefficient of side walls.	6.3	$\mathrm{W/(m^2 \cdot °C)}$
ν^{surf}	Condensation surface coefficient.	1.8e-3	$\mathrm{m/(°C^{1/3} \cdot s)}$
V^{gh}	Indoor volume.	3.351e3	$\mathrm{m^3}$
$\bar{V}^{\mathrm{fan}}$	Maximum mechanical ventilation rate.	48	$\mathrm{m^3/s}$
$\bar{V}^{\mathrm{nat}}$	Maximum natural ventilation rate.	5	$\mathrm{m^3/s}$
ω^{T}	Temperature buffering coefficient.	30	-
ω^{H}	Humidity buffering coefficient.	15	-
ω^{C}	CO_2 buffering coefficient.	1	-
χ	Latent-to-sensible ratio (sat air).	2.5	-
ϕ^{solar}	Solar radiation-to-PPFD coefficient.	2.0	$\mu\mathrm{mol/(W \cdot s)}$
ϕ^{LED}	LED radiation-to-PPFD coefficient.	5.17	$\mu\mathrm{mol/(W \cdot s)}$
λ^{leak}	Air leakage rate.	1.0	$\mathrm{h^{-1}}$
ζ	Empirical coefficient.	0.2522	$\mathrm{g/(m^3 \cdot °C)}$
σ	Smoothing coefficient.	1e-3	°C
δ^{tran}	Temperature sensitivity coefficient.	0.0518	$\mathrm{°C^{-1}}$
δ^{sat}	Temperature sensitivity coefficient.	0.0572	$\mathrm{°C^{-1}}$
δ^{vc}	Temperature sensitivity coefficient.	0.0485	$\mathrm{°C^{-1}}$
δ^{sr}	Temperature sensitivity coefficient.	0.023	$\mathrm{°C^{-2}}$
$\eta^{\mathrm{LED-r}}$	Fraction of LED electrical power emitted as radiation (light).	0.59	–
$\eta^{\mathrm{LED-cano}}$	Attenuation of LED radiation to canopy.	0.40	-
η^{evap}	Water evaporation fraction.	0.70	-
η^{cover}	Cover shortwave transmissivity.	0.50	-
η^{short}	Shortwave absorption ratio.	0.86	-
η^{ext}	Light extinction coefficient.	0.70	-
η^{tran}	Empirical coefficient.	0.7584	-
η^{shad}	Radiation attenuation of shading screen.	0.35	-
η^{warm}	Heat insulation of warm-keeping screen.	0.50	-

The indoor CO_2 concentration dynamics are modeled by (3).

$$\frac{\mathrm{d}C^{\mathrm{in}}}{\mathrm{d}t} = \frac{D^{\mathrm{dos}} - D^{\mathrm{vent}} - D^{\mathrm{ass}}}{\omega^{\mathrm{C}} \cdot V^{\mathrm{gh}}} \tag{3a}$$

$$D^{\mathrm{dos}} = \bar{D}^{\mathrm{dos}} \cdot U^{\mathrm{dos}} \tag{3b}$$

$$D^{\mathrm{vent}} = (C^{\mathrm{in}} - C^{\mathrm{out}}) \cdot V^{\mathrm{vent}} \tag{3c}$$

$$D^{\mathrm{ass}} = \bar{D}^{\mathrm{ass}} \cdot \frac{C^{\mathrm{in}}}{C^{\mathrm{in}} + \hat{C}^{\mathrm{in}}} \cdot \left[1 - \exp\left(-\rho \cdot X^{\mathrm{cano}}\right)\right] \cdot A^{\mathrm{floor}} \tag{3d}$$

The daily light integral is modeled by (4):

$$\frac{\mathrm{d}L}{\mathrm{d}t} = \frac{X^{\mathrm{cano}}}{10^6} \tag{4}$$

Note that the transpiration model in (1h) and (2e) is adopted from [1, 2]. The condensation vapor humidity model in (2f) is adopted from [2, 3]. The CO_2 assimilation model in (3d) is adopted from [4, 5, 6].

Hereafter, we introduce the intermediate variables.

$$T^{\mathrm{i-o}} = T^{\mathrm{in}} - T^{\mathrm{out}} \tag{5}$$

$$V^{\mathrm{vent}} = \bar{V}^{\mathrm{fan}} \cdot U^{\mathrm{fan}} + \bar{V}^{\mathrm{nat}} \cdot U^{\mathrm{nat}} + \frac{\lambda^{\mathrm{leak}} \cdot V^{\mathrm{gh}}}{3600} \tag{6}$$

We follow references [1, 2, 3, 7] to calculate g^{tran}:

$$g^{\text{tran}} = \frac{2 \cdot I}{\left[1 + \eta^{\text{tran}} \cdot \exp\left(\delta^{\text{tran}} \cdot T^{\text{in}}\right)\right] \cdot r^{\text{b}} + r^{\text{s}}} \tag{7}$$

$$r^{\text{s}} = \left[\underline{r}^{\text{s}} + \bar{r}^{\text{s}} \cdot \exp\left(-\frac{\tau \cdot R^{\text{cano-abs}}}{I}\right)\right] \cdot \left[1 + \delta^{\text{sr}} \cdot (T^{\text{in}} - T^{\text{sr}})^2\right] \tag{8}$$

$$R^{\text{cano-abs}} = \eta^{\text{short}} \cdot \left[\frac{\exp\left(\eta^{\text{ext}} \cdot I\right) - 1}{\exp\left(\eta^{\text{ext}} \cdot I\right)}\right] \cdot R^{\text{cano-glo}} \tag{9}$$

$$R^{\text{cano-glo}} = R^{\text{cano-solar}} + R^{\text{cano-LED}} \tag{10}$$

$$R^{\text{cano-solar}} = \eta^{\text{cover}} \cdot \left(1 - \eta^{\text{shad}} \cdot U^{\text{shad}}\right) \cdot R^{\text{out}} \tag{11}$$

$$R^{\text{cano-LED}} = \frac{\eta^{\text{LED-r}} \cdot \eta^{\text{LED-cano}} \cdot \bar{P}^{\text{LED}} \cdot U^{\text{LED}}}{A^{\text{floor}}} \tag{12}$$

We follow references [1, 2, 3] to calculate H^{cano}:

$$H^{\text{cano}} = H^{\text{in,sat}} + \chi \cdot \frac{r^{\text{b}} \cdot R^{\text{cano-abs}}}{2 \cdot I \cdot q^{\text{evap}}} \tag{13}$$

$$H^{\text{in,sat}} = \tilde{H} \cdot \exp\left(\delta^{\text{sat}} \cdot T^{\text{in}}\right) \tag{14}$$

We follow references [2, 3] to calculate g^{vc}:

$$g^{\text{vc}} = v^{\text{surf}} \cdot \left[\frac{\left(T^{\text{in}} - T^{\text{cover}}\right) + \sqrt{\left(T^{\text{in}} - T^{\text{cover}}\right)^2 + \sigma^2}}{2}\right]^{1/3} \tag{15}$$

$$T^{\text{cover}} = \frac{2 \cdot T^{\text{out}} + T^{\text{in}}}{3} \tag{16}$$

We follow [6] to calculate the photon flux density of photosynthetically active radiation, known as photosynthetic photon flux density (PPFD):

$$X^{\text{cano}} = \phi^{\text{solar}} \cdot R^{\text{cano-solar}} + \phi^{\text{LED}} \cdot R^{\text{cano-LED}} \tag{17}$$

Next, we define more variables and parameters to build the MPC framework.
The state vector is defined as

$$\boldsymbol{x} = \left[T^{\text{in}}, H^{\text{in}}, C^{\text{in}}, L^{\text{DLI}}\right]^\top \tag{18}$$

By default, the initial state vector is set as

$$\boldsymbol{x}^{\text{ini}} = \left[19\,{}^\circ\text{C}, 7.41\,\text{g/m}^3, 0.92\,\text{g/m}^3, 0\,\text{mol/m}^2\right]^\top \tag{19}$$

The control input vector is defined as

$$\boldsymbol{u} = \left[U^{\text{heat}}, U^{\text{fan}}, U^{\text{nat}}, U^{\text{pad}}, U^{\text{dos}}, U^{\text{LED}}, U^{\text{hum}}, U^{\text{deh}}, U^{\text{shad}}, U^{\text{warm}}\right]^\top \tag{20}$$

The outdoor disturbance vector is defined as

$$\boldsymbol{d} = \left[T^{\text{out}}, H^{\text{out}}, C^{\text{out}}, R^{\text{out}}\right]^\top \tag{21}$$

The nonlinear continuous-time dynamics can be compactly written as

$$\dot{\boldsymbol{x}}(t) = f(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t)), \tag{22}$$

where $f(\cdot)$ is defined by the temperature, humidity, CO_2, and DLI dynamics in (1), (2), (3), and (4).

Within the MPC framework, the continuous-time state-space model can be discretized using integration with time step Δt, yielding (23):

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + f(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{d}_k) \cdot \Delta t \tag{23}$$

Table 3
Variables to build the MPC framework.

	Definition	Unit
E_k^{heat}	Cost of heating in step k.	\$
E_k^{fan}	Cost of fan electricity in step k.	\$
E_k^{LED}	Cost of LED electricity in step k.	\$
E_k^{pad}	Cost of cooling pad in step k.	\$
E_k^{hum}	Cost of humidifying in step k.	\$
E_k^{deh}	Cost of dehumidifying in step k.	\$
E_k^{dos}	Cost of CO_2 dosing in step k.	\$
k	Step index.	–
κ_k	Time-of-day step index, $\kappa_k \in \{0, \dots, 287\}$.	–
K	Number of steps.	–
$S_k^{\mathrm{T+}}, S_k^{\mathrm{T-}}$	Slacking variables.	°C
$S_k^{\mathrm{H+}}, S_k^{\mathrm{H-}}$	Slacking variables.	$\mathrm{g/m^3}$
$S_k^{\mathrm{C+}}, S_k^{\mathrm{C-}}$	Slacking variables.	$\mathrm{g/m^3}$
S_k^{L}	Shortage of daily light integral.	$\mathrm{mol/m^2}$

Table 4
Parameters to build the MPC framework (values shown as day/night when applicable).

	Definition	Value	Unit
α^{heat}	Price of heating.	0.05	\$/kWh
α^{fan}	Price of ventilation.	0.125	\$/kWh
α^{LED}	Price of LED lighting.	0.125	\$/kWh
α^{pad}	Price of using cooling pads.	1.48e-6	\$/g
α^{hum}	Price of humidifying.	4.79e-6	\$/g
α^{deh}	Price of dehumidifying.	6.5e-5	\$/g
α^{dos}	Price of CO_2 dosing.	1.5e-4	\$/g
S^{fan}	Specific fan power.	93.4	$\mathrm{W/(m^3/s)}$
$\bar{T}_k^{\mathrm{in}}$	Upper bound of T_k^{in}.	27/19	°C
$\underline{T}_k^{\mathrm{in}}$	Lower bound of T_k^{in}.	21/16	°C
$\bar{H}_k^{\mathrm{in}}$	Upper bound of H_k^{in}.	9.54	$\mathrm{g/m^3}$
$\underline{H}_k^{\mathrm{in}}$	Lower bound of H_k^{in}.	3.89	$\mathrm{g/m^3}$
$\bar{C}_k^{\mathrm{in}}$	Upper bound of C_k^{in}.	2.73/2.73	$\mathrm{g/m^3}$
$\underline{C}_k^{\mathrm{in}}$	Lower bound of C_k^{in}.	1.64/0	$\mathrm{g/m^3}$
$L_k^{\star}$	Reference for L_k.	$\begin{cases} 0, & 0 \le \kappa_k < 72, \\ \frac{22\cdot(\kappa_k - 72)}{192}, & 72 \le \kappa_k < 264, \\ 22, & 264 \le \kappa_k \le 287, \end{cases}$	$\mathrm{mol/m^2}$
$\lambda^{\mathrm{T+}}, \lambda^{\mathrm{T-}}$	Penalty coefficients.	100	\$/(°C)
$\lambda^{\mathrm{H+}}, \lambda^{\mathrm{H-}}$	Penalty coefficients.	100	$\$/(\mathrm{g/m^3})$
$\lambda^{\mathrm{C+}}, \lambda^{\mathrm{C-}}$	Penalty coefficients.	100	$\$/(\mathrm{g/m^3})$
λ^{L}	Penalty coefficients.	100	$\$/(\mathrm{mol/m^2})$
γ	Discount factor.	0.95	–

Cost of resource consumption of the greenhouse during step k:

$$E_k^{\mathrm{heat}} = \alpha^{\mathrm{heat}} \cdot Q_k^{\mathrm{heat}} \cdot \frac{\Delta t}{3.6 \times 10^6} \tag{24}$$

$$E_k^{\mathrm{fan}} = \alpha^{\mathrm{fan}} \cdot S^{\mathrm{fan}} \cdot \bar{V}^{\mathrm{fan}} \cdot U_k^{\mathrm{fan}} \cdot \frac{\Delta t}{3.6 \times 10^6} \tag{25}$$

$$E_k^{\mathrm{LED}} = \alpha^{\mathrm{LED}} \cdot \bar{P}^{\mathrm{LED}} \cdot U_k^{\mathrm{LED}} \cdot \frac{\Delta t}{3.6 \times 10^6} \tag{26}$$

$$E_k^{\mathrm{pad}} = \alpha^{\mathrm{pad}} \cdot U_k^{\mathrm{pad}} \cdot \Delta t \tag{27}$$

$$E_k^{\mathrm{hum}} = \alpha^{\mathrm{hum}} \cdot \bar{F}^{\mathrm{hum}} \cdot U_k^{\mathrm{hum}} \cdot \Delta t \tag{28}$$

$$E_k^{\mathrm{deh}} = \alpha^{\mathrm{deh}} \cdot \bar{F}^{\mathrm{deh}} \cdot U_k^{\mathrm{deh}} \cdot \Delta t \tag{29}$$

$$E_k^{\mathrm{dos}} = \alpha^{\mathrm{dos}} \cdot \bar{D}^{\mathrm{dos}} \cdot U_k^{\mathrm{dos}} \cdot \Delta t \tag{30}$$

The MPC model is given in (31).

$$\min_{\boldsymbol{u}_0,\dots,\boldsymbol{u}_{K-1}} \sum_{k=0}^{K-1} \gamma^k \begin{bmatrix} E_k^{\mathrm{heat}} + E_k^{\mathrm{fan}} + E_k^{\mathrm{LED}} + E_k^{\mathrm{pad}} + E_k^{\mathrm{hum}} + E_k^{\mathrm{deh}} + E_k^{\mathrm{dos}} \\ + \lambda^{\mathrm{T+}} S_k^{\mathrm{T+}} + \lambda^{\mathrm{T-}} S_k^{\mathrm{T-}} + \lambda^{\mathrm{H+}} S_k^{\mathrm{H+}} + \lambda^{\mathrm{H-}} S_k^{\mathrm{H-}} \\ + \lambda^{\mathrm{C+}} S_k^{\mathrm{C+}} + \lambda^{\mathrm{C-}} S_k^{\mathrm{C-}} + \lambda^{\mathrm{L}} S_k^{\mathrm{L}} \end{bmatrix}$$

$$\text{s.t.} \quad \boldsymbol{x}_0 = \boldsymbol{x}^{\mathrm{ini}}, \tag{31a}$$

$$\boldsymbol{x}_{k+1} = \boldsymbol{M}\boldsymbol{x}_k + \boldsymbol{N}\boldsymbol{u}_k + \boldsymbol{O}\boldsymbol{d}_k + \boldsymbol{m}, \quad k = 0, ..., K-1 \tag{31b}$$

$$\underline{T}_k^{\mathrm{in}} - S_k^{\mathrm{T-}} \le T_k^{\mathrm{in}} \le \bar{T}_k^{\mathrm{in}} + S_k^{\mathrm{T+}}, \quad k = 0, ..., K-1 \tag{31c}$$

$$\underline{H}_k^{\mathrm{in}} - S_k^{\mathrm{H-}} \le H_k^{\mathrm{in}} \le \bar{H}_k^{\mathrm{in}} + S_k^{\mathrm{H+}}, \quad k = 0, ..., K-1 \tag{31d}$$

$$\underline{C}_k^{\mathrm{in}} - S_k^{\mathrm{C-}} \le C_k^{\mathrm{in}} \le \bar{C}_k^{\mathrm{in}} + S_k^{\mathrm{C+}}, \quad k = 0, ..., K-1 \tag{31e}$$

$$S_k^{\mathrm{L}} \ge L_k^{\star} - L_k, \quad k = 0, ..., K-1 \tag{31f}$$

$$S_k^{\mathrm{T+}}, S_k^{\mathrm{T-}}, S_k^{\mathrm{H+}}, S_k^{\mathrm{H-}}, S_k^{\mathrm{C+}}, S_k^{\mathrm{C-}}, S_k^{\mathrm{L}} \ge 0 \quad k = 0, ..., K-1 \tag{31g}$$

$$0 \le U_k^{\mathrm{heat}} \le Y_k^{\mathrm{heat}}, \quad k = 0, ..., K-1 \tag{31h}$$

$$0 \le U_k^{\mathrm{fan}} \le Y_k^{\mathrm{fan}}, \quad k = 0, ..., K-1 \tag{31i}$$

$$0 \le U_k^{\mathrm{nat}} \le Y_k^{\mathrm{nat}}, \quad k = 0, ..., K-1 \tag{31j}$$

$$0 \le U_k^{\mathrm{pad}} \le Y_k^{\mathrm{pad}}, \quad k = 0, ..., K-1 \tag{31k}$$

$$0 \le U_k^{\mathrm{dos}} \le Y_k^{\mathrm{dos}}, \quad k = 0, ..., K-1 \tag{31l}$$

$$0 \le U_k^{\mathrm{LED}} \le Y_k^{\mathrm{LED}}, \quad k = 0, ..., K-1 \tag{31m}$$

$$0 \le U_k^{\mathrm{shad}} \le Y_k^{\mathrm{shad}}, \quad k = 0, ..., K-1 \tag{31n}$$

$$0 \le U_k^{\mathrm{warm}} \le Y_k^{\mathrm{warm}}, \quad k = 0, ..., K-1 \tag{31o}$$

$$0 \le U_k^{\mathrm{hum}} \le Y_k^{\mathrm{hum}}, \quad k = 0, ..., K-1 \tag{31p}$$

$$0 \le U_k^{\mathrm{deh}} \le Y_k^{\mathrm{deh}}, \quad k = 0, ..., K-1 \tag{31q}$$

$$U_k^{\mathrm{fan}} \ge U_k^{\mathrm{pad}}, \quad k = 0, ..., K-1 \tag{31r}$$

$$U_k^{\mathrm{fan}} \le Y_k^{\mathrm{fan}},\ U_k^{\mathrm{dos}} \le Y_k^{\mathrm{dos}},\ Y_k^{\mathrm{fan}} + Y_k^{\mathrm{dos}} \le 1 \quad k = 0, ..., K-1 \tag{31s}$$

$$U_k^{\mathrm{hum}} \le Y_k^{\mathrm{hum}},\ U_k^{\mathrm{deh}} \le Y_k^{\mathrm{deh}},\ Y_k^{\mathrm{hum}} + Y_k^{\mathrm{deh}} \le 1 \quad k = 0, ..., K-1 \tag{31t}$$

$$Y_k^{\mathrm{heat}}, Y_k^{\mathrm{fan}}, Y_k^{\mathrm{nat}}, Y_k^{\mathrm{pad}}, Y_k^{\mathrm{dos}}, Y_k^{\mathrm{LED}}, Y_k^{\mathrm{hum}}, Y_k^{\mathrm{deh}}, Y_k^{\mathrm{shad}}, Y_k^{\mathrm{warm}} \in \{0, 1\}, \quad k = 0, ..., K-1 \tag{31u}$$

where $\Delta \boldsymbol{x}_k$ is the state incremental term; $\boldsymbol{M}$, $\boldsymbol{N}$, and $\boldsymbol{O}$ are the discrete-time system matrices, and $\boldsymbol{m}$ is the constant offset term.

References

[1] P. J. M. Van Beveren, J. Bontsema, G. Van Straten, E. J. Van Henten, Minimal heating and cooling in a modern rose greenhouse, Applied Energy 137 (2015) 97–109.

[2] C. Stanghellini, T. de Jong, A model of humidity and its applications in a greenhouse, Agricultural and Forest Meteorology 76 (2) (1995) 129–148.

[3] J. Bontsema, J. Hemming, C. Stanghellini, P. De Visser, E. van Henten, J. Budding, T. Rieswijk, S. Nieboer, On-line estimation of the transpiration in greenhouse horticulture, Proceedings agricontrol (2007) 29–34Net radiation at crop level.

[4] P. J. M. van Beveren, J. Bontsema, G. van Straten, E. J. van Henten, Optimal control of greenhouse climate using minimal energy and grower defined bounds, Applied Energy 159 (2015) 509–519.

[5] C. Stanghellini, L. Incrocci, J. C. Gázquez, B. Dimauro, Carbon dioxide concentration in mediterranean greenhouses: How much lost production?, International Society for Horticultural Science (ISHS), Leuven, Belgium, 2008, pp. 1541–1550.

[6] C. Stanghellini, J. Bontsema, A. de Koning, E. Baeza, An algorithm for optimal fertilization with pure carbon dioxide in greenhouses, International Society for Horticultural Science (ISHS), Leuven, Belgium, 2023, pp. 119–124.

[7] J. Goudriaan, J. L. Monteith, A mathematical function for crop growth based on light interception and leaf-area expansion, Annals of Botany 66 (6) (1990) 695–701.