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Drying Technology, 20(7), 1319-1345 (2002) – mailto:courtois@ensia.inra.fr

DYNAMIC OPTIMAL CONTROL OF BATCH RICE DRYING PROCESS

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Key Words and Phrases: grain breakage, dynamic optimization, optimal control; paddy rice drying; sequential quadratic programming

ABSTRACT

The drying of paddy rice may result in quality degradation, expressed as a head kernel yield, leading to significant commercial depreciation of the product. A mathematical model of the drying and of the quality degradation process was combined with a dynamic optimization algorithm to determine the drying conditions (air temperature and relative humidity as functions of time) that ensured the highest possible final product quality for a specified drying time and a specified final moisture content. The robustness of the optimal drying strategy with respect to the initial state of the product, to the model parameters and to the initialization of the optimization algorithm was verified. The compromise between the highest achievable final quality and the allowed total drying time was studied. The combination of simulation and optimization yielded a new insight in the rice drying process and in the quality preservation strategies.

INTRODUCTION

The technological processing of paddy rice includes its drying from an initial moisture content contained between 220 and 750 g water / kg d.b. (dry basis) after harvesting down to a final moisture content of 140 g/kg d.b. or less. For some operating conditions the drying process may lead to endosperm breakage due to mechanical stress (1). From an economic point of view, the quality of rice is expressed as a head kernel yield. The term "head rice" denotes milled rice comprised of kernels three-fourths or more the original kernel. The rice price falls with each percentage point lost, so it is critical to maintain optimum conditions during drying, storage and milling operation to obtain a high head rice yield. (2)

Different process strategies in order to improve head rice yield like grain tempering and process interruptions have been proposed. (3, 4). This approach mainly keeps uniform (inner and outer) grain moisture, however a longer operation time is required.

Specific works determined that grain breakage is caused by an unequal shrinking of the endosperm resulting from uneven dehydration of the kernel (5) due to high drying temperature (6) and/or high drying rate (7). Abud et al. (8) showed that the combination of operating conditions (drying temperature, drying time and air humidity) produces a moisture content gradient inside the grain that can either increase or decrease the mechanical stress. Fissuring and thus breakage occur if the stress exceeds a certain threshold (9). Abud, et al (10) state an empirical equation for the quality degradation rate as a function of the operating conditions.

The optimal process control is concerned with the selection of the process operating conditions that maximize or minimize a function that relies technical and/or economic parameters called optimization criterion. The optimal operating conditions are usually computed off-line and then applied to the process without change (11). Thus, control could be successfully accomplished by a very simple controller like the PID (12). In drying processes, quality improvement and operational cost reduction are two main objectives that, in some cases, are conflicting ones hence both optimization method and criterion have to be carefully chosen.

Boxtel, *et al* (13) calculated the optimal control variables trajectories, temperature and flow rate, of a drying process were product quality depends in biological components that could be inactivated by the operation conditions. A deterministic dynamic optimization method is applied. The process model included quality degradation. The optimization criterion is expressed in benefits (quality depended) nets (operational costs are deducted).

Kiranoudis (14) optimized a potato slice drying process with a similar objective). Quality was defined as product color and the operating conditions were drying air temperature and relative humidity, both kept constant during the process. The mathematical model included the drying state equations, the color evolution kinetics and an estimation of the operation cost. The best operating conditions were determined based on a Pareto graph.

Instead of including quality reduction in the mathematical model, several authors, indirectly avoided quality degradation through the optimization criterion: reducing drying rate

(15) or applying features (e.g. maximal grain temperature and maximal moisture distribution of the product) on the main target as penalty factors (16).

Trelea *et al*. (17) proposed an optimal strategy for corn drying. The optimization criterion was the drying cost taken as a weighted sum of the batch duration and the estimated energy consumption. The optimized operating conditions were the total drying time, the air temperature and relative humidity, subject to constraints on the final product moisture content and the final wet-milling quality. The mathematical model included drying and quality degradation kinetics. The current product state was estimated on-line based on available measurements and the operating conditions were adjusted in real time in order to compensate various disturbances such as higher or lower initial grain moisture content and temporary equipment failures.

In the present work, optimal drying conditions for paddy rice (air temperature and relative humidity trajectories) were determined. The optimization criterion was the final rice quality, expressed as a head kernel yield. The final product moisture content was constrained to a target value in a fixed operation time. The drying time – quality degradation compromise was studied by performing the optimization for several specified batch durations. The dynamic model used for optimization consisted of a compartment drying model for thin layers of rice together with an empirical quality degradation kinetic (10, 18). The dynamic optimization algorithm was based on a sequential quadratic programming technique.

MATERIALS AND METHODS

Product and dryer

The experimental data used in this work was obtained from Abud et al. (19). Homogeneous samples of paddy of the Ariete variety from Camargue, France were used. The product was harvested at 250 g/kg d.b. moisture content before vacuum packing at ambient temperature in the dark. The absence of mold was checked. A thin product layer (30 mm, i.e. 600 g of wet paddy) was dried in each experiment.

Moisture content was determined by drying in an oven at 130 °C during 2 hours, whit pre-drying for high initial moisture content, at the beginning and at the end of the drying according to the NF V03-707 norm; during the process, moisture content was calculated by mass loss. The measurement accuracy stated by the norm is at least 1.5 g/kg. Rice quality was determined using the NF ISO 6646 norm: samples of rough rice were hulled in a husker with two-rubber disk and milled on an abrasive con. Head rice yield is the weight percentage between milled "head rice" and total milled rice. The stated accuracy of the quality determination was 3%.

The automatically controlled grain dryer is schematically shown in Figure 1. It allows time-varying drying conditions ranged in the following bounds: air temperature between 15 and 160°C, air moisture content between the ambient value and 300 g/kg of dry air and air velocity between 0.25 and 2.7 m/s. Drying air is conditioned before entering to the dryer by sensors and PID controllers that assured specific values of air temperature, relative humidity and velocity. Product weight was measured at regular time intervals using electronic scales (air flow was deviated during weighting).

Mathematical model

A compartment model of thin-layer paddy drying kinetics proposed by Abud *et al* (18) is used in this work.

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The process state vector (X) consists of the moisture content in the inner compartment (x_1), in the outer compartment (x_2), of the grain temperature (T_g) and of the grain quality (Q):

$$X = \begin{bmatrix} x_1 & x_2 & T_g & Q \end{bmatrix}^T \qquad [1]$$

The control variables vector (U) depend on control capabilities of the dryer in order to apply the optimal trajectories directly using the dryer controllers. Since air velocities, between 0.26 and 2.12 m/s, have no significant effect in thin layer drying, only air temperature (T_a) and relative air humidity (H_R) were chosen:

$$U = \begin{bmatrix} T_a & H_R \end{bmatrix}^T \qquad [2]$$

The two compartment model equations are:

$$\frac{dx_1}{dt} = \frac{\beta_1}{\rho_g \cdot \tau_1}(x_2 - x_1) \qquad [3]$$

$$\frac{dx_2}{dt} = \frac{\beta_2 \cdot S_{sg}}{\rho_g \cdot \tau_2}(p_a - p_g) - \frac{dx_1}{dt} \cdot \frac{\tau_1}{\tau_2} \qquad [4]$$

$$\frac{dT_g}{dt} = \frac{\alpha \cdot S_{sg} \cdot (T_a - T_g) + \beta_2 \cdot S_{sg} \cdot (p_a - p_g) \cdot L_v}{\rho_g \cdot (C_{pg} + C_{pw} \cdot x_m)} \qquad [5]$$

Equation 3 describes the moisture transfer for the inner compartment, Equation 4 for the outer compartment and Equation 5 represents a heat balance, the grain temperature is considered uniform and equal for all the compartments. The significance of the variables is given in Figure 2 and in the nomenclature section.

The rice quality evolution, as described by Abud *et al* (10), follow a second order kinetic (10):

$$\frac{dQ}{dt} = -K \cdot Q^2 \qquad [6]$$

The quality degradation rate coefficient (K) is expressed as a function of the moisture content gradient between the two compartments and of the grain temperature (T_g) via an Arrhenius-type law:

$$K = -K_0 \cdot \left(x_2 - x_1 \right)^5 \cdot \exp\left(\frac{-E_a}{R \cdot \left(T_g + 273.1 \right)} \right) \qquad [7]$$

The average moisture content of the grain takes into account the volume fraction of each compartment (τ_1 and τ_2):

$$x_m = x_1 \cdot \tau_1 + x_2 \cdot \tau_2 \qquad [8]$$

The mass transfer coefficients between the two compartments (β_1) and between the outer compartment and the air (β_2) are:

$$\beta_1 = B_{10} \cdot \exp\left(B_{11} \cdot x_m \cdot T_g \right) \qquad [9]$$

$$\beta_2 = B_{20} \cdot \exp\left(B_{21} \cdot T_a \right) \qquad [10]$$

The heat transfer coefficient between the grain surface and the drying air is computed using the empirical relationship proposed by Loncin and Merson (20):

$$\alpha = C_5 \cdot L_v \cdot \beta_2 \qquad [11]$$

The water activity at the grain surface is computed with a formula similar to the one used by Pfost (21):

$$A_w = \exp\left(\frac{-\exp\left(\frac{C_1 - x_2}{C_2} \right)}{C_3 \cdot \left(T_g - C_4 \right)} \right) \qquad [12]$$

The partial vapor pressure at the grain surface is thus:

$$p_g = p_{g\,sat} \cdot A_w \qquad [13]$$

The numerical values of model parameters are listed in Table 1. For more details on the model derivation and on parameter identification the interested reader is referred to (19).

Model validation

The mathematical model was validated in the following range of operating conditions: air temperature between 40 and 80°C, relative humidity between 5 and 80% and air velocity between 0.26 and 2.12 m/s. The model accuracy was assessed using the mean absolute error between the simulated and the measured values of the grain moisture content and of the grain quality:

$$\overline{E}_x = \frac{\sum |x_m - x_{meas}|}{\text{No. of measurements}} \quad [14]$$

$$\overline{E}_Q = \frac{\sum |Q - Q_{meas}|}{\text{No. of measurements}} \quad [15]$$

A graphical comparison between the simulated and the measured grain moisture content is given in Figure 3a. The computed values are very close to the experimental ones. The mean absolute error for the 17 drying experiments performed in various operating conditions is 15.1 g/kg of dry rice. In Figure 3b the model accuracy is reported for the various combinations of drying conditions used in the experimental design. The poorest accuracy is obtained for the lowest drying temperature and the highest relative humidity. Except this relatively small area in Figure 3b, the model accuracy is always better than 10 g/kg.

Figure 4a shows the plot of the simulated rice quality against the measured one for 15 drying experiments performed in various operating conditions. The mean modeling error is 3.4%. It can be seen in Figure 4b that the quality is predicted accurately for all combinations of drying conditions, including those with an extreme evaporating capacity: low temperature - high relative humidity and *vice versa*. It should be noted that even the largest modeling error (6.5%) is of the order of the measurement error allowed by the quality determination procedure (3%).

Evaporating capacity is the maximum water quantity than can be evaporated adiabatically for one kilogram of drying air. It is calculated as the difference in humidity rations (expressed in g of water per kilogram of dry air) between drying air and the adiabatically saturated one. (22)

Constrained optimization problem

The selected optimization goal was the maximization of the final rice quality. In order to fit the standard problem formulation required by the optimization algorithm, the optimization criterion (J) was defined as the negative value of the final quality and minimization of this modified criterion was performed:

$$\min_{U(t),\, t\in[0 \quad t_f]} J \qquad [16]$$

$$J = -Q(t_f) \qquad [17]$$

Since moisture content reduction and quality preservation are conflicting objectives, a target value for the final moisture content had to be specified as a constraint. Otherwise, too mild-drying conditions would have been selected:

$$x_m(t_f) = x_{target} \qquad [18]$$

The control variables were constrained to lie in the model validity range:

$$U_{\min} \le U(t) \le U_{\max}$$

$$U_{\min} = \begin{bmatrix} T_{a\min} & H_{R\min} \end{bmatrix}^T \qquad [19]$$

$$U_{\max} = \begin{bmatrix} T_{a\max} & H_{R\max} \end{bmatrix}^T \qquad [20]$$

The total drying time reduction is another main economic goal. The tradeoff between fast drying and quality preservation was dealt with by running several optimization calculations with various fixed drying times and constructing a Pareto graph of the highest achievable final quality ($Q(t_f)$) versus the specified batch duration (t_f). The final economic decision was thus left to the user.

Initial control profile

The optimization algorithm needs a feasible control profile to start, i.e. temperature and relative humidity profiles that satisfy all the constraints, including the achievement of the final moisture content target in the specified drying time. The calculations were initialized with random control variable profiles so an auxiliary optimization criterion (J_{aux}) was used to obtain feasible (but generally sub-optimal with respect to the grain quality) controls:

$$\min_{U(t),\, t\in[0 \quad t_f]} J_{aux} \qquad [21]$$

$$J_{aux} = \left(x_m(t_f) - x_{target}\right)^2 \qquad [22]$$

Control profiles obtained from the minimization of the auxiliary criterion (J_{aux}) were then used as initial profiles for the product quality maximization based on the main criterion (J).

Optimization algorithm

The considered optimal control problem is a dynamic one since the unknown control variables are functions of time. The optimization criterion is either a linear (J) or a quadratic (J_{aux}) function of the state variables. The constraints are linear functions of the state and control variables. The non-linearity comes from the dynamic model of the process. Taking into account these characteristics of the control problem, a sequential quadratic programming (SQP) algorithm was used for solving it (23) coupled with a collocation (time discretization) technique (24) and a safeguarded line search based on a "confidence region" method (25). The main steps of the algorithm are:

Step 1: **Discretization of the dynamic problem**. The state and control variables are sampled at a finite number of time points. This reduces an infinite-dimensional problem to a finite-dimensional one, which can be handled by a numerical computer. The optimization criterion, the constraints and the dynamic model equations are discretized on the same time grid.

Step 2: Construction of a local optimization sub-problem. The non-linear optimization problem is approximated locally (using limited Taylor series expansion) by a quadratic one with linear constraints. The discretized dynamic model equations are treated as additional constraints. The limited Taylor series expansion being valid only locally, a limited search region around the current solution is established using a set of "box" (min-max) constraints.

Step 3: **Solution of the local optimization sub-problem**. Reliable numeric software exists for the solution of quadratic optimization problems with linear constraints. Commercial software based on an "active constraint set" method was used (24).

Step 4: **Convergence test**. The non-linear state equations are solved using the determined control variables. The value of the optimization criterion is computed and the satisfaction of the constraints is checked. If the control variables, the state variables and the optimization criterion are modified by less than a pre-specified amount and if all constraints are satisfied, than calculations are halted. Else a new iteration is made starting with step 1. Reference batch

Unless stated otherwise, the results presented in the paper were obtained for the conditions of a typical paddy drying process called "reference batch" in the following. The parameters of the reference batch are listed in Table 2. Some analyses required the modification of one or more parameters of the reference batch as indicated in each specific case. All unspecified parameters, however, are those of the reference batch.

RESULTS AND DISCUSSION

Convergence of the optimization algorithm

The optimization algorithm is always initialized with random control trajectories as described previously. Robust convergence of the optimization procedure to a unique solution was verified. Figure 5a shows the average and the extreme control profiles obtained after six random initializations of the optimization algorithm for the reference batch. The corresponding state trajectories are given in Figure 5b.

It appears that there is no significant difference between the results of the six calculations. The average standard deviation along the moisture content trajectory equals 1.03 g/kg d.b., which is much less than the model accuracy (15 g/kg) and also less than the allowed experimental error for moisture content measurement (1.5 g/kg). The quality variations seem larger at the figure scale, with an average standard deviation of 0.19% along the trajectory. This variation is, however, insignificant compared to the model accuracy (3.4%) and to the allowed experimental error for quality measurement (3%). The quality uncertainty diminishes at the end of the batch: the final quality equals 76±0.17% for all six runs. Thus, the variability of the optimal control trajectories in Figure 5a does not have any significant effect on the state variables and the convergence of the optimization algorithm appears satisfactory.

Similar studies were performed to check if the convergence was maintained for a different total drying time and various ranges of allowed operating conditions. The observed variations were not significant in all cases. For example, in a 10 hours drying experiment standard deviations were found to be 0.27 g/kg for the moisture content and 0.007% for the product quality, both of them are lower than the reference batch ones.

Based on Figure 5 one can estimate the admissible tolerances for the practical implementation of an optimal drying experiment, without producing significant deviations of the process state.

Robustness of the optimal control policy to changes in the initial product state

Case 1. The robustness of the optimal control policy was studied by applying without change the optimal control profiles determined for the reference batch to batches with different values of one of the initial product states.

Firstly, the initial moisture content was varied between 230 and 310 g/kg d.b. When the initial moisture content is under the reference value. The drying rate is unnecessarily high since it was calculated for a target final moisture content of 270 g/kg, thus producing a significant quality loss. The opposite is true for the higher initial moisture content (Figure 6a): where it is impossible to achieve the final moisture target and its final quality is only marginally improved though.

Secondly the initial grain temperature was varied between 20 and 60°C. In all cases the moisture content target is achieved. For 60°C the initial condensation phase (zone A) disappears (Figure 6c) and significant quality degradation occurs during the first 30 minutes (Figure 6d). At 40°C the drying and quality degradation kinetics are relatively similar to the reference conditions (20°C). Finally, the initial grain quality has been varied between 70 and 90%. This has not effect on the drying kinetic (Figure 6e). The quality evolution curves are almost parallel so the differences in the final product quality exclusively reflect the differences in the initial quality (Figure 6f).

Case 2. The optimization algorithm was used to re-compute optimal control profiles for each of the initial product state values mentioned previously. For the initial grain temperature and initial product quality variations the results are not significantly different from those of the reference batch (not shown). However, for various initial moisture contents, specifically determined control profiles always ensure a final moisture content equal to the target value (Figure 7a). In order to reach the final moisture content in the specified time, the drying rate at the beginning of the batch was either strongly increased or decreased compared to the reference batch (Figure 7b) by changing the air evaporation capacity (Figure 7c). The quality degradation kinetics (Figure 7d) exhibit the expected behavior: drying conditions are less aggressive in the case of lower initial moisture content. The final product quality was improved compared to the results in Figure 6b (75 instead of 70%).

In summary, appropriate optimal control profiles are worth re-computing only for variations in the initial moisture content of the rice.

Robustness of the optimal control policy to changes in the model parameter values

The consequence of using optimal trajectories computed with a model with either underestimated or overestimated parameters was investigated. The moisture content profiles exhibited significant differences only for variations in the water activity. The grain quality, however, appeared much more sensitive to model parameters. An overestimation of the water activity makes the optimization algorithm to use higher evaporation capacities that cause significant quality degradation (Figure 8a). If the mass transfer coefficient between the inner and the outer grain compartment (β_1) is underestimated, the moisture content gradient is higher and the quality degradation is also increased (Figure 8b). A similar effect occurs if the mass transfer coefficient between the outer grain compartment and the air (β_2) is higher than expected (Figure 8c): the moisture content of the outer compartment decreases faster, increasing the moisture content gradient between the two compartments. The effects of the mass transfer coefficients on quality degradation are relatively limited, however. Five percent variation of the quality degradation rate coefficient (K_0) has a negligible effect (Figure 8d).

In contrast to the case of variations in the initial product state, re-computing optimal control profiles for the various values of the model parameters does not lead to significant performance improvement except for the water activity : the final quality decrease compared to the reference batch becomes 1% instead of 5% in Figure 8a.

Description of the optimal rice drying kinetic

The optimization results of the drying conditions for the reference batch (parameters in Table 2) are reported in Figure 9. The optimization algorithm computes the control variable profiles from which the state and the output variable trajectories are determined using the dynamic process model. Five zones can be distinguished in Figure 9:

Zone A. Water condensation on the product surface occurs at the very beginning of the drying process (Figure 9d) because the grain temperature is below the dew point temperature of the air. The water activity of the outer compartment is close to one (Figure 9f) which allows the usage of relatively intense drying conditions without any quality degradation (Figure 9d). Although superficial water activity is equal to 1, the model simulation program calculates the water activity in the whole outer compartment that is slightly less than 1.

Both the air evaporating capacity (Figure 9c) and the drying rate (Figure 9e) are high at the beginning of this zone but they decrease gradually due to the increase of the relative air humidity.

Zone B begins when the grain average moisture content falls below its initial value. The air evaporating capacity is decreased in order to limit internal moisture gradients and thus quality degradation. Two drying strategies are possible: working with conditions of low temperature-low air humidity or high temperature-high air humidity. Both assure weak evaporating capacities, but the drying rate is higher with the second choice.

Since operation duration is one of the constrains, the optimization algorithm uses preferably higher temperature conditions. Therefore, in this zone, the algorithm increases the relative humidity instead of decreasing the air temperature(Figure 9a).

Zone C begins when the relative air humidity reaches its maximum allowed value. Subsequent decrease of the evaporating capacity is only achieved through a temperature decrease (Figure 9a). The drying rate continues to decrease (Figure 9e).

Zone D. The water activity at the grain surface reaches the air relative humidity (Figure 9f) and the moisture content in the outer compartment attains its equilibrium value. The quality degradation rate begins to decrease and the drying rate reaches a minimum (Figure 9e). To continue the drying process, the evaporating capacity has to be increased. However that increase is dosed in order to cause a succession of mild drying conditions with a quasi-equilibrium state between the superficial water activity and the relative humidity of the air (characteristic in Zone D). The optimization algorithm decreases the relative humidity as much as required in order to slightly decrease the water activity in the outer compartment. Hence, the intercompartmental moisture content gradient, thus quality degradation rate, is reduced to a minimum.

Zone E. Moisture content is far of the target moisture content so the drying rate has to be increased (Figure 9e). Actually, in this zone one third of the total extracted water is removed. This is achieved by a sharp decrease of the relative air humidity (Figure 9a) that causes an increased quality degradation rate, which attains its highest value at the end of the drying process (Figure 9e).

Dependence of the optimal drying conditions on the total drying time

The evolution of the optimal drying strategy when total drying time increases is illustrated in Figure 10. Long drying times allow the usage of mild drying conditions. Lower temperature and higher relative humidity at the beginning of the batch are favored. Additionally, the control variable profiles become flat for long drying times, approaching constant drying conditions. The average air evaporating capacity decreases as duration increases but its “total” value, i.e. the area under each curve, increases indicating a lower efficiency since the evaporated amount of water is the same in all cases.

Higher drying time allows lower drying rate and leads to reduced quality degradation. The optimization algorithm has the possibility to extend the drying phases with a low quality damage (zones A and D) and to reduce those with high quality degradation rates (zones B and E). It is well-known that the longer drying time, the better final product quality but also a higher drying cost is thus confirmed. This economic tradeoff is stated explicitly in the next section.

The final quality – total drying time tradeoff

A given product, characterized by his initial state (moisture content, quality, grain temperature), dried at the optimal process conditions calculated by the optimization algorithm, yields a particular final quality value. The only way to modify this final value is to change the total drying time.

The highest achievable final product quality is plotted against the allowed drying time in Figure 11. Very fast drying necessarily leads to unacceptable grain breakage. Very slow drying, however, results in minor quality savings. The most convenient drying time has to be selected at the point where the increase of the product price due to higher quality compensates the increase of the process operation cost due to longer drying (principle of zero marginal cost or highest profit). This is essentially an economic decision, which is beyond the scope of this paper.

CONCLUSION

A sequential quadratic programming technique was used to determine the drying air temperature and relative humidity profiles that maximize the final head kernel yield of paddy rice. The optimization algorithm used a dynamic compartment model of the drying process coupled with a quality degradation kinetic. Constraints on total drying time, final moisture content and allowed range of operating conditions were imposed. The control profiles issued by the optimization method showed robust convergence.

Both simulation and optimization yielded a new insight in rice drying process. Quality optimization strategy favored mild drying conditions. Low quality degradation phases (e.g. condensation and quasi equilibrium drying zones)were extended as much as allowed by the total drying time. The optimal control strategy was very sensitive to the initial moisture content and water activity of the product. In practice, these parameters should be determined carefully in order to apply the most appropriate control profile. The drying time / final quality product tradeoff showed that in shorter operations quality degradation is important, but in too longer ones the quality improvement became negligible. The most appropriate drying conditions should be selected based on economic considerations including product price as a function of its quality and processing cost a function of the total drying time and the drying air parameters.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge to Consejo Nacional de Ciencia y Tecnología (CONACYT – Mexico) for the financial support of this work.

NOMENCLATURE

Symbol	Units	Significance
A_w	none	Water activity
B_{10}	kg m^{-3} s^{-1}	Mass transfer coefficient between the two grain compartments at 0°C
B_{11}	kg^{-1} kg °C^{-1}	Sensitivity coefficient of the mass transfer between the two grain compartments with respect to the mean moisture content and to the grain temperature
B_{20}	kg m^{-2} Pa^{-1} s^{-1}	Mass transfer coefficient between the outer grain compartment and the air at 0°C
B_{21}	°C^{-1}	Sensitivity coefficient of the mass transfer between the outer grain compartment and the air with respect to the air temperature
C_1, C_2	kg kg^{-1}	Sensitivity coefficients of the water activity with respect to the moisture content in the outer grain compartment
C_3, C_4	°C^{-1}, °C	Sensitivity coefficients of the water activity with respect to the grain temperature
C_5	Pa °C^{-1}	Constant used in [11] between heat and mass transfer coefficients
C_{pg}	J kg^{-1} °C^{-1}	Specific heat capacity of the dry grain
C_{pw}	J kg^{-1} °C^{-1}	Specific heat capacity of water
E_a	J mol^{-1}	Equivalent activation energy for the quality degradation kinetic
E_v	(kg water) (kg dry air)$^{-1}$	Air evaporation capacity
$\overline{E}_Q$	%	Mean absolute error between the simulated and the measured values of the grain quality
$\overline{E}_X$	kg kg^{-1}	Mean absolute error between the simulated and the measured values of the grain moisture content
H_R	%	Relative air humidity
$H_{R\,\min}$	%	Minimum allowed relative air humidity
$H_{R\,\max}$	%	Maximum allowed relative air humidity
J	%	Optimization criterion: negative final product quality
J_{aux}	kg^2 kg^{-2}	Auxiliary optimization criterion: squared difference between the final and the target moisture content
K	%$^{-1}$ s^{-1}	Quality degradation rate coefficient

K_0	kg^{-5} kg^{5} %$^{-1}$ s^{-1}	Quality degradation rate coefficient of the Arrhenius-type law
L_v	J kg^{-1}	Specific water vaporization heat
p_a	Pa	Partial water vapor pressure in the drying air
p_g	Pa	Partial water vapor pressure at the surface of the grain
$P_{g\,sat}$	Pa	Saturation vapor pressure at the grain temperature
Q	%	Rice quality (head kernel yield)
Q_{meas}	%	Measured value of the rice quality (head kernel yield)
R	J mol^{-1} K^{-1}	Perfect gas constant
S_{sg}	m^2 m^{-3}	Specific dry grain surface
t	s	Time
T_a	°C	Drying air temperature
$T_{a\,\min}$	°C	Minimum allowed drying air temperature
$T_{a\,\max}$	°C	Maximum allowed drying air temperature
t_f	s	Total drying time
T_g	°C	Grain temperature
U		Vector of control variables
$U_{\min}$		Minimum allowed value for the vector of control variables
$U_{\max}$		Maximum allowed value for the vector of control variables
X		Vector of state variables
x_1	(kg water) (kg dry matter)$^{-1}$	Moisture content of the inner grain compartment
x_2	(kg water) (kg dry matter)$^{-1}$	Moisture content of the outer grain compartment
x_m	(kg water) (kg dry matter)$^{-1}$	Average grain moisture content
x_{meas}	(kg water) (kg dry matter)$^{-1}$	Measured value of the average grain moisture content
x_{target}	(kg water) (kg dry matter)$^{-1}$	Target value for the final average grain moisture content
α	W m^{-2} °C^{-1}	Heat transfer coefficient between the grain and the air
β_1	(kg dry matter) m^{-3} s^{-1}	Mass transfer coefficient between the two grain compartments
β_2	(kg water) m^{-2} Pa^{-1} s^{-1}	Mass transfer coefficient between the outer grain compartment and the drying air
ρ_g	kg m^{-3}	Dry rice density
τ_1	m^3 m^{-3}	Volume fraction of the inner grain compartment
τ_2	m^3 m^{-3}	Volume fraction of the outer grain compartment

REFERENCES

1. Kunze O.R. and Prasad S., 1978, Grain fissuring potentials in harvesting and drying of rice, Transactions of the ASAE, 21(2) pp. 361-366.
2. Siebenmorgen T.J., 1994, Role of moisture content in affecting head rice yield, in Marshal W.E. and Wadsworth, J.I. Rice Science and Technology, Marcel Dekker, Inc., NY, 470p.
3. Chen C. and Wu P., 2000, The study of interrupted drying technique for rough rice. Drying Technology, 18(10) pp. 2381-2397.
4. Inprasit C. and Noomhorm A., 2001, Effect of drying air temperature and grain temperature of different types of dryer and operation on rice quality, Drying Technology, 19(2) pp. 389-404.
5. Kunze O.R., 1991, Moisture adsorption in cereal grain technology – a review with emphasis on rice, Transactions of the ASAE, 7(6) pp. 717-723.
6. Arora V.K., Henderson S.M. and Burkhardt, T.H., 1973, Rice drying cracking versus thermal and mechanical properties, Transactions of the ASAE pp. 320-327.
7. Ban T., 1971, Rice cracking in high rate drying, Japan Agricultural Research Quarterly, 6(2) pp. 113-116.
8. Abud M., Courtois F., Bonazzi C. and Bimbenet J.J., 2000, Processing quality of rough rice during drying – modelling of head rice yield versus moisture gradients and kernel temperature, Journal of Food Engineering, 45 pp. 161-169.
9. Kamst F.G., Bonazzi C., Vasseur J. et Bimbenet J.J., 2002, Experimental study of the mechanical properties of rice grains in relation to drying stresses. Transactions of the ASAE, 45(1) sous presse
10. Abud A.M., Courtois F., Bonazzi C. and Bimbenet J.J., 1998, Kinetics of mechanical degradation of paddy rice during drying/ Influence of process operations conditions and modelling for control design, in Proceedings of the 11th International Drying Syposium (IDS'98), Greece, Vol B, pp. 1303-1310.
11. Lee M.H., Han C. and Chang K.S., 1999, Dynamic optimization of a continuous polymer reactor using a modified differential evolution algorithm. Industrial and Engineering Chemistry Research, 38(12) pp. 4825-4831.
12. Altinten A. and Erdogan S., 2000, Tracking performance of control methods. Chemical Engineering Communications, 181 pp. 21-36.
13. Boxtel A.J.B. and Knol L., 1996. A preliminary study on strategies for optimal fluid-bed drying, Drying Technology, 14 (3&4), 481-500.

14. Kiranoudis C.T. and Markatos N.C. , 2000, Pareto design of conveyor-belt dryers. Journal of Food Engineering, 46 pp. 145-155.
15. Mao Z. and Cao C., 1999, Simulation and optimization of cross flow grain dryers,Drying Technology, 17(9) pp. 1767-1777.
16. Vasconcelos L.G.S. and Maciel F.R., 1998, Development of a supervisory control strategy for the optimal operation of grain dryers, Drying Technology, 16(9&10) pp. 2017-2031.
17. Trelea I.C., Trystram G., Courtois F., 1997, Optimal constrained non-linear control of batch processes: application to corn drying, Journal of Food Engineering, 31(4) pp. 403-421.
18. Abud M., Courtois F., Bonazzi C. and Bimbenet J.J., 2000, A compartmental model of thin-layer drying kinetics of rough rice. Drying Technology 18, 17, pp. 1389-1414.
19. Abud Archila, M., 2000, Modélisation simultanée des transferts et de l'évolution de la qualité technologique du riz paddy en vue d'optimiser les conditions de séchage. Thèse ENSIA-Massy, France.
20. Loncin M. and Merson R.L., 1997, Food Engineering : principles and selected applications, Academic Press, New York, U.S.A., 494 p.
21. Pfost H.B., Maurer S.G, Chung D.S. and Milliken G.A., 1976, Summarizing and reporting equilibrium moisture data for grains, Drying Technology, 16(8) pp. 1533-1565.
22. Bonazzi C., Peuty M.A. and Themelin A., 1997, Influence of drying conditions on the processing quality of rough rice, Drying Technology, 15(3&4) pp. 1141-1157.
23. Dohrmann C.R., Robinett R.D., 1999, Dynamic programming method for constrained discrete-time optimal control, Journal of Optimization Theory and Applications, 101(2) pp. 259-283.
24. Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.P., 1997, Numerical recipes in C, Chapter 17: Two point boundary value problems, Cambridge University Press, 994p.

TABLE 1

Dynamic Model Constants and Parameters by Abud 2000 (19)

Constants		
Symbol	Units	Value
C_5	Pa °C^{-1}	65
C_{pg}	J (kg dry matter)$^{-1}$ °C^{-1}	1300
C_{pw}	J (kg water)$^{-1}$ °C^{-1}	4210
ρ_g	(kg dry matter) m^{-3}	1500
S_{sg}	m^2 m^{-3}	2000
τ_1	m^3 m^{-3}	0.6
τ_2	m^3 m^{-3}	0.4
R	J mol^{-1} K^{-1}	8.32
Parameters determined from experimental data		
B_{10}	(kg dry matter) m^{-3} s^{-1}	0.01316
B_{11}	(kg water)$^{-1}$ (kg dry matter) °C^{-1}	0.3083
B_{20}	(kg water) m^{-2} Pa^{-1} s^{-1}	2.304×10^{-9}
B_{21}	°C^{-1}	0.0442
C_1	(kg water) (kg dry matter)$^{-1}$	0.319
C_2	(kg water)	0.0493

	(kg dry matter)$^{-1}$	
C_3	°C^{-1}	1.8994
C_4	°C	2.5457
K_0	(kg water)$^{-5}$ (kg dry matter)^{5} %$^{-1}$ s^{-1}	1.56×10^{27}
E_a	J mol^{-1}	1.657×10^{5}

TABLE 2

Reference Batch Conditions

Category	Symbol	Value
Initial product state	$x_m(0)$ $T_g(0)$ $Q(0)$	270 g/kg d.b. 20 °C 80 %
Admissible range of the control variables	$T_{a\,\min}$ $T_{a\,\max}$ $H_{R\,\min}$ $H_{R\,\max}$	40 °C 80 °C 5 % 80 %
Imposed conditions	x_{target} t_f	130 g/kg d.b. 2 hours

The limit values of control variables and the imposed conditions are considered in the optimization strategy as constrains

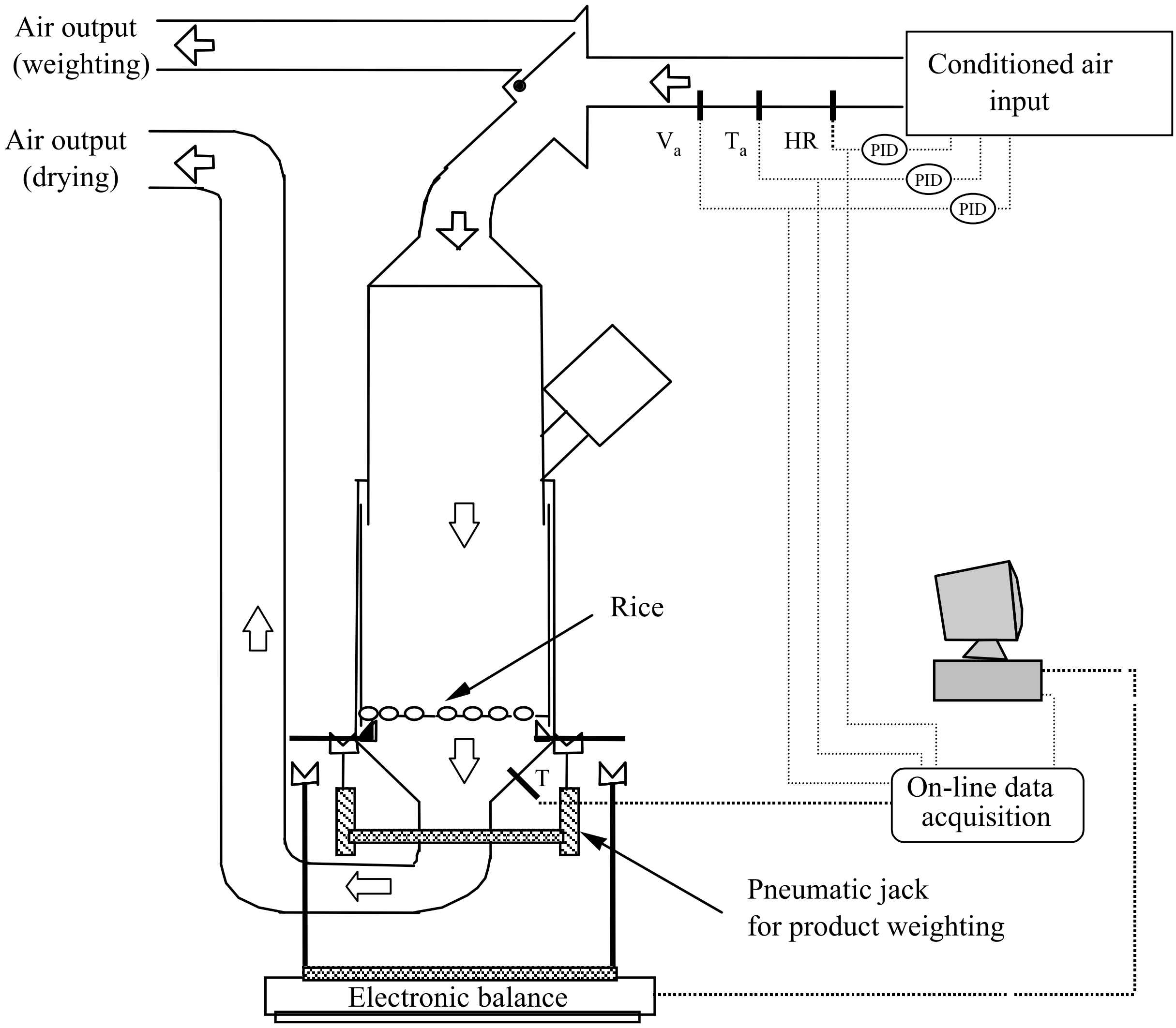


FIGURE 1. Schematic representation of the computer controlled grain dryer.

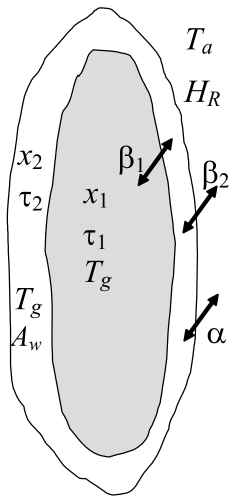


FIGURE 2. Schematic representation of the grain compartments.

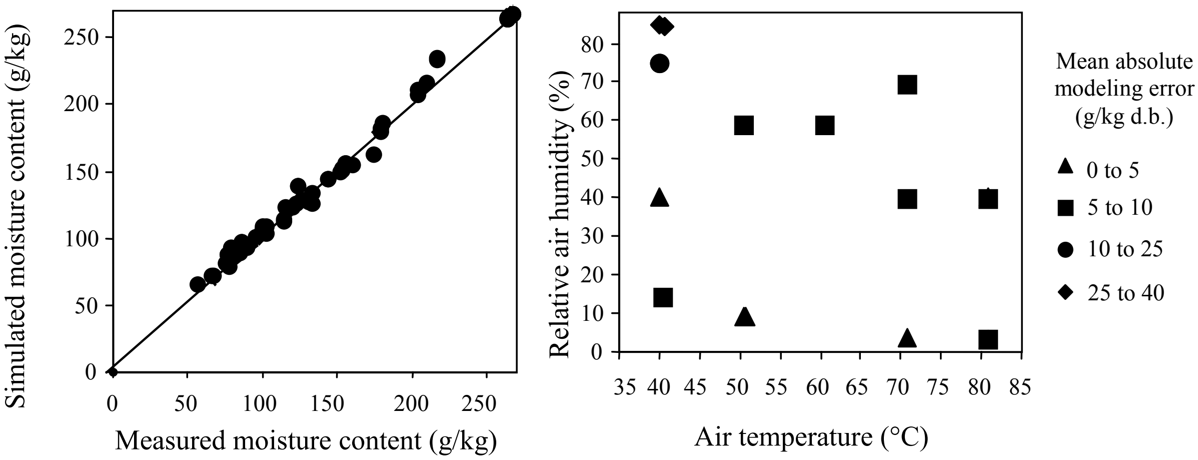


FIGURE 3. Validation of the dynamic drying model. (a) Simulated versus measured moisture content. (b) Model accuracy for various combinations of operating conditions.

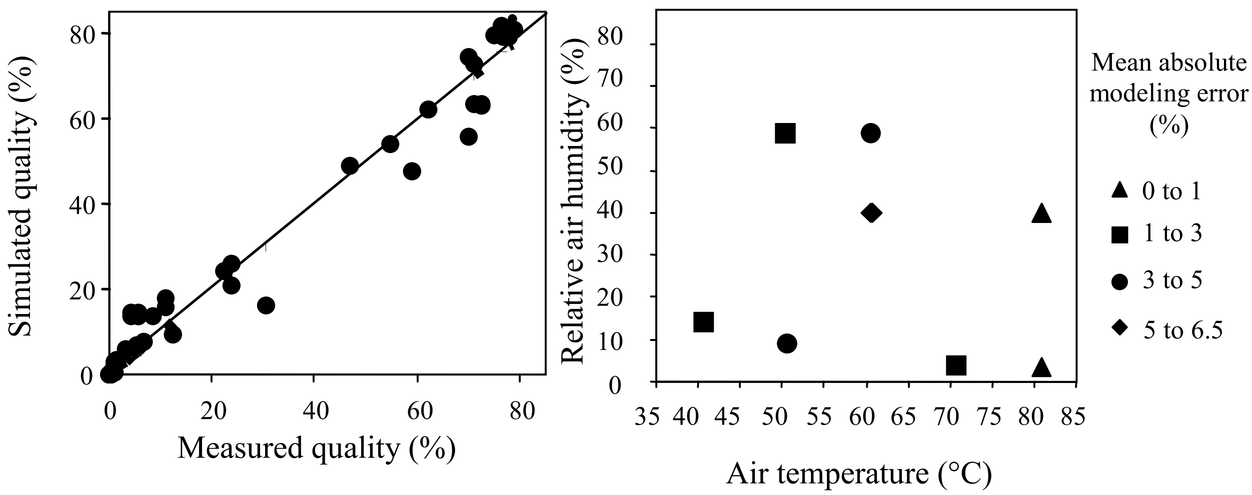


FIGURE 4. Validation of the dynamic grain quality model. (a) Simulated versus measured product quality. (b) Model accuracy for various combinations of operating conditions.

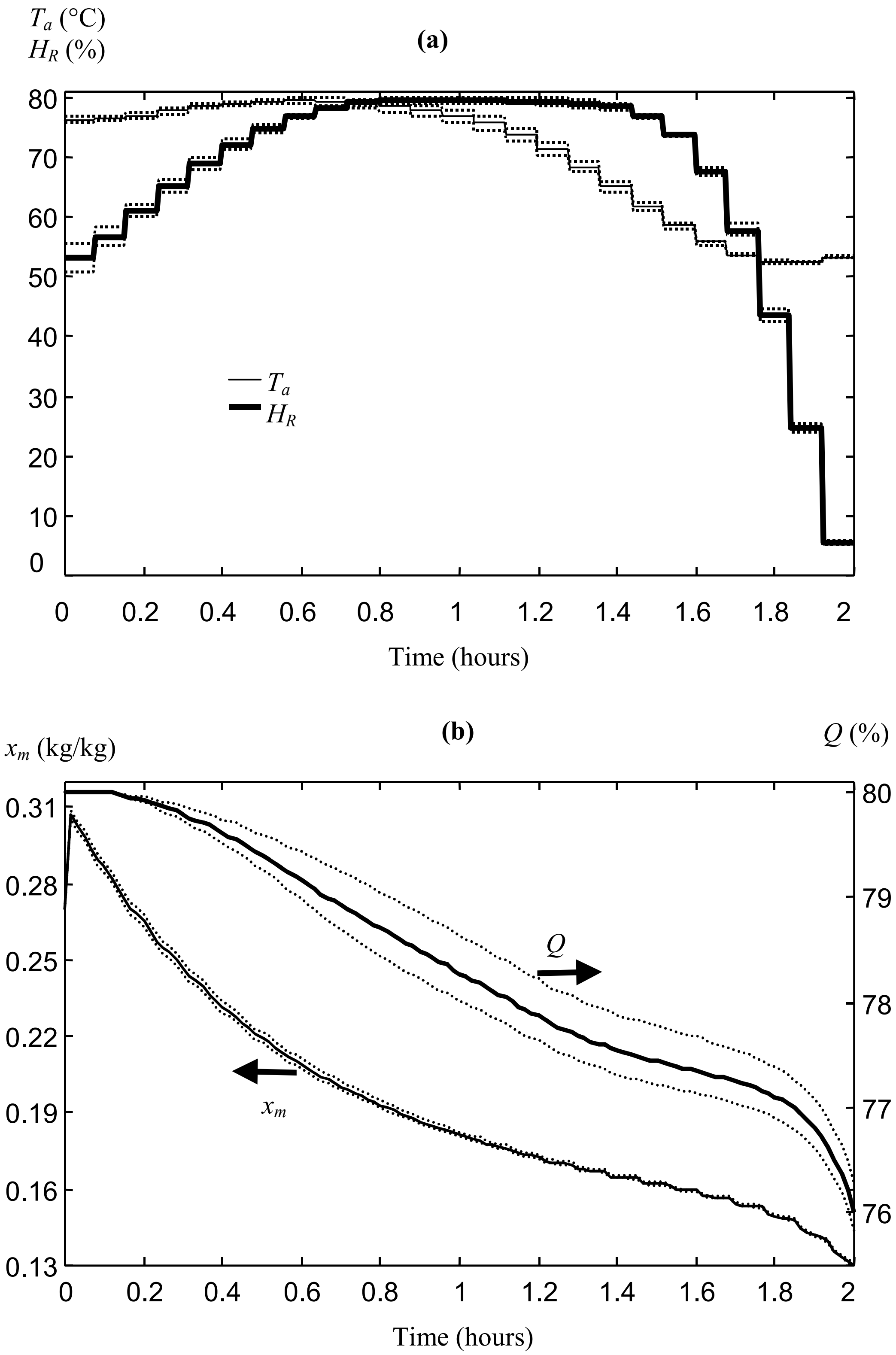
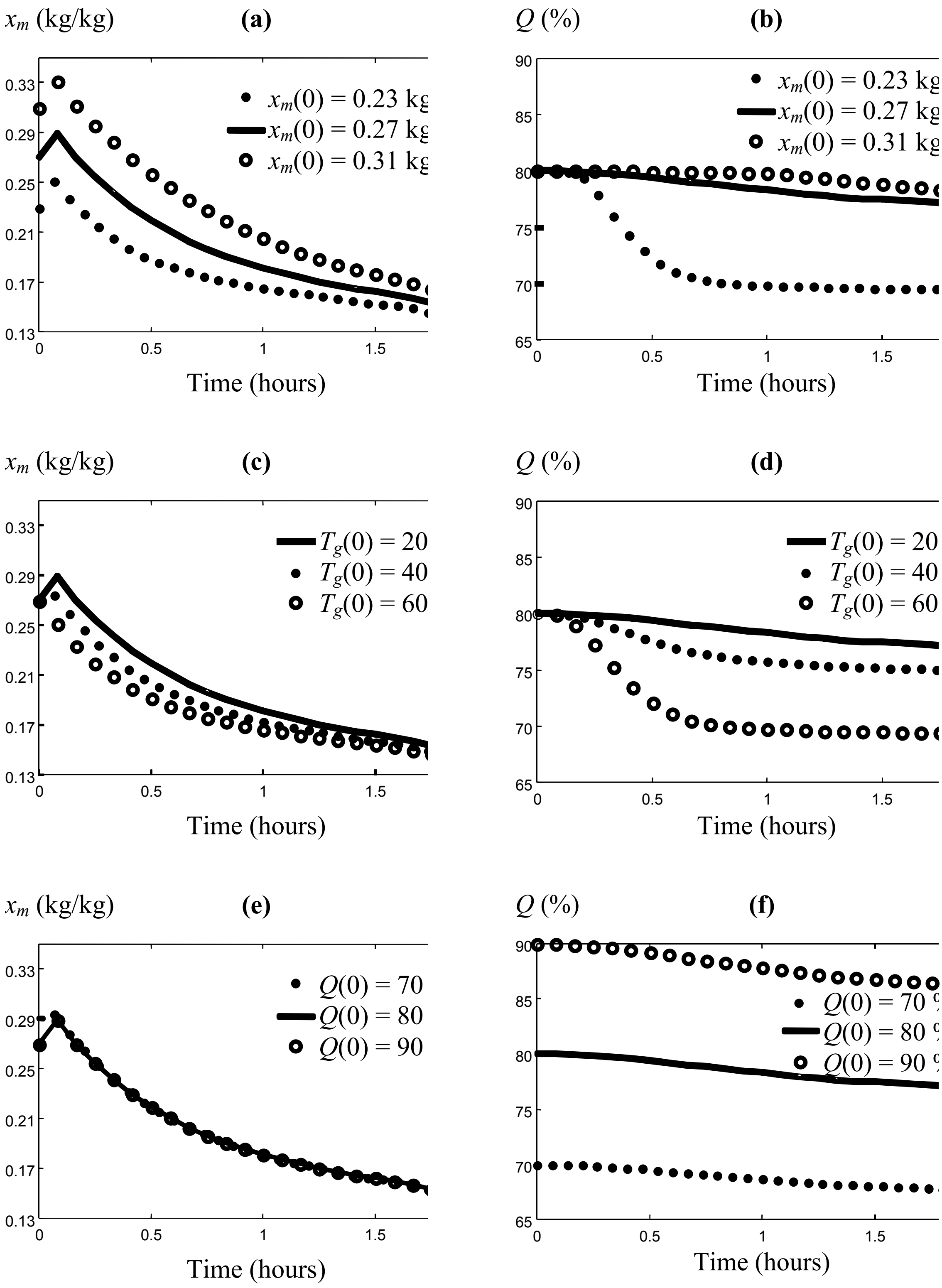


FIGURE 5. Convergence of the optimization algorithm from six random initial control profiles. (a) Control variable profiles: air temperature and relative humidity. (b) Process output trajectories: product moisture content and quality. Solid lines are mean values and dotted lines are extreme values of the six calculations.



x_m (kg/kg)
(a)
$x_m(0) = 0.23$ kg
$x_m(0) = 0.27$ kg
$x_m(0) = 0.31$ kg
Time (hours)
Q (%)
(b)
$x_m(0) = 0.23$ kg
$x_m(0) = 0.27$ kg
$x_m(0) = 0.31$ kg
Time (hours)
x_m (kg/kg)
(c)
$T_g(0) = 20$
$T_g(0) = 40$
$T_g(0) = 60$
Time (hours)
Q (%)
(d)
$T_g(0) = 20$
$T_g(0) = 40$
$T_g(0) = 60$
Time (hours)
x_m (kg/kg)
(e)
$Q(0) = 70$
$Q(0) = 80$
$Q(0) = 90$
Time (hours)
Q (%)
(f)
$Q(0) = 70$
$Q(0) = 80$
$Q(0) = 90$
Time (hours)

FIGURE 6. Robustness of the optimal control strategy with respect to changes in the initial product state. The optimal control profiles computed for the reference batch are applied without change. (a, b) Variations in the initial grain moisture content. (c, d) Variations in the initial grain temperature. (e, f) Variations in the initial grain quality. Symbols: (—) reference batch, (●) low value of the initial state, (○) high value of the initial state.

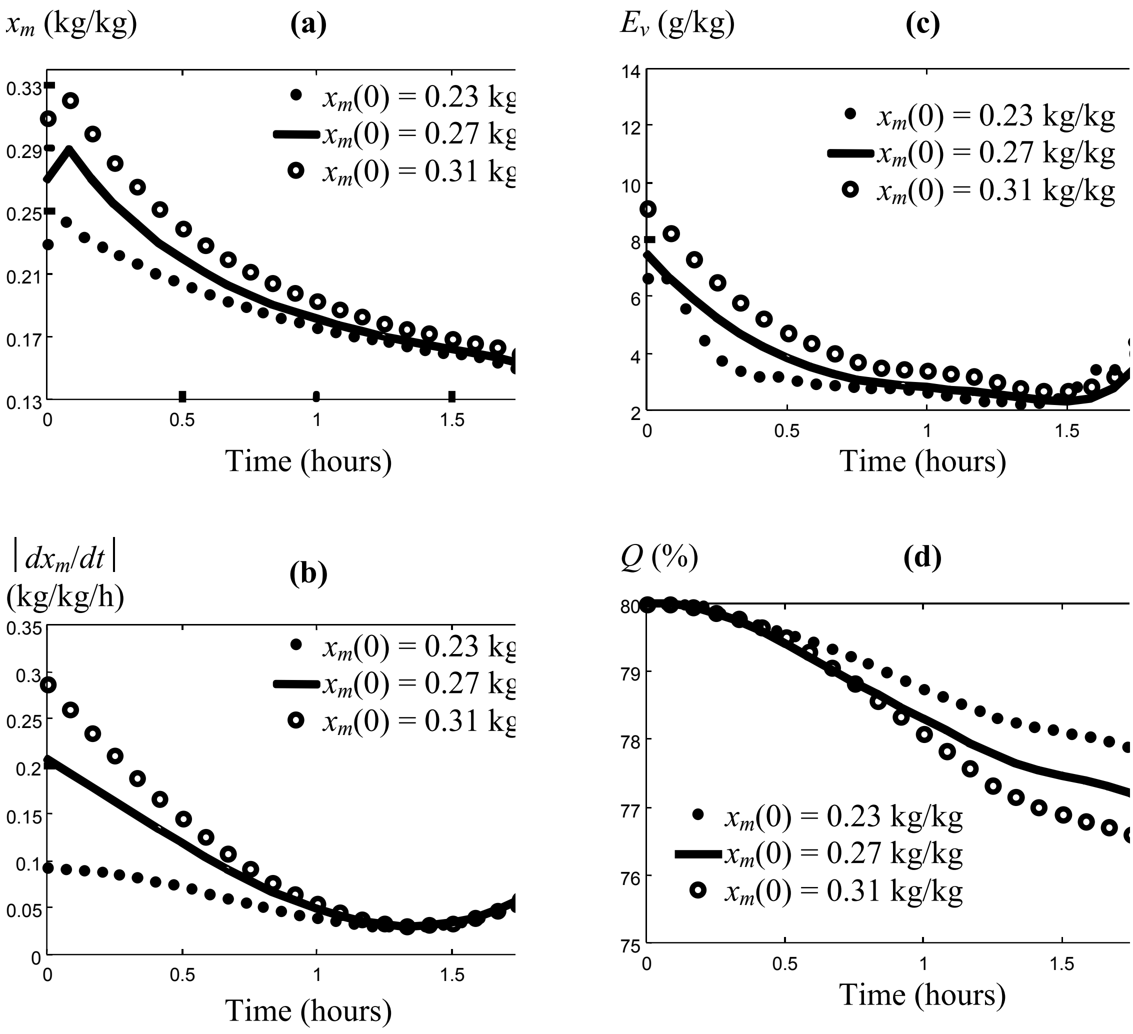


FIGURE 7. Robustness of the optimal control strategy with respect to changes in the initial moisture content of the grain. The optimal control profiles are re-computed for each value of the initial moisture content. (a) Average product moisture content. (b) Drying rate. (c) Evaporation capacity of the drying air. (d) Grain quality.

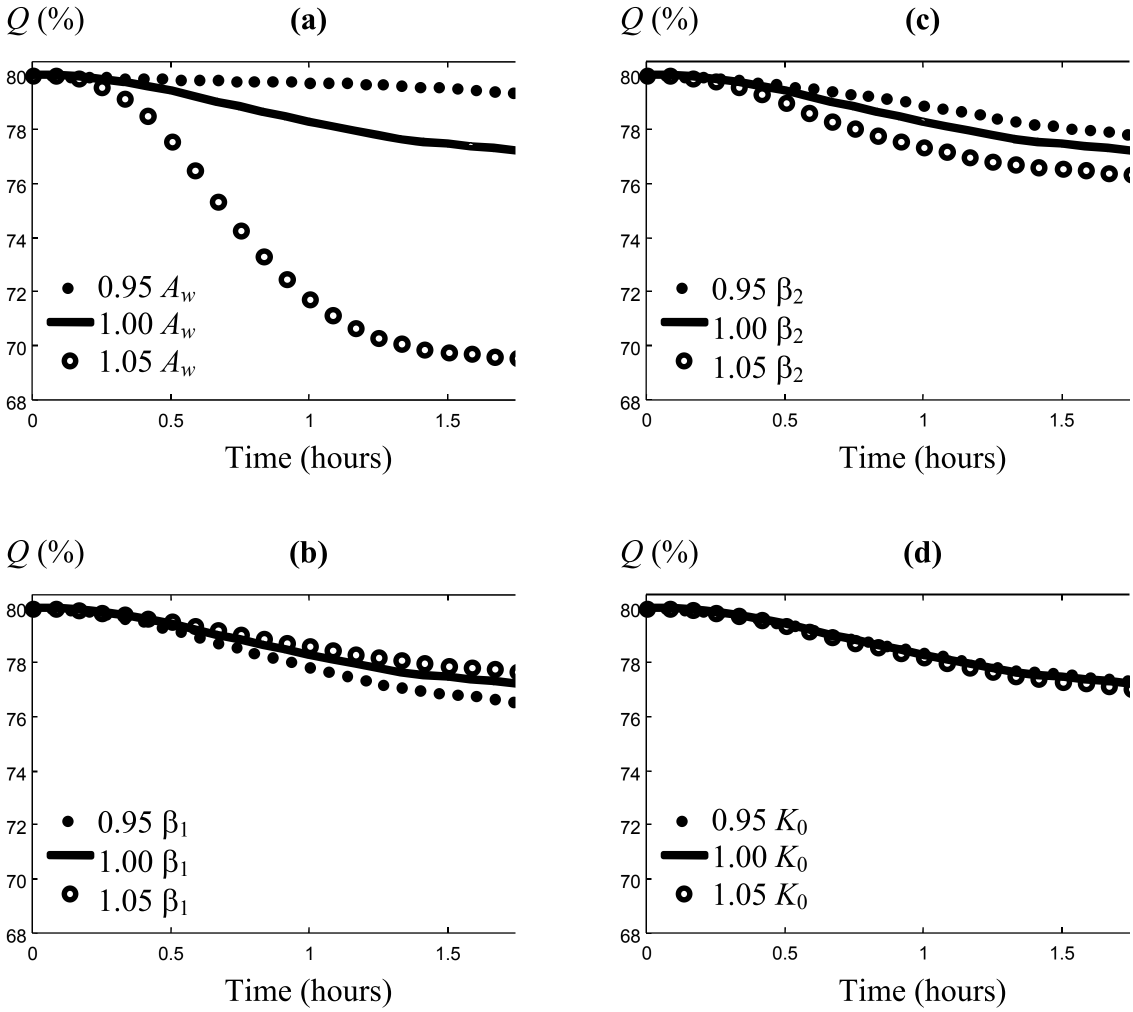


FIGURE 8. Sensitivity of the quality degradation kinetic with respect to changes in the model parameters. The optimal control profiles computed for the reference batch are applied without change. (a) Variations in the water activity at the surface of the grain. (b) Variations in the mass transfer coefficient between the inner and the outer grain compartment. (c) Variations in the mass transfer coefficient between the outer grain compartment and the

drying air. (d) Variations in the quality degradation rate. Symbols: (—) reference batch, (●) low value of the model parameter, (○) high value of the model parameter.

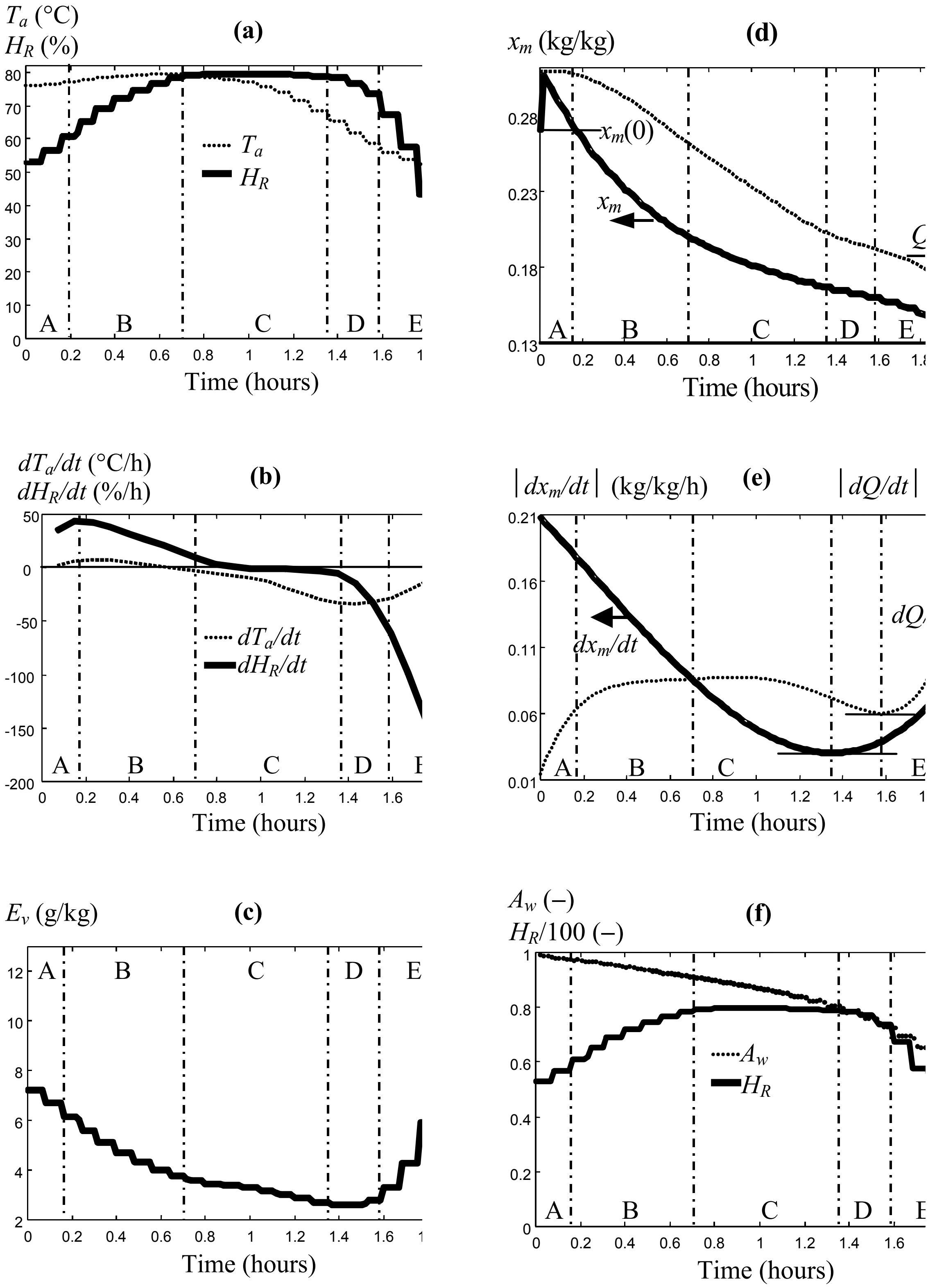
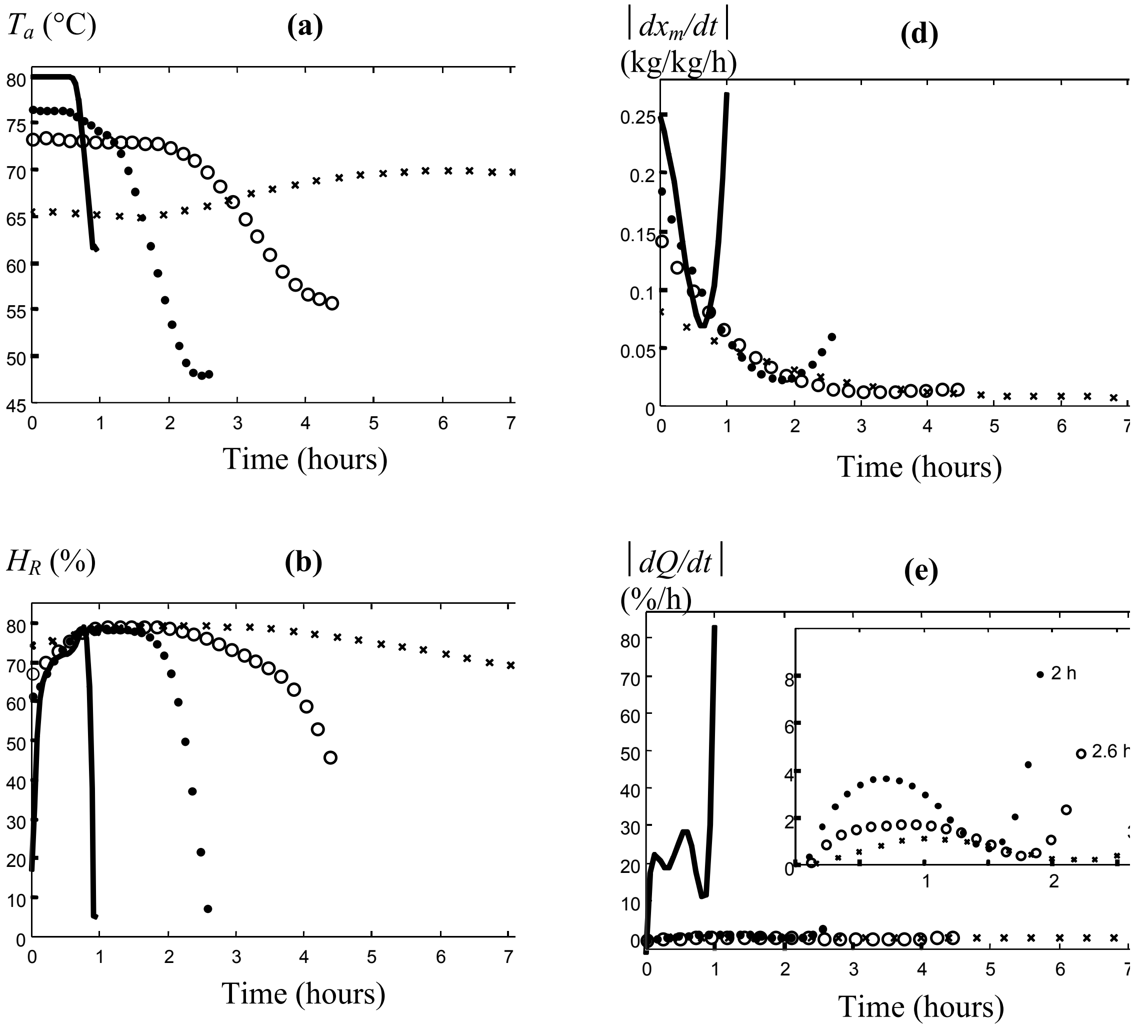


FIGURE 9. Optimal control strategy for the reference batch. (a) Optimal profiles of the control variables: air temperature and relative humidity. (b) Rates of change of the control variables. (c) Air evaporation capacity. (d) Optimal trajectories of the output process variables: grain moisture content and quality. (e) Rates of change of the output variables. (f) Comparison between the water activity at the product surface and the relative humidity of the drying air.



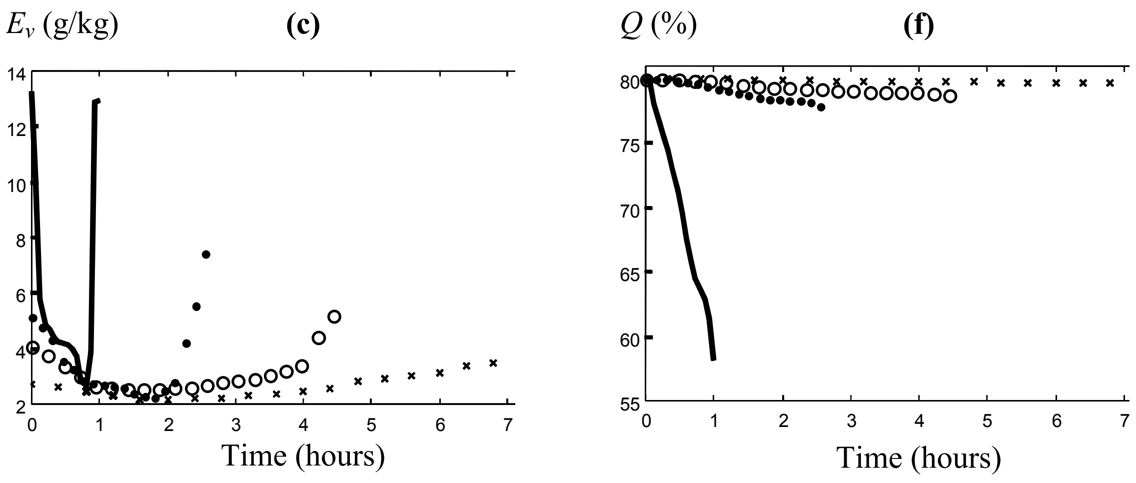


FIGURE 10. Optimal control policies for various total drying times. Symbols: (—) 1 hour, (●) 2.67 hours, (O) 4.5 hours, (×) 7.5 hours. (a) Air temperature. (b) Relative humidity. (c) Evaporation capacity of the drying air. (d) Drying rate. (e) Quality degradation rate. Insert: Quality degradation rate for short drying times. (f) Quality degradation.