EVALUATION OF A MULTI-STAGE AIRFLOW CONTROL-ALGORITHM FOR NEAR-AMBIENT DRYING OF STORED WHEAT IN MANITOBA

by

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A thesis
presented to the University of Manitoba
in partial fulfillment of the
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DAVID ARLEN EPP

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

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ABSTRACT

Near-ambient drying of grain is an effective method of reducing the moisture content of freshly harvested grain to a safe storage level, but use of continuous fixed airflows can result in high airflow rates in some years, causing over-drying of the grain as well as consuming excessive energy. This contributes to high costs of drying in some years. One method of optimizing the cost of drying is to effectively utilize the fluctuations in ambient weather conditions on the Canadian Prairies to control the drying process.

An airflow controller which optimizes cost of drying by varying the airflow through the grain based on diurnal fluctuations in ambient air and predicted progress of drying and spoilage was modified to use airflow rates typical of those recommended for near-ambient drying in Manitoba, and to facilitate drying over a range of harvest dates and initial moisture contents. The resulting multistage controller (MC) simulated drying with four possible airflow rates (0, 15, 25, and 40 $L \cdot s^{-1} \cdot t^{-1}$) produced by two drying fans operating singly or in parallel. The performance of the MC was simulated using 30 yr of hourly Winnipeg weather, 1961 - 1990.

The multistage controller with two optimized control parameters (MC2P) was successful in simulating drying of wheat for seven out of nine combinations of harvest dates ranging from Aug. 15 to Sept. 15, and initial moisture contents ranging from 16.0% to 19.0% (wet mass basis). The MC2P reduced simulated cost of drying as much as 77% when compared with continuous-airflow drying simulations under the same nine input scenarios. Using a Sept. 1 harvest date, 19.0% initial moisture content, and 30 yr of Winnipeg weather, the MC2P reduced the cost of drying from 4.83 $/t to 1.77 $/t. Over-drying was reduced from 15.93 kg/t to 1.58 kg/t although energy consumption was higher by 17%. The mean spoilage index was 0.72 for the 30 yr of drying, and did not exceed 1.0, the maximum value of safe storage, in any one of the 30 yr.

Practical considerations may prevent the MC2P from being developed into a marketable controller for near-ambient drying. When the additional capital costs needed for the MC2P system were included with the cost of drying, the MC2P had a cost of drying of 12.78 $/t, compared with the continuous-airflow cost of 12.11 $/t (based on drying 115 t of wheat in an 8.2 m diameter bin). Also, the economy of the MC2P is dependent on grain prices, which can fluctuate widely from year to year. Finally, although the MC2P shows great success in reducing the operating costs of near-ambient drying compared with continuous-airflow, it has not yet been validated experimentally.

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1. INTRODUCTION

1.1 Near-Ambient Grain Drying

Near-ambient drying is a term used to describe the drying of grain in storage bins using air that is either unheated or supplemented by a small amount of heat. In western Canada the storage bins are usually cylindrical steel bins, up to 11 m in diameter (Friesen and Huminicki 1987). A fan forces ambient air into a plenum beneath the perforated floor of the grain bin, up through the grain, and out through exhaust vents in the bin roof. By moving the air past the fan motor and through the ducting it is heated by friction, usually 1 to 5 °C above the ambient-air temperature (Sanderson et al. 1988). This added heat improves the drying capability of the ambient air, thus the term 'near-ambient' drying.

Near-ambient drying requires airflow rates in the range of 7 - 55 $L \cdot s^{-1} \cdot t^{-1}$, compared with 1 - 3 $L \cdot s^{-1} \cdot t^{-1}$ for cooling grain using aeration (Friesen and Huminicki 1987). The required airflow rates for drying depend on the grain moisture content at harvest, the harvest date, the depth of the grain in the bin, the type of grain, and the regional weather. The purpose of aeration is to cool the grain, a process which requires less airflow than drying. Thus the lower airflow rates used in aeration are usually insufficient to reduce the grain moisture content more than one percentage point (Friesen and Huminicki 1987).

The alternative to near-ambient drying of grain is heated-air drying, which is not dependent on ambient weather conditions. The operator has more control of the drying process with heated air drying, and it takes less time than near-ambient drying. Nevertheless, near-ambient driers require less equipment, labour, management (Wilcke et al. 1993), capital cost and energy input (Sharp 1982, Bruce and Ryniecki 1991), and preserve grain quality better than conventional high-temperature driers (Wilcke et al. 1993). Near-ambient driers represent a major proportion of grain driers in Britain (Sharp 1982), are preferred by many corn producers in the northern U.S. (Wilcke et al. 1993), and are common on the Canadian Prairies (Sokhansanj et al. 1991). Grain drying with near-ambient air is potentially the most energy efficient of existing methods of drying (Ryniecki and Nellist 1991a).

Manitoba Department of Agriculture (MDA) recommends airflow rates for near-ambient drying systems based on computer simulation of drying (Friesen and Huminicki 1987). The recommended rates are airflows which are most likely to provide drying without grain spoilage even in poor drying years. One problem with this approach is that in a year with average or good drying conditions, the fan is over-sized, uses more energy than necessary, and can over-dry the grain. Both of these situations increase the cost of drying.

The recommended method of operating a near-ambient drying system is to turn the fan on when the grain is put in the bin, and let the fan run continuously until the drying front has moved through the grain bulk and the grain at the top of the bin is at the desired moisture content (Friesen and Huminicki 1987). For wheat in Canada, this moisture content is 14.5% (unless otherwise stated, all moisture contents in this thesis are reported on a wet mass basis), the maximum allowable level for marketing grain. This method of drying is simple and effective, but does not take advantage of the changes in temperature and relative humidity of air which occur throughout each day. These changes affect the ability of the ambient air to remove moisture from the grain.

To realize the potential of near-ambient drying as an energy-efficient method of drying grain, the problems of high airflow rates and unfavourable weather conditions need to be addressed. Ryniecki et al. (1993b) did so by developing a generalized control algorithm (GCA) which varied the airflow through the grain depending on the ambient weather conditions and the progress of drying and progress of spoilage in the grain. Although computer simulations showed the algorithm to be cost effective and energy efficient, it was impractical for adapting to a real drying system. Modifying the GCA to fit certain design criteria is a prerequisite step to developing an actual drying system.

1.2 Objectives

The objectives of this thesis were:

1. To develop a control strategy that would improve the energy efficiency and reduce the over-drying associated with near-ambient drying of wheat when tested using computer simulations for Manitoba harvest conditions.
2. To evaluate the performance of the controller by comparing it with drying simulations using optimized continuous-airflows.
3. To have the controller meet practical design criteria so that implementation in a field situation would be possible.

2. LITERATURE REVIEW

2.1 Problem Definition

Drying grain with near-ambient air is a commonly used method of on-farm drying of grain, yet improper control systems and management procedures can result in high energy use, over-drying, and spoiled grain. Control systems for near-ambient drying should optimize the cost of drying but be flexible enough to accommodate the variations in input variables that affect the success of drying. This literature review summarizes the control strategies for near-ambient drying that have been reported by various researchers and identifies which strategies are most appropriate for Canadian prairie weather.

2.2 Near-Ambient Drying Systems

2.2.1 Management objectives Proper management objectives of a near-ambient drying system are to dry grain in the available time at a minimum cost while maintaining the quality of the grain to permit long-term storage. The cost of drying is comprised of over-drying, energy, capital, and labour costs. In the northern hemisphere, the time period for drying is usually between harvest and the onset of winter, although drying may also be continued in spring. Grain quality is affected by pre-harvest conditions such as weed seeds and the freezing or weathering of the grain and by post-harvest conditions including the growth of mould, dry-matter decomposition, loss in germination, and the presence of insects (multiplying primarily shortly after harvest in warm grain).

The over-drying cost is one of the main costs associated with near-ambient drying, and is incurred when the average final moisture content of the grain is below the maximum moisture content specified for marketing, resulting in a financial loss. In Canada the maximum moisture content for marketing wheat is 14.5%. Any loss in mass due to a moisture content lower than 14.5% will result in a financial loss when the wheat is sold, regardless of the fact that the dry mass of the grain may be the same. Near-ambient grain drying is highly dependent on weather conditions and in many years will dry the grain to an average moisture content below 14.5%.

The cost of energy consumption in a near-ambient drying system usually consists only of the power to the fan motor, but energy used to supply supplemental heat may also be included in some systems. Energy can be measured simply as the total energy consumed (MJ), or in terms of specific energy (MJ/kg H_2O), which is the energy per unit mass of moisture removed from the grain. The energy consumed by the fan depends on the size of fan and on the time it takes to dry the grain. These factors in turn are dependent on the condition of the grain at harvest, the physical characteristics of the drying system, harvest date, and regional weather. Fan efficiency also affects the energy consumption, and is related to the mechanical design of the fan and whether it is appropriately matched to the drying system. The use of supplemental heat to increase the drying potential of the air can be cost-effective for drying wheat in humid climates (Ryniecki et al. 1993a), but not in dry areas such as the Canadian Prairies when using typical moisture contents and harvest dates (Ryniecki et al. 1993a, Fraser and Muir 1981). Ultimately, the local power utility determines the cost of any electrical energy used.

Sokhansanj et al. (1991) and Arinze et al. (1993) included the cost of capital and labour in the cost analyses for their drying simulations. The capital costs were calculated as a fixed annual cost based on the initial cost of the system (including bin with perforated floor, heater, fan, and controllers), the annual interest rate, the ratio of the salvage value to the original value, and the life of the drying system. Labour costs were calculated based on the time required for regular inspection of the bin, and the time needed to mix the grain after drying if necessary. Many other studies have omitted both labour and capital costs when calculating the cost of near-ambient drying (Gunasekaran and Shove 1983, Sharp 1984, Ryniecki and Nellist 1991b, Ryniecki et al. 1993a, 1993b). The labour required to operate a near-ambient drying system is not much more than what is already required to store and inspect grain in non-ventilated bins. Omitting capital costs may be justified by assuming that many farms already have much of the equipment needed for a near-ambient drying system (storage bin with perforated floor and air plenum). The initial capital cost of a near-ambient drying system is also much less than the investment needed for a heated air drying system. Furthermore, optimal operation of existing equipment is more important than minimizing yearly fixed costs of equipment given the large number of near-ambient driers already in existence (Ryniecki et al. 1993a).

Drying with near-ambient air is weather dependent, thus one of the management objectives of near-ambient drying is to have the grain dried to completion in a certain time period. Usually this is before winter, when the drying potential of ambient air decreases with decreasing temperatures (Sanderson et al. 1988). Low airflows may achieve the objective of reduced energy costs, but the time available for drying becomes a limiting factor which determines the necessary airflow rate. One management alternative is to design the system with a low airflow and continue drying in spring when necessary. If the grain is not dried to completion in fall, it can be preserved over winter if it has been cooled to 0 °C or less and can be dried to completion in spring when average daily temperatures exceed 5 °C (Friesen and Huminicki 1987).

Fungal deterioration related to high moisture content in grain is a common cause of spoilage (Wicklow 1995). The effects of fungal deterioration of grain include the loss of seed viability, dry matter loss, increased fat acidity, grain heating, and sprouting (Wicklow 1995). Mould spores require a relative humidity of 75% or more to germinate (Wicklow 1995), and near-ambient drying can provide effective control by drying the grain to a safe equilibrium moisture content at which fungal growth is inhibited.

Insect infestation is another storage problem that can be controlled in Western Canada using near-ambient drying and winter storage. Most grain storage insects can be eliminated if the temperature is maintained at 14 °C or less for several months because their multiplication rate will fall below their replacement rate, although eradication of rusty grain beetles *Cryptolestes ferrugineus* (Stephens) (the most common stored-grain insects in Western Canada) requires -5 °C for several months (Banks and Fields 1995). Using near-ambient drying, the grain temperature equilibrates with the temperature of the ventilated air. When ambient temperatures remain cold enough and the cooling front has passed through the grain, the insects do not reproduce. Survival is also decreased in dry grain. Thus in Western Canada the practice of drying grain in fall and storing it on the farm through the cold winters is usually an effective means of eliminating insect problems.

2.2.2 Validation of drying models Many researchers (Pierce and Thompson 1979; Fraser and Muir 1981; Morey et al. 1979; Smith and Bailey 1983; Ryniecki and Nellist 1991a, 1991b; Ryniecki et al 1993b) have used computer simulations to optimize control systems for near-ambient drying because the costs of testing a near-ambient drying system with field experiments are expensive and time consuming (Fraser and Muir 1981). Different mathematical models were used in simulations to predict the movement of temperature and moisture fronts through the grain bulk. Equilibrium models which predict the effect of grain aeration assume conditions that are valid for low-temperature, low-airflow grain drying (Sharp 1982). These models have been modified to accommodate high airflows and shallow beds resulting in near-equilibrium models which can predict grain moisture profiles with reasonable accuracy (Sinicio 1994).

Airflow rates for near-ambient drying can be determined most accurately using field experimentation (Fraser and Muir 1981), but field experiments are limited by weather conditions at the time of testing and a small number of years in which testing can be done. Given these limitations, field experiments are most commonly used to validate computer simulation programs which are then used to test a variety of drying strategies and input parameters for many years of simulated weather.

Sanderson et al. (1989) used small diameter (0.61 to 1.22 m) test bins to validate the near-equilibrium drying model of Metzger and Muir (1983), and concluded that the model adequately predicted temperatures and moisture contents in ventilated grain bins.

The Manitoba Department of Agriculture used the model to determine airflow rates for various inputs of grain type, initial moisture content, and harvest date and published these airflows as recommended rates for designing near-ambient drying systems in Manitoba (Friesen and Huminicki 1987).

2.2.3 Control strategies for near-ambient drying The control strategies for near-ambient drying vary from simple fan-only systems to microprocessor-controlled systems of different airflow and heating levels. To ensure economic drying the choice of strategies to control the fan and heater are critical. The correct choice depends on many variables, but the most influential factor is the ambient weather conditions of any particular region (Bruce and Ryniecki 1991).

Continuous-airflow with no supplemental heat is the simplest strategy for near-ambient drying. It is also the least expensive, especially in regions with favourable weather conditions (Bruce and Ryniecki 1991). Recommended airflows for drying grain in a particular region are determined based on grain type and condition, bin characteristics, and harvest date (Friesen and Huminicki 1987). This airflow is usually chosen to ensure successful drying over a range of historic weather conditions, and may result in excessive energy consumption or over-drying in certain years (Ryniecki et al. 1993b). The fan is operated continuously from the time the grain is put into the bin until the drying front has passed through the grain bulk, or until the grain temperature drops to 0 °C (Friesen and Huminicki 1987). If drying has not been completed at this point, it is then resumed in spring (Friesen and Huminicki 1987). Many researchers have recommended drying with continuous-airflow rather than strategies using intermittent airflow or supplemental heat, because these strategies may increase energy consumption, increase over-drying, or increase the risk of spoilage (Sharp 1984, Sanderson et al. 1988, Lynch and Morey 1989, Arinze et al. 1993).

Another strategy for fan-only control is to use a combination of continuous and intermittent ventilation. Pierce and Thompson (1979) tested a fan management technique for drying corn in which the fan was operated continuously in the autumn until winter or until the drying front had passed through the grain bed. During the winter, two hours per day of intermittent fan operation cooled the grain and equalized the temperature differentials. For years in which drying was not completed before winter, continuous ventilation was resumed in spring when the ambient temperature was greater than 13 °C and was continued until the entire bed was dry. Simulation results indicated drying performances similar to continuous fan operation. Morey et al. (1979) tested a similar strategy involving continuous-airflow in autumn followed by humidistat or timer controlled fan operation in spring and concluded that dry-matter decomposition and over-drying increased with decreased fan time because the movement of the drying front through the bin was delayed. The method did reduce fan time and energy requirements, but not enough to off-set the cost of over-drying and dry-matter decomposition (Morey et al. 1979). Lynch and Morey (1989) made similar conclusions after simulating nine control strategies for drying corn using Minnesota weather data.

Supplemental heating is a means of increasing the drying potential of the ambient air and reducing drying time. The temperature is usually increased no more than 5 °C above ambient (Sharp 1982). Supplemental heat may be necessary for humid climates or for certain drying conditions (Mittal and Otten 1983, Ryniecki et al. 1993a). Even in the worst drying conditions the heater should not be run continuously because of increased over-drying and energy costs (Bruce and Ryniecki 1991). Humidistats and timers are used to control intermittent use of the heater. Generally, supplemental heat results in faster drying, but increases both energy usage and over-drying (Morey et al. 1979). Solar collectors can be used to provide a source of supplemental heat with reduced energy costs, but may not be cost-effective when capital costs are considered. Pierce and Thompson (1979) reported that increases in both over-drying and capital costs resulted in a higher overall cost of drying using solar heat than with other strategies. Depending on the climate, solar heat may simply be replaced with a fan-only system using high airflows (Morey et al. 1979, Fraser and Muir 1981). Morey et al. (1979) reported that increasing airflow rates 10 - 15% achieved the same effect as drying with the assistance of solar heat, and the increase in energy costs was minimal when compared with the capital cost of a solar dryer.

Multiple set-point control of supplemental heat, airflow levels, or a combination of the two has potential as an optimal control strategy for near-ambient drying. Multiple set-points are based both on relative humidity measurements of ambient air and on grain moisture content at specified locations in the bin. Computer control of such a system is required to predict the conditions in the grain using simulations, and for some strategies, to recalculate the set-points as drying progresses.

Automatic control of near-ambient drying of corn is necessary in Southern

Ontario to achieve significant energy savings because poor drying conditions are frequent (Mittal and Otten 1983). Microprocessor control of a low-temperature corn-drying system using multiple set-points was tested by Mittal and Otten (1983). Their algorithm used a modified version of the drying model of Morey et al. (1979) to predict grain moisture conditions. The algorithm used three relative-humidity set-points and one set-point based on grain-moisture content in the upper 10% of the bin. These set-points were used to determine the combination of drying fan, aeration fan, and heater levels, and the autumn shut-off date. Computer simulations were used to test combinations of each set-point and indicated that energy savings of at least 10 - 19.0% could be achieved with microcomputer control when compared with typical near-ambient drying. Even greater savings were reported when the microprocessor-control was compared with near-ambient drying using simple heater control. Over-drying was reduced when compared with continuous fan-only drying. Energy savings from results of a field experiment using the same system compared well with the simulation results (Mittal et al. 1984).

Microprocessor-control of near-ambient drying can also be optimized by using variable set-points. Ryniecki and Nellist (1991a) developed a generalized control strategy which combined several strategies for fan-and-heater control. The microprocessor used a drying simulation model to calculate grain moisture content at specific locations in the grain bed. The algorithm calculated the equilibrium point between air and grain for drying or wetting, and compared this value with multiple set-points. Satisfaction of set-point conditions determined the combination of two levels of airflow and several levels of supplemental heat. The multiple set-points were recalculated every time step according to the progress of drying. The parameters used to calculate the control set-points were optimized for drying wheat at Waddington, England (Ryniecki and Nellist 1991b). Simulations indicated the algorithm reduced drying cost compared with near-ambient drying using fixed-airflow or simple fan-and-heater strategies.

The performance of the generalized fan-and-heater control strategy (Ryniecki and Nellist 1991a) in a continental climate was tested by Ryniecki et al. (1993a). They compared simulation results using weather data from Waddington, England (a maritime climate) and Winnipeg, Canada (a continental climate). Three control policies were optimized and compared: the generalized fan-and-heater strategy (Ryniecki and Nellist 1991a), the simple fan-and-heater strategy using a single relative-humidity set-point, and a continuous-airflow fan-only strategy. For Winnipeg weather, the heater in the generalized fan-and-heater strategy used a mean of only 7.3% of the total energy consumption, and the heater in the simple fan-and-heater strategy did not use any heat. This is because it was optimal in Winnipeg weather to use a larger airflow than to add heat. The output factors for the generalized strategy had a high variation from year to year, thus Ryniecki et al. (1993a) concluded that some of the controlling parameters should vary according to current weather conditions. They also proposed varying the airflow as an alternative to adding supplemental heat.

A generalized control strategy which used variable airflow and no supplemental heat was developed using Winnipeg weather data by Ryniecki et al. (1993b). The algorithm adjusted the airflow at one-hour time increments based on daily changes in ambient humidity, and set the base level of airflow according to yearly weather variations. Parameters used to calculate the various set-points were optimized using 20 yr of weather data. The results of simulations using the generalized control algorithm (GCA) indicated reductions of 7%, 59%, and 42% in specific energy consumption, over-drying, and overall cost, respectively, when compared with continuous-airflow results.

2.3 Summary

The success of near-ambient drying of grain is highly dependent on the control strategy used. Successful control strategies in turn are determined by yearly variations in weather patterns, regional location, type and condition of grain, and date of harvest.

For near-ambient drying with Canadian prairie weather, two control strategies seem to be most appropriate: 1) continuous-airflow with no supplemental heat, or 2) the generalized control-algorithm (GCA) using variable or multi-staged airflow. The first option is suggested because of its recommendation by numerous researchers for a variety of conditions and because of its widespread use. The GCA is suggested because of its potential in cost savings over conventional continuous-airflow. The remainder of this thesis will present the research done to develop a practical application of this algorithm.

3. MATERIALS AND METHODS FOR DRYING SIMULATIONS

3.1 The Generalized Control-Algorithm (GCA)

The simulations in this study were done using the basic approach developed by Ryniecki et al. (1993b). The original intent of the research was to validate experimentally the generalized control-algorithm (GCA) of Ryniecki et al. (1993b). Pursuit of this goal was delayed by the revisions to the GCA which needed to be done prior to validation. The purpose of the modifications was to make the GCA a more practical controller that could be applied to an actual near-ambient drying system. To do this, the basic airflow levels, set-points, and airflow controls were altered but the original concept of the GCA (Ryniecki et al. 1993b) was retained.

The GCA (Ryniecki et al. 1993b) is an algorithm designed to minimize the cost of near-ambient grain drying by controlling the airflow level through the grain bed. The GCA is a combination of two control strategies. The first strategy takes advantage of diurnal variations in temperature and relative humidity, and adjusts the airflow to provide the optimum drying rate given the air conditions. The second strategy responds to the overall weather pattern of that season by predicting the rate of drying and the rate of spoilage in the grain, and adjusting the airflow level accordingly. Each strategy requires a set of control parameters to determine various functions of the algorithm. Altogether 11 optimized controlling parameters are used by the GCA.

3.1.1 Optimization method The goal of optimizing the control parameters is to find the combination that can provide the minimum cost of drying while still successfully drying the grain in each year of a set of historical weather years. Optimization requires a repeated running of the drying simulation to test each combination of control parameters. The optimization routine searches for the optimum value of each parameter by varying them within the initial bounds set at the beginning of the search. Any combination of parameters which fails to dry the grain by Nov. 15, without any occurrence of spoilage, in all years of the weather data set is rejected. Spoilage is calculated using the equations of Fraser and Muir (1981). If the spoilage index (Θ) exceeds 1.0 for any layer during the drying period, spoilage is considered to have occurred. After all the combinations of parameters have been simulated with the weather data file, the best set of parameters is selected based on the lowest cost of drying. The bounds and increments are then narrowed, and the search is repeated. This procedure is described in detail by Ryniecki and Nellist (1991a) and Ryniecki et al. (1993b).

3.1.2 Control parameters Understanding the changes to the GCA requires a basic explanation of the original GCA. Previously published articles (Ryniecki and Nellist 1991a, 1991b; Ryniecki et al. 1993a, 1993b) give detailed explanations of the parameters and the development of the algorithm. A brief explanation of the control parameters and the structure of the algorithm is included here for ease of reference.

The algorithm developed to respond to diurnal weather variations requires six optimized control parameters. These parameters are used to determine relative-humidity set-points and the corresponding airflows associated with three possible states defined by the relationships between the plenum air and the grain.

The first state is the state of high drying potential, when the ambient-air relative humidity is low. In this state, the plenum air humidity, ψ_p (all the terms are defined in the List of Symbols) must be lower than the first humidity set-point, ψ_{s1} ($\psi_p < \psi_{s1}$), defined by the following equation (Ryniecki and Nellist 1991a):

$$\psi_{s1} = 100\{1 - \exp[17.03 - 0.1256(M_w - \beta_1) - 2.847\ln(T_w + 273)]\} \qquad (1)$$

The parameter β_1 (found by the optimization routine) determines the shift in value of ψ_{s1} from the equilibrium relative humidity of the wettest layer of grain.

The airflow (q_{a1}) associated with this state is relatively large to utilize the high drying potential of the air. This airflow is gradually decreased with time to reduce over-drying, measured by the dimensionless average moisture content, M^D_{av}. The defining equation for q_{a1} is (Ryniecki et al. 1993b):

$$q_{a1} = q_{ar} + a_{g1}(M^D_{av} - M^D_{r1}) \qquad (2)$$

The optimization procedure is used to find control parameters M^D_{r1} (reference moisture content for the average of the whole bed of grain) and a_{g1}. The reference airflow, q_{ar}, is fixed at the level optimized for drying using a continuous-airflow only. Ryniecki et al. (1993b) used a continuous-airflow of 37.5 $L \cdot s^{-1} \cdot t^{-1}$ as q_{ar}.

The second state of drying potential occurs when the plenum humidity is greater than that of the first state, but still less than that which would cause excessive rewetting of the wettest layer ($\psi_{s1} < \psi_p \leq \psi_{s2}$). The airflow corresponding to this state, q_{a2}, is lower than q_{a1}, and allows the over-dried bottom layers to rewet while still moving the drying front through the grain bed. The set-point ψ_{s2} is calculated using Eq. 1, but β_1 is replaced by β_2 which is found by optimization. The airflow q_{a2} is defined similarly to q_{a1} by the following equation (Ryniecki et al. 1993b):

$$q_{a2} = q_{ar} - r_g \cdot a_{g1} \cdot (M^D_{av} - r_r \cdot M^D_{r1}) \tag{3}$$

The parameters r_g (ratio of a_{g2} to a_{g1}) and r_r (ratio of M^D_{r2} to M^D_{r1}) are found by optimization.

The third state of drying occurs when the plenum humidity is greater than that of State 2 ($\psi_p > \psi_{s2}$). In this condition, the plenum air is humid enough to wet even the wettest layers. To maintain a cooling effect on the grain, the airflow is reduced to a minimal level of 0.83 $L \cdot s^{-1} \cdot t^{-1}$. At this level, the effect of the airflow is mainly that of aeration to prevent spoilage, and the rewetting is negligible (Ryniecki et al. 1993b).

The second control strategy uses a proportional controller to take advantage of the year to year variations in the general weather patterns. The proportional controller alters the general level of airflow to keep the progress of drying close to the progress of spoilage. The dimensionless average moisture content of the whole bed (M^D_{av}) is used to represent the progress of drying. Progress of spoilage is represented as $[1 - (\Theta/a_s)]$, where a_s (to be optimized) is the desired final value of the spoilage index, Θ. At the beginning of drying, both M^D_{av} and $[1 - (\Theta/a_s)]$ are equal to 1.0. To minimize cost of drying, they should be close to zero at the end of drying. If M^D_{av} is not less than or equal to zero or if Θ is greater than 1.0 by the end of drying (Nov. 15), then that combination of parameters is eliminated.

The proportional controller functions by setting the initial airflow, $q_a(t_k=0)$ equal to q_{ar} for the first hour of drying. A new airflow is calculated hourly based on the following proportional controller function (Ryniecki et al. 1993b):

$$q_a(t_k) = q_a(t_{k-1}) + K_p \cdot [2e(t_k) - e(t_{k-1})] \quad (4)$$

The controller gain, K_p, is the parameter optimized at this stage. A larger K_p results in greater airflow changes for any error e, where $e(t_k)$ is defined (Ryniecki et al. 1993b) as:

$$e(t_k) = M^D_{av}(t_k) - [1 - \Theta(t_k)/a_s] \quad (5)$$

and is a measure of the difference between the progress of drying and the progress of spoilage. The controller increases airflow (q_a) for positive e to bring the progress of drying to the same level as the progress of spoilage. When e is negative, the airflow decreases to slow the progress of drying. To keep the airflow within a reasonable range maximum and minimum limits to the airflow, q_{us} and q_{ls}, respectively, are found by optimization, such that $q_{ls} < q_a < q_{us}$. Figure 3.1 illustrates the variation in airflow during the autumn drying period in 1969, based on simulations with Winnipeg weather data.

To reduce the amount of both over-drying and grain spoilage, the minimum airflow rate (q_{min}) of 0.83 $L \cdot s^{-1} \cdot t^{-1}$ is set for very dry plenum air conditions ($\psi_p < \psi_{s3}$) and when M^D_{av} is below the target value of 14.5% (but drying is not yet complete). The humidity set-point ψ_{s3} is calculated using Eq. 1 and optimizing β_3. The minimum ventilation rate is also used for very humid conditions when $\psi_p > \psi_{s2}$. Note that q_{min} is not the same term as q_{ls}, nor is q_{us} the maximum value the airflow can be. This is because q_{ls} and q_{us} just limit q_{ar}, not the final airflow. Ultimately, the airflow is set according to the increment added to or subtracted from q_{ar} based on the plenum air conditions and M^D_{av}. This can be seen in the flowchart of the algorithm, Fig. 3.2.

The GCA combines the two preliminary strategies into one (Fig. 3.2). In total, 11 parameters (a_{g1}, a_s, β_1, β_2, β_3, K_p, M^D_{r1}, q_{ls}, q_{us}, r_g, and r_r) are optimized . The set of optimum parameters reported by Ryniecki et al. (1993b) are shown in Table 3.1. These parameters were optimized using a 20 yr Winnipeg weather data file.

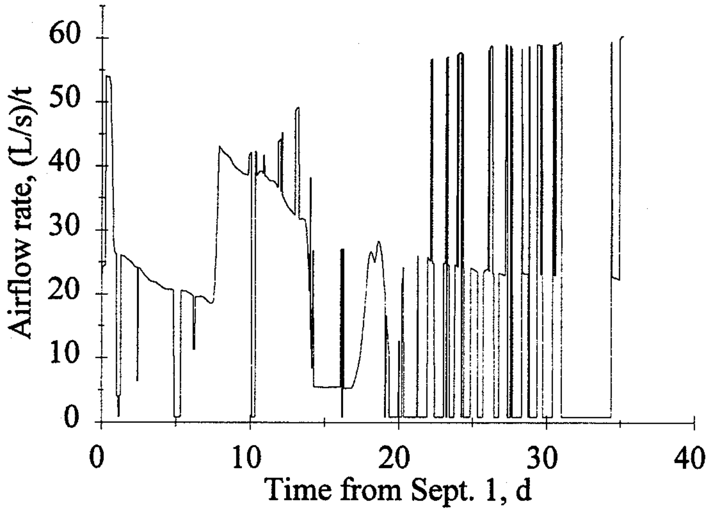


Fig. 3.1 Airflow calculated by the generalized control-algorithm (GCA) for simulated drying in 1969.

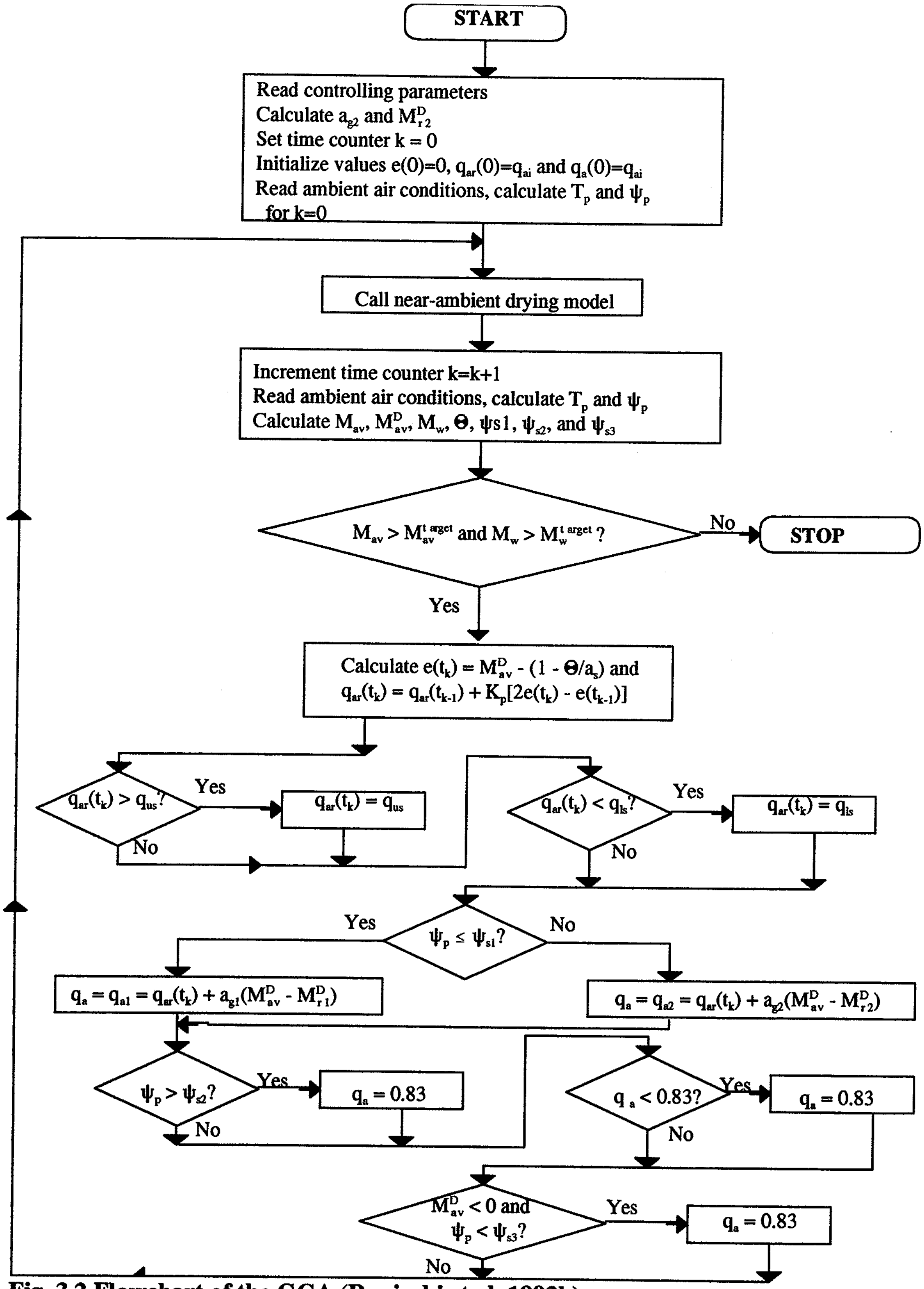


Fig. 3.2 Flowchart of the GCA (Ryniecki et al. 1993b)

Table 3.1 Initial bounds and final optimization results for the parameters used in the generalized control algorithm by Ryniecki et al. (1993b).

	Initial Bounds		
Controlling Parameter	Lower	Upper	Final Value[1]
a_{gl}	30	60	30
a_s	0.7	0.9	0.75
β_1	1.0	3.0	2.5
β_2	-1.5	-0.5	-0.75
β_3	9.0	13.0	8.25
K_p	7.0	15.0	5.0
M^D_{r1}	0.4	0.6	0.5
q_{ls}	15.0	22.5	3.75
q_{us}	33.8	56.3	39.4
r_g	0.8	1.2	0.9
r_r	0.8	1.2	0.9

[1] Units given in List of Symbols.

3.1.3 Modifications to the GCA Ryniecki et al. (1993b) demonstrated by computer simulation that using the generalized control-strategy lowered the cost of drying by 42% when compared with near-ambient drying using a constant airflow. However, modifications to the algorithm were necessary to make it adaptable to a real drying system. First of all, the continuous optimized airflow that the algorithm was compared with was 37.5 $L \cdot s^{-1} \cdot t^{-1}$. This is much greater than the airflow of 20 $L \cdot s^{-1} \cdot t^{-1}$ based on MDA recommendations for drying wheat under similar conditions (Friesen and Huminicki 1987), and would contribute to both the operating and capital costs of a drying system by requiring a large fan. Reducing this continuous-airflow rate necessitated changing the control mechanisms in the algorithm.

A fundamental difference in the approach between the algorithm used by Ryniecki et al. (1993a, 1993b) and the continuous-airflow drying model on which the MDA recommendations are based (Metzger 1980) is the conditions which determine when drying is stopped. The strategy of Ryniecki et al. (1993b) stops the drying when the average grain moisture content of the whole bed, M_{av}, and the moisture content of the wettest layer, M_w, are no greater than the target moisture content of 14.5%. If the bottom layers of the bed of grain experience some re-wetting near the end of the drying period, one of these layers can become the wettest layer and control the drying time. Metzger's model, validated experimentally by Sanderson et al. (1989), uses the average moisture content M_{av} and the moisture content of the top layer of grain, M_t, as a stop condition. With sufficient airflows, the moisture content of the top layer normally reaches the target value when the initial drying front has passed through the entire grain bed. Any re-wetting that occurs at the bottom of the bin is considered beneficial because it reduces the amount of over-dried grain. As a result, the airflow necessary for successful drying using Metzger's model is lower than that required by the model used by Ryniecki et al. (1993b).

The model used by Ryniecki et al. (1993a, 1993b) is very sensitive to re-wetting of the bottom layers of grain, because the simulation uses many thin layers. For a 3-m deep bin of grain, Metzger's model (Metzger 1980) divides the grain bed into 10 layers (each 30-cm deep) compared with 30 layers (each 10-cm deep) used by Ryniecki et al. (1993b) for the same bin. Small amounts of rewetting that would be averaged over a thicker layer in the model of Metzger (1980) are detected by the Ryniecki et al. (1993b) model, and affect the drying time and the airflows required.

To control the time of drying by using the top grain-layer moisture content, one of the stop conditions of the GCA was changed from $M_w \leq 14.5\%$ to $M_t \leq 14.5\%$. The other stop condition, $M_{av} \leq 14.5\%$, was unchanged. This modification resulted in a lower optimized-continuous-airflow of 26 $L \cdot s^{-1} \cdot t^{-1}$ compared with the original continuous-airflow rate of 37.5 $L \cdot s^{-1} \cdot t^{-1}$ (Ryniecki et al. 1993b). The new rate is closer to the 20 $L \cdot s^{-1} \cdot t^{-1}$ recommended by Friesen and Huminicki (1987) for drying wheat under similar conditions. The second modification to the GCA was to set the airflow (q_{ar}) and the initial airflow level for the first time step of drying (q_{ai}) to the new optimized value (26 $L \cdot s^{-1} \cdot t^{-1}$).

Preliminary simulations using top grain layer control in the algorithm reduced the overall cost of drying by 45% compared with the original GCA, but the airflow range was quite large. Simulation results indicated that although the average airflow over 30 yr of autumn drying (16 $L \cdot s^{-1} \cdot t^{-1}$) was low relative to an optimized continuous-airflow rate of 26 $L \cdot s^{-1} \cdot t^{-1}$, there was a wide range of airflows, from 0.83 $L \cdot s^{-1} \cdot t^{-1}$ to 59 $L \cdot s^{-1} \cdot t^{-1}$. To provide the maximum airflow required, the fan size would have to be large, resulting in a high capital cost for the drying system.

The third modification to the GCA was to reduce the upper limit of the airflow determined by the algorithm to a more practical range. Evaluation of the airflow patterns revealed that in most simulation years the highest airflow occurred during the first or second day of drying, after which the airflow varied within a smaller range. In no year between 1961-1990 did the maximum airflow ever occur after the first few days of drying, so it was assumed that the success of drying would not be greatly affected by imposing a maximum airflow level, q_{max}. This airflow level was determined by evaluating the airflow range in the later stages of drying. Simulations were run using q_{max} equal to 50 and 40 $L \cdot s^{-1} \cdot t^{-1}$. A value of 50 $L \cdot s^{-1} \cdot t^{-1}$ did not noticeably affect the results, whereas 40 $L \cdot s^{-1} \cdot t^{-1}$ reduced the mean cost of drying and increased the mean of the spoilage index. Levels of q_{max} below 40 $L \cdot s^{-1} \cdot t^{-1}$ were not tested because at 40 $L \cdot s^{-1} \cdot t^{-1}$ the drying time of 76 d became a limiting factor in most of the 30 yr of preliminary simulations. Furthermore, 40 $L \cdot s^{-1} \cdot t^{-1}$ is within the range of airflows recommended by MDA for near-ambient drying in Manitoba (Friesen and Huminicki 1987). Based on these considerations, a maximum airflow of 40 $L \cdot s^{-1} \cdot t^{-1}$ was set in the new control strategy.

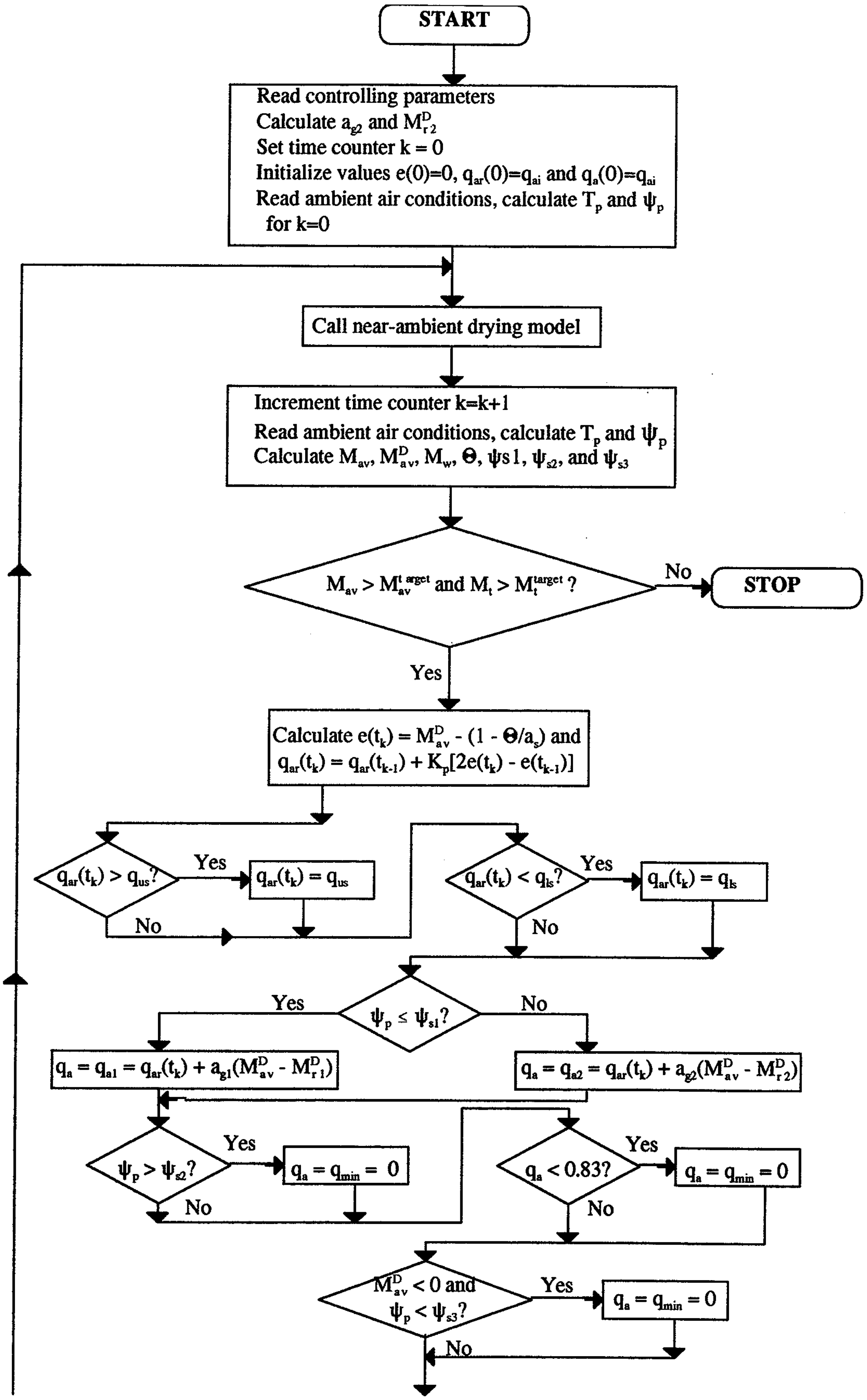
A minimum airflow level of 0.83 $L \cdot s^{-1} \cdot t^{-1}$ was proposed by Ryniecki et al. (1993b) to prevent spoilage by cooling the grain with aeration at times of poor drying. Inspection of simulation output from 30 yr of weather (1961-1990) indicated that q_{min} was maintained for only short periods of time (the longest period in all 30 yr was 91 h). The fourth modification to the GCA was to set q_{min} equal to 0.0 based on the assumption that short periods of time without aeration would not greatly increase the rate of grain spoilage because the grain temperatures are usually low. The airflow often alternates between the minimum and a high level (Fig. 3.1). Airflow control in a field situation would be simplified by turning the fan off during periods of poor drying rather than maintaining a low flow rate. Again, note that q_{min} is not equal to q_{ls}, and similarly the maximum airflow, q_{max} is not the same as q_{us} (Sect. 3.1.2).

Simulations by the revised algorithm using 30 yr of Winnipeg weather demonstrated that the algorithm still performed successfully. In fact, using this version of the algorithm, the cost of drying was reduced by 51% when compared with the original GCA, and 62% when compared with a continuous-airflow rate of 26 $L\cdot s^{-1}\cdot t^{-1}$ (Epp et al. 1996).

Implementing this algorithm as a controller for an actual drying system proved difficult, however. Although the airflow had been limited to a reasonable range, it was difficult to design a fan system that could produce a variable airflow over such a wide range and with the high static pressure requirement typical in grain drying and aeration. One method would be to design a fan or blower with a variable speed motor which could provide the full range of airflows at the required pressures. According to several local fan manufacturers and dealers such a fan is not currently available, and would be difficult to design. This would also increase the capital cost. Another alternative would be to vary the airflow by using a fan which would provide the maximum airflow, and either venting the air to reduce the flow rate, or manipulating the back-pressure in the duct. Both of these alternatives would require considerably lower capital cost, but would defeat the purpose of varying the flow rate to save energy. The fan would be operating at the maximum flow rate for the duration of the drying, using more energy than a conventional fixed-airflow system.

As a further simplification, then, the continuously-variable airflow was replaced with a multistage airflow. This concept was based on the premise that using two different sized fans in combination, four airflow levels could be produced: q_{min} (both fans off), q_{low} (small fan on), q_{med} (large fan on), and q_{max} (small and large fan on). Assuming that the flow rates of two fans in parallel are additive, the following airflows were used as the fifth modification to the GCA: 0, 15, 25, and 40 $L \cdot s^{-1} \cdot t^{-1}$. The algorithm calculated an airflow between 0 and 40 $L \cdot s^{-1} \cdot t^{-1}$ as before, but the staged airflows were determined according to the flowchart (Fig. 3.3). This version of the GCA (shown in Fig. 3.3) will be referred to in the rest of the thesis as the multistage controller (MC). A typical airflow pattern using the MC is shown in Fig. 3.4 for the simulation year 1969.

The same method of optimizing the parameters was used for the MC as for the original GCA (Sect. 3.1.1), although the parameter set was simplified. Initial bounds and increments were chosen for each parameter to be optimized, and 30 yr of simulations were run for each combination of parameters. Elimination of parameters from the optimization stage will be discussed in Sect. 3.3.3.


START
Read controlling parameters
Calculate a_{g2} and M^D_{r2}
Set time counter k = 0
Initialize values e(0)=0, $q_{ar}(0)=q_{ai}$ and $q_a(0)=q_{ai}$
Read ambient air conditions, calculate T_p and ψ_p for k=0
Call near-ambient drying model
Increment time counter k=k+1
Read ambient air conditions, calculate T_p and ψ_p
Calculate M_{av}, M^D_{av}, M_w, Θ, $\psi s1$, ψ_{s2}, and ψ_{s3}
$M_{av} > M^{target}_{av}$ and $M_t > M^{target}_t$?
No
STOP
Yes
Calculate $e(t_k) = M^D_{av} - (1 - \Theta/a_s)$ and
$q_{ar}(t_k) = q_{ar}(t_{k-1}) + K_p[2e(t_k) - e(t_{k-1})]$
$q_{ar}(t_k) > q_{us}$?
Yes
$q_{ar}(t_k) = q_{us}$
No
$q_{ar}(t_k) < q_{ls}$?
Yes
$q_{ar}(t_k) = q_{ls}$
No
$\psi_p \le \psi_{s1}$?
Yes
No
$q_a = q_{a1} = q_{ar}(t_k) + a_{g1}(M^D_{av} - M^D_{r1})$
$q_a = q_{a2} = q_{ar}(t_k) + a_{g2}(M^D_{av} - M^D_{r2})$
$\psi_p > \psi_{s2}$?
Yes
$q_a = q_{min} = 0$
No
$q_a < 0.83$?
Yes
$q_a = q_{min} = 0$
No
$M^D_{av} < 0$ and $\psi_p < \psi_{s3}$?
Yes
$q_a = q_{min} = 0$
No

... continued

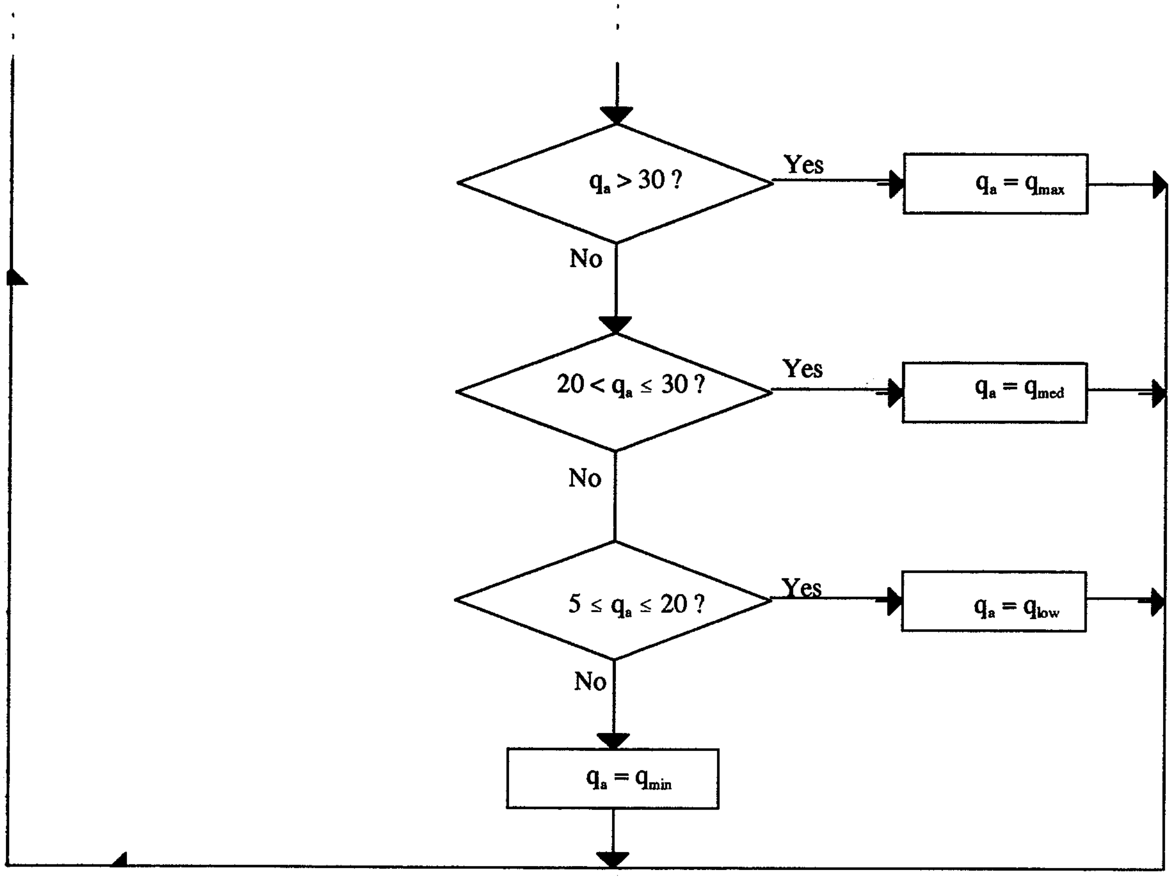


Fig. 3.3 Flowchart of multistage-controller (MC) (continued from previous page).

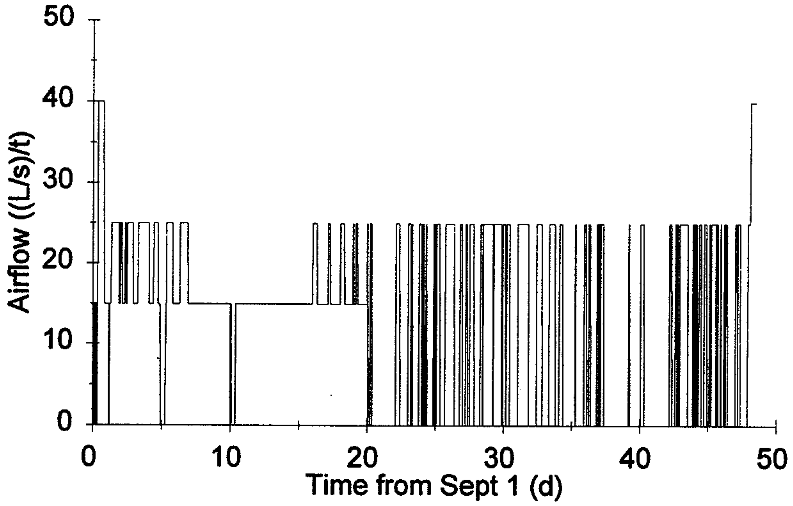


Fig. 3.4 Airflow calculated by the multistage controller (MC) for simulated drying in 1969.

3.2 Continuous-airflow Optimization

3.2.1 Need for optimization The most common method of near-ambient drying on the Canadian Prairies is to use a continuous-airflow. Although the main interest of this thesis was to investigate a multi-stage airflow drying system, it is still useful to obtain an optimum continuous-airflow rate for a given set of conditions. This airflow rate can be used to compare to airflow rates reported in the literature for similar conditions. Also, the GCA requires a reference fixed airflow, q_{ar}, to calculate the increase or decrease in airflow level (Sect. 3.1.2). The method reported by Ryniecki et al. (1993b) uses the optimized continuous-airflow for q_{ar}.

3.2.2 Input conditions The input conditions to the drying simulations run in this thesis differ from those used in previous studies using the GCA. Prices of grain and electrical power were changed to reflect the current rates, and the grain density was changed to a value more compatible with research done on the physical properties of Manitoba wheat (Muir and Sinha 1988).

The weather file consisted of 30 yr of hourly temperature and relative humidity data from Environment Canada for Winnipeg, 1961-1990. The start date was varied with different simulations, but in all cases, drying had to be completed by Nov. 15 for drying to be successful. Grain spoilage was calculated using the equations of Fraser and Muir (1981), and for drying to be successful, Θ had to be less than 1.0 at the end of drying in each of the 30 yr tested. The price of the grain, 228 $/t, was based on Canadian Wheat Board prices for No. 1 Canadian Western Red Spring wheat, 14.5% protein (Canada Grains Council 1995). Electrical energy was priced at 0.04853 $/kWh (Manitoba Hydro 1995). The grain density was 725 kg/m^3 (Muir and Sinha 1988). The initial moisture content of the grain was varied with different simulations, but in all cases the target moisture content was 14.5%. The depth of grain was 3 m, and was divided into 30 layers of 0.1 m depth.

3.2.3 Method of optimization and analysis Obtaining the optimum airflow level using the GCA was done using a simplified version of the control algorithm. The only parameter optimized is the airflow level. This control algorithm is shown in Fig. 3.5. The airflow level was kept at a fixed airflow rate throughout the drying period, and drying was complete when the average moisture content and the top layer moisture content were both at 14.5% or lower. The 30 yr averages of energy consumption, spoilage, over-drying, time, and overall cost of drying were then calculated.

The continuous-airflow rate was optimized for nine different combinations of drying times and initial moisture contents. The drying times of 92, 75, and 61 d corresponded to start dates of Aug. 15, Sept. 1, and Sept. 15, respectively (drying had to be completed by Nov. 15 for all harvest dates). Initial moisture contents were 16, 17.5, and 19.0%. The airflow rates were optimized by repeated running of the simulation program using the input conditions given in Sect. 3.2.2.

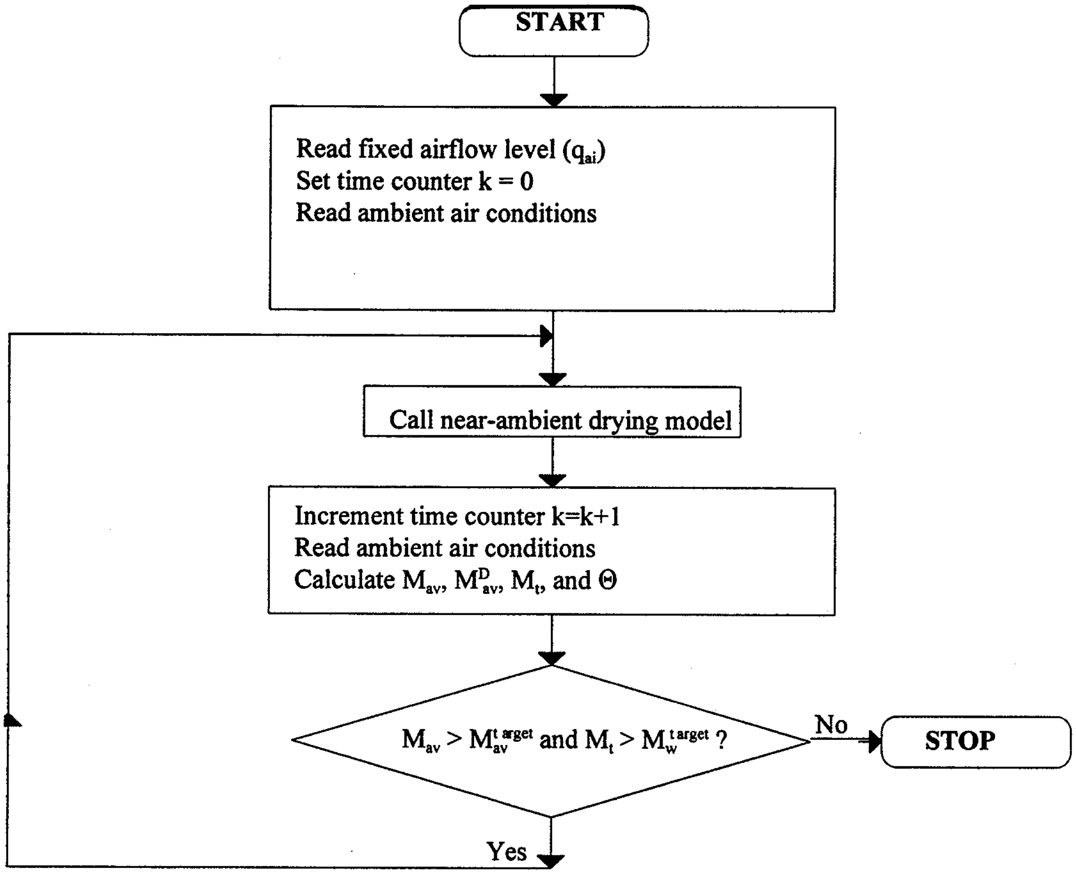


Fig. 3.5 Flowchart of the continuous-airflow control algorithm.

A regression equation to predict the continuous-airflow rate was fitted to the airflows using the procedure STEPWISE in SAS (SAS Institute Inc. 1982). This procedure searches for the best fit equation by evaluating models with different combinations of variables and comparing the resulting r^2 values. The basic quadratic equation was of the form:

$$\text{airflow} = C_0 + C_1 \cdot d + C_2 \cdot M_i + C_3 \cdot d^2 + C_4 \cdot M_i^2 + C_5 \cdot M_i \cdot d \qquad (6)$$

where C_i's are the coefficients, d is the drying period expressed in number of days until Nov. 15, and M_i is the initial grain moisture content.

3.2.4 Optimization results Optimizing the airflow using a 30 yr weather data file produced the airflow levels shown in Table 3.2 for nine combinations of harvest dates and initial moisture contents. The quadratic regression using these airflows yielded the coefficients shown in Table 3.3, with $r^2 = 0.93$. Using this equation to predict airflows within the range of moisture contents and harvest dates given in Table 3.2 is a faster method of determining airflow rates than doing a 30 yr optimization/simulation for each new input. Note that the flow rate for Sept. 1, 19.0% M_i is 24.5 $L \cdot s^{-1} \cdot t^{-1}$, compared with the previous 26 $L \cdot s^{-1} \cdot t^{-1}$ (Sect. 3.1.3). The reason for the slight difference is that a different grain density was used for the previous optimizations.

Table 3.2 Optimum continuous-airflow levels ($L \cdot s^{-1} \cdot t^{-1}$).

Initial Moisture Content (%)	Start Date		
	Aug. 15	Sept. 1	Sept. 15
16.0	15	18	34
17.5	15	22	41
19.0	34	25	43

Table 3.3 Quadratic coefficients and r^2 value for continuous-airflow regression (Eq. 5). Airflow in $L \cdot s^{-1} \cdot t^{-1}$.

C_0	C_1	C_2	C_3	C_4	C_5	r^2
628	-8.57	-33.3	0.0388	0.803	0.119	0.93

3.3 Reduction of Optimization Time

3.3.1 Sensitivity analysis of optimized parameters For the multistage controller (MC) to be used in a real near-ambient drying system, it must be able to accommodate the range of input conditions that are common to grain drying on the Prairies. The GCA reported by Ryniecki et al. (1993b) was optimized for a specific harvest date, initial moisture content, initial grain temperature, depth of grain, and weather data set. All of these factors could change from year to year for a given location, and the general pattern of weather could change with different locations across the Prairies. Whereas some of the factors can be controlled to some extent by the farmer, the year-to-year weather and how that weather will impact drying cannot be predicted. The only way to accommodate that uncertainty when optimizing the GCA is to use a weather-data file containing data for many years. The depth of grain will depend on the bin dimensions and on the amount of grain to be dried. Depth of grain greatly affects the airflows needed (Friesen and Huminicki 1987) for near-ambient drying, but is something a farmer has more control over and was kept constant for the simulations in this thesis. Initial grain temperature can vary from year to year, but has less effect on near-ambient drying than either harvest date or initial grain moisture content. Harvest date can greatly influence drying because it can affect initial grain moisture content, the ambient-air condition, and the length of time available for drying. Initial grain moisture content is important because it determines how much moisture needs to be removed from the grain to dry it to a safe level.

The original GCA was designed to handle these variations in harvest date and initial moisture content by using a different set of control parameters specific to a given set of input conditions. For any combination of input conditions, a different set of control parameters will produce optimal performance by the GCA. Obtaining the set of control parameters is a very time consuming and computer-intensive process, depending on how many years of weather data are used for the optimization. Fewer years in the weather data set speed up the optimization, but limit the variety of weather conditions the drying simulation is exposed to, decreasing the chances that successful drying will occur in future years.

Re-optimizing the parameters for every different set of input conditions is impractical in an actual control system. The optimization process would be simplified if there were fewer parameters. Ryniecki et al. (1993b) optimized a set of 11 parameters, using three steps for each parameter and splitting the optimization into two steps of five and six parameters, respectively. Using this method, each round of optimization took $3^5 + 3^6 = 972$ simulations. The optimization and simulation process searched for the best combination of parameters by narrowing the bounds on the parameters (Ryniecki and Nellist 1991a), so this process was repeated until the best combination was found. If five steps were needed to find the right combination, then 5 x 972 = 4860 simulations were run, each using a full weather data set. One 30 yr drying simulation takes approximately 40 min of computer time (using a Sparc ELC workstation with SunOS 5.4). Thus, 4860 simulations could take up to 17017 h of computer time. Elimination of a parameter exponentially reduces the number of simulations needed. The purpose of the sensitivity analysis was to investigate the possibility of eliminating of certain parameters to make the

MC more adaptable to different harvest dates and initial moisture contents.

Elimination of the optimization process altogether limited the effectiveness of the GCA, which was designed to provide optimal drying for any given set of inputs. For the algorithm to be effective, some means of optimizing the algorithm had to be retained, but kept to a reasonable time frame. As a controller for a real drying system, the optimization would be done every year, once the pertinent input variables were known. These variables would be the start date of drying, type of grain, the initial grain-moisture content, and the initial grain temperature. The time for optimization could be about 24 h (depending on the computer used), after which the parameters would be known by the controller, and drying could commence. Reducing the optimization time to approximately 24 h required the number of parameters to be optimized had to be reduced from 11 to 2. Some means of varying the other parameters needed to be developed.

A quadratic regression predicting the parameter value based on the inputs of start date and initial moisture content for each parameter could eliminate the need for time-consuming optimization, allowing the parameters to be estimated mathematically. Developing a regression equation for all 11 parameters similar to the method used in Sect. 3.2.3 was not possible in the time available, because it would have required doing a 30 yr optimization for each parameter for several combinations of start dates and initial moisture contents.

3.3.2 Sensitivity analysis method The sensitivity analysis examined which parameters had the least effect on the output variables, especially the overall cost of drying. The control parameters were optimized over a practical range of start dates and initial moisture contents, using a 2 yr weather file to reduce computer time. This produced an estimate of the range of each parameter for a number of start dates and initial moisture contents.

The two years selected for the weather data file were chosen based on the amount of over-drying when using a continuous-airflow. In 30 yr of simulated drying (1961 - 1990) the maximum over-drying with a continuous-airflow occurred in 1966 (Sept. 1 harvest, 19.0% M_i). The minimum was in 1969. Although using two years in the weather file instead of 30 was much less desirable for optimizing the parameters, it was assumed that selecting two extreme years might expose the controller to a similar range of weather as found in the 30 yr file. Over-drying was used as the basis for selection because it reflected whether the overall weather pattern for that year was 'wet' or 'dry.'

The control parameters were optimized for nine different input conditions (Table 3.4). These conditions were the same as those used to optimize the continuous-airflow levels (Sect. 3.2.2). The start dates were Aug. 15, Sept. 1 and Sept. 15, and the initial moisture contents were 16.0, 17.5, and 19.0%. Previous work had indicated that varying the parameter K_p over a wide range (5 - 75) had little effect on the output variables, and it was thus fixed at 15, based on earlier optimizations. Similarly, the initial 2 yr optimizations indicated that varying β_1 and r_{qus} (the ratio of q_{us} to q_{ar}) had no effect on the cost of drying at either extreme of the drying conditions (Aug. 15, 16.0% and 19.0% M_i, and Sept. 15, 19.0% M_i). Setting r_{qus} to 1.0 equated q_{us} to q_{ar} (the optimized continuous-airflow) for each different start condition. Thus β_1 and q_{us} were eliminated from the other optimizations to save time. The remaining eight parameters were optimized for all input conditions. The parameters resulting from the optimization are presented in Table 3.5.

The sensitivity of the output variables (specific energy, spoilage, over-drying, time, and cost of drying) to changes in the parameters indicated which parameters were most important in determining the success of drying. A set of simulations was done to check the effect of varying each parameter on the output variables by varying them individually over the range given in Table 3.4, using the Sept. 1, 19.0% M_i drying scenario. For example, parameter a_{g1} was tested with a low value of 9.0 and a high value of 43. The change in output variables compared with the optimum values for Sept. 1 and 19.0% initial moisture content are shown in Table 3.6

To test the possibility of using equations to predict the parameters, the data given in Table 3.4 were used for quadratic regressions for each parameter. The method used was the same as that reported in Sect. 3.2.3, except that the data used (Table 3.4) were derived from optimizations using a 2 yr, not 30 yr weather data file. The regression coefficients of some of the parameters are given in Table 3.7. Those that were omitted did not have satisfactory results when fitted with a regression equation.

Table 3.4: Optimum parameters for nine drying conditions using a 2 yr (1966 and 1969) weather data file (high and low values indicated by superscripts H and L, respectively)

Control	Aug. 15			Sept. 1			Sept. 15		
Parameter	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%
a_{gl}	31	31	43^H	20	31	15	9.0^L	27	9.3
a_s	0.34	0.48	0.01^L	0.33	0.54	1.37^H	0.92	0.42	0.70
β_1	6.36	NA	6.36	NA	NA	NA	NA	NA	6.36
β_2	-5.42	-5.58	-6.94^L	-6.16	-5.58	-4.52	-4.02^H	-4.55	-4.42
β_3	0.28	0.25	0.61	0.05^L	0.25	2.45^H	1.94	1.33	0.28
M^D_{r1}	0.53	0.42	0.39	0.54^H	0.22	0.15^L	0.33	0.18	0.31
q_{ls}	7.3	4.8	20^H	11	5.5	12	9.8	4.7^L	8.8
q_{us}	q_{ar}	NA	q_{ar}	NA	NA	NA	NA	NA	q_{ar}
r_g	0.83	1.23	1.11	1.03	0.42^L	1.01	0.55	0.90	1.53^H
r_r	0.38^L	0.56	1.39	0.53	1.23	1.14	0.88	0.69	1.82^H

Table 3.5: Mean, standard deviation, and coefficient of variation for optimized parameters

Parameter	Mean	s	C.V. (%)
a_{gl}	24.0	11.4	47
a_s	0.57	0.393	69
β_2	-5.24	0.946	18
β_3	0.83	0.869	105
M^D_{r1}	0.341	0.142	42
q_{ls}	9.3	4.75	51
r_g	0.96	0.337	35
r_r	0.96	0.473	49

Table 3.6 Change (%) in output variables corresponding to changes in control parameters (for Sept. 1 harvest, 19.0% M_i).

Control	Specific Energy		Spoilage		Over-drying		Time		Cost	
Parameter	low	high	low	high	low	high	low	high	low	high
a_{gl}	-12.3	+41.7	+9.6	-10.8	+232.3	+147.7	+14.1	-22.3	+5.8	+51.8
a_s	+13.7	-3.4	-16.7	+1.2	+435.4	+3.1	-27.2	+1.1	+46.5	-2.9
β_2	+1.4	+1.4	-3.6	-1.2	-24.6	-4.6	-5.1	-0.3	-0.5	+0.6
β_3	+5.5	0.0	+3.6	0.0	-35.4	0.0	+4.7	0.0	+2.9	0.0
M^D_{r1}	-17.1	+4.1	+20.5	-2.4	+140.0	-1.5	+20.4	-1.6	-5.3	+3.7
q_{ls}	+11.0	+37.0	+21.7	-25.3	+81.5	+346.2	+21.0	-35.1	+16.7	+62.2
r_g	+2.1	+1.4	+9.6	-2.4	+236.9	+4.6	+12.0	-2.1	+20.3	+1.7
r_r	-7.5	+25.3	0.0	+18.1	+289.2	-46.1	-3.6	+26.9	+14.5	+20.4

Table 3.7 Quadratic coefficients[1] and r^2 value for regression of control parameters using 2 yr (1966 and 1969) weather file.

Control Parameter	C_0	C_1	C_2	C_3	C_4	C_5	r^2
a_{gl}	-2.82e+01	-1.13e-01	3.69e+00	4.22e-04	-1.13e-01	3.89e-03	0.75
a_s	1.01e+01	1.89e-01	-1.90e+00	-1.19e-03	5.85e-02	-1.22e-03	0.38
q_{ls}	6.28e+01	-1.43e-01	-6.62e+00	-5.93e-05	1.72e-01	9.00e-03	0.91
r_g	1.48e+01	-2.67e-04	-1.76e+00	9.11e-04	7.11e-02	-7.78e-03	0.57
r_r	2.42e+01	-1.64e-02	-2.83e+00	-5.93e-05	8.74e-02	7.78e-04	0.79

[1] Equation of the form: control parameter = $C_0 + C_1 \cdot d + C_2 \cdot M_i + C_3 \cdot d^2 + C_4 \cdot M_i^2 + C_5 \cdot M_i \cdot d$

3.3.3 Simplification of the parameters Using the results of the sensitivity analysis (Tables 3.4 - 3.6), there were several approaches available for simplifying the parameter set. The simplest method was to fix each parameter at a constant value for all combinations of inputs. The value of the parameters would be such that drying would be successful in all 30 yr for any of the input scenarios. Another option was to use the regression equations given in Table 3.4 to predict each parameter given the harvest date and initial moisture content. Finally, certain parameters could be optimized provided there were only two or three, so that excessive optimization time would not be required. Thus each parameter had to be examined individually to analyse its effect on the drying performance and its role in the algorithm.

Over the range of values obtained from nine combinations of harvest dates and initial moisture contents, variations in β_2, β_3 and M^D_{r1} caused less than 10% change in the overall cost of drying. The parameter β_2 had a low coefficient of variation, 18% (Table 3.5), indicating that it did not change much over the range of input conditions, and fixing it at its mean value (Table 3.5) would not likely affect the success of drying in any of the drying scenarios. By contrast, β_3 had a relatively high coefficient of variation, 105% (Table 3.5), but because it did not have a great effect on the overall cost of drying (Table 3.4) it was also fixed at its mean value. Using the low value of M^{D}_{r1}, 0.15 (Table 3.4), the overall cost of drying changed only 5.3%, and using the high value of 0.54 (Table 3.6), the cost of drying only changed 3.7%. However, the low value of M^{D}_{r1} increased the time of drying by 20.4%. Instead of fixing M^{D}_{r1} at the average value, it was fixed at 0.54, the maximum. This would increase the cost of drying slightly, but the algorithm would be more likely to complete drying successfully in all the drying scenarios.

Both r_g and a_s were dropped from the algorithm altogether. The parameter r_g had less of a predictable effect on the drying results than the other parameters. Also, its quadratic regression yielded a correlation coefficient of only 0.57 (Table 3.7), not a good enough fit to confidently use the equation for predicting r_g. The average value of r_g (Table 3.5) was 0.96. Fixing r_g at 1.0 allowed Eq. 3 (Sect. 3.1.2) to be simplified by dropping the r_g term altogether. Similarly, the regression equation for a_s did not have a good fit ($r^2 = 0.38$) (Table 3.7). Setting a_s at a constant of 1.0 eliminated it from the algorithm as well, simplifying the progress of spoilage term (Eq. 5, Sect. 3.1.2) to $[1 - \Theta]$.

The remaining three parameters (a_{g1}, q_{ls}, and r_r) affected cost of drying and time of drying to the extent that they could not be fixed at an average value. The quadratic regression for a_{g1} (Table 3.7) had a fairly good fit ($r^2 = 0.75$), so the equation was used to determine a_{g1} for all the input conditions. Finally, although q_{ls} and r_r had high r^2 values (Table 3.7), both caused large changes in the output variables (Table 3.6), therefore these two parameters were chosen as the ones to optimize. Optimization of these two parameters compensated for fixing some of the other parameters at constant values, yet did not demand too much computer time for any new combination of harvest date or initial moisture content.

The changes made to the parameters produced a controller which could be optimized in a short time (approximately 24 h), and was versatile enough to handle combinations of drying time and initial moisture content within the ranges given. This version of the MC will be referred to in the rest of the thesis as the 2-parameter multistage controller (MC2P).

3.4 Optimizing the Full Multistage Controller (MC8P)

The original method of optimizing all parameters (Ryniecki et al. 1993b) is still superior in terms of producing an algorithm which optimizes the cost of drying within the limits of spoilage and drying time. Although the time requirements were too great to optimize using 30 yr weather for all the combinations of start dates and initial moisture contents as was done with the sensitivity analysis and continuous-airflow, one full 30 yr optimization of the MC was done to obtain a set of optimum parameters to use for comparison purposes. For ease of reference, this will be referred to as the full multistage controller (MC8P), because eight parameters were optimized.

The time of optimization was shortened by eliminating those parameters which had little effect on the overall cost of drying. The parameters which were eliminated were K_p, β_1, and q_{us} (Sect. 3.3.2). The start date was Sept. 1, and the initial moisture content was 19.0%. The other inputs were the same as reported in Sect. 3.2.2.

4. RESULTS AND DISCUSSION

4.1 Simulations Using Nine Input Scenarios

4.1.1 Optimized parameters One of the objectives of this thesis was to develop a simplified control algorithm that would be capable of operating over the range of harvest dates and initial moisture contents typical of the Winnipeg region. The MC2P met this criterion for all but two of the drying conditions (Sect. 3.3): Aug. 15 harvest, 19.0% M_i, and Sept. 15 harvest, 19.0% M_i. In the first case the best combination of q_{ls} and r_r (Table 4.1) resulted in successful drying in 27 of the 30 yr. The spoilage index exceeded 1.0 in 1969, 1983, and 1984. In the latter case (Sept. 15, 19.0% M_i), the optimization search produced no combination of q_{ls} and r_r that could complete drying in even half of the 30 yr tested.

Using the parameters shown in Table 4.1, drying was successful in each of the 30 yr (1961 - 1990) for the remaining seven combinations of start date and M_i. Parameters q_{ls} and r_r were optimized, and a_{g1} was calculated using the quadratic regression equation (Sect. 3.3.3). A different reference airflow (q_{ar}) was used for each of the nine drying conditions. These airflow rates were shown in Table 3.2.

There are several possible explanations for the failure of the MC2P in Aug. 15 at 19.0% M_i and in Sept. 15, 19.0% M_i. For the Aug. 15 case, the high moisture content of the grain, combined with high temperatures increased the likelihood of grain spoilage. This is probably why the optimized continuous-airflow for Aug. 15 and 19.0% M_i (Table 3.2) appears to be an anomaly. One would expect the airflow requirement to increase

Table 4.1 Control parameters optimized (q_{ls} and r_r) and calculated (a_{g1}) for nine drying conditions using the MC2P

Control	Aug. 15			Sept. 1			Sept. 15		
Parameter	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%
a_{g1}	42.1	15.2	54.9[1]	25.5	39.2	28.4	20.6	30.9	NA[2]
q_{ls}	8.7	21.7	40.1[1]	18.1	10.3	18.4	29.8	24.4	NA[2]
r_r	0.74	0.74	1.33[1]	1.62	0.98	0.94	0.70	0.82	NA[2]

[1] Spoilage index over 1.0 in 1969, 1983, and 1984.
[2] No optimum combination of parameters found. Drying incomplete in most years

with increasing moisture content and with late harvest dates. The optimized continuous-airflow for Aug. 15, 19.0% M_i, however, is higher than Sept. 1, 19.0% M_i. The increment in airflow from 17.5% to 19.0% for both Sept. 1 and Sept. 15 start dates is not very large, yet for Aug. 15, the airflow for 19.0% M_i is roughly twice that of 17.5% M_i. This trend is also apparent in the parameters optimized using the 2 yr weather file (Sect. 3.3.2). Many of the parameters had a much larger difference between the Aug. 15, 19.0% level and either the Aug. 15, 17.5% or the Sept. 1, 19.0% levels.

The recommended airflow rates for near-ambient drying in Manitoba (Friesen and Huminicki 1987) provide a means of checking the airflows shown in Table 3.2. Table 4.2 shows the airflows for four initial moisture contents and three harvest dates (the units of airflow were converted to $L \cdot s^{-1} \cdot t^{-1}$ from $L \cdot s^{-1} \cdot m^{-3}$ using a bulk density of 0.725 t/m^3). Two observations can be made from comparing Table 4.2 to Table 3.2. The first is that the airflows optimized for Table 3.2 are reasonably close to those in Table 4.2, but generally higher. Differences in the simulation models and weather data years could account for this. The other observation is that in both cases, the airflow for Aug. 15, 19.0% M_i is higher than the airflow for Sept. 1, 19.0% M_i.

Table 4.2 Recommended minimum airflow rates ($L \cdot s^{-1} \cdot t^{-1}$) for Manitoba (adapted from Friesen and Huminicki 1987).

Initial Moisture Content (%)	Start Date Aug. 15	 Sept. 1	 Sept. 15
16	12	14	26
17	12	15	32
18	14	17	39
19	21	18	41

Another explanation for the failure of the MC2P in optimizing q_{ls} and r_r may be that the regression equation did not produce the best value of a_{gl} for those conditions. Also, the remaining parameters were fixed at values which were to satisfy all input conditions. Although this resulted in successful drying for most of the nine conditions, at two of the extremes it did not. Furthermore, both the regression equation for a_{gl} and the set parameters were determined based on a simplified optimization of the control parameters using only two years of weather. The 2 yr weather file could not represent all the possible variations in weather that occur over a 30 yr period, even though two extreme years (in terms of over-drying) were selected.

The failure of the MC2P for Aug. 15, 19.0% M_i was due to the spoilage index (Θ) exceeding 1.0. The assumption that when $\Theta = 1.0$ the grain has deteriorated enough to cause a loss in grade or is unsafe to store is probably a conservative one. Sanderson (1986) evaluated results from experimental near-ambient drying tests, and did not notice any increases in fat acidity value (a measure of grain quality) or decreases in germination in stored grain, despite its calculated spoilage index being greater than 1.0. He speculated that the deterioration model was too conservative, and concluded that though the model was useful in giving an indication of the change in grain quality, it could not be used as a measure for quantifying it (Sanderson 1986). If the deterioration model used to calculate the spoilage index is indeed too conservative, then perhaps the spoilage limit in the simulations using the MC should have been set higher. In that case, the optimization for Aug. 15, 19.0% M_i would be more likely to produce an optimal set of parameters that would ensure complete drying in all years. In 1969, the worst year of drying with the Aug. 15 start date, the final spoilage index was 1.14. In the other two years (1983 and 1984) it was 1.05 and 1.08, respectively. Increasing the maximum spoilage limit by only 15% would have resulted in successful drying in all three of these years.

The failure of the MC2P in Sept. 15 at 19.0% M_i was due to incomplete drying by Nov. 15 in most of the 30 yr tested, compared with excessive spoilage as the cause for failure for Aug. 15, 19.0% M_i. This is likely because the cooler weather after Sept. 15 slowed the predicted mould growth and germination loss resulting in a lower calculated spoilage index. The shorter time of drying (61 d instead of 92 d) combined with a decreasing moisture deficit did not allow the MC2P to complete drying in most of the 30 yr. In other words, either the average moisture content, M^D_{av}, or the top layer moisture content, M^D_t, was not at the target level by the end of the drying period. Again, the fixed parameters may not have been at appropriate levels for this drying condition. Also, the optimized continuous-airflow of 43 $L \cdot s^{-1} \cdot t^{-1}$ may have been a problem when used as the reference airflow (q_{ar}) in the MC2P. This is because the algorithm limits the airflow to a maximum of 40 $L \cdot s^{-1} \cdot t^{-1}$ (Fig. 3.3). The 40 $L \cdot s^{-1} \cdot t^{-1}$ maximum limit was selected based on previous simulation work, all of which used either Aug. 15 or Sept. 1 harvest dates. Nevertheless, incomplete drying by Nov. 15 is not a problem if spring drying is considered. The cold winter weather of the Prairies preserves the grain despite its high moisture content, and drying can continue in spring. Although this scenario was not included in the drying simulations, it is a recommended practice for use with continuous-airflow drying in Manitoba and becomes necessary with late harvest dates (Friesen and Huminicki 1987).

4.1.2 Cost of drying Another objective of developing the MC2P was to have a near-ambient drying control algorithm that would reduce the cost of drying compared with conventional continuous-airflow systems. Despite the changes to the MC that reduced its ability to provide the optimum control for all drying scenarios (because most of the parameters were fixed, not optimized), it still reduced the cost of drying when compared with continuous-airflows in the seven drying scenarios that were successful (Table 4.3). In Aug. 15 at 19.0% M_i, the mean cost of drying for the 27 successful years was also lower than the cost using the continuous-airflow. The improvement in cost over the continuous-airflow ranged from 63% to 77% (airflows used for the continuous-airflow results are given in Table 3.2).

The improvement in cost of drying for Aug. 15, 19.0% M_i (66%) was similar to the other drying conditions. Cost of drying for this harvest date and M_i was the highest of all the nine drying conditions for both the continuous-airflow and the MC2P (Table 4.3). The high reference airflow required for Aug. 15, 19.0% M_i would result in higher energy costs and possibly more over-drying.

Table 4.3 Mean cost of drying ($/t) using the MC2P and continuous-airflow for nine drying conditions based on 30 yr of simulations using 3 harvest dates and 3 initial moisture contents

Control	Aug. 15			Sept. 1			Sept. 15		
Algorithm	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%	16.0%	17.5%	19.0%
Fixed airflow	4.89	4.92	7.34	4.11	4.53	4.83	5.29	6.49	6.97
MC2P	1.18	1.14	2.38[1]	1.54	1.45	1.77	1.49	1.71	NA[2]

[1] Mean based on the 27 yrs of successful drying. Spoilage index was over 1.0 in 1969, 1983, and 1984.
[2] No optimum combination of parameters found. Drying incomplete in most years

For both the Aug. 15 and Sept. 1 start dates, the cost of drying with the MC2P was higher at 16.0% than at 17.5% M_i. This is not the expected result, because less time and energy should be used to dry grain from 16.0% to 14.5% average moisture content than from 17.5% to 14.5%.

4.2 Comparison of Three Control Strategies

4.2.1 Output variables To examine the response of the MC in more detail, the output variables are given in Table 4.4 for 30 yr of simulations using the Sept. 1, 19.0% M_i start condition. This date was chosen as a more typical harvest date in the Winnipeg area than either Aug. 15 or Sept. 15. The 19.0% initial moisture content was chosen because for the MC to be used to its full advantage, grain should be harvested at a high moisture content and dried with the dryer, not in the swath. Lower moisture content grain at harvest may not justify the expense of a complicated system such as the MC.

For comparison purposes, the output results of the continuous-airflow of 25 $L \cdot s^{-1} \cdot t^{-1}$ (Table 3.2), the MC8P (Section 3.4) and the MC2P are given in Table 4.4. Comparison with the MC8P provides an indication of the effect of fixing most of the parameters at set levels and only varying a_{g1}, q_{ls}, and r_r according to the harvest date and initial moisture content.

Table 4.4 Comparison of results of 30 yr of autumn drying simulations for Sept. 1 harvest, 19.0% M_i from strategies: CA - the optimized continuous-airflow of 25 $L \cdot s^{-1} \cdot t^{-1}$; MC8P - the MC with eight optimized parameters; and MC2P - the MC with two optimized parameters.

Variable	Mean			Standard Deviation			Minimum			Maximum		
	CA	MC8P	MC2P	CA	MC8P	MC2P	CA	MC8P	MC2P	CA	MC8P	MC2P
Yearly average airflow, $L \cdot s^{-1} \cdot t^{-1}$	25	13.5	15.8	NA	0.58	0.01	NA	12.2	15.8	NA	14.2	15.8
Drying time, d	27.5	49.0	44.7	5.57	7.5	9.0	17.8	37.9	31.1	47.0	71.5	68.3
Final moisture content												
average bed, % w.b.	13.1	14.4	14.4	1.00	0.08	0.14	11.6	14.3	14.1	14.5	14.5	14.5
wettest layer, % w.b.	15.0	16.0	15.8	1.07	0.92	0.95	14.4	14.8	14.5	16.9	17.0	17.0
Maximum spoilage index of all layers	0.61	0.83	0.72	0.10	0.11	0.11	0.45	0.63	0.54	0.81	0.99	0.89
Specific energy consumption, MJ/(kg H_2O evap)	1.27	1.46	1.82	0.39	0.27	0.41	0.71	1.06	1.26	2.49	2.54	3.35
Energy consumption, MJ/t	89.1	81.9	104.2	17.5	14.7	23.3	58.3	61.0	75.7	150.9	141.3	195.2
Over-drying, kg/t	15.93	0.65	1.58	8.86	0.72	1.18	0.30	0.00	0.04	33.54	2.59	4.33
Cost, $/t	4.83	1.25	1.77	1.91	0.02	0.38	1.36	0.98	1.27	8.82	1.92	3.20

4.2.2 Continuous-airflow control algorithm The continuous airflow output results of 30 yr simulations for Sept.1 harvest, 19.0% M_i are given in Table 4.4. The airflow was fixed at 25 $L \cdot s^{-1} \cdot t^{-1}$ thus no maximum, minimum, or standard deviation are given for the continuous-airflow. The mean drying time for 30 yr was 27.5 d, out of 75 d available for drying. The maximum time of drying in all 30 yr was 47.0 d, which is still much less than the 75 available days. Reducing the airflow level below 25 $L \cdot s^{-1} \cdot t^{-1}$ to make better use of the drying time and reduce energy costs would have caused incomplete drying in some years.

The 30 yr mean of the wettest layer moisture content, M_w, indicates that in most years M_w is higher than the target average moisture content of 14.5%. If this high moisture content grain is limited to a small part of the bin (i.e. one or two layers), the grain might equilibrate to the average moisture content of the whole bin. The maximum moisture content of the wettest layer in all 30 yr was 16.9%. This is quite a high level, although the average moisture content of the bin was 14.5% or lower (one of the criteria for successful drying). Some method of grain storage management such as turning the grain to mix it would be necessary to ensure that localized concentrations of high moisture content grain would not cause spoilage.

The spoilage index had a 30 yr mean of 0.61 and a maximum of 0.81, indicating that it was not a limiting factor in any of the 30 yr. Over-drying, the result of the average moisture content being less than 14.5%, had a 30 yr mean of 15.93 kg/t. Together with the energy consumption of 89.1 MJ/t, this contributed to a mean total drying cost of 4.83 \$/t (prices of wheat and electrical energy were 228 \$/t and 0.04853 \$/kWh, respectively).

4.2.3 The multistage controller (MC) The MC2P was successful in reducing the cost of drying lower than the continuous-airflow strategy, but not lower than the MC8P. The output results of 30 yr of simulations for Sept. 1 harvest, 19.0% M_i are shown in Table 4.4. Ideally, an optimized strategy would minimize the output variables related to cost of drying (airflow, energy consumption, over-drying, and overall cost) by maximizing the limiting constraints (drying time, spoilage index, and final moisture content).

Using the MC resulted in a considerable reduction in mean airflow for the 30 yr of simulation compared with the continuous-airflow. The MC8P operated more efficiently, with a mean airflow of 13.5 $L{\cdot}s^{-1}{\cdot}t^{-1}$, compared with 15.82 $L{\cdot}s^{-1}{\cdot}t^{-1}$ for the MC2P (Table 4.4). The grain was not ventilated continuously during the drying period, thus the time of drying for the two multistage controllers was longer than with continuous-airflow: 49.0 d for the MC8P and 44.7 d for the MC2P, compared with only 27.5 d using continuous-airflow.

The control algorithm for all three strategies terminated drying when the average moisture content was no more than 14.5% ($M_{av} \leq 14.5\%$), and when the drying front had reached the top of the grain bed ($M_t \leq 14.5\%$). The MC2P had a 30 yr mean M_{av} of 14.4%, which indicates it was successful at approaching the target value. The mean for the continuous-airflow was lower, 13.1%. For all three strategies, M_{av} reached a maximum of 14.5% in one or more of the drying years. The wettest layer moisture content, M_w, had a 30 yr mean of 15.8% with the MC2P and 16.0% with the MC8P. In years such as when M_w was 17.0%, the re-wetting was even greater. These moisture contents are higher than the safe storage level of 14.5%, and would require the operator to mix the grain to let it equilibrate to the average moisture content. In some years the wettest layer moisture content was not much greater than 14.5%, indicating that the rewetting was probably limited to a small part of the bin.

The MC8P was better at maximizing the spoilage limit than the MC2P, with a mean spoilage limit of 0.83 compared with 0.72. The highest value of the spoilage limit in 30 yr of drying with the MC2P was 0.89. This was not as high as the MC8P (maximum of 0.99), and indicates that setting the parameters at a value that satisfies a range of harvest dates and initial moisture contents means that it is probably not optimal for any one combination.

The MC2P was more energy-intensive than the continuous-airflow strategy. The total energy consumption was 17% higher with the MC2P. Specific energy was also higher with the MC2P. The same was true of the MC8P, but the total energy consumption was less, 81.9 compared with 89.1 MJ/t (Table 4.4). This reflects the fact that the average airflow was greater with the MC2P than with the MC8P, and more energy was used to operate the fans. The reason both MC strategies had higher specific-energy consumption (energy consumed for every unit mass of water removed, MJ/kg H_2O) than the continuous airflow was because the continuous airflow had higher levels of over-drying.

Although the energy consumption with the MC2P was higher than with the continuous-airflow, the reduction in over-drying was enough to reduce the cost of drying to 1.77 \$/t compared with 4.83 \$/t with the optimized continuous-airflow. The MC8P had the lowest cost of drying, at 1.25 \$/t.

In most categories of output variables presented in Table 4.4, the standard deviation was higher with the MC2P than with the MC8P. This was expected, because the MC8P was better able to handle the yearly variations in weather patterns than the MC2P. With the MC8P, eight parameters were optimized to provide the best mean cost of drying over 30 yr of weather with the Sept. 1, 19.0% M_i drying condition. The optimization made the MC8P better suited to handle the specific case of Sept. 1 harvest with 19.0% M_i grain. Using the same parameters, the MC8P was unable to complete drying without spoilage using other harvest dates or initial moisture contents. By comparison, the MC2P was designed to be more general, and most of the parameters were fixed at a level that would dry in 30 yr of weather over a range of harvest dates and initial moisture contents. Only two of the parameters were optimized for the Sept. 1, 19.0% M_i start condition, and one parameter was varied according to the regression equation. This explains why the results of the MC2P were not as good as the MC8P, and why the standard deviation was higher with the MC2P in all but two of the output categories.

The range associated with cost of drying was reduced using the MC2P compared with the continuous airflow. Standard deviations were 0.38 \$/t and 1.91 \$/t, respectively. This improvement in the variation in cost is important because it affects the farmer's profits. The cost of drying was 8.82 \$/t in the worst year using the continuous airflow. Such an increase in cost of drying compared with the mean (4.83 \$/t) could be enough to reduce the farmer's profits to 0 \$/t or less. The MC2P had a smaller range (1.27 \$/t to

3.20 $/t) and would thus be more predictable, allowing the farmer more security in financial planning.

Although the MC2P did not reduce cost of drying as low as the MC8P, it was certainly more cost-efficient than the continuous-airflow. This satisfies the objectives set out in the beginning of the thesis (Sect. 1.2), to develop a controller that would improve cost of drying compared with continuous-airflow near-ambient drying.

4.3 Performance of the MC2P in Extreme Years

4.3.1 Selection of 'dry' and 'wet' years In the previous section, the 30 yr mean results of the controller for Sept. 1, 19.0% M_i were discussed. Also of interest is the behaviour of the controller in certain years, especially years which could be considered extreme in terms of 'wet' or 'dry' weather conditions. Given the complicated system of setting airflow levels, overall weather patterns , and predicted progress of drying and spoilage, selecting 'wet' or 'dry' weather years is not a straightforward task. One criterion for selection is to use the performance of the continuous-airflow as an indicator, because continuous-airflow drying is the method generally used for near-ambient drying. The level of over-drying with continuous-airflow is indicative of the overall weather pattern of that year. The highest level of over-drying with 25 $L \cdot s^{-1} \cdot t^{-1}$ continuous-airflow (for Sept. 1 harvest, 19.0% M_i) using 30 yr of simulations occurred in 1966, and the lowest in 1969. These years were chosen as 'dry' and 'wet' years, respectively, to analyse the response of the MC2P.

Several other years are of interest when examining simulations using the MC2P from 1961 - 1990. In 1967 (Sept. 1, 19.0% M_i), maximum levels of over-drying and spoilage, and minimum specific energy consumption occurred. In 1977, the maximum levels of specific energy consumption, cost, and time were reached. These years will also be looked at in more detail.

For the start date of Aug. 15 and 19.0% M_i, the years 1969, 1983, and 1984 are of interest, because in those years the MC2P failed to complete drying before grain spoilage occurred.

4.3.2 Characteristics of weather in selected years The temperature and relative humidity of the ambient air are the most important variables which affect grain drying with the MC2P. Temperature and relative humidity determine the psychrometric properties of air. The amount of moisture that the ambient air can absorb from the wet grain will depend on its moisture deficit. This is defined as the difference between the vapour content of the air at the equilibrium relative humidity of the grain and the actual vapour content at ambient conditions (Fig. 4.1). For comparison purposes, Fig. 4.2 shows the mean daily moisture deficits for the drying period between Sept. 1 and Nov. 15 in 1966, 1969, 1967, 1977. The cumulative moisture deficits (total of the average daily moisture deficits until Nov. 15) are also given.

In 1966, the ‘dry’ year of maximum over-drying with continuous-airflow, the cumulative moisture deficit was 65.2 g/kg, compared with 46.2 g/kg in 1969, the ‘wet’ year (Fig. 4.2). The MC2P reached the highest level of over-drying in 1967. In that year, the cumulative moisture deficit was again higher (72.9 g/kg) than in 1977 (65.6 g/kg), suggesting that a higher cumulative moisture deficit results in more over-drying.

The drying potential of the air decreases as winter approaches (Figure 4.2). This is most pronounced in 1969, when the moisture deficit fluctuates about 0.5 g/kg after 20 d. In 1967, there is a gradual decrease in moisture deficit as winter approaches, but the high values in the beginning of the drying period contribute to its high cumulative moisture deficit.

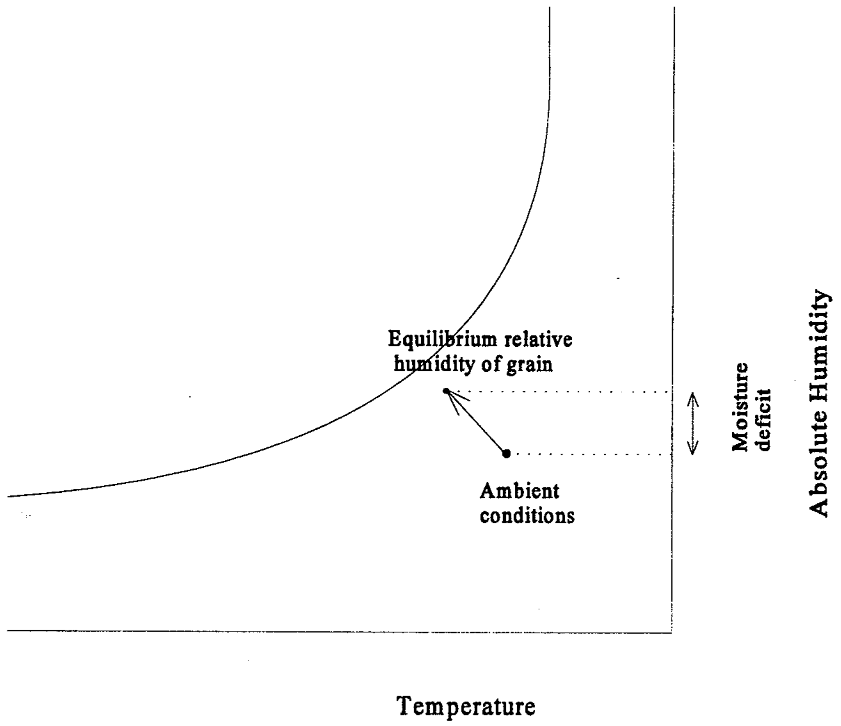


Fig. 4.1 Skeleton psychrometric chart showing the moisture deficit in air.

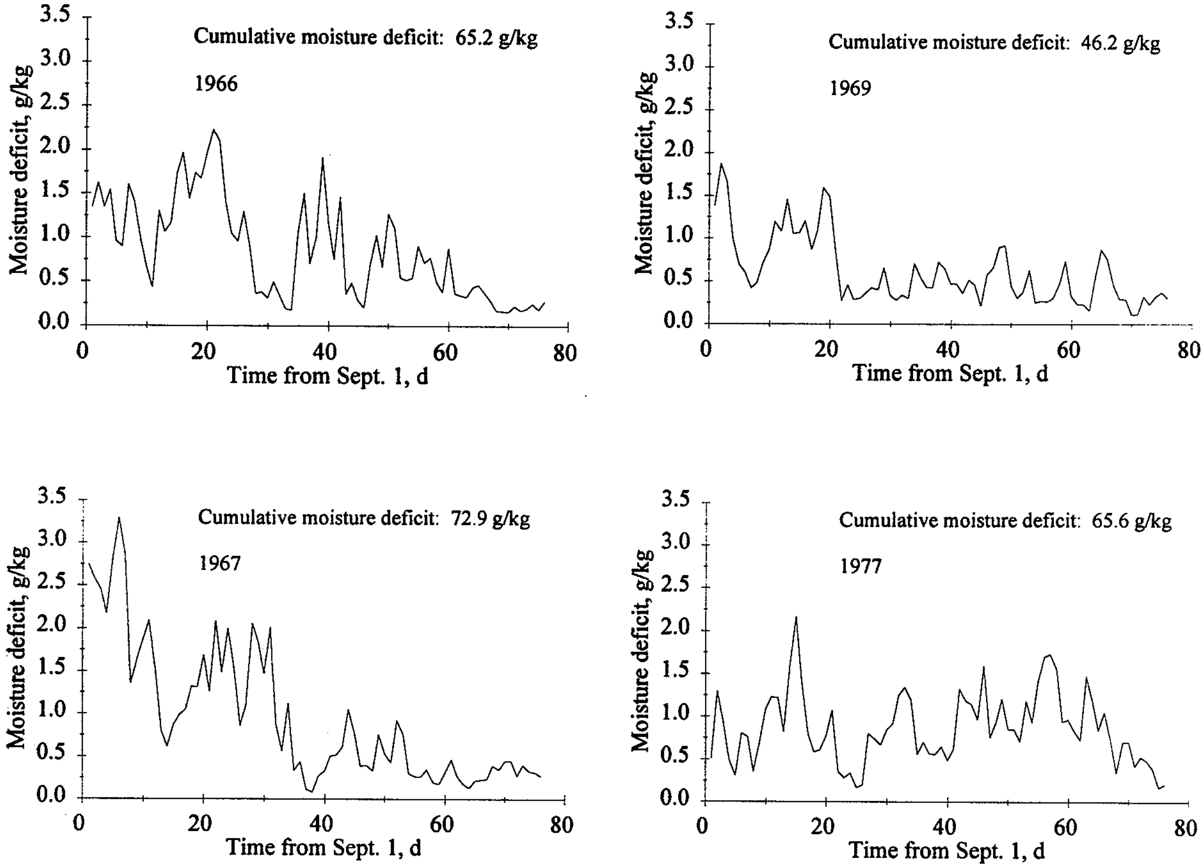


Fig. 4.2. Mean daily moisture deficit of ambient air for selected weather years.

4.3.3 Response of the control strategies The continuous-airflow is not able to use the changes in ambient-air conditions to its advantage, thus it is more susceptible to extremes in weather. Figure 4.3 compares the dimensionless grain moisture content and spoilage indices for the 'dry' year (1966) and the 'wet' year (1969) for the Sept. 1, 19.0% M_i harvest condition. Note the excessive over-drying in 1966 as M^D_{av} drops below the target value of 0.0 (14.5% moisture content) by about 17 days, and continues to fall. Drying continues because the drying front has not yet reached the top layer. When M^D_t drops to the target level, then the drying front has passed through, and the entire bed is dry. Rewetting of the bottom layer (M^D_b) occurs near the end of drying, but not in excess of the target moisture content. The final over-drying in 1966 was 33 kg/t.

In 1969 (Fig. 4.3) the pattern is different. The moisture content of the bottom layer does not become as dry as in 1966, and more re-wetting occurs after 20 d, bringing the bottom layer moisture content well above the target level by the time M^D_t reaches 0.0. The rewetting of the bottom layers keeps the average moisture content higher, and it remains near the target level at the end of drying. Final over-drying in 1969 was 5.75 kg/t, much less than in 1966. In both years, the progress of spoilage ($1 - \Theta$) follows a similar pattern, with final Θ values of 0.74 and 0.81 for 1966 and 1969, respectively.

The MC2P is better able to respond to changes in weather patterns because the algorithm can control the airflow levels according to the ambient-air conditions. In 1966 there was some over-drying (0.87 kg/t by the end of drying) but the controller was able to minimize this by manipulating the airflow. Thus although M^D_{av} reached the target level by approximately 25 d (Fig. 4.4) it was maintained near that level for the remainder of

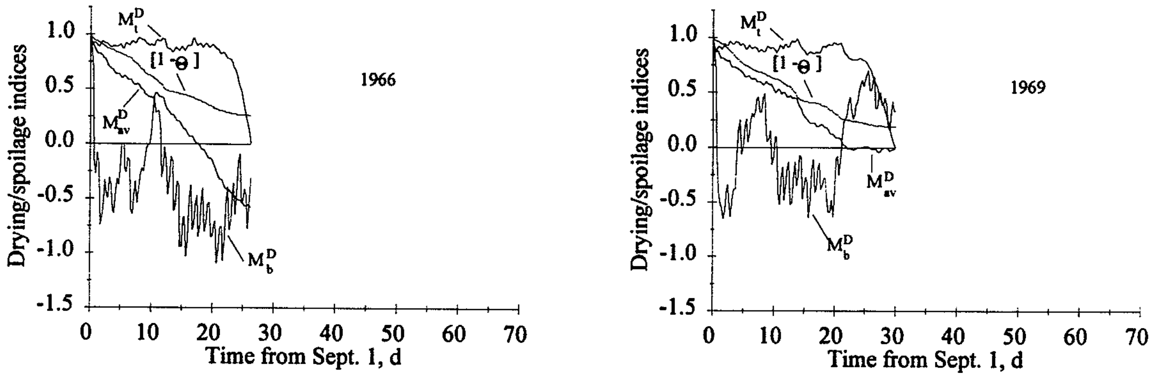


Fig. 4.3 Dimensionless moisture contents and progress of spoilage for simulations using 25 (L/s)/t continuous airflow with Sept. 1 harvest, 19% initial moisture content.

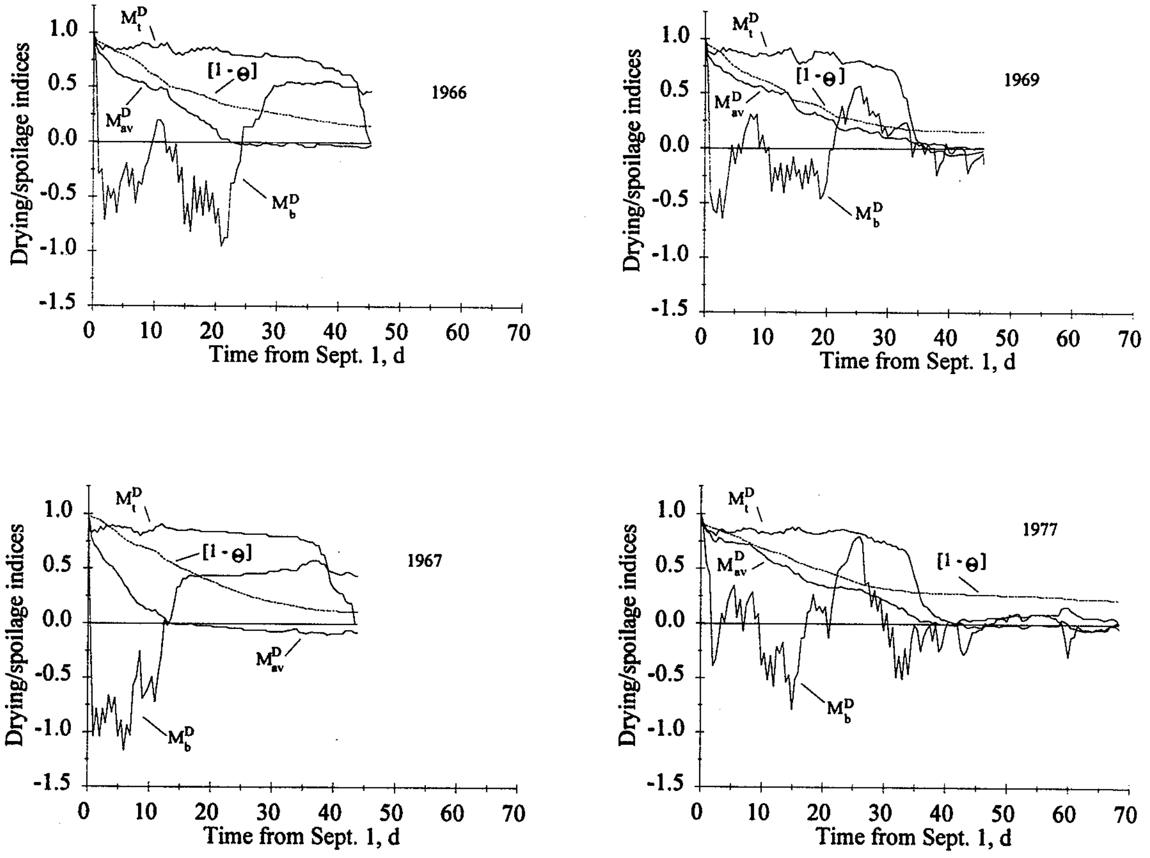


Fig. 4.4 Dimensionless moisture contents and progress of spoilage for simulations using the 2-parameter multistage controller (MC2P) with Sept. 1 harvest, 19% initial moisture content.

drying, until M_t^p reached the target level. Excessive over-drying such as with the continuous-airflow was prevented by allowing the bottom layers to rewet. At the end of drying, the bottom layer moisture content (M_b^p) was quite high.

In 1969, the average moisture content did not decrease as rapidly (Fig. 4.4), reflecting the lower cumulative moisture deficit compared with 1966 (Fig 4.2). The average moisture content had not reached the target value by the time the drying front had reached the top layer. This is why drying continued until 48 d, even though M_t^p had already dried. The final spoilage index was the same in both 1966 and 1969 when using the MC2P.

The over-drying reached the highest level in 1967 when using the MC2P, at 4.33 kg/t. In that year, the average moisture content reached the target of 14.5% moisture content by about 12 days (Fig. 4.4). The high daily averages of the moisture deficit in the early days of drying (Fig 4.2) helps explain why this occured. By the end of drying in 1967, the cumulative moisture deficit was 72.9 g/kg. To counter the low M_{av}, the algorithm re-wet the bottom grain layers by using the fan in periods of high ambient-air relative humidity. The final moisture content of the bottom layers was quite high by the end of drying (see M_b^p, Fig. 4.4), and would increase the chance of localized spoilage if the grain were not mixed upon completion of drying.

In 1977, the specific energy consumption, time, and overall cost were the maximum of the 30 yr when drying with the MC2P. The reason for this is probably because the top layer (M_t^p) failed to reach the target level after the drying front passed through. By 35 d the drying front had reached the top, but M_t^p remained just above 0.0

until 68 d (Fig. 4.4). This prolonged time of drying increased the power used by the fans, thus increasing the cost of drying. The performance of the MC2P for Aug. 15 harvest and 19.0% M_i is shown in Fig. 4.5 for the three years in which the spoilage index exceeded 1.0. This can be seen by the progress of spoilage, $[1 - \Theta]$. When $[1 - \Theta]$ falls below 0.0, spoilage is considered to have occurred, and the drying simulation is terminated for that year. The progress of spoilage in 1969 (Fig. 4.5) provides a good example. At the end of the drying time, the spoilage index was 1.14. The progress of spoilage in 1969 fell below 0.0 around day 21, and continued to drop (Fig. 4.5). In 1983 and 1984, maximum spoilage, Θ, was only 1.05 and 1.08, respectively. In 1984, rewetting of the bottom grain layers likely contributed to this problem. The drying front reached the top layer by about 33 d, but the high moisture content of the bottom layers (see M_b^D) increased M_{av}^D, prolonging the drying time to 67.9 d (Fig. 4.5).

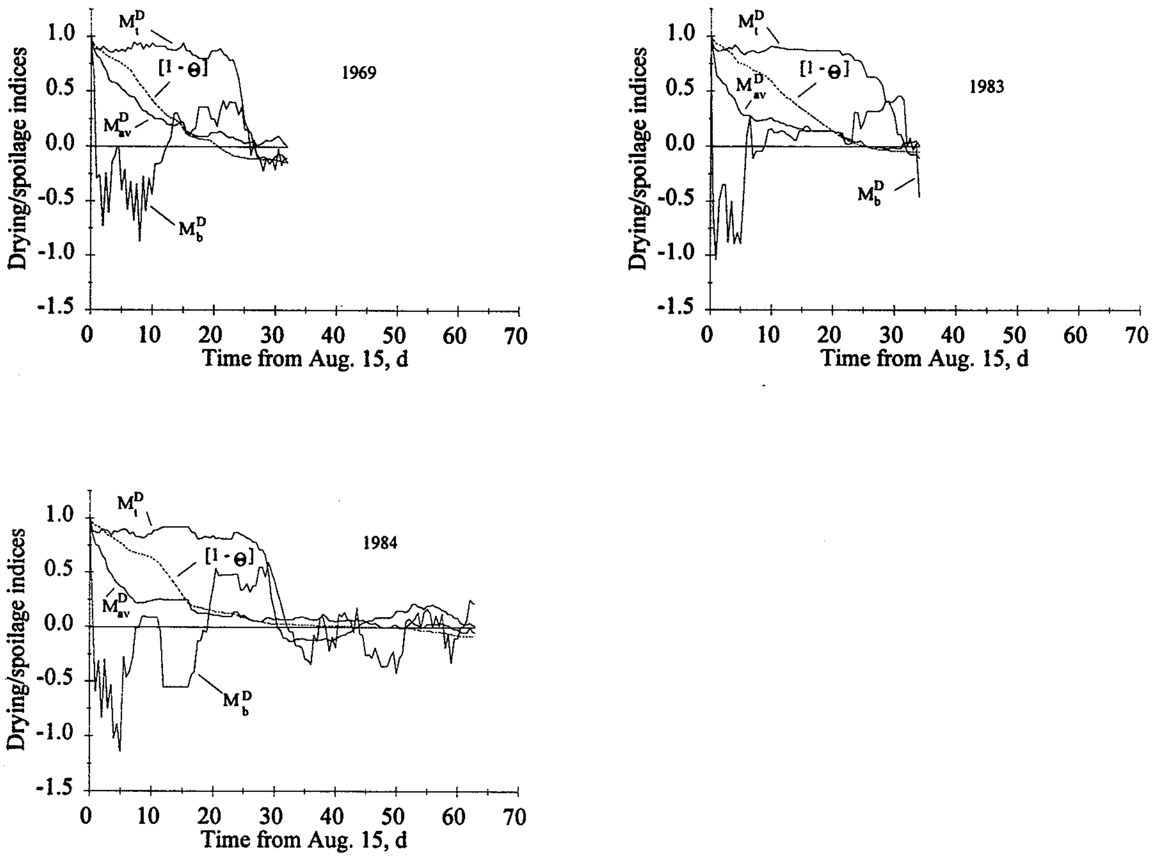


Fig. 4.5 Dimensionless moisture contents and progress of spoilage for simulations using the 2-parameter multistage controller (MC2P) with Aug. 15, 19% initial moisture content.

4.4 Practical Considerations

4.4.1 Application of the MC2P Ultimately, the MC2P should be used as a controller in near-ambient drying systems on farms. Several problems should be discussed when considering this scenario. One disadvantage of the MC2P is that it is more management-intensive. The operator must mix the grain after drying to ensure that the bulk equilibrates to the average moisture content.

Durability of the system and its components could also be a disadvantage. The MC2P requires more equipment, some of it electronic, than does the continuous airflow strategy. The fan is the only component subject to failure using continuous airflow. Using the MC2P, the system could fail in several ways. There are two fans, not simply one, which require maintenance. The microprocessor-controller could be affected by power failures or surges, or could malfunction for other reasons. Contamination of the relative-humidity sensor could result in incorrect readings, which would certainly affect the controller. The MC2P receives input from the relative-humidity sensor and thermocouples, and must output a signal to control the fans. Here again, there is a potential for malfunction which does not exist when using continuous airflow. Also, the MC2P requires a much longer time of drying than the continuous airflow strategy, which could increase the likelihood of equipment breakdown.

Another uncertainty regarding the cost of drying with the MC2P is the effect of fluctuating grain prices on the cost of drying. The ability of the MC2P to save drying costs depends on the price of electrical energy and the price of wheat. Electrical energy rates increase predictably, but grain prices do not. The price of #1 CWRS wheat fluctuated considerably in the period from 1983/84 to the 1993/94 (Table 4.5). For the 11 years given in Table 4.5, the minimum price was 130.00 \$/t (1986/87) and the maximum was 228.02 \$/t (1993/94). This uncertainty means that the amount of savings using the MC2P compared with the continuous-airflow will vary from year to year, depending on the grain price. Higher grain prices improve the cost effectiveness of the MC2P compared with the continuous-airflow, because over-drying costs are driven up.

Table 4.5 Canadian Wheat Board total payment to producers for wheat, basis instore Thunder Bay or Vancouver, 1983/84 - 1993/94 (Canada Grains Council 1995)

Crop Year	#1 CWRS total payment (\$/t)
83/84	193.98
84/85	186.37
85/86	160.00
86/87	130.00
87/88	134.02
88/89	197.14
89/90	172.11
90/91	135.00
91/92	134.14
92/93[1]	191.36
93/94[1]	228.02

[1] Payment based on 14.5% protein content.

None of these problems are insurmountable, but they illustrate some of the potential difficulties in applying the MC2P to a farm situation. For the MC2P to be accepted for use on farms, it must be perceived as reliable, requiring little maintenance, and effective, as well as an improvement over existing methods.

4.4.2 Capital cost of equipment Thus far, comparison of the MC2P with continuous-airflow has been on the basis of operating costs alone. The capital costs of the system needed to operate the multistage controller have not been considered. From a practical perspective, this should certainly not be overlooked, because it contributes to the overall cost of drying.

Sokhansanj et al. (1991) calculated the total cost of drying as the sum of yearly capital, labour, over-drying, inventory loss, quality loss, and late harvest costs. For the purpose of comparing the MC2P to a continuous-airflow system, a simpler approach was used. Many of the costs are common to both systems, and both methods of drying are susceptible to the same losses mentioned above. Apart from operating costs, the main difference in cost between the two systems is the capital cost of the equipment. The cost calculation for labour, inventory loss, and late harvest costs was omitted, but the capital costs of both systems were calculated for a 5 000 bu bin. The basic equipment items (1 fan, perforated floor, transition, and vents) are common to both, but the MC2P requires an additional equipment (Table 4.6). The cost of the bin itself was omitted on the assumption that the farmer would be modifying an existing bin.

Table 4.6 Estimated costs of near-ambient drying equipment

Item	Estimated Cost ($)	
	Continuous Airflow	MC2P
10 hp centrifugal fan[1]	2000	2000
Fully perforated floor[1]	3200	3200
Fan transition[1]	520	520
Roof vents (2)[1]	180	180
7.5 hp centrifugal fan[2]	NA	1500
Second fan transition[1]	NA	520
Solid state relay switches[3]	NA	160
Relative-humidity sensor[4]	NA	350
Microprocessor-controller[3]	NA	500
Total additional capital cost	5900	8930

[1] Telephone conversation with D. McEwan, Westeel Inc., July 1996.
[2] Estimated.
[3] Personal communication with M. McDonald, Electronics Technician, Dept. of Biosystems Engineering, University of Manitoba, June 1996.
[4] Written quotation from Dycor Industrial Research, June 1995.

The calculation of capital costs was done using the method reported by Sokhansanj et al. (1991). Capital costs, C, were determined on an annual basis using the equation $C = C_0(Fr + Rc)$, where C_0 is the initial cost of the equipment, Fr is the ratio of annual capital cost to the initial cost of the drying system, and Rc is the ratio of maintenance costs to the initial cost of the drying system. Sokhansanj et al. (1991) used a value of 0.01 for Rc, and calculated Fr with the following equation: $Fr = I\{(1+r)/2 + (1-r)/2n)\} + (1-r)/n$, where I is the interest rate as a decimal fraction, r is the ratio of salvage value to the original value, and n is the life of the drying system. Assuming $I = 0.07$, $r =$

0.1, and n = 10 yr, the annual cost of the equipment was calculated per mass of grain. Assuming a 8.2 m diameter bin filled to a depth of 3 m, the mass of grain at 0.725 t/m^3 is 115 t. The annual capital cost based on amount of grain dried is 7.28 \$/t using the continuous airflow, and 11.01 \$/t using the MC2P. Adding these values to the operating costs given in Table 4.4, the total cost of drying is 12.11 and 12.78 \$/t for the continuous airflow and the MC2P, respectively. Thus, the cost of drying wheat is slightly greater when using the MC2P once capital costs of the additional equipment have been included. This comparison depends on the size of bin used in the calculation. A larger system dries more grain for the capital investment, so the comparison becomes more favourable with larger bin size. Regardless of its ability to conserve energy and reduce over-drying costs, the MC2P system will not be an attractive option unless the total cost is low enough to justify switching from the commonly used method (continuous-airflow drying).

The MC2P is more cost effective when higher grain prices are used for comparison. This could be the case if the price of wheat were greater, or if higher value crops were dried. For example, the average closing price for canola in the 1993/94 crop year was 391.38 \$/t and the highest price was 539.00 \$/t (Canada Grains Council 1995). All else being equal, using the high price of canola with the 30 yr simulation results for Sept. 1 harvest, 19.0% M_i (Table 4.4), the cost of drying would then be 9.79 \$/t and 2.26 \$/t for the continuous-airflow and the MC2P, respectively. Capital cost would remain similar to drying with wheat, so the total costs would be 21.90 and 13.27 \$/t for the continuous airflow and the MC2P, respectively. In this case, the total cost using MC2P is only 60% of the cost using the continuous airflow. Even if it were cost effective to use the

MC2P with canola, the need for such a system would be much less than the need for a dryer for wheat. The average annual production of spring wheat in Manitoba was 4.1 Mt from 1984 to 1993, and for canola in the same period, the average annual production was 0.6 Mt (Canada Grains Council 1995), only 15% of the production of wheat. Nevertheless, wheat prices have been rising, and as they increase, the benefits of using the MC2P become greater.

4.4.3 Assumptions Simulating biological and physical processes using computer models requires many assumptions. This study is no exception. Assumptions have been made regarding fan efficiency, bulk density of the grain, grain depth, and airflow resistance of the grain during the drying process.

Some of the original assumptions made by Ryniecki et al. (1993b) were retained. The fan efficiency was assumed to be 50%. This assumption affects the energy cost portion of the cost of drying, and higher fan efficiency results in a lower cost of drying. An implicit assumption regarding fan efficiency is that it is constant throughout drying. This would probably not be the case in an actual drying scenario, especially using the original GCA (Ryniecki et al. 1993b) which simulated drying with a variable airflow ranging from 0.83 $L \cdot s^{-1} \cdot t^{-1}$ to over 60 $L \cdot s^{-1} \cdot t^{-1}$. Within such a large range, the fan efficiency would likely vary considerably. The fan system proposed with the MC2P consists of two fans of different size, sometimes used individually and sometimes together. Here again, the fan efficiency would probably change depending on whether the fans were used singly or together.

Three of the other assumptions are related, and also impact on fan performance. The bulk density of the grain would change during the drying process. Based on experimental work, Muir and Sinha (1988) report standard bulk densities of 763 and 725 kg/t for Neepawa wheat at 12.7 and 16.4% moisture content, respectively. In a grain bin, this change in bulk density can result in shrinkage of the grain bulk. Sanderson (1986) reports bulk shrinkage as high as 13.7% after drying wheat from 18% to 13%. The simulation model used in this thesis did not take this into account, but rather assumed no shrinkage occurred. Shrinkage may affect airflow by changing the airflow resistance offered by the grain. Another factor affecting the airflow rate as the grain dries is that as the grain loses mass (with loss of moisture) the airflow on a per tonne basis increases. This is also true if airflows are measured on a volume basis, because volume decreases as the grain dries.

4.5 Future Possibilities

The potential of using the MC2P as an airflow controller would be more feasible if the capital costs were reduced. One method of doing this would be to have the controller connected via telephone lines to a weather station. If the weather station could provide ambient-air conditions reasonably close to those at the bin site, and if those data could be read automatically on an hourly basis, then the controller would not need to have temperature and relative-humidity sensors and the accompanying hardware. Another possibility would be to have the control parameters optimized by a central computer, and then read by the controller via an on-line connection. This would greatly simplify the controller, also reducing the capital cost of the system. Both of these scenarios are not possible with the existing services from Environment Canada, but the technology is available.

If the MC2P can be improved to the point of being cost effective compared with continuous-airflow drying (when capital costs are included), then it needs to be validated experimentally. A set of experiments similar to those of Sanderson (1986) would be an appropriate method of validation.

5. CONCLUSIONS

1. The multistage controller with two optimized parameters (MC2P) was successful in simulating drying of wheat for seven out of nine combinations of harvest dates (Aug. 15, Sept. 1 and Sept 15), and initial moisture contents (16.0%, 17.5%, and 19.0%).

2. The MC2P can be optimized for any combination of harvest date and initial moisture content (in the range stated above) within approximately 24 h of computer time, and requires airflow rates within the range currently used for near-ambient drying.

3. The MC2P improved the simulated operating cost of drying by as much as 77% when compared with continuous-airflow drying simulations with optimized fixed-airflows in nine combinations of harvest dates and initial moisture contents.

4. Using a Sept. 1 harvest date and 19.0% initial moisture content for drying simulations using 30 yr of Winnipeg weather, the MC2P reduced the cost of drying from 4.83 \$/t to 1.77 \$/t compared with continuous-airflow drying. Energy consumption with the MC2P was higher by 17%, but over-drying was reduced to 1.58 kg/t from 15.93 kg/t. The mean of the maximum yearly spoilage index was

0.72 for the 30 yr of drying.

5. When the capital costs needed for near-ambient drying were included with the cost of drying (based on an 8.2 m diameter bin containing 115 t of wheat), the MC2P had a cost of drying of 12.78 $/t, compared with the continuous-airflow cost of 12.11 $/t.

LIST OF SYMBOLS

a_{g1}, a_{g2}	values used to calculate airflows q_{a1} and q_{a2} in periods of low and high relative humidities, respectively, $L\cdot s^{-1}\cdot t^{-1}$
a_s	desired final value of the spoilage index
e	error in the proportional control-action (the difference between the progress of drying and spoilage), dimensionless
$C_{0\text{-}6}$	coefficients used in the regression equation $P = C_0 + C_1\cdot d + C_2\cdot M_i + C_3\cdot d^2 + C_4\cdot M_i^2 + C_5\cdot M_i\cdot d$, where P is the control parameter, d is the drying period expressed in number of days until Nov. 15, and M_i is the initial grain moisture content.
GCA	the generalized control algorithm of Ryniecki et al. (1993b).
k	counter of time-increments
K_p	proportional controller gain
m_o	over-drying, kg/t
M	grain moisture content, % wet mass basis (w.b.).
M_{av}	average grain moisture content of whole bed, % w.b.
M_{av}^{target}	target value for average grain moisture content of whole bed (equal to 14.5%), %w.b.
M_{av}^{D}	dimensionless average moisture content of whole bed: $(M_{av} - M_{av}^{target})/(M_i - M_{av}^{target})$
M_b	grain moisture content of the bottom layer (which has contact with the inlet air), % w.b.
M_b^D	dimensionless grain moisture content of the bottom layer: $(M_b - M_{av}^{target})/(M_i - M_{av}^{target})$
M_i	initial grain moisture content, % w.b.
M_r	reference moisture content for the average of whole bed, used as a coefficient to

	calculate airflow q_a in the control strategy responding to the diurnal variations in weather, % w.b.
M^D_{r1}, M^D_{r2}	reference moisture contents for the average of whole bed, used to calculate airflows q_{a1} and q_{a2}, respectively; $M^D_{r1} = (M_{r1} - M^{target}_{av})/(M_i - M^{target}_{av})$; $M^D_{r2} = (M_{r2} - M^{target}_{av})/(M_i - M^{target}_{av})$, dimensionless
M_t	grain moisture content of the top layer, % w.b.
M^D_t	dimensionless grain moisture content of the top layer: $(M_t - M^{target}_{av})/(M_i - M^{target}_{av})$
M^{target}_t	target value for top layer grain moisture content (equal to 14.5%), %w.b.
M_w	grain moisture content of the wettest layer, % w.b.
M^D_w	dimensionless grain moisture content of the wettest layer: $(M_w - M^{target}_{av})/(M_i - M^{target}_{av})$
M^{target}_w	target value for wettest layer grain moisture content (equal to 14.5%), %w.b.
MDA	Manitoba Department of Agriculture
MC	multistage controller version of the GCA
MC2P	MC with two optimized parameters
MC8P	MC with eight optimized parameters
q_a	airflow level determined by the control algorithm
q_{a1}, q_{a2}	airflows per tonne of grain in low and high humidities, respectively; $L \cdot s^{-1} \cdot t^{-1}$
q_{ar}	reference airflow per tonne of grain, $L \cdot s^{-1} \cdot t^{-1}$
q_{ai}	initial airflow per tonne of grain, $L \cdot s^{-1} \cdot t^{-1}$
q_{ls}	minimum level of q_{ar}, $L \cdot s^{-1} \cdot t^{-1}$
q_{low}	low final airflow level, $L \cdot s^{-1} \cdot t^{-1}$
q_{max}	maximum final airflow level, $L \cdot s^{-1} \cdot t^{-1}$
q_{med}	medium final airflow level, $L \cdot s^{-1} \cdot t^{-1}$

q_{min}	minimum final airflow level, $L \cdot s^{-1} \cdot t^{-1}$
q_{us}	maximum level of q_{ar}, $L \cdot s^{-1} \cdot t^{-1}$
r_g	ratio of a_g in periods of high/low relative humidities, a_{g2}/a_{g1}
r_{qus}	ratio used to determine q_{us}, q_{us}/q_{ar}
r_r	ratio of M_r^D in periods of high/low relative humidities, M_{r2}^D/M_{r1}^D
t	elapsed time, h
t_k	elapsed time after k-th time-increments, h
w.b.	wet mass basis for reporting grain moisture contents
β	coefficient used to calculate set-point relative humidity ψ_s; determines the shift in value of ψ_s from the equilibrium relative humidity of the wettest layer of grain (ψ_e); for $\beta = 0$, $\psi_s = \psi_e$; for $\beta > 0$, $\psi_s < \psi_e$; for $\beta < 0$, $\psi_s > \psi_e$ (Ryniecki and Nellist, 1991a), % w.b.
β_1, β_2, β_3	coefficients used to calculate set-points ψ_{s1}, ψ_{s2} and ψ_{s3}, respectively; see also description of β, % w.b.
Θ	spoilage index for the layer of grain having maximum spoilage
ψ_e	equilibrium relative humidity of the wettest layer of grain, %.
ψ_p	plenum air relative humidity, %
ψ_s	set-point relative humidity defined by eq. (1), %
ψ_{s1}, ψ_{s2}, ψ_{s3}	set-point relative humidities (defined by eq. (1) and parameters β_1, β_2 and β_3, respectively), %
\$	Canadian dollars

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