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EVALUATION OF THREE NA/LT IN−BIN DRYING STRATEGIES IN FOUR CORN BELT LOCATIONS

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ABSTRACT. *The performance of the variable heat (VH), continuous natural air (CNA), and continuous constant heat (CH) fan and burner control strategies were evaluated using simulation for four locations (Indianapolis, Ind.; Des Moines, Iowa; Lansing, Mich.; and Minneapolis, Minn.), three airflow rates (0.83, 1.1, and 1.7* m^3 min^{-1} t^{-1}*), and two harvest dates (25% and 75% of the harvest period). The ideal airflow rate for each location/harvest date combination was determined based on the criterion of limiting the dry matter loss (DML) to 0.5% or less, and minimizing the total drying cost. An airflow rate of 1.1* m^3 min^{-1} t^{-1} *was identified as optimum for the VH and the CH in−bin drying control strategies in all locations. In a comparison based on total drying cost, final moisture content (MC) range, average final MC, and drying ending date, the VH strategy outperformed the other two strategies (CNA and CH) for all location and harvest date combinations. A sensitivity analysis showed that the VH strategy costs were sufficiently stable to make it the least−cost option for the entire range of propane, electricity, and grain prices explored.*

Keywords. *Corn, Drying simulation, Fan and burner control, Natural air/low temperature drying, Variable heat.*

The demand for high−quality corn by the milling and snack food industries creates opportunities for farmers to receive premiums for their food−grade grains. However, processors of food−grade corn require adherence to strict quality standards, including fewer than 20% stress−cracked corn. Most on−farm systems use high−temperature drying with air heated from 82°C to 104°C. This often leads to overdrying, excessive levels of stress cracks, and brittleness (Watkins and Maier, 1997). The primary alternative drying process to achieve the best food corn quality is natural air / low temperature (NA/LT) in−bin drying. This involves in−bin drying of corn using airflow rates of 1.1 to 2.2 m^3 min^{-1} t^{-1} and natural air, or air heated by only 3°C to 8°C.

The efficiency of NA/LT drying is greatly affected by weather conditions. Morey et al. (1979) stated that site−specific solutions must be found and implemented to successfully solve the control problem. Supplemental heat allows LT drying to be less dependent on the weather, but it generally results in overdrying of the bottom layers. Stroshine et al. (1992) reported that producers use supplemental heat more often than they need to, and when they use it they use more heat than they need to.

Despite significant research efforts in the past, NA/LT in−bin drying has not been widely adopted by farmers. To address these problems, Saksena et al. (1998) simulated nine different NA/LT in−bin drying strategies using the Purdue University Post−Harvest Aeration and Storage Simulation Tool−Finite Difference Method (PHAST−FDM). A new variable heat control strategy was ranked first based on drying cost, dry matter loss, and shrink compared to the target moisture content of 15% for two Midwest corn−growing areas based on 29 years of historic weather data. The VH strategy was implemented by Bartosik and Maier (2001, 2002) and Bartosik (2003) in bins that ranged from 2,500 bu to 45,000 bu. It was concluded that the VH strategy reached the target moisture content (MC) of 15% with minimal moisture gradient and without overdrying of the bottom layers. Bartosik and Maier (2002) validated the PHAST−FDM computer model for the VH and CNA strategies, and simulation runs were performed for Indianapolis (Ind.) and Des Moines (Iowa). The VH control strategy was consistently the least−cost strategy for all location and airflow rate combinations.

In this current research, the PHAST−FDM model was used to evaluate the VH strategy in four key corn production locations for two harvest dates (early vs. late in the harvest season) and three airflow rates. These locations were chosen to cover key weather patterns throughout the Midwestern Corn Belt. The performance of the VH fan and burner control strategy was compared against fan−only continuous natural air (CNA) drying and continuous low−temperature drying with a fixed amount of heat (CH).

The main objectives of this study were: (1) to establish the ideal airflow rate for each location and harvest date combination; (2) to determine the ideal variable heat lower and higher equilibrium moisture content controller setpoints for each location, harvest date, and airflow rate combination; (3) to determine the best in−bin drying strategy (VH vs. CH vs. CNA) for each location and harvest date combination; and

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(4) to evaluate the sensitivity of the three in−bin drying strategies to variations in grain, propane (LP), and electricity prices.

METHODS

To study the performance of the VH strategy under different conditions, four locations were chosen to cover key weather patterns throughout the Midwestern Corn Belt: Indianapolis (Ind.), Des Moines (Iowa), Lansing (Mich.), and Minneapolis (Minn.). Weather data for each location was obtained from the SAMSON database (SAMSON, 1961−1989). A typical farm bin of 12 m (39 ft) diameter and 7 m (23 ft) depth that held 791.7 m^3 (22,440 bu) level filled was selected. Three airflow rates were investigated: 0.83 m^3 min^{-1} t^{-1} (0.75 cfm/bu), 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu) and 1.7 m^3 min^{-1} t^{-1} (1.5 cfm/bu). These airflow rates cover the typical range used for in−bin drying in the Midwest. The size and characteristics of the fans were selected with the FANS program (Minnesota Extension Service, 1996). Commercially available fan performance curves (The GSI Group, Assumption, Ill.) were used to estimate the power requirement for each one of the airflow rates investigated. Two drying start dates were investigated for each location. The first drying start date corresponded to the date when 25% of the corn harvest has been completed for each location. It represented the situation when the drying process started early in the season. The second drying date corresponded to the date when 75% of the corn harvest has been completed. It represented the situation when the drying process started late in the season. The dates for the early (25%) and late (75%) harvest periods for each location were obtained by averaging 5−year harvest progress data from the USDA−NASS (2003). The USDA−NASS database does not list harvest moisture content. Thus, the same initial corn moisture content of 22% was assumed for each drying simulation. All other parameters related to the drying simulation and cost analysis were also the same for the two harvest dates. The corn test weight was 720 kg/m^3 (56 lb/bu).

Three drying strategies (CNA, CH, and VH) were investigated for each location and airflow rate combination. In the CNA strategy, the fan ran continuously until the maximum and the average grain MC dropped below 16% and 15%, respectively. In the CH strategy the fan and the burner ran continuously, adding 2°C (3.6°F) to the ambient air (in addition to the fan pre−warming of 0.7°C for 0.83 and 1.1 m^3 min^{-1} t^{-1} airflow rates, and 1.2°C for 1.7 m^3 min^{-1} t^{-1}) until the maximum and the average grain MC dropped below 16% and 15%, respectively. The size and energy consumption of the burner changed with the airflow rate. It was determined that to increase the air temperature by 2°C, an LP burner equivalent to 20 kW was required for 0.83 m^3 min^{-1} t^{-1} (0.75 cfm/bu) airflow, 26 kW for 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu), and 39 kW for 1.7 m^3 min^{-1} t^{-1} (1.5 cfm/bu). From previous research (Bartosik and Maier, 2001) it was determined that the average temperature increase in the plenum drying air for the VH strategy was 2°C. Thus, in order to compare the best possible CH strategy vs. the VH and CNA strategy, a 2°C (3.6°F) temperature increment was chosen. A more typical temperature increase would be from 3°C to 8°C (5.4°F to 14.4°F). However, larger temperature increases would produce larger amounts of grain overdrying.

The VH strategy was based on a selecting/conditioning mechanism of the ambient air. Two parameters had to be provided: the lower equilibrium moisture content (EMC) limit, and the higher EMC limit. The equilibrium moisture content (EMC) of the ambient air was computed, and then three decisions were made. To avoid overdrying of the bottom grain layers, the ambient air that was too dry and would tend to bring the moisture content of the grain below a pre−determined value was rejected (ambient EMC below the lower EMC limit). The ambient air with good drying conditions was used "as is" (ambient EMC between the lower and higher EMC limits), and the ambient air that was too wet for drying grain was conditioned by adding supplemental heat (ambient EMC above the higher EMC limit). The precise amount of heat to be added was calculated so that it reduced the air EMC in the plenum to a prescribed setpoint (higher EMC limit). Thus, the EMC of the drying air of the VH strategy was always between the lower and higher EMC limits. In the VH strategy, the fan and burner ran intermittently according to the weather conditions until the maximum and the average grain MC dropped below 16% and 15%, respectively. Six different higher and lower EMC limit combinations were tested for the VH strategy, i.e., 11/15%, 12/15%, 12/16%, 13/15%, 13/16%, and 13/18%.

For each location, harvest date, airflow rate, drying strategy and year, a single PHAST−FDM run was performed. A total number of 5,688 simulation runs were completed (4 locations × 2 harvest dates × 3 airflow rates × 8 strategies × 29 years). The different strategies were mainly compared based on the average drying cost. This cost included the energy cost (fan and burner) and the shrink cost (overdrying and dry matter loss (DML)). Thus, this single parameter was considered to be sufficient to quantify the energy consumption and, in an indirect way, the quality of the grain at the end of the drying process. The PHAST−FDM program estimated the energy consumption in kWh. To convert that energy to gallons of propane, conversion factors of 3,414 BTU/kWh and 92,000 BTU/gallon LP were used. The burner efficiency was assumed to be 85%, which yielded an effective propane heating value of 77,605 BTU/gallon (92,000 BTU/gallon × 0.85). The efficiency of the fan was assumed to be 50%.

DML is defined as the loss of physical mass of grain due to seed respiration and fungi growth (Wilcke et al., 1998). DML was computed according to the procedure of Saul and Steele (1966). The equations were taken from the papers published by Thompson (1972), Brook (1987), and Stroshine and Yang (1990). The DML equations used were:

$$Y = 1.3[\exp(0.006t_r) - 1] + 0.015t_r \qquad (1)$$

$$t_r = \frac{t}{M_T M_M M_D M_F} \qquad (2)$$

where Y is grams of CO_2 produced per kg initial dry matter, t_r is storage time (h) at reference conditions (15.55°C, 25% moisture content, and 30% kernel damage), M_T is the temperature multiplier, M_M is the moisture multiplier, M_D is the kernel damage multiplier, and M_F is the fungicide multiplier. M_T and M_M changed hourly as a function of the grain temperature and moisture contents in the grain bins. M_D and M_F were constant at 30% and 1, respectively.

The total drying cost was computed as follows:

$$\text{drying cost (\$/t)} = \text{energy cost (\$/t)} + \text{shrink cost (\$/t)} \qquad (3)$$

The energy cost had two components: one related to the electricity consumption, and the other related to the propane consumption. The energy cost was computed as follows:

$$\text{energy cost (\$/ton)} = \frac{(\text{kWh} \times \text{\$/kWh}) + (\text{LP gallons} \times \text{\$/gal})}{\text{tonnes@15\%}} \qquad (4)$$

where “kWh” is kilowatts per hour consumed, “LP gallons” is gallons of liquid propane consumed, and “tonnes@15%” is the total tonnes of grain at 15% moisture content.

The shrink cost also had two components: one related to the DML, and the other related to overdrying of the grain bottom layers. The predicted average DML of the grain mass was multiplied by the total amount of grain and the corn price. When DML was greater than 0.5%, no reductions in corn price due to potential quality losses were considered. However, the airflow rate that caused DML to be greater than 0.5% was not recommended as the ideal for that particular NA/LT strategy. When overdrying occurred, the difference between the weight of the grain bulk at 15% MC and the weight of the grain bulk at the final MC was multiplied by the corn price. The shrink cost was computed as follows:

$$\begin{aligned} &\text{shrink cost (\$/t)} = \\ &[\text{DML} \times \text{tonnes@final MC} \times \text{\$/t} \\ &+ (\text{tonnes@15\%} - \text{tonnes@final MC}) \times \text{\$/t}] \\ &\div \text{tonnes@15\%} \qquad (5) \end{aligned}$$

where “tonnes@final MC” is the total tonnes of grain at the final moisture content, “$/t” is the price of one tonne of corn, and “tonnes@15%” is the total tonnes of grain at 15% moisture content.

To obtain a realistic drying cost, average values for corn, propane, and electricity prices at the four drying sites were used. A sensitivity analysis was performed to investigate the sensitivity of the in−bin drying strategies to price variations. Table 1 shows the prices of corn, propane, and electricity used for this study.

The cost analysis used to compare the performance of the three different in−bin drying strategies (VH, CH, and CNA) considered only the direct operational costs incurred, i.e., electricity consumption, propane consumption, and grain weight loss (due to overdrying of the grain mass and DML). Ownership (fixed) and investment costs for the burner and controller required for the VH and CH strategies were not taken into account. An investment analysis of the different in−bin drying strategies was beyond the scope of this research as components of the VH system are still in the field testing stage and are not yet commercially available.

Table 1. Ranges of corn, propane, and electricity prices used for the sensitivity analysis of the in−bin drying simulations.

Rank	Prices Corn, $/t ($/bu)	Propane, $/gallon	Electricity, $/kWh
Lowest (L)	75.2 (1.88)	0.38	0.065
Average (M)	93.6 (2.34)	0.5	0.09
Highest (H)	132.5 (3.31)	0.8	0.13

In addition to average drying cost, other important parameters to evaluate the performance of the in−bin drying strategies were drying end date, DML, final MC, minimum MC (an indicator of the amount of overdrying of the bottom grain layers), final range of MC, total moisture removed, and fan (and burner) run hours.

RESULTS AND DISCUSSION

DETERMINING THE IDEAL AIRFLOW RATE

Past researches have indicated that when DML is greater than 0.5%, corn may have decreased by one grade according to the USDA federal grain inspection standard (Saul and Steele, 1966; Steele et al., 1969). In this research, a limit of 0.5% DML or less for at least 27 of the 29 years simulated (equivalent to a proportion of 0.93) was considered to determine the minimum airflow rate. Table 2 shows the number of years when DML was lower than 0.5% and its associated proportion at 1.1 $m^3\ min^{-1}\ t^{-1}$ airflow rate.

According to these results, an airflow rate of 1.1 $m^3\ min^{-1}\ t^{-1}$ (1 cfm/bu) was enough to limit DML to 0.5% or less for the CH and VH strategies for all locations and harvest progress dates for at least 90% of the time ($P > 0.90$). For the CNA strategy, a higher airflow rate of 1.7 $m^3\ min^{-1}\ t^{-1}$ (1.5 cfm/bu) was required for Indianapolis (25% of the harvest) and Des Moines (75% of the harvest) to limit DML to 0.5% or less for at least 90% of the time ($P = 0.97$ and 1.0 for Indianapolis and 25% of the harvest, and Des Moines and 75% of the harvest, respectively). These results are similar to those of Wilcke et al. (1993), who predicted that for Minnesota conditions, the probability of drying corn with CNA from 22% to 15% at 1.1 $m^3\ min^{-1}\ t^{-1}$ (1 cfm/bu) with less than 0.5% of DML was about 50%. They showed that it was necessary to increase the airflow rate to at least 1.4 $m^3\ min^{-1}\ t^{-1}$ (1.3 cfm/bu) to raise the probability to 90% or higher. Increasing the airflow rate for the CNA strategy by 30% to 50% would undoubtedly also raise the associated drying cost because of the higher energy requirement of a larger fan.

Table 2. Number of years out of 29 years analyzed with average dry matter loss (DML) less than or equal to 0.5% and its associated proportion (P) for the continuous natural air (CNA), continuous heat (CH) and variable heat (VH) strategies, for each location and harvest progress combination. The airflow rate was 1.1 $m^3\ min^{-1}\ t^{-1}$.

	CNA		CH		VH	
Location	Years	P	Years	P	Years	P
Indianapolis						
25% harvest	19	0.66	28	0.97	27	0.93
75% harvest	27	0.93	29	1	29	1
Des Moines						
25% harvest	28	0.97	29	1	29	1
75% harvest	23	0.79	29	1	29	1
Lansing						
25% harvest	29	1	29	1	29	1
75% harvest	29	1	29	1	29	1
Minneapolis						
25% harvest	29	1	29	1	29	1
75% harvest	29	1	29	1	29	1

The primary reason for the need of a higher airflow rate for the CNA strategy is to shorten the time corn remains at high temperature and MC during the drying period compared to the drying period of the CH or VH strategies. Most of the past research related to DML and airflow rates was carried out for CNA drying strategies. The addition of small amounts of heat shortened the drying period sufficiently to minimize DML. For a harvest date of October 1 and initial MC of 22%, the recommended design airflow rate has been 2.2 $m^3\ min^{-1}\ t^{-1}$ (2 cfm/bu) (Midwest Plan Service, 1980). The ideal airflow rates for the CH and VH strategies determined in this research were 50% lower. The need for a lower airflow rate (50%) could increase the adoption of the VH in−bin drying strategy because of the lower fan power requirements (lower cost). Likewise, the addition of a VH burner to a CNA drying system would allow for successful in−bin drying in deeper bins. This has been observed in practice with farmers implementing in−bin drying systems with supplemental heat and lower airflow rates in taller bins (than recommended in the past) without appreciable loss in grain quality.

Hereinafter, the DML value was used as an index for loss of grain mass with an economic impact on the total drying cost. The airflow rate of 1.1 $m^3\ min^{-1}\ t^{-1}$ (1 cfm/bu) was also found to yield the lowest average drying cost of the three airflow rates explored for the VH strategy for all locations and harvest dates. Thus, this airflow rate was chosen to subsequently compare the performance of the three in−bin drying strategies for each location/harvest date combination.

DETERMINING THE BEST VARIABLE HEAT SETPOINTS

Once the best airflow rate was determined, the best VH lower and higher setpoints among the six combinations investigated for each location/harvest date combination were selected. The main selection criterion was average drying cost. Drying ending date, final average MC, and final MC range were also selection criteria in addition to average drying cost. Table 3 lists the best VH strategy setpoints selected for each location/harvest date combination. Over 29 years, three out of six setpoint combinations were identified as the best for all location/harvest date combinations, i.e., 11/15%, 12/15%, and 12/16%. In most of the cases, the differences in the evaluation parameters between these three setpoint combinations were small. This was sometimes also true for the 13/15% setpoint, but for the 13/16% and 13/18% setpoints, the differences were always larger, causing significantly higher costs. A clear trend was not observed with respect to changing these setpoints with the late harvest season or with the annual weather pattern. The selected setpoints were not the best for each year. However, they were the best on average for the 29 years investigated. Choosing the correct setpoints for the VH strategy turned out to be critical. The “ideal” setpoints were site−specific, and depended on annual weather pattern of the location and the airflow rate. Choosing the wrong setpoints increased the drying costs, reduced the grain quality, and extended the drying period.

Table 3. Ideal lower and higher EMC setpoints for the VH strategy selected for each location/harvest date combination.

	Best VH Setpoints (EMCL/EMCH)	
Location	25% Harvest	75% Harvest
Indianapolis	12/15%	11/15%
Des Moines	12/16%	12/16%
Lansing	11/15%	11/15%
Minneapolis	11/15%	11/15%

Table 4. Results for simulation runs corresponding to Indianapolis (Indiana), 25% and 75% of the harvest progress, and 1.1 $m^3\ min^{-1}\ t^{-1}$ airflow rate. Average, absolute maximum, and absolute minimum values for 29 years (1961−1989) for the variable heat (VH) (higher and lower burner air EMC setpoints), continuous natural air (CNA), and continuous heat (CH) drying strategies.

Strategy	End Date	DML (%)	MC (%)	MCmin (%)	MCr (%)	Fan Run (h)	Energy Cost ($/t)	Shrink Cost ($/t)	Drying Cost ($/t)
25% of the harvest									
CNA average	**25 Jan.**	**0.4**	**14.4**	**13.1**	**2.8**	**2707**	**7.8**	**1.0**	**8.8**
maximum	10 May	1.9	15.1	14.4	4.7	5259	15.1	2.6	15.7
minimum	31 Oct.	0.1	13.1	11.3	1.4	659	1.9	0.2	2.9
CH average	**6 Nov.**	**0.3**	**13.7**	**12.7**	**3.2**	**789**	**3.2**	**1.7**	**4.7**
maximum	10 Nov.	0.7	14.9	14.4	4.8	893	3.5	3.7	6.1
minimum	27 Oct.	0.1	11.8	11.2	1.6	568	2.2	0.4	3.8
VH (12/15%)[a, b]	**21 Nov.**	**0.3**	**14.5**	**14.3**	**1.6**	**979**	**3.7**	**0.8**	**4.5**
maximum	26 Nov.	0.8	15.0	14.9	2.2	1046	4.2	1.5	5.1
minimum	13 Nov.	0.2	14.1	13.8	1.0	933	3.2	0.3	4.1
75% of the harvest									
CNA average	**31 March**	**0.3**	**14.6**	**13.0**	**2.9**	**3636**	**10.5**	**0.7**	**11.2**
maximum	10 May	0.5	15.1	14.4	5.1	4611	13.2	2.2	13.7
minimum	23 Feb.	0.2	13.3	10.8	1.6	2783	8.0	0.2	8.4
CH average	**3 Jan.**	**0.2**	**14.6**	**13.6**	**2.2**	**1536**	**5.9**	**0.6**	**6.5**
maximum	24 March	0.4	15.0	14.5	4.6	3494	13.5	1.3	14.5
minimum	1 Dec.	0.1	13.9	11.3	0.8	758	2.9	0.1	3.6
VH (11/15%)[a, b]	**11 Dec.**	**0.2**	**14.5**	**13.8**	**2.1**	**968**	**3.8**	**0.7**	**4.5**
maximum	14 Dec.	0.3	15.1	14.9	6.4	1078	4.7	2.0	5.7
minimum	7 Dec.	0.1	13.3	9.6	0.7	864	3.3	0.1	3.7

End Date = end of the drying simulation, DML = final average dry matter loss of the grain in the bin, MC = final average moisture content of the grain in the bin, MCmin = final minimum moisture content, MCr = final range of moisture content, (12/15%) = lower and higher VH setpoints, ([a]) best variable heat setpoints selected, and ([b]) best in−bin drying strategy selected.

Table 5. Results for simulation runs corresponding to Des Moines (Iowa), 25% and 75% of the harvest progress, and 1.1 m^3 min^{-1} t^{-1} airflow rate . Average, absolute maximum, and absolute minimum values for 29 years (1961−1989) for the variable heat (VH) (higher and lower burner air EMC setpoints), continuous natural air (CNA), and continuous heat (CH) drying strategies.

Strategy	End Date	DML (%)	MC (%)	MCmin (%)	MCr (%)	Fan Run (h)	Energy Cost ($/t)	Shrink Cost ($/t)	Drying Cost ($/t)
25% of the harvest									
CNA average	**30 Jan.**	**0.2**	**14.5**	**13.5**	**2.4**	**2541**	**7.3**	**0.7**	**8.0**
maximum	9 May	0.5	15.1	14.6	5.6	4954	14.2	2.5	16.7
minimum	18 Nov.	0.1	13.0	10.4	0.7	794	2.3	0.1	2.4
CH average	**28 Nov.**	**0.2**	**13.8**	**12.9**	**3.1**	**1024**	**4.0**	**1.4**	**5.4**
maximum	6 April	0.3	14.9	14.5	4.8	4174	16.2	2.8	17.4
minimum	13 Nov.	0.1	12.5	11.2	1.5	688	2.7	0.3	3.6
VH (12/16%)[a, b]	**5 Dec.**	**0.2**	**14.4**	**13.2**	**2.7**	**1050**	**3.5**	**0.8**	**4.3**
maximum	24 Dec.	0.4	15.0	14.6	5.3	1492	5.3	2.4	5.7
minimum	29 Nov.	0.1	12.8	10.7	0.9	889	2.8	0.2	3.6
75% of the harvest									
CNA average	**12 March**	**0.2**	**14.5**	**13.2**	**2.7**	**3059**	**8.8**	**0.7**	**9.5**
maximum	9 May	0.4	15.1	14.6	5.6	4450	12.8	2.4	15.1
minimum	11 Dec.	0.0	12.9	10.4	0.7	843	2.4	0.1	2.8
CH average	**6 Jan.**	**0.1**	**14.5**	**13.4**	**2.5**	**1479**	**5.7**	**0.7**	**6.4**
maximum	23 April	0.2	15.0	14.4	3.7	4071	15.8	1.9	16.6
minimum	9 Dec.	0.0	13.4	12.2	1.0	807	3.1	0.1	3.4
VH (12/16%)[a, b]	**17 Dec.**	**0.1**	**13.8**	**12.4**	**3.5**	**937**	**3.2**	**1.4**	**4.6**
maximum	26 Dec.	0.1	15.0	14.5	6.8	1177	4.4	3.4	6.9
minimum	10 Dec.	0.0	11.8	9.2	1.5	698	2.1	0.1	3.6

End Date = end of the drying simulation, DML = final average dry matter loss of the grain in the bin, MC = final average moisture content of the grain in the bin, MCmin = final minimum moisture content, MCr = final range of moisture content, (12/16%) = lower and higher VH setpoints, ([a]) best variable heat setpoints selected, and ([b]) best in−bin drying strategy selected.

Table 6. Results for simulation runs corresponding to Lansing (Michigan), 25% and 75% of the harvest progress, and 1.1 m^3 min^{-1} t^{-1} airflow rate. Average, absolute maximum, and absolute minimum values for 29 years (1961−1989) for the variable heat (VH) (higher and lower burner air EMC setpoints), continuous natural air (CNA), and continuous heat (CH) drying strategies.

Strategy	End Date	DML (%)	MC (%)	MCmin (%)	MCr (%)	Fan Run (h)	Energy Cost ($/t)	Shrink Cost ($/t)	Drying Cost ($/t)
25% of the harvest									
CNA average	**13 April**	**0.4**	**14.5**	**13.0**	**2.9**	**4366**	**12.5**	**0.9**	**13.4**
maximum	14 May	0.7	15.0	14.4	5.0	5132	14.7	2.3	16.6
minimum	21 Nov.	0.2	13.4	11.0	0.9	932	2.7	0.3	3.5
CH average	**5 Jan.**	**0.2**	**14.6**	**13.6**	**2.2**	**1983**	**7.7**	**0.6**	**8.3**
maximum	19 April	0.5	15.1	14.7	4.8	4534	17.6	2.0	18.1
minimum	10 Nov.	0.1	13.4	10.9	0.9	671	2.6	0.1	3.4
VH (11/15%)[a, b]	**25 Nov.**	**0.2**	**14.7**	**14.4**	**1.6**	**990**	**3.9**	**0.5**	**4.4**
maximum	27 Nov.	0.5	15.0	14.8	3.3	1056	4.5	1.1	4.8
minimum	23 Nov.	0.1	14.1	12.7	0.6	911	3.0	0.1	3.9
75% of the harvest									
CNA average	**18 April**	**0.2**	**14.5**	**13.0**	**2.9**	**3770**	**10.9**	**0.7**	**11.6**
maximum	14 May	0.4	15.0	14.4	5.0	4412	12.7	2.0	14.3
minimum	5 March	0.1	13.4	11.0	0.9	2726	7.8	0.2	8.0
CH average	**19 Feb.**	**0.1**	**14.9**	**13.7**	**2.0**	**2360**	**9.1**	**0.3**	**9.4**
maximum	22 April	0.2	15.1	14.7	4.8	3866	15.0	1.9	15.2
minimum	22 Dec.	0.1	13.4	10.9	0.8	957	3.7	0.1	4.2
VH (12/16%)[a, b]	**23 Dec.**	**0.1**	**14.3**	**13.4**	**2.5**	**950**	**4.0**	**0.9**	**4.9**
maximum	2 Jan.	0.1	15.0	14.9	5.7	1214	5.8	1.8	6.2
minimum	15 Dec.	0.0	13.3	10.3	0.7	781	2.8	0.1	4.0

End Date = end of the drying simulation, DML = final average dry matter loss of the grain in the bin, MC = final average moisture content of the grain in the bin, MCmin = final minimum moisture content, MCr = final range of moisture content, (11/15%), (12/16%) = lower and higher VH setpoints, ([a]) best variable heat setpoints selected, and ([b]) best in−bin drying strategy selected.

EVALUATION OF THE PERFORMANCE OF THE THREE NA/LT IN–BIN DRYING STRATEGIES

Tables 4 to 7 present the average, absolute maximum, and absolute minimum values of nine drying parameters for 29 years of simulation results. Note that the year that had the maximum energy cost in the 29−year series analyzed may not be the same year that had, for instance, the maximum shrink cost. Thus, the value of the maximum energy cost and the value of the maximum shrink cost may correspond to different years and may not add up to the maximum drying cost.

Table 7. Results for simulation runs corresponding to Minneapolis (Minnesota), 25% and 75% of the harvest progress, and 1.1 m^3 min^{-1} t^{-1} airflow rate. Average, absolute maximum, and absolute minimum values for 29 years (1961−1989) for the variable heat (VH) (higher and lower burner air EMC setpoints), continuous natural air (CNA), and continuous heat (CH) drying strategies.

Strategy	End Date	DML (%)	MC (%)	MCmin (%)	MCr (%)	Fan Run (h)	Energy Cost ($/t)	Shrink Cost ($/t)	Drying Cost ($/t)
25% of the harvest									
CNA average	**31 Jan.**	**0.2**	**14.5**	**13.3**	**2.6**	**2814**	**8.1**	**0.8**	**8.9**
maximum	12 May	0.4	15.1	14.6	4.9	5268	15.1	2.0	16.6
minimum	7 Nov.	0.1	13.3	11.2	1.2	785	2.3	0.1	3.0
CH average	**10 Nov.**	**0.2**	**13.7**	**12.8**	**3.1**	**836**	**3.2**	**1.6**	**4.8**
maximum	17 Nov.	0.3	14.9	14.4	5.0	1015	3.9	3.3	6.3
minimum	2 Nov.	0.1	12.0	11.0	1.6	667	2.6	0.2	3.6
VH (11/15%)[a, b]	**17 Nov.**	**0.2**	**14.3**	**13.8**	**2.2**	**931**	**3.4**	**0.9**	**4.3**
maximum	19 Nov.	0.3	14.9	14.8	4.9	1009	4.0	2.0	5.2
minimum	13 Nov.	0.1	13.2	11.1	1.2	831	2.6	0.3	3.8
75% of the harvest									
CNA average	**6 March**	**0.1**	**14.6**	**13.4**	**2.5**	**3207**	**9.2**	**0.5**	**9.7**
maximum	12 May	0.4	15.1	14.6	4.9	4836	13.9	2.2	15.3
minimum	27 Nov.	0.0	13.1	11.2	1.4	837	2.4	0.1	3.0
CH average	**16 Dec.**	**0.1**	**14.6**	**13.7**	**2.2**	**1267**	**4.9**	**0.6**	**5.5**
maximum	12 Feb.	0.2	15.1	14.7	3.9	2665	10.3	2.3	10.6
minimum	23 Nov.	0.0	12.9	12.1	0.7	739	2.9	0.1	3.5
VH (11/15%)[a, b]	**2 Dec.**	**0.1**	**14.0**	**12.7**	**3.3**	**900**	**3.5**	**1.2**	**4.5**
maximum	5 Dec.	0.2	14.9	14.7	5.8	1019	4.0	2.7	5.9
minimum	26 Nov.	0.0	12.5	10.2	1.3	754	2.3	0.2	3.8

End Date = end of the drying simulation, DML = final average dry matter loss of the grain in the bin, MC = final average moisture content of the grain in the bin, MCmin = final minimum moisture content, MCr = final range of moisture content, (11/15%) = lower and higher VH setpoints, ([a]) best variable heat setpoints selected, and ([b]) best in−bin drying strategy selected.

In general, the VH strategy was the best choice for each location and harvest date combination investigated. The main evaluation criteria was drying cost, although overdrying, final MC range, final ending date, and final average MC were also taken into account. The VH strategy, with the ideal lower and higher EMC setpoints combination, consistently yielded the lowest average drying costs for the range of grain, electricity, and propane prices explored. The second best strategy was CH, which was from 4% to 91% more expensive than the VH strategy (average costs). The CNA strategy was from 86% to 205% more expensive than the VH strategy (average costs). The drying costs for the VH strategy did not change significantly across locations. Drying costs ranged from 4.3 to 4.9 $/t for the VH strategy, from 8.0 to 13.4 $/t for the CNA strategy, and from 4.7 to 9.4 $/t for the CH strategy. Additionally, the year−to−year average cost variability was always smaller for the VH strategy compared to the CNA and CH strategies (1.84 $/t, 10.3 $/t, and 8.5 $/t, respectively).

For most location and harvest date combinations, the minimum absolute drying cost was almost always observed for the CNA and CH strategies. This indicates that even though over the long term the VH strategy performed consistently better than the CNA and CH strategies, for a specific year the best performance could be observed at times with the CNA or CH strategies.

Electricity cost was the major component of the drying cost for all strategies. When overdrying or DML became significant, then grain price also had an important impact on drying cost. To delay the drying season from the first 25% period of the harvest to the last 25% period of the harvest (75% of the harvest progress) resulted generally in a cost increase (with the exception of Indianapolis). That cost increase was mainly due to a higher overdrying level, higher electricity consumption, or both. To delay the drying season did not produce a consistent change in the length of the drying period. In some locations, a late drying season caused grain to dry faster, and in others slower.

The CH strategy was the fasted strategy in three of the four locations investigated for 25% of the harvest. In contrast, when drying started late in the season (75% of the harvest), the VH strategy was the fastest (in three of the four locations). The fixed temperature increase of the CH strategy (2°C) was enough to dry grain faster than VH early in the fall (25% of the harvest), but it was not enough for the late fall (75% of the harvest). The VH strategy regulated the amount of heat added to the ambient air based on the weather conditions. As the fall progressed, the amount of heat provided by the drying system increased. As a result, the drying period was shortened compared to the CH strategy when a late drying season was simulated.

Effect of the Cost Components on the Selection of the Best In−Bin Drying Strategy

In order to establish the stability of the results presented above, a cost sensitivity analysis was performed for each

Table 8. Combinations of grain, propane, and electricity prices used for the sensitivity analysis of the in−bin drying simulation (L = lowest price, M = average price, and H = highest price).

Sensitivity Analysis	Grain Price	Propane Price	Electricity Price
1	L	M	M
2	M	M	M
3	H	M	M
4	M	L	M
5	M	H	M
6	M	M	L
7	M	M	H

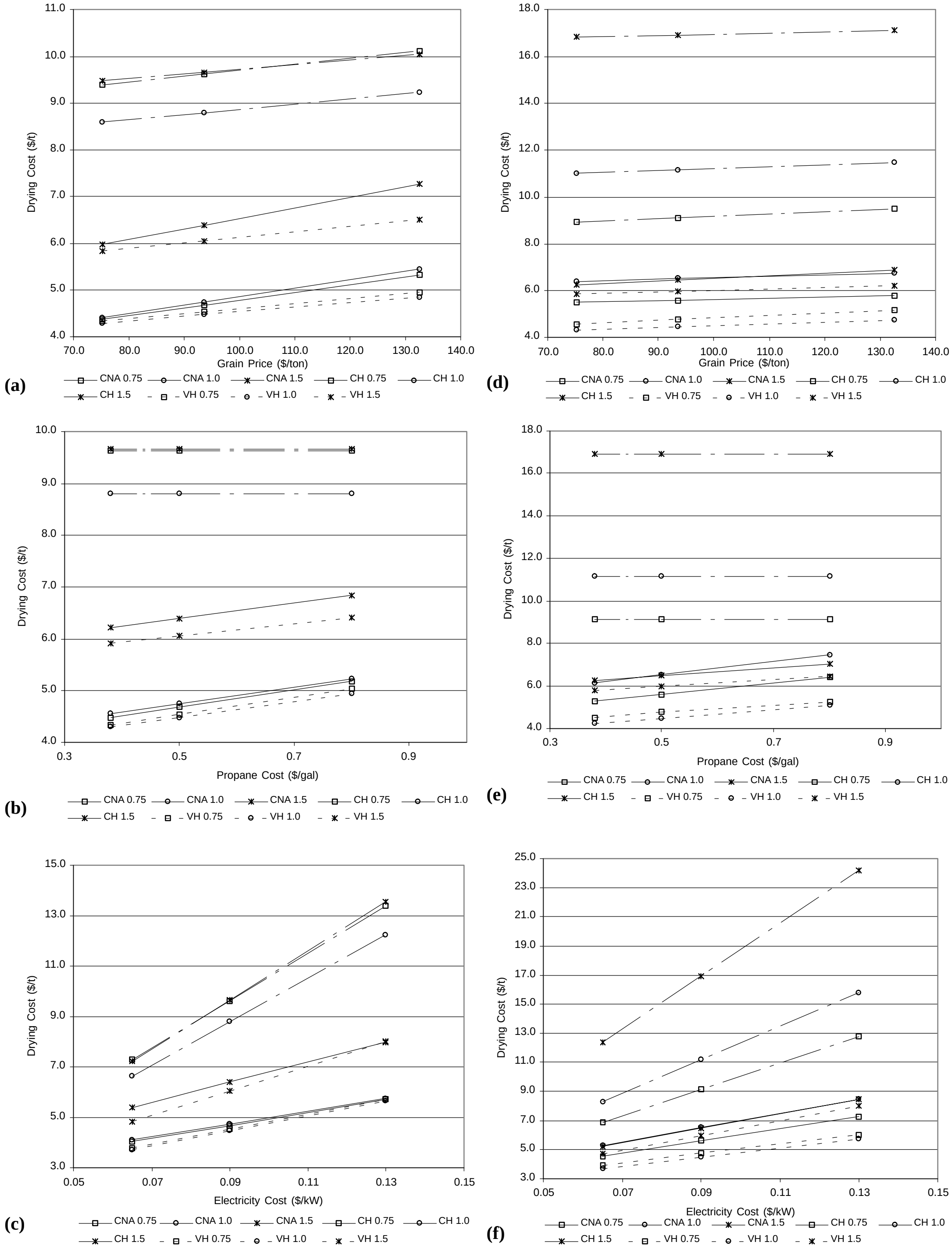

Figure 1. Sensitivity analysis for in−bin drying cost for Indianapolis: (a) grain price, 25% harvest; (b) propane price, 25% harvest; (c) electricity price, 25% harvest; (d) grain price, 75% harvest; (e) propane price, 75% harvest; (f) electricity price, 75% harvest; CNA = continuous natural air; CH = continuous heat; VH = variable heat; and 0.75, 1.0, and 1.5 = airflow rates (cfm/bu).

location/harvest date/airflow combination, and for each in−bin drying strategy explored (CNA, CH, and VH). The main question to be answered was: does the selection of the best in−bin drying strategy for each location/harvest date/airflow combination change if the cost components change?

The average, minimum, and maximum value of grain and propane prices for the last five years were collected from federal statistics sources (table 1). The values for electricity prices were estimated from information collected from our test sites (Bartosik, 2003). The sensitivity study was conducted by fixing, for example, the propane and electricity prices at their average values, and then changing the price of corn from its minimum to its average and then to its maximum value. The same procedure was repeated for the propane and electricity prices. Table 8 summarizes the combinations explored.

In general, the VH strategy always had the lowest cost for any location/harvest date combination (figs. 1 to 4, dashed

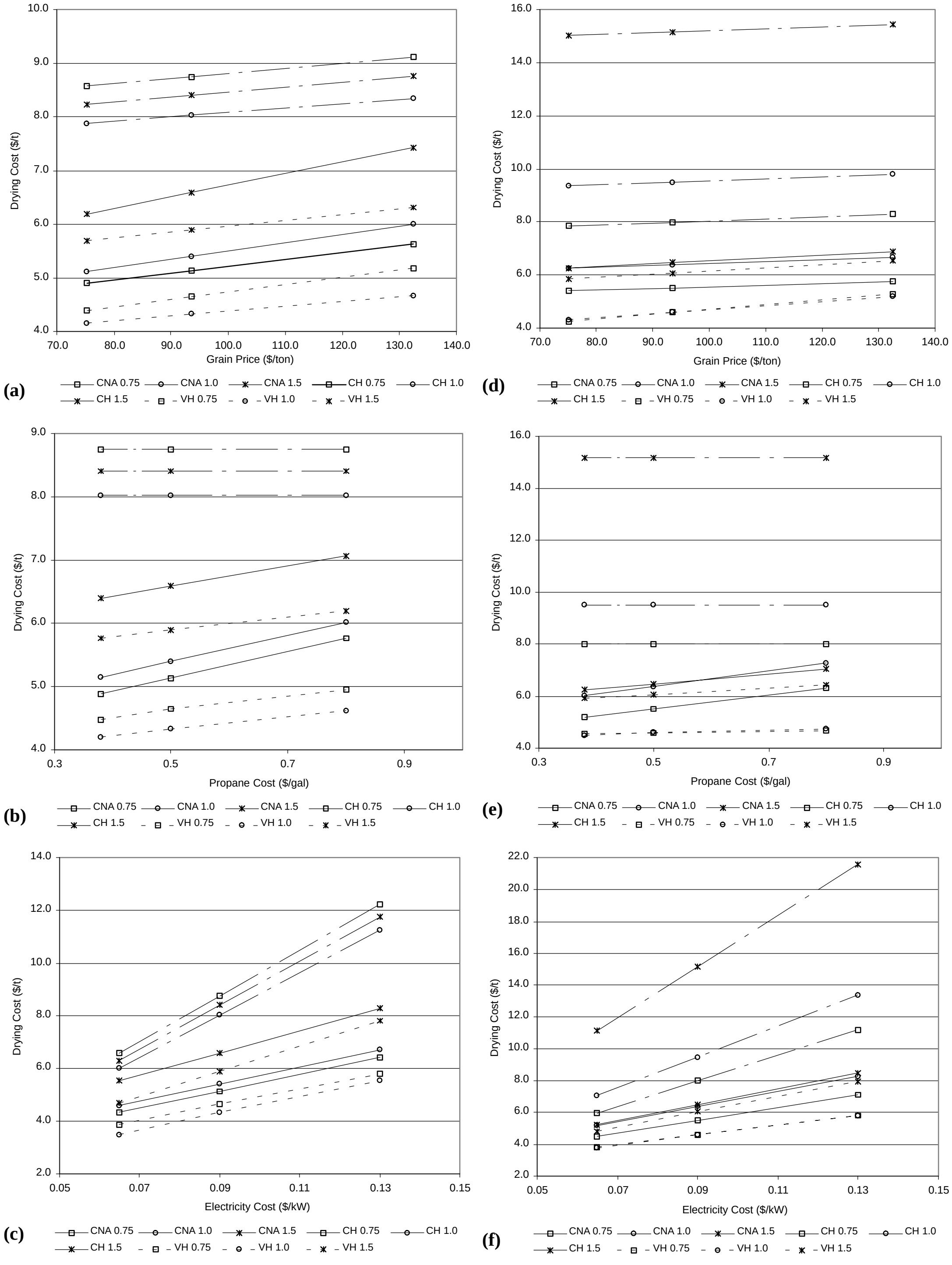

Figure 2. Sensitivity analysis for in−bin drying cost for Des Moines: (a) grain price, 25% harvest; (b) propane price, 25% harvest; (c) electricity price, 25% harvest; (d) grain price, 75% harvest; (e) propane price, 75% harvest; (f) electricity price, 75% harvest; CNA = continuous natural air; CH = continuous heat; VH = variable heat; and 0.75, 1.0, and 1.5 = airflow rates (cfm/bu).

lines). Changes in grain, propane, or electricity prices did not seem to change the ranking of the strategies. The first alternative to the VH strategy was the CH strategy. For the same airflow rate, the CH strategy always had a lower cost than the CNA strategy.

Effect of Electricity Price

The drying costs of all strategies were more sensitive to electricity price than to propane or grain price (figs. 1 to 4, c and f). The CNA strategy was more sensitive to electricity price than the CH and VH strategies for all location/harvest date combinations. For Indianapolis and 25% of the harvest (fig. 1c), the doubling of the electricity price (from 0.065 to 0.13 $/kWh) at 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu) airflow rate increased drying cost by 85%, 41%, and 54% for the CNA, CH, and VH strategies, respectively. For the same location/harvest date/airflow rate combination, the CNA strategy had a significantly higher kWh demand than the other two strategies. Regardless of the in−bin drying strategy selected,

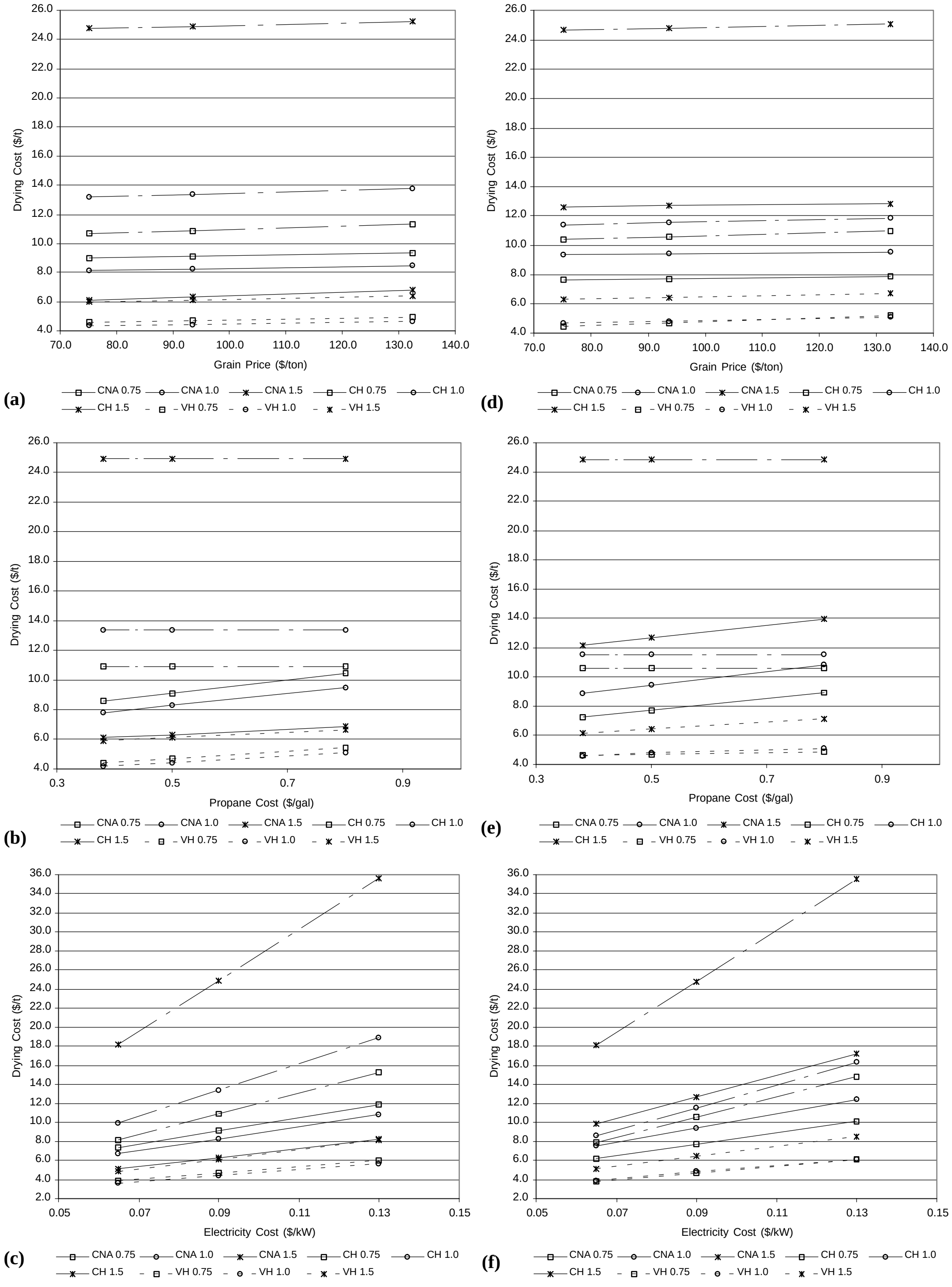

Figure 3. Sensitivity analysis for in−bin drying cost for Lansing: (a) grain price, 25% harvest; (b) propane price, 25% harvest; (c) electricity price, 25% harvest; (d) grain price, 75% harvest; (e) propane price, 75% harvest; (f) electricity price, 75% harvest; CNA = continuous natural air; CH = continuous heat; VH = variable heat; and 0.75, 1.0, and 1.5 = airflow rates (cfm/bu).

the highest airflow rate (1.7 m^3 min^{-1} t^{-1}) also demanded the most kWh for the same location/harvest date combination than the lower airflow rates (0.83 and 1.1 m^3 min^{-1} t^{-1}). The sensitivity to electricity price was higher for the 1.7 m^3 min^{-1} t^{-1} (1.5 cfm/bu) airflow rate than for the other two rates investigated. For Indianapolis and 25% of the harvest (fig. 1c), when the electricity price increased by 100% (from 0.065 to 0.13 $/kWh) at 1.7 m^3 min^{-1} t^{-1} (1.5 cfm/bu) airflow rate, drying cost increased by 88%, 48%, and 67% for the CNA, CH, and VH strategies, respectively. There was no significant difference between the CH and VH strategies in the sensitivity to the electricity price because both drying strategies used fuel at fairly similar levels to reduce fan run hours (electricity consumption). Sensitivity to electricity price did not significantly vary among locations or between different stages of the drying season in the same location.

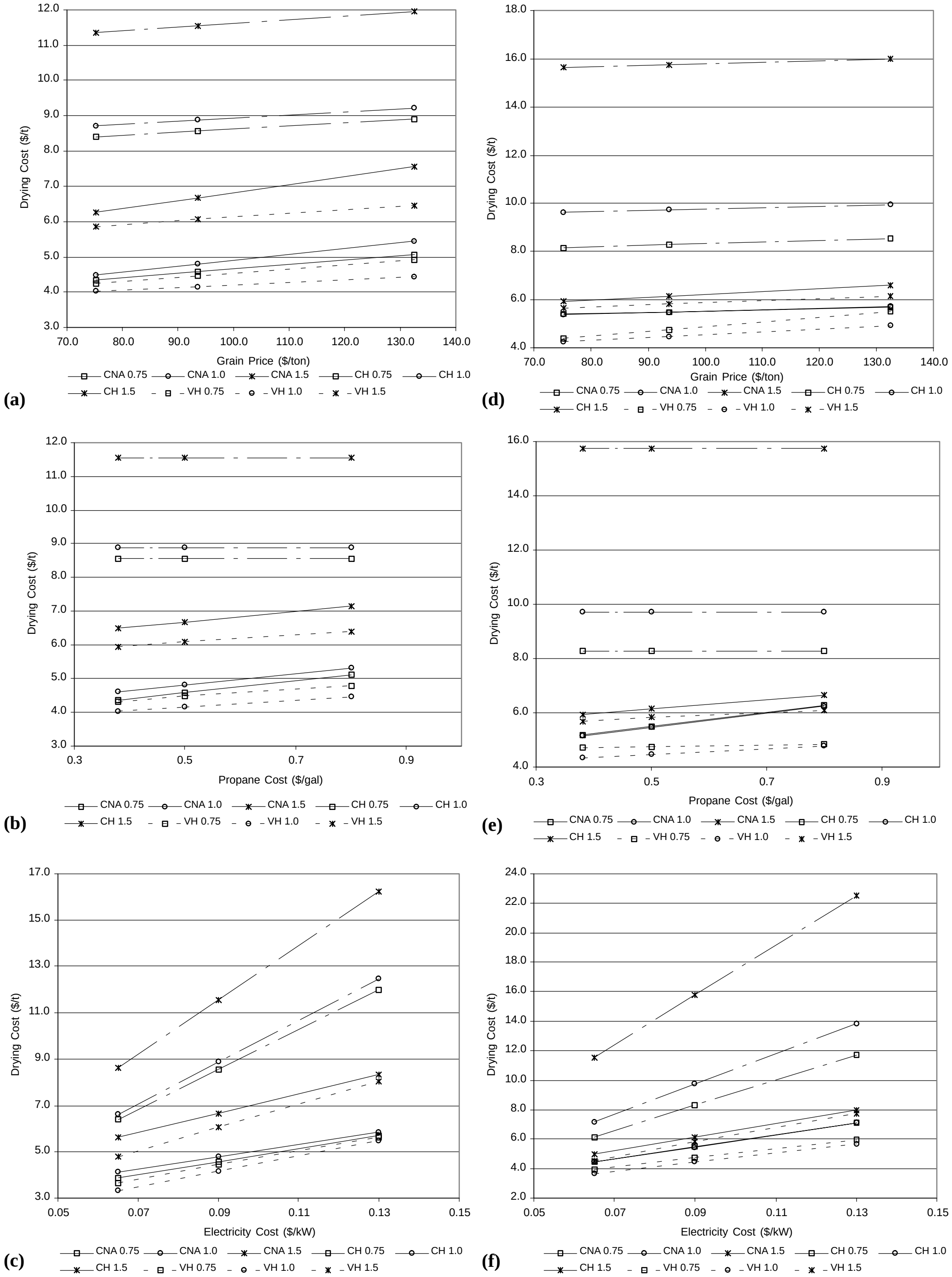

Figure 4. Sensitivity analysis for in−bin drying cost for Minneapolis: (a) grain price, 25% harvest; (b) propane price, 25% harvest; (c) electricity price, 25% harvest; (d) grain price, 75% harvest; (e) propane price, 75% harvest; (f) electricity price, 75% harvest; CNA = continuous natural air; CH = continuous heat; VH = variable heat; and 0.75, 1.0, and 1.5 = airflow rates (cfm/bu).

Effect of Propane Price

The CNA strategy did not use propane, so average drying cost for this strategy was not affected by propane cost. The drying cost of the CH and VH strategies was less sensitive to propane than electricity price changes. This would be expected because in both strategies the electricity cost comprised about 58% to 75% of the total energy cost (electricity and propane combined), and the propane cost about 25% to 42% (table 9). For example, for Indianapolis and 25% of the harvest, at 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu) airflow rate, when propane price increased by 110% (from 0.38 to 0.8 $/gal), the drying cost increased by only 13% and 14% for the CH and VH strategies, respectively (fig. 1b). For both CH and VH strategies, lines for different airflow rates were almost parallel. This indicated that for any location/harvest date combination there was no significant effect of airflow rate on cost sensitivity to propane price (figs. 1 to 4, b and e). When for some location/harvest date combination more heat than average was needed, then the drying cost became more sensitive to propane price. For Des Moines, drying grain early in the season with the VH strategy required higher propane consumption than later drying. Thus, drying cost was more sensitive to propane for the early stage of the harvest compared to the later one (when propane price increased 110%, drying cost increased by 10% and 4% for the early and late stage of the harvest season, respectively).

Effect of Grain Price

Grain overdrying and DML affected drying cost. When grain price was higher, the weight of this drying cost component increased. For all locations, grain price had little effect on cost sensitivity. Sensitivity of drying cost to grain price was directly related to the amount of overdrying caused by the drying strategy. For instance, for Indianapolis and 25% harvest at 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu) airflow, when grain price changed by 76% (from 75.2 \$/t to 132.5 \$/t), drying cost increased by 7%, 23%, and 14% for the CNA, CH, and VH strategies, respectively (fig. 1a). For these conditions, the amount of overdrying was 0.6, 1.3, and 0.5 percentage points for the CNA, CH, and VH strategies, respectively (table 4). When comparing the different locations, airflow rates, and harvest dates, drying cost was not highly sensitive to corn price because shrink cost (overdrying plus DML) was only about 4% to 34% of the total drying cost (figs. 1 to 4, a and d).

CONCLUSIONS

- An airflow rate of 1.1 m^3 min^{-1} t^{-1} (1 cfm/bu) was identified as the optimum for the VH and CH in−bin drying strategies for Indianapolis (Ind.), Des Moines (Iowa), Lansing (Mich.), and Minneapolis (Minn.). This airflow rate minimized the energy consumption and allowed for the completion of the drying process in a reasonable time. This airflow rate was 50% lower than the current MWPS recommendation for CNA drying (2.2 m^3 min^{-1} t^{-1}). The CNA strategy required a higher airflow rate (1.7 m^3 min^{-1} t^{-1}) for some location and harvest date combinations.
- The ideal lower and higher EMC setpoint combinations for the VH strategy were obtained for each location and harvest date combination on the basis of total drying cost. Three lower and higher EMC setpoint combinations were the ideal for all locations, i.e., 11/15%, 12/15%, and 12/16%. These setpoints also yielded the least variability in drying cost.
- The VH strategy (with the ideal lower and higher EMC setpoints) was preferred over the CNA and CH strategies for each location and harvest date combination, based on total drying cost. The second best strategy was CH, which was from 4% to 87% more expensive than the VH strategy. The CNA strategy was from 86% to 205% more expensive than the VH strategy.
- The drying cost for the VH strategy did not change significantly across locations. Drying cost ranged from 4.3 to 4.9 \$/t for the VH strategy, 8 to 13.4 \$/t for the CNA strategy, and 4.7 to 9.4 \$/t for the CH strategy. Additionally, the year−to−year average cost variability was always smaller for the VH strategy than for the CNA and VH strategies (1.84, 10.3, and 8.5 \$/t, respectively).
- The VH strategy was typically the fastest strategy for completion of drying, or the second fastest behind the CH strategy.
- The VH strategy was the least sensitive to changes in grain, propane, and electricity prices and was always the lowest−cost option. For all locations, the energy cost (electricity and propane) for the VH and CH strategies accounted for 66% to 96% of the total drying cost, with an average of around 80%.
- The CNA strategy was more sensitive to the electricity price than the other two strategies. The VH and CH strategies were more sensitive to electricity price than to propane price. For a 100% increase in electricity price, the drying cost increased by about 85%, 41%, and 54% for the CNA, CH, and VH strategies, respectively. For a 110% increase in propane price, the drying cost increased by 13% and 14% for the CH and VH strategies, respectively.

Table 9. Relative composition of energy cost (electricity and propane) and drying cost (energy and shrink) for the CNA, CH, and VH strategies at the respective ideal airflow rate for all location and harvest date combinations.

Location and Harvest Date[a]	Strategy	Electricity (%)	Propane (%)	Energy Cost (%)	Shrink Cost[b] (%)
Indianapolis					
5 Oct.	CNA	100	0	88	12
	CH	58	42	67	33
	VH (11/15%)	62	38	78	22
1 Nov.	CNA	100	0	93	7
	CH	59	41	91	9
	VH (11/15%)	58	42	85	15
Des Moines					
17 Oct.	CNA	100	0	91	9
	CH	59	41	73	27
	VH (12/16%)	75	25	81	19
7 Nov.	CNA	100	0	91	9
	CH	58	42	90	10
	VH (12/16%)	71	29	66	34
Lansing					
15 Oct.	CNA	100	0	93	7
	CH	59	41	93	7
	VH (11/15%)	56	44	89	11
14 Nov.	CNA	100	0	91	9
	CH	58	42	96	4
	VH (12/16%)	62	38	77	23
Minneapolis					
7 Oct.	CNA	100	0	91	9
	CH	59	41	67	33
	VH (11/15%)	67	33	78	22
25 Oct.	CNA	100	0	94	6
	CH	59	41	90	10
	VH (11/15%)	62	38	74	26

[a] The early harvest date corresponded to the average date of the first 25% of harvest progress, and the late date corresponded to the last 25% of the harvest progress for each location.

[b] Shrink cost included MC shrink and DML loss.

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REFERENCES

Bartosik, R. E. 2003. Implementation and evaluation of a new variable heat fan and burner in−bin drying control strategy. MS thesis. West Lafayette, Ind.: Purdue University, Department of Agricultural and Biological Engineering.

Bartosik, R. E., and D. E. Maier. 2001. Evaluation of a new variable heat in−bin low−temperature drying control strategy. ASAE Paper No. 016063. St. Joseph, Mich.: ASAE.

Bartosik, R. E., and D. E. Maier. 2002. Validation and application of the variable heat in−bin low−temperature drying control strategy. ASAE Paper No. 026072. St. Joseph, Mich.: ASAE.

Brook, R. C. 1987. Modelling grain spoilage during near−ambient grain drying. Divisional Note 1388. Silsoe, U.K.: AFRC Institute of Engineering Research.

Midwest Plan Service. 1980. Low−temperature and solar grain drying handbook. MWPS−22. Ames, Iowa: Iowa State University.

Minnesota Extension Service. 1996. Post−harvest handling of crops. Minneapolis, Minn.: University of Minnesota, Department of Biosystems and Agricultural Engineering. Available at: www.bae.umn.edu/extens/postharvest/.

Morey, R. V., H. A. Cloud, R. J. Gustafson, and D. W. Peterson. 1979. Evaluation of the feasibility of solar energy grain drying. *Trans. ASAE* 22(2): 409−417.

Saksena, V., M. D. Montross, and D. E. Maier. 1998. NA/LT drying strategies for white corn in two corn belt locations. ASAE Paper No. 986049. St. Joseph, Mich.: ASAE.

SAMSON. 1961−1990. Solar and meteorological surface observation network: Weather years 1961−1990. Ashville, N.C.: National Climatic Data Center.

Saul, R. A., and J. L. Steele. 1966. Why damaged shelled corn costs more to dry. *Agric. Eng.* 47(6): 326−329, 337.

Steele, J. L., R. A. Saul, and W. V. Hukill. 1969. Deterioration of shelled corn as measured by carbon dioxide production. *Trans. ASAE* 12(5): 685−689.

Stroshine, R. L. and X. Yang. 1990. Effects of hybrids and grain damage on estimated dry matter loss for high−moisture shelled corn. *Trans. ASAE* 33(4): 1291−1298.

Stroshine, R. L., B. A. McKenzie, G. Sarwar, and T. L. Thompson. 1992. Improving management of low−temperature drying of corn. TR−100445 Research Report 2782−04. Palo Alto, Cal.: Electric Power Research Institute.

Thompson, T. L. 1972. Temporary storage of high−moisture shelled corn using continuous aeration. *Trans. ASAE* 15(2): 333−337.

USDA−NASS. 2003. National Agricultural Statistics Database. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov. Accessed January 2003.

Watkins, A., and D. E. Maier. 1997. Thin−layer drying rates and stress cracking of white food corn hybrids. ASAE Paper No. 976065. St. Joseph, Mich.: ASAE.

Wilcke, W. F., R. V. Morey, and D. J. Hansen. 1993. Reducing energy use for ambient−air corn drying. *Applied Eng. in Agric.* 9(2): 241−248.

Wilcke, W. F., H. F. Ng, R. V. Morey, R. A. Meronuck, and J. P. Lang. 1998. Effect of iprodione fungicide application on deterioration rate of stored shelled corn. *Trans. ASAE* 41(6): 1761−1765.