Optimization of Commercial Ear-Corn Dryers

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ABSTRACT

Drying seed corn as ear-corn is a complex process, which traditionally depends on operator experience. Therefore, there is significant opportunity to improve the process in terms of preserving quality, minimizing cost, and/or maximizing capacity. A simulation model, based on heat and mass transfer, was used in a process optimization program. Optimal values of the initial bed-depth, the up-air and the down-air temperatures, the up-air and down-air airflows, and the reversal moisture content were calculated, using the Box complex method, for maximizing the capacity or for minimizing the energy cost of in-bin ear-corn drying at different initial product moisture contents. Operating the dryer under the capacity-optimization strategy increases the capacity by 26-43% but also increases the cost by 25-33%, compared to operating under the cost-minimization strategy. Additionally, sensitivity analyses showed that the air temperature has the greatest influence on the capacity, and the air flow rate has the largest effect on the drying cost.

Keywords: seed corn, ear-corn, optimization, capacity maximization, cost minimization.

INTRODUCTION

Seed corn is usually harvested as ear-corn at a moisture content of 30 – 40% (w.b.). Immediate drying to 12 – 13% is required to maintain seed viability. Therefore, optimal design and operation of drying system is critical to ensuring seed quality.

Figure 1 shows a conventional commercial seed-corn dryer. Freshly-harvested ears are placed in bins with a angled floors. The drying air is first forced from the bottom of the bins to the top (the so-called *up-air*) for 30 – 60 h; then the direction of the air is reversed (the so-called *down-air*) during the subsequent 30 – 50 h. The temperature of the up-air is typically 35 – 40.5°C (95 and 105°F), and the down-air is typically 40.5– 46°C (105 and 115°F), depending on the seed genotype and the initial moisture content of the ears. Typical airflow rates are 15 – 40 m^3 min^{-1} m^{-2} (5 – 12 cfm ft^{-2}) for both the up-air and down-air.

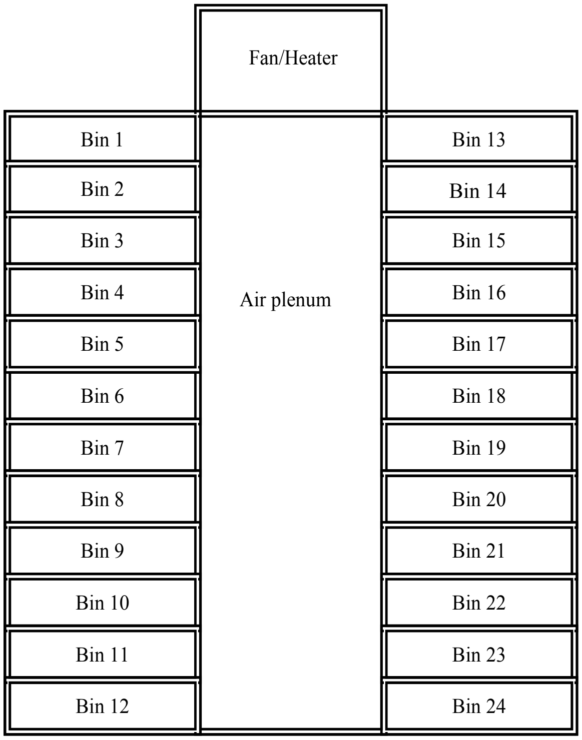
Drying temperature is particularly critical in ear-corn drying. Harrison et al. (1929) investigated the effect of in-bin (1.5 to 2.1 m deep bed) drying of ear-corn at 40 – 70°C (104 – 158°F) on seed viability. Ear-corn dried to less than 10% moisture content at temperatures of 40 – 45°C (104 – 113°F) was not injured either in viability, seedling growth, or field performance; however, corn dried at 50°C (122°F) was damaged, and at 60°C (140°F) had zero percent viability. Burris and Navratil (1981) studied the drying of ear-corn below 47% moisture content at 40°C in a conventional air-reversal deep-bed ear-corn dryer; after 72 h of drying, the ear temperatures throughout the bed were nearly uniform, the moisture content ranged from 8% at the top to 12% at the bottom of the bed, and the viability of the seed was not affected by the drying process. However, McRostie (1949) reported significant seed viability loss when ear-corn with an initial moisture content of over 50% was dried at a temperature over 41°C (105°F).

The operation of multiple ear-corn dryers (usually two parallel rows, each consisting of 8 to 12 bins) is a complicated process. Lacking any science-based tools for dryer-operating decisions, human operators must select the time for air-reversal, and for stopping the drying process. Currently their decisions are based solely on experience.

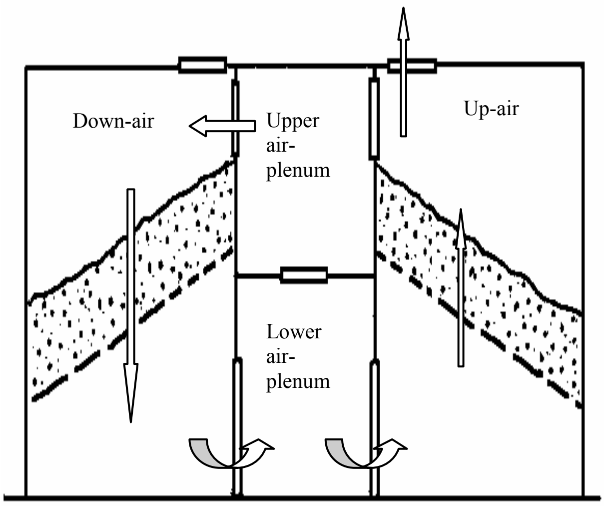
Given the human dimension in dryer operation, it is typical that underdrying or overdrying occurs in 40 – 55% of the drying runs at a given commercial ear-corn drying facility (Precetti, 2001). Overdrying is considered by the authors to be drying to an average bed-moisture content of 11.9% or below; it results in excessive energy consumption, decreased throughput, and loss of product mass. Underdrying is considered as drying to 13% or above; it results in loss of seed viability, and necessitates the restarting of the drying process, resulting in logistical problems for the drying facility. Drying to within the 12.0 – 12.9% range is rated as “acceptable” by the authors. The frequent occurrence of over- and under-drying clearly suggests the need for optimizing the drying process using scientific tools.

Several researchers have used process optimization techniques in studying the drying of biological products. For the drying of potato disks, Mishkin et al. (1984) used the complex-optimization method (under specified constraints) to establish the optimal drying-air temperature-control path for either minimizing the drying time or for maximizing the ascorbic acid retention. Liu (1998) used a neural network model to find the optimal drying air temperature for producing acceptable and uniform grain-corn quality. Trelea et al. (1997) used a neural network model for controlling a corn batch-drying process. They reported that the optimal solution resulted in a 3.4% decrease in the processing time and a 4.1% decrease in the fuel consumption compared to that of the standard dryer. However, optimization techniques have not been previously applied to ear-corn drying processes.

Therefore, a simulation model of commercial ear-corn drying, based on basic heat and mass transfer principles, has been developed and validated (Islam et al., 2004). The principal objective of this study was to use that model for finding the optimal drying parameter values (i.e., bed depth, airflow rate, drying air temperatures, air reversal time) that maximize the dryer capacity or minimize the dryer energy cost.



Top View



End View

Figure 1. Schematic diagram of an ear-corn dryer.

PROCEDURES

A differential-equation type, coupled heat and mass transfer model for ear-corn drying (Islam et al., 2004) was linked to the complex optimization procedure (Box et al., 1969). The drying model predicts the air-reversal time and the stopping time for the dryer operation, given the following inputs: (i) initial moisture content, (ii) reversal moisture content, (iii) final moisture content, (iv) ear-corn bed depth, (v) ambient dry-bulb temperature, (vi) dry-bulb and wet-bulb temperatures of the drying air, and (vii) static pressures of the up-air and down-air.

The input parameters (ii) through (vii) are the control variables for the optimization of the dryer capacity or the minimization of the cost. The control variables were numerically searched by the Box complex method. The search ranges for the different control variables are discussed in the constraint section below. The optimization procedure (figure 2), and the embedded ear-corn drying model, were coded in FORTRAN – IV. The details of the search technique can be found in Umeda and Ichikawa (1972) and in Islam (2004).

The standard ear-corn dryer operating parameters are: (1) heater thermal efficiency, (2) motor efficiency, (3) fan efficiency, (4) natural gas price, (6) electricity price, (7) ambient dry-bulb temperature, and (8) ambient wet-bulb temperature (Table 1). The effects of different drying parameters (including the wet-bulb temperature) on dryer capacity and energy cost have been discussed in Islam et al. (2004).

Objective Functions

The optimization had two goals: (1) capacity maximization or (2) energy cost minimization. It is critically important that a drying facility keeps up with the harvest rate, so that drying of wet ear-corn can begin immediately after harvest. Therefore, capacity maximization often surpasses cost minimization in importance. However, at other times, such as when dryer capacity easily surpasses the harvest rate, cost minimization would be the preferred way to operate a drying system.

The capacity-optimization objective function was calculated from the drying time, the test weight (TW) of the wet ear-corn, and the volume dried:

$$\text{Capacity (tonne h}^{-1}\text{ m}^{-2}\text{)} = \text{weight of wet ear-corn (tonne m}^{-2}\text{) / total time of drying (h)} \quad (1)$$

The energy cost objective function had two components: (1) the cost associated with the fuel for heating the drying air, and (2) the cost associated with the electrical energy for operating the

fan. Thus, the total cost was:

$$\text{Total Cost} = \text{fuel cost} + \text{electricity cost} \quad (2)$$

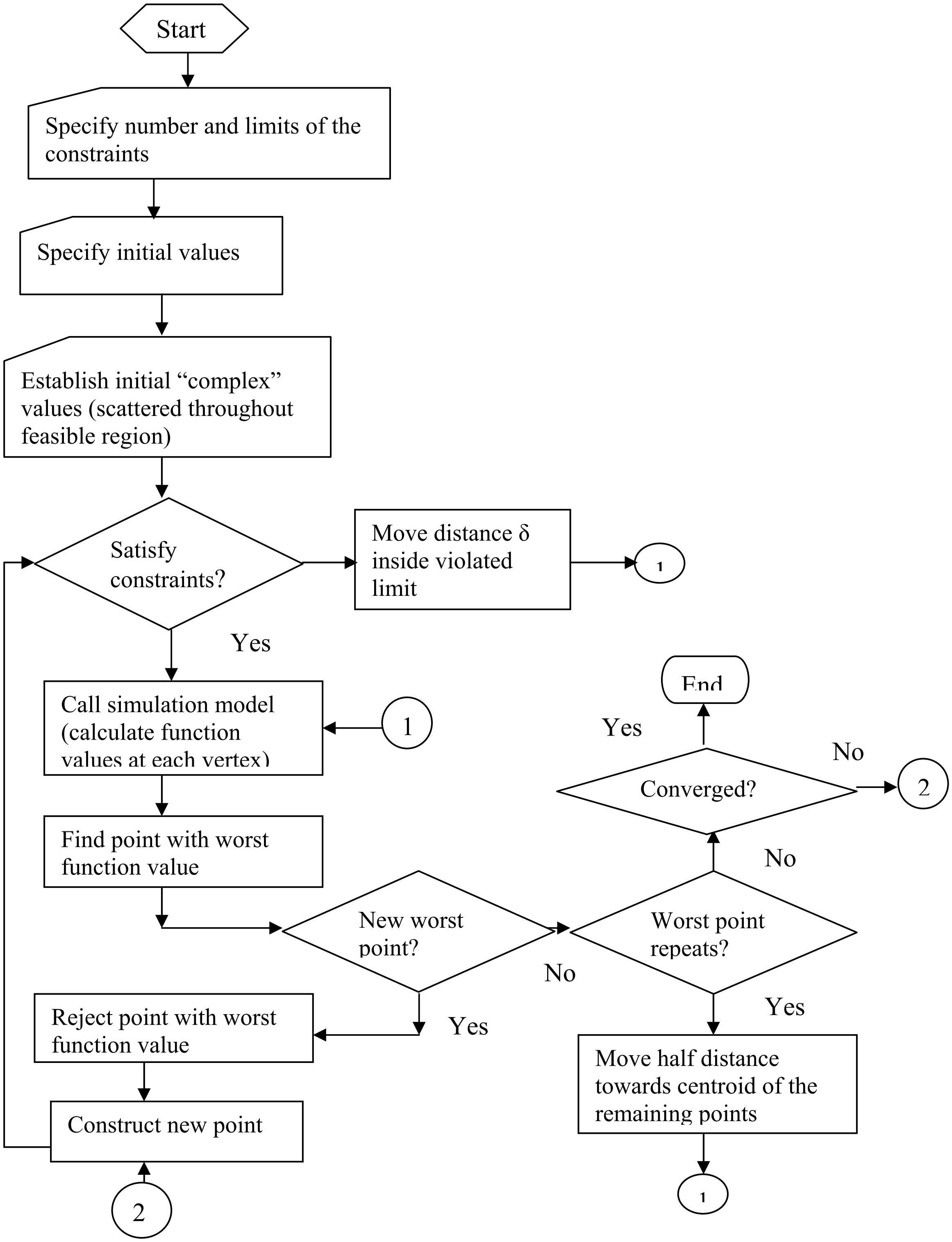


Figure 2. Flow diagram of the computer program for optimizing the fixed-bed ear-corn drying process.

Table 1. Standard input parameters used in the optimization program.

Inputs / parameters	Value	Reference
Heater thermal efficiency, %	70	Hall, 1957
Motor efficiency, %	70	(65-85%, Anon., 1958)
Fan efficiency, %	70	(40-70%, Perry et al., 1963)
Natural gas price, \$/(1055 MJ)	5.9	The Wall Street Journal, May 8, 2003
Electricity price, \$/megawatt-hour	43.9	The Wall Street Journal, May 8, 2003
Ambient wet-bulb temp. (°C)	13	ASAE (2001a)
Ambient dry-bulb temp. (°C)	16	ASAE (2001a)
Test weight (kg m^{-3})	901	ASAE (2001b)

In a two pass ear-corn dryer, the ambient air is heated and blown downward (down-air) through the bed in the second pass; the exhaust air from the second pass is blown upward (up-air) in the first pass for a different bin in the same dryer. Thus, depending on the mass of up-air relative to the mass of down-air, there are three different scenarios for calculating the fuel energy requirements in ear-corn drying: ***case 1:*** the mass of up-air is more than the mass of down-air, ***case 2:*** the mass of up-air is less than the mass of down-air, and ***case 3:*** the mass of up-air is equal to the mass of down-air. The power (kJ m^{-2} h^{-1}) required for the three cases was calculated using the following two equations:

$$Q_{up} = G_{tup} \left[(c_a\ T_{up} + (h_{fg} + c_v\ T_{up})\ H_1) - (c_a\ T_{amb} + (h_{fg} + c_v\ T_{amb})\ H_0)\right] \tag{3}$$

$$Q_{down} = G_{tdown} \left[(c_a\ T_{down} + (h_{fg} + c_v T_{down})\ H_1) - (c_a\ T_{ex} + (h_{fg} + c_v\ T_{ex})\ H_0)\right] \tag{4}$$

The total fuel energy (kJ) is the sum of the up- and down-air power times drying area times total drying time :

$$E_{total} = (Q_{up} + Q_{down})\ t_{drying}\ \cdot \text{Area} \tag{5}$$

The fuel component of the cost function is calculated from the price of the fuel (V_f), the total fuel energy (E_{total}), and the thermal efficiency of the heater (η_{therm}):

$$\text{Fuel cost} = \frac{V_f\ E_{total}}{\eta_{therm} \cdot 1000} \tag{6}$$

The energy required for the fan is:

$$E_{fan} = \mathit{Total\ time}(h)\ [\text{air delivery}(m^3 s^{-1}) \cdot \text{Static pressure}(\text{Pa})]/10^6 \tag{7}$$

where E_{fan} is the fan energy in MWh.

The electrical component of the cost function is calculated from the price per unit of electricity (V_e), the electrical energy consumption (E_{fan}), the motor efficiency (η_m), and the fan efficiency (η_{fan}):

$$\text{Electricity cost } = \frac{V_e \, E_{fan}}{\eta_m \, \eta_{fan}} \tag{8}$$

Given the above equations for calculating capacity and cost, the objective functions for the two optimization schemes were:

$$\text{Max. Capacity } (L, T_{up}, T_{down}, P_{up}, P_{down}, M_{rev}, M_f) \tag{9}$$

or

$$\text{Min. Cost } (L, T_{up}, T_{down}, P_{up}, P_{down}, M_{rev}, M_f) \tag{10}$$

Subject to the following constraints:

1. depth (L), m : $2.4 \leq L \leq 3.4$
2. Up-air temperature (T_{up}), °C : $35 \leq T_{up} \leq 41$
3. Down-air temperature (T_{down}), °C : $41 \leq T_{down} \leq 46$
4. Up-air pressure (P_{up}), Pa : $249 \leq P_{up} \leq 746$
5. Down-air pressure (P_{down}), Pa : $249 \leq P_{up} \leq 746$
6. Reversal moisture content (M_{rev}), % : $17.5 \leq M_{rev} \leq 0.42\, M_i + 7.5$
7. Final moisture content (M_f), % : $M_f \leq 12.5$

The seed industry follows a 60/40 rule-of-thumb for air-reversal; i.e., the up-air time should at least be 60% of the total drying time in order to properly balance the airflows in a 24-bin commercial ear-corn drying system. The equation under constraint #6 listed above, developed empirically (Islam, 2004), was used in the program to result in an overall balance that was within the range of this industry rule-of-thumb.

Sensitivity analysis method

"In an operating-system design, a constraint can rarely be known with absolute precision. Thus, it is essential to know the effect of constraint uncertainty on the objective function. The analysis that determines the rate of change of the optimum capacity and cost value with respect to a perturbation in the constraint is called the sensitivity analysis" (Beightler et al., 1979). A sensitivity analysis provides insight in a physical process and is useful in manipulating the control variables without resolving the problem all over again. Therefore, the effect of small changes in the constraints on the optimum capacity and the minimum cost of an ear-corn dryer were considered for the case of 30% initial moisture content ear-corn. The small changes in the constraints were termed as standard error and were set at 0.15 m for the depth, 0.25% for the initial moisture content, 1.1°C for the temperatures, and 50 Pa for the air- pressure.

The constraints were modified to one and two standard errors above and below the selected values, and the effects on the maximum capacity (table 4) and the minimum cost (table 5) values were calculated. For each constraint, the result obtained by varying the constraint above the standard value was subtracted from the result obtained by varying the constraint below the standard value and divided by the number of standard error variation (2 or 4) to give a normalized sensitivity.

RESULTS AND DISCUSSION

The results of the capacity maximization and the cost minimization are presented in this section, followed by the results of the sensitivity analysis.

Capacity Maximization

As expected, the maximum capacity decreases as the initial moisture content increases. For drying ear-corn from 25 to 12.5% moisture content, the maximum capacity is 25.1 kg of wet ears per square meter of dryer surface per hour ($kg\ h^{-1}m^{-2}$), which is achieved when the bed-depth is 3.3 m, the up-air temperature is 41°C, the down-air temperature is 46°C, the up-air/down-air pressures are 746 Pa, and the reversal average ear-corn moisture content is 18.0% (Table 2). Overall, maximum capacity for a given initial moisture content is achieved when the bed depth, air temperature, air pressure, and reversal moisture content are all maximized, except at the highest initial moisture content (35%), when the optimal depth and pressures are lower than the maximum values.

Table 2. Capacity optimization of the commercial ear-corn dryer.

Input	Control variables						Output				
Average initial MC (% w.b.)	Depth (m)	Up-air temp. (°C)	Down-air temp. (°C)	Up-air pressure (Pa)	Down-air pressure (Pa)	Average reversal MC (%w.b.)	Total time (h)	Capacity (kg m^{-2} h^{-1}	Cost ($/tonne)	Energy (kJ kg^{-1}	Reversal time (h)
20	3.3	41	46	746	746	15.9	32	35.2	6.1	5841	18
25	3.4	41	46	746	746	18.0	42	25.1	9.2	5485	24
30	3.4	41	46	746	746	20.1	48	20.3	12.5	5726	30
35	2.9	41	46	722	722	22.0	45	17.2	17.1	6438	31

Cost Minimization

As expected, the minimum cost increases as the initial moisture content increases. At 25% initial moisture content, the optimum values for the bed-depth and the up-air/down-air temperatures reach the maximum (3.2 m, 41/46°C, respectively) while the air pressures (274 Pa) (thus the airflow rates) are at minimum (Table 3). Overall, minimum cost is achieved when the bed-depth and air-temperatures are maximized but the air flow is minimized.

It is instructive to compare Tables 2 and 3. Under the capacity optimization scenario, the total drying time for 25% moisture content ear-corn is 42 h at a cost of 9.2 \$/tonne and an energy expenditure of 5,485 kJ kg^{-1}, while under cost minimization condition, it requires 51 h at a cost of 7.2 \$/tonne and an energy expenditure of 4,611 kJ kg^{-1}. The capacity optimization strategy dries 26 – 43% more wet-corn per square meter per hour, with a cost increase of 25 – 33%, when compared to the cost minimization strategy, depending on the initial moisture content.

Table 3. Cost minimization of the commercial ear-corn dryer.

Input	Control variables						Output				
Average initial MC (% w.b.)	Depth (m)	Up-air temperature (°C)	Down-air temperature (°C)	Up-air pressure (Pa)	Down-air pressure (Pa)	Average reversal MC (%w.b.)	Total time (h)	Capacity (kg m^{-2} h^{-1})	Cost ($/tonne)	Energy (kJ kg^{-1})	Reversal time (h)
20	3.3	41	46	274	274	15.8	41	28	4.6	4642	23
25	3.2	41	46	274	274	18.0	51	20	7.2	4611	30
30	3.2	40	46	249	249	19.9	63	15	10.0	4851	40
35	3.3	41	46	249	249	21.7	72	12	13.3	5283	49

Sensitivity Analysis

Under optimal operating conditions, the capacity is sensitive (in descending order) to the up-air temperature, the down-air temperature, and the air pressure (table 4). If the up-air temperature varies, or the measurement is uncertain by one standard error, the capacity is affected by 0.9 kg h^{-1} m^{-2}. The normalized sensitivity of the other control variables is to be interpreted in a similar manner.

By following similar reasoning, it can be inferred (Table 5) that the cost function value is most affected by the change in the down-air pressure. The negative normalized sensitivity value indicates that this control variable inversely affects the cost; i.e., as the down-air temperature decreases from its optimal value, the cost function value increases. In terms of temperature, the cost function value remains unchanged even if the down-air temperature increased from its optimal value within the allowable range. Better function values may only be obtained by violating the constraints (Table 4 and Table 5).

Table 4. Sensitivity analysis of the capacity function at 30% initial moisture content.

Parameter	Depth (m)	Up-air temp. (°C)	Down-air temp. (°C)	Up-air pressure (Pa)	Down-air pressure (Pa)	Reversal MC (%w.b.)	Capacity (kg m^{-2} h^{-1})	Normalized Sensitivity	Constraint violation
Standard	3.4	41	46	746	746	20.1	20.3		
Depth	3.2	41	46	746	746	20.1	20.2		
	3.5	41	46	746	746	20.1	20.4	0.1	Depth
Pressure	3.4	41	46	697	697	20.1	19.9		
	3.4	41	46	796	796	20.1	20.8	0.5	Pressure
Up-air temperature	3.4	39	46	746	746	20.1	19.5		
	3.4	42	46	746	746	20.1	21.2	0.9	Up-Air Temp.
Down-air temperature	3.4	41	45	746	746	20.1	19.5		
	3.4	41	47	746	746	20.1	20.8	0.7	Down-Air Temp.
RMC	3.4	41	46	746	746	19.9	19.9		
	3.4	41	46	746	746	20.4	20.3	0.2	

Table 5. Sensitivity analysis of the cost function at 30% initial moisture content.

Parameter	Depth (m)	Up-air temp. (°C)	Down-air temp. (°C)	Up-air pressure (Pa)	Down-air pressure (Pa)	Reversal MC (%w.b.)	Cost ($/tonne)	Normalized Sensitivity	Constraint violation
Standard	3.2	40	46	249	249	19.9	10.0		
Depth	3.1	40	46	249	249	19.9	10.1		
	3.4	40	46	249	249	19.9	10.0	0.0	
Pressure	3.2	40	46	199	199	19.9	9.7		Pressure
	3.2	40	46	299	299	19.9	10.5	0.4	
Up-air temperature	3.2	39	46	249	249	19.9	10.2		
	3.2	41	46	249	249	19.9	10.0	-0.1	
Down-air temperature	3.2	40	45	249	249	19.9	10.2		
	3.2	40	47	249	249	19.9	10.0	-0.1	
RMC	3.2	40	46	249	249	19.6	10.1		
	3.2	40	46	249	249	20.1	10.0	0.0	

CONCLUSIONS

An optimization procedure has been developed to either maximize the capacity or minimize the energy cost of ear-corn drying. The maximum capacity is achieved when the bed depth, air temperature, and air pressure are maximized, except at the highest initial moisture content (35%). The minimum cost is achieved when the bed depth and the air temperatures are maximized and the air pressure is minimized. The sensitivity analysis has shown that the air temperature has the greatest influence on the dryer capacity, and the airflow has the greatest influence on the drying costs.

ACKNOWLEDGEMENTS

This project was partially supported by Pioneer Hi-Bred International Inc., Johnston, Iowa and the Bangladesh Rice-Research Institute, Gazipur, Bangladesh.

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NOMENCLATURE

c	Specific heat, kJ kg^{-1} °C
E	Energy, kJ
G	Airflow rate, kg h^{-1} m^2
H, H_0, H_1	Humidity ratio, kg kg^{-1}
h_{fg}	Latent heat of vaporization, kJ kg^{-1}
L	Bed depth, m
M_i	Initial ear-corn moisture content, decimal d.b.
M_{rev}	Reversal ear-corn moisture content, decimal d.b.
M_f	Final ear-corn moisture content, decimal d.b.
P	Pressure, Pa
Q	Power, kJ m^{-1} h^{-1}
T	Temperature, °C
t_{drying}	Drying time, h
V_e	\$ $(MWH)^{-1}$
V_f	Fuel price, \$ $(1055\ MJ)^{-1}$
w.b.	Wet basis
d.b.	Dry basis
η	Efficiency

Subscripts

amb	Ambient
down	Down-air
ex	Exhaust-air
therm	Thermal
up	Up-air
v	Vapor
a	air
