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► **To cite this version:**

Marianne Le Bail, David Makowski. A model based approach for optimizing segregation of soft wheat in country elevators. *European Journal of Agronomy*, 2004, 21 (2), pp.171-180. 10.1016/j.eja.2003.07.002 . hal-02681766

**HAL Id: hal-02681766**

**<https://hal.inrae.fr/hal-02681766>**

Submitted on 31 May 2020

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# A model-based approach for optimizing segregation of soft wheat in country elevators

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Received 22 November 2002; received in revised form 23 June 2003; accepted 23 July 2003

## Abstract

In order to satisfy agro-industrial firm requirements, soft wheat grains stored in country elevators are often divided into batches characterized by different values of grain protein content. The decision to allocate farmer's production to a high grain protein content batch or to a low grain protein content batch is often based on grain protein content measurements performed at harvest in trailers carrying wheat grains. This approach is quite expensive, does not always give a satisfactory result, and cannot be used to predict before harvest the quantity, and the quality of the production for crop collecting organization at a regional level. This paper presents a new method for optimizing batches segregated in country elevators. The general principle is to define and solve Linear Programming (LP) models including constraints on the batch weight and on the batch average grain protein content. The LP model coefficients are calculated by using field measurements or by using a crop model that predicts the values of yield and of grain protein content for the different fields of the collecting area. This method can be used to determine before harvest the optimal combination of wheat fields that would give a batch with a satisfactory average grain protein content and with a maximal weight. A case study is presented in which several optimal batches are determined for various objectives and for a collecting area including 46 wheat fields. The characteristics of the batches obtained with our method are satisfactory when the grain protein content lower bound of the LP model is not higher than 11.5%.

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**Keywords:** Grain protein content; Segregation; Soft wheat; Linear programming model; Crop model

## 1. Introduction

Grain protein content is an essential quality criterion for agro-industrial firms. It is one of the most important international standards. For example, a grain protein content higher than 11.5% is required for mak-

ing French bread, whereas a low grain protein content is required for making biscuits and some African breads (Leygue et al., 2000). Soft wheat (*Triticum aestivum* L.) produced by farmers' is stored in country elevators and the collected production is generally divided into several wheat batches with different levels of grain protein content. These batches are then sold to agro-industrial firms (millers, biscuit, and noodles factories) having different quality standard requirements.

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Three approaches can be used to improve the quality of the collected production: improving cropping systems, drawing quality territories, and optimizing the segregation of the production in the country elevator (Habib et al., 1997; Heintz, 1994; Le Bail, 1997, 2000). The third approach is considered in this paper. In order to obtain batches with satisfactory grain protein content, some collecting firms perform grain protein content measurements at the country primary elevator delivery points. The principle is to allocate each year the wheat crops of the collecting area to high or low grain protein content batches depending on the results of grain protein measurements performed by near infra-red (NIR) analysis of grain samples taken in trailers carrying farmers' productions (Orlando et al., 2000). This method has three main drawbacks. First, the systematic installation of NIR instruments in all numerous delivery points can be quite expensive. Second, grain protein content measurements can be performed only after harvest and, consequently, cannot be used to plan the organization of crop segregation or to forecast the average quality of the crop harvest and, so, do not allow a collecting firm to anticipate interesting protein-specified contracts on cereal market. Third, it is difficult to optimize the average protein content of a wheat batch by using only grain protein content measurements performed at elevator entrance. For instance, let assume that a country elevator operator is interested in making a batch with grain protein content higher than 11.5%. With the current approach based on grain protein content measurement, farmer's production will be allocated to the batch if the measured grain protein content is higher than 11.5%. If only fields with grain protein content higher than 11.5% are included in the batch, the average grain protein content of the resulting batch may be higher than 11.5%, which may be unsatisfactory for agro-industrial firms. Moreover, if all fields with grain protein content lower than 11.5% are excluded, the batch may include only a small fraction of the collected production. In such cases, the collecting firm could add low protein content grains to the batch in order to decrease the average grain protein content and to increase the weight of the batch. However, this would require some exchanges of grains between silos that can be very costly for a collecting firm.

In this paper, we present a model-based approach that can help country elevator operators to obtain optimal wheat batches with specific values of protein

content. An optimal batch is defined here as a batch with a satisfactory average grain protein content and with a maximal weight. The method is described in detail in Section 2 and a case study is then presented in Section 3. The first objective of our approach for calculating optimal batches. In order to study this problem, we consider a collecting area located in the north of France and we compare the characteristics of optimal batches obtained with our method to the characteristics of batches obtained with the collecting firms' current method. The second objective is to analyze the consequences of the errors of prediction of the crop models used for calculating optimal batches.

## 2. Methods

The general principle of our method is to define and solve a linear programming (LP) model including constraints on the weight and average grain protein content of the batch. The LP model coefficients are calculated from the yield and grain protein content values of the different fields of the collecting area. These values can be obtained at harvest from field measurements or can be predicted before harvest by using a crop model.

Various crop models can be used to predict each year, before harvest, the yield and grain protein content values of the different fields of a collecting area in function of soil characteristics, crop characteristics, and farmers' practices (e.g. Brisson et al., 1998; Makowski et al., 2001; Jeuffroy et al., 2000; Asseng et al., 2002). However most of these models include many input variables that cannot be easily measured by an economic operator. The crop model used in this paper was developed by Makowski et al. (1999, 2001) and predicts yield, grain protein content, and residual soil mineral nitrogen at harvest by using only two simple input variables, specifically the total rate of applied nitrogen, and the amount of mineral soil nitrogen at the end of winter. These variables can be easily measured by farmers or by country elevator operators. An important limitation of this model (and of all the simple models predicting yield and grain protein content) is that the errors of prediction can be important. The consequences of these errors of prediction are analyzed in Section 3.

In order to take into account objectives and constraints of country elevators, we propose two types of LP models. The first model can be used to define one batch with a maximal weight and a grain protein content higher or lower than a given threshold. The second type of LP model can be used to define two batches that differ significantly in their grain protein content values.

2.1. LP models for optimizing one batch with high (or low) grain protein content

We consider a collecting area including  $N$  cereal fields. The following LP model can be used to identify the wheat fields that should be allocated to the batch:

$$\text{Max}\{w\} \tag{1}$$

$$p \geq T_{\text{MIN}} \tag{2}$$

where  $w$  is the weight of the batch,  $p$  is the batch average grain protein content, and  $T_{\text{MIN}}$  is a lower bound of grain protein content. The value of  $T_{\text{MIN}}$  should be chosen in accordance with the objective of the collecting firm.  $w$  and  $p$  are defined by

$$w = \sum_{j=1}^N A_j Y_j I_j \tag{3}$$

$$p = \frac{\sum_{j=1}^N A_j Y_j C_j I_j}{w} \tag{4}$$

where  $A_j$ ,  $Y_j$ , and  $C_j$  are, respectively, the area, yield, and grain protein content of the  $j$ th field,  $j = 1, \dots, N$ .  $I_j$  is a binary decision variable equal to 1 if the  $j$ th field is allocated to the batch and equal to zero if not. The left-hand side of constraint (2) is not a linear function of the decision variables  $I_j$ ,  $j = 1, \dots, N$ . Consequently, model (1)–(4) cannot be solved by linear programming. To avoid this problem, it is useful to replace constraint (2) by  $pw - T_{\text{MIN}}w \geq 0$ . With our notations, this last constraint is defined by

$$\sum_{j=1}^N A_j Y_j (C_j - T_{\text{MIN}}) I_j \geq 0 \tag{5}$$

Constraint (5) is equivalent to constraint (2). However, the left-hand side of (5) is a linear function of the decision variables  $I_j$ ,  $j = 1, \dots, N$ . If constraint (2)

is replaced by (5), the optimal solution  $I^*$  can be found by pure integer programming which is a special type of linear programming (Hazell and Norton, 1986; Wayne, 1995). This kind of method can be implemented by using standard linear programming software.

When the values of  $A_j$ ,  $Y_j$ ,  $C_j$ ,  $j = 1, \dots, N$ , are known, solving model (1)–(4) gives an optimal solution, noted  $I^*$ , which defines a batch with a grain protein content  $p^*$  higher than  $T_{\text{MIN}}$  and a maximal weight  $w^*$ . Solution  $I^*$  is an  $N$ -vector defined by  $I^* = [I_1^*, \dots, I_j^*, \dots, I_N^*]^{\text{Transpose}}$ . The  $N$  elements of  $I^*$  are the optimal values of the decision variables  $I_j$ ,  $j = 1, \dots, N$ . These values indicate which fields should be allocated to the batch. Thus, the  $j$ th field of the collecting area should be allocated to the batch if  $I_j^* = 1$ .

When the objective of the collecting firm is to determine a grain batch with a grain protein content lower than a threshold  $T_{\text{MAX}}$ , constraint (5) must be replaced by

$$\sum_{j=1}^N A_j Y_j (C_j - T_{\text{MAX}}) I_j \leq 0 \tag{6}$$

Another objective may be to determine a batch with a grain protein content in a range  $T_{\text{MIN}}-T_{\text{MAX}}$ . In this case, constraints (5) and (6) must be considered simultaneously.

2.2. LP model for optimizing two batches

We define here a second LP model that allows a collecting firm to allocate fields either to a batch with an high grain protein content (batch 1) or to a batch with a low grain protein content (batch 2). In the model, the weight of batch 1 is maximized whereas the weight of batch 2 is constrained to be higher than a given fraction of the whole collected production. The model is defined by

$$\text{Max}\{w_1\} \tag{7}$$

$$p_1 \geq T_{\text{MIN}} \tag{8}$$

$$p_2 \leq T_{\text{MIN}} - \delta \tag{9}$$

$$w_2 \geq \alpha(w_1 + w_2) \tag{10}$$

where  $w_1$  and  $w_2$  are the weights of batch 1 and batch 2 respectively,  $p_1$  and  $p_2$  are the grain protein contents of batch 1 and batch 2 respectively.  $T_{\text{MIN}}$  is a lower

bound for the grain protein content of batch 1,  $\delta$  is a positive scalar ( $0 \leq \delta \leq T_{\text{MIN}}$ ) that defines an upper bound for the grain protein content of batch 2, and  $\alpha$  is a positive scalar ( $0 \leq \alpha \leq 1$ ) that defines a lower bound for the weight of batch 2. The constraint (8) ensures that the grain protein content of batch 1 is higher than  $T_{\text{MIN}}$ . The constraints (9) and (10) ensure that the grain protein content of batch 2 is lower than  $T_{\text{MIN}} - \delta$  and that the weight of batch 2 is higher than a fraction of the total weight of grains collected in the area. The coefficients  $\delta$  and  $\alpha$  must be chosen in function of the objectives of the collecting firm.

We define  $w_1$ ,  $w_2$ ,  $p_1$ , and  $p_2$  as follows:

$$w_1 = \sum_{j=1}^N A_j Y_j I_j \quad (11)$$

$$w_2 = \sum_{j=1}^N A_j Y_j (1 - I_j) \quad (12)$$

$$p_1 = \frac{\sum_{j=1}^N A_j Y_j C_j I_j}{w_1} \quad (13)$$

$$p_2 = \frac{\sum_{j=1}^N A_j Y_j C_j (1 - I_j)}{w_2} \quad (14)$$

With these notations, batch 2 includes all the fields that are not selected in batch 1. Model (7)–(14) can be defined as a pure integer programming model if (8) is replaced by  $p_1 w_1 - T_{\text{MIN}} w_1 \geq 0$  and if (9) is replaced by  $p_2 w_2 - (T_{\text{MIN}} - \delta) w_2 \leq 0$ . An optimal solution  $I^* = [I_1^*, \dots, I_j^*, \dots, I_N^*]^{\text{Transpose}}$  can then be found by using a linear programming software. With these notations, the  $j$ th field is allocated to batch 1 if  $I_j^* = 1$  and is allocated to batch 2 if  $I_j^* = 0$ . The optimal weight and grain protein content of batch 1 and of batch 2 are noted  $w_1^*$ ,  $p_1^*$ ,  $w_2^*$ , and  $p_2^*$  respectively.

### 3. Application

#### 3.1. Objectives

In this section, we present an application of our methods to a collecting area including 46 winter wheat fields. Two series of optimal batches are calculated by using the LP models defined in Section 2. For the first

series, the LP coefficients are derived from measured values of yield and grain protein content obtained for each of the 46 fields of the area. For the second series of optimal batches, the LP coefficients are derived from yield and grain protein content values predicted for each field by using a simple crop model. The first series of optimal batches is used to study the potential interests of LP models for optimizing the segregation of soft wheat in country elevators. The second series of optimal batches is used to study the consequences of calculating the coefficients of the LP models from crop model predictions instead of field measurements. The characteristics of the optimal batches obtained with the LP models are compared to the characteristics of batches obtained with a more simple method corresponding to the current collecting firms' practices. With this last method, the wheat produced on a field is allocated to the batch only if the grain protein content measured in this field is lower or higher than a given threshold.

#### 3.2. Materials and methods

##### 3.2.1. Data

We consider 46 winter wheat fields located in the collecting area of a co-operative (Oise department, north of France) (Le Bail, 1997). Wheat crops were cultivated in 1993–1994 on loam soil according to current farmers' practices. Preceding crops were sugar beet, peas, and oil seed rape. Two cultivars of winter wheat (Soissons and Scipion) were sown in autumn 1993 and harvested in July 1994. Soissons is a cultivar generally used by industrials for making bread whereas Scipion is a cultivar used either for making bread or for making biscuits. In each field, yield and grain protein content were measured at harvest time in eight micro-plots of about  $25 \times 30$  cm. Yield values ( $\text{Mg of dry matter ha}^{-1}$ ) were obtained from grains dried during 48 h at  $85^\circ\text{C}$ . Grain protein content (percentage of dry matter) was measured by using the Kjeldhal method (Horwitz et al., 1975). Yield and grain protein content values were averaged over micro-plots. The quantity of mineral nitrogen in the soil (nitric and ammonia nitrogen) ( $\text{kg ha}^{-1}$ ) was analyzed in February once water had drained from the uppermost three horizons (0–30 cm, 30–60 cm, 60–90 cm). Mineral nitrogen was extracted from four cores per horizon and per field with 1 M KCl. Mineral

Table 1  
Characteristics of the 46 fields of the collecting area

	Min	Mean	Max	Standard deviation	Variation coefficient (%)
Applied N fertilizer (kg ha <sup>-1</sup> )	110	177	242	35	20
Mineral soil N at the end of winter (kg ha <sup>-1</sup> )	12	31	54	12.1	39
Field area (ha)	5	12.1	24	5.6	46.7
Yield (Mg ha <sup>-1</sup> )	6.23	8.73	11.65	1.30	15
Grain protein content (percentage of dry matter)	8.15	10.6	14.82	1.4	13.4

nitrogen values were then averaged over cores. Table 1 gives the main characteristics of the 46 fields.

### 3.2.2. LP models

Three LP models are tested. The first model (LP<sub>1</sub>) is defined by (1), (3), (4), and (5) and is used to obtain batches with grain protein content higher than  $T_{\text{MIN}}$ . In order to study the sensitivity of the optimal solution to  $T_{\text{MIN}}$ , we consider successively five values of  $T_{\text{MIN}}$  (10, 10.5, 11, 11.5, 12%). The second LP model (LP<sub>2</sub>) is defined by (1), (3), (4), and (6). This model is used to obtain batches with grain protein content lower than  $T_{\text{MAX}}$ . Here also we consider five values of  $T_{\text{MAX}}$  (10, 10.5, 11, 11.5, 12%). Finally, the third LP model (LP<sub>3</sub>) is defined by (7)–(14). This model is used to obtain two batches with different grain protein content values. In order to study the sensitivity of the optimal solution to parameters  $T_{\text{MIN}}$ ,  $\delta$ , and  $\alpha$ , two values of  $T_{\text{MIN}}$  (11 and 11.5%), two values of  $\delta$  (0.5 and 0.8%), and two values of  $\alpha$  (0.2 and 0.5) are considered successively.

Two series of LP model coefficients are calculated for each LP model. The first series is calculated directly from the yield and grain protein content measurements obtained on the 46 fields of the collecting area (Table 1). The second series of coefficients is calculated from the yield and grain protein content values predicted for the individual fields by the crop model of Makowski et al. (1999, 2001). The crop model parameters were estimated in a previous study by using 112 nitrogen fertilizer experiments carried out between 1990 and 1996 in the Paris Basin (Makowski and Wallach, 2001). These data are completely independent from the measurements obtained on the 46 fields of the collecting area. Previous studies showed that the errors of prediction of this model can be important. Thus, the root mean squared error

of prediction of the model estimated by Makowski et al., 2001 are equal to 1.28 t ha<sup>-1</sup> and 1.49% for yield and grain protein content respectively.

### 3.2.3. Calculation of batches

LP models are implemented with the VISUAL XPRESS software (XPRESS-MP, 1997). Optimal batches are derived for the three types of LP models and for the two series of coefficients described above. The weights and average grain protein contents of the optimal batches are calculated from (3), (4), (11), (12), (13), and (14) by using successively two series of values for  $Y_j$ , and  $C_j$ ,  $j = 1, \dots, 46$ : the values predicted by the crop model and the values measured on the 46 fields.

In order to study the interest of our approach, optimal batches calculated with LP models are compared to batches resulting from the application of a simple method that consists in including into batches either all fields with measured NIR grain protein content higher than  $T_{\text{MIN}}$  or all fields with measured grain protein content lower than  $T_{\text{MAX}}$ . This method corresponds to current collecting firms' practices.

## 3.3. Results

### 3.3.1. Batches obtained by using field measurements

Tables 2A and 3A present the characteristics of the batches calculated with the LP models, when the LP model coefficients are calculated from field measurements. These tables show that the average grain protein contents of the batches are always satisfactory. The average grain protein contents of the batches calculated by LP<sub>1</sub> and LP<sub>2</sub> are respectively higher than  $T_{\text{MIN}}$  and lower than  $T_{\text{MAX}}$  (Table 2A). The difference between the average grain protein contents of the two batches

Table 2  
Characteristics of the batches

$T_{\text{MIN}}$ (%)	Average grain protein content of batch (%)	Batch weight (Mg)	Number of fields allocated to batch	$T_{\text{MAX}}$ (%)	Average grain protein content of batch (%)	Batch weight (Mg)	Number of fields allocated to batch
(A) Obtained with LP <sub>1</sub> (or LP <sub>2</sub> ) for different values of lower bound $T_{\text{MIN}}$ (or upper bound $T_{\text{MAX}}$ ) <sup>a</sup>							
Model LP <sub>1</sub>				Model LP <sub>2</sub>			
10.0	10.7	4922.2	46	10.0	10.0	3387.4	31
10.5	10.7	4922.2	46	10.5	10.5	4512.9	42
11.0	11.0	4266.8	38	11.0	10.7	4922.2	46
11.5	11.5	3037.2	26	11.5	10.7	4922.2	46
12.0	12.0	1979.6	18	12.0	10.7	4922.2	46
(B) Including all fields with measured grain protein content higher than $T_{\text{MIN}}$ or lower than $T_{\text{MAX}}$							
Grain protein content higher than $T_{\text{MIN}}$				Grain protein content lower than $T_{\text{MAX}}$			
10.0	11.4	3194.3	26	10.0	9.3	1727.9	3
10.5	11.7	2722.6	23	10.5	9.5	2199.6	13
11.0	12.0	1979.5	18	11.0	9.8	2942.7	28
11.5	12.3	1396.4	13	11.5	10.1	3525.8	33
12.0	12.8	725.8	6	12.0	10.3	4196.5	40

<sup>a</sup> LP coefficients and batch characteristics were calculated from yield and grain protein content measurements.

calculated by LP<sub>3</sub> is always higher than  $\delta$  (Table 3A). In all cases, the average grain protein contents of the batches are very near from the grain protein content thresholds used in the LP models. Table 3A shows also that the weight of the batch number 2 calculated with LP<sub>3</sub> is always higher than  $\alpha \times 100\%$  of the weight of the total wheat production.

Table 2B presents the characteristics of the batches obtained by using the current collecting firms' method. These batches include either all the fields with mea-

sured grain protein content values higher than  $T_{\text{MIN}}$  or all the fields with measured grain protein content values lower than  $T_{\text{MAX}}$ . Compared to the batches obtained with LP<sub>1</sub> and LP<sub>2</sub>, the batches presented in Table 2B have lower weights. For instance, the weight of the batch including all the fields with measured grain protein contents higher than 11% is only equal to 1979.5 Mg (Table 2B) whereas the weight of the batch obtained with LP<sub>1</sub> for the same grain protein content threshold is equal to 4266.8 Mg (Table 2A).

Table 3

Characteristics of batches 1 and batches 2 obtained with LP<sub>3</sub> for different values of  $T_{\text{MIN}}$  (11%, 11.5%), of  $\delta$  (0.5%, 0.8%), and of  $\alpha$  (0.2, 0.5)

$T_{\text{MIN}}$	$T_{\text{MIN}} - \delta$	$\alpha$	Average grain protein content (%) of		Weight (Mg) of		Number of fields allocated to	
			Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
(A) LP <sub>3</sub> coefficients and batch characteristics were calculated from yield and grain protein content measurements								
11	10.5	0.2	11.0	9.4	3937.8	984.4	34	12
11	10.5	0.5	11.0	10.4	2461.1	2461.1	18	28
11.5	10.7	0.2	11.5	9.4	3037.2	1885.0	26	20
11.5	10.7	0.5	11.5	9.9	2461.1	2461.1	23	23
(B) LP <sub>3</sub> coefficients were calculated with the crop model								
11	10.5	0.2	11.0	9.6	3803.1	1119.0	32	14
11	10.5	0.5	11.3	10.2	2427.8	2494.4	21	25
11.5	10.7	0.2	12.1	10.4	832.7	4089.5	9	37
11.5	10.7	0.5	12.1	10.4	832.7	4089.5	9	37

Batch weights and batch average grain protein contents were calculated from field measurements for A and B.

Another result is that the average grain protein contents of the batches obtained with the current method of field allocation are always very different from the required values. For instance, when  $T_{\text{MIN}} = 11\%$ , the average batch grain protein content is equal to 12% if the current method is used (Table 2B).

These results demonstrate the interest of using LP models for optimizing the segregation of wheat grains when yield and grain protein content values are known for all the fields of a collecting area. Such models allow collecting firms to obtain batches with satisfactory average grain protein content and maximal weight. This is not possible with the current method of field allocation based on grain protein content measurements. Batches obtained with this method are characterized by very low weights and their average grain protein contents are very different from the required values.

### 3.3.2. Batches obtained by using crop model predictions

Tables 3B and 4 present the characteristics of the batches calculated with the LP models, when the LP model coefficients are calculated from crop model predictions. The characteristics of these batches (batch weights and batch average grain protein contents) were evaluated by using successively field measurements and crop model predictions.

Table 4A shows that the characteristics of the batches obtained with LP<sub>1</sub> are satisfactory when

$T_{\text{MIN}}$  is lower than 11.5%. Then, both the measured and predicted values of average batch grain protein content are equal or higher than  $T_{\text{MIN}}$ . Moreover, for these values of  $T_{\text{MIN}}$ , the batch weights are very near from the values obtained when the LP coefficients are calculated from field measurements (Table 2A). On the contrary, the characteristics of the batches obtained with LP<sub>1</sub> are not satisfactory when  $T_{\text{MIN}}$  is equal or higher than 11.5%. In this case, the numbers of fields allocated to the batches are very low (even equal to zero when  $T_{\text{MIN}} = 12\%$ ) and the batch weights are much lower than the weights obtained when the LP coefficients are calculated from field measurements (Table 2A). These results can be explained by the errors of prediction of the crop model. Fig. 1 shows that the crop model underestimates the grain protein content values of the individual fields when these values are higher than 11.5%. Thus, when  $T_{\text{MIN}}$  is higher than 11.5%, some of the fields are not allocated to the batches because their grain protein content values are underestimated by the crop model.

Similar results are obtained with LP<sub>2</sub>. Table 4B shows that the characteristics of the batches obtained with LP<sub>2</sub> are satisfactory when  $T_{\text{MAX}}$  is higher than 10.5%. Then, both the measured and predicted values of average batch grain protein content are lower than  $T_{\text{MAX}}$ . For these values of  $T_{\text{MAX}}$ , the batch weights are very near from the weights obtained when the LP coefficients are calculated from field measurements

Table 4

Characteristics of batches obtained by using (A) LP<sub>1</sub> for different values of  $T_{\text{MIN}}$  or (B) LP<sub>2</sub> for different values of  $T_{\text{MAX}}$

Threshold of protein content (%)	Average grain protein content of batch (%)		Batch weight (Mg)		Number of fields allocated to batch
	Measured	Predicted	Measured	Predicted	
<b>(A) Model LP<sub>1</sub> (<math>T_{\text{MIN}}</math>)</b>					
10.0	10.7	10.8	4922.2	4764.0	46
10.5	10.7	10.8	4922.2	4764.0	46
11.0	11.0	11.0	3803.1	3461.7	32
11.5	12.1	11.5	832.7	797.9	9
12.0	–	–	0	0	0
<b>(B) Model LP<sub>2</sub> (<math>T_{\text{MAX}}</math>)</b>					
10.0	9.1	10.0	264.7	284.5	5
10.5	10.1	10.5	2636.7	2558.4	26
11.0	10.7	10.8	4922.2	4764.0	46
11.5	10.7	10.8	4922.2	4764.0	46
12.0	10.7	10.8	4922.2	4764.0	46

LP coefficients were calculated with the crop model. Batch weights and batch average grain protein contents were calculated successively from field measurements and crop model predictions.



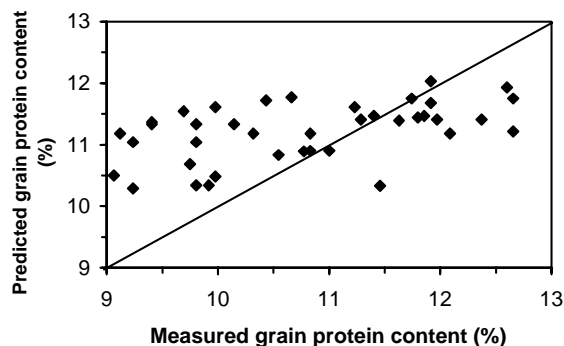


Fig. 1. Comparison of predicted and measured values of grain protein content for the 46 fields of the dataset (Root mean squared error = 1.3%).

(Table 2A). On the contrary, the characteristics of the batches obtained with LP<sub>2</sub> are not satisfactory when the grain protein content upper bound  $T_{MAX}$  is equal or lower than 10.5%. The numbers of fields allocated to the batches are then very low and the batch weights are much lower than the weights obtained when the LP coefficients are calculated from field measurements (Table 2A). These results are due to the fact that the grain protein content values of the individual fields are overestimated by the crop model when the grain protein content is lower than 10.5% (Fig. 1).

The comparison of the columns “predicted” and “measured” in Table 4 shows the accuracy of the predictions of batch weights and batch average grain protein content is satisfactory when the value of  $T_{MIN}$  is lower than 11.5% and when the value of  $T_{MAX}$  is higher than 10.5%. Errors of predictions are much more important when  $T_{MIN}$  is higher than 11.5% and when  $T_{MAX}$  is lower than 10.5%. This is due also to the errors of prediction of the crop model (Fig. 1).

Table 3B shows that the average grain protein content of the batches obtained with LP<sub>3</sub> are satisfactory. The grain protein content of batch 1 is always higher than  $T_{MIN}$  and the grain protein content of batch 2 is always lower than  $T_{MIN} - \delta$ . However, compared to the results reported in Table 3A, the weight of batch 1 tends to be too low when the LP coefficients are calculated from crop model predictions and when the value of  $T_{MIN}$  is fixed to 11.5% (Table 3B). Moreover, in this case, the number of field allocated to batch 1 is only equal to 9 (Table 3B). The number of field al-

located to batch 1 is in the range 23–26 for the same value of  $T_{MIN}$  when the LP coefficients are calculated from field measurements (Table 3A). When  $T_{MIN}$  is higher than 11.5%, some of the fields are not allocated to batch 1 because their grain protein content values are underestimated by the crop model predictions.

#### 4. Discussion and conclusion

The LP models presented in this paper require values of yield and of grain protein content for the different fields of the collecting area. In some cases, these values can be known before beginning batches segregation. This is possible when farmers store their wheat grains in their farms or when measurements are made in each field few days before harvest. However, yield and grain protein content cannot always be measured for all the individual fields of a collecting area. Moreover, the accuracy of the measurements depends highly on the method used to perform the measurements. In the case study presented in this paper, yield and grain protein content were measured from eight plots per field and soil mineral nitrogen was measured from four cores per horizon and per field. This method of sampling is satisfactory for the considered collecting area because the different fields are quite homogeneous (only one type of soil is represented and all the fields are located in a small area). However, other methods of measurements should be used in large collecting areas including heterogeneous fields. Another approach considered in this paper for calculating LP coefficients consists in using crop models for predicting yield and grain protein content. This approach is useful when accurate field measurements are not available.

A first interest of our approach is that it gives batches with specific values of average grain protein content and maximal weights. The results presented in this paper show that our model-based approach for field segregation performs often better than the current approach based on grain protein measurements. The performance of the latter approach can be improved by doing exchanges of grains between batches. However, such exchanges are quite expensive for collecting firms and do not lead necessarily to optimal results.

Another interest of our approach is that it allows collecting firms to plan in advance the allocation of

fields to batches and to predict the future characteristics of the harvest (batch weight and average grain protein content). This is possible when the coefficients of the LP models are calculated by using a crop model. On a practical point of view, the chosen crop model must be simple enough to be used by collecting firms' operators. This is the case of the crop model used in this paper. This model includes only two input variables that can be easily measured by farmers, farmers' advisers or collecting firms' operators. However, this paper shows that the use of a simple crop model for calculating LP coefficients has an important drawback. Errors of prediction of simple crop models can be important because these models do not take into account all the important factors that influence yield and grain protein content (mineralized nitrogen during the growing season, water deficiency, diseases ...). We have shown that characteristics of batches calculated by using LP models are not satisfactory when the LP coefficients are calculated from inaccurate crop model predictions. One promising way for improving the performances of simple crop models is to correct the predictions of such models by using measurements of the nitrogen status of the crop (e.g. stem nitrogen concentration and leaf chlorophyll concentration) performed during the growing season. Such measurements could be used in combination with crop models to predict more accurately yield and grain protein content values.

In conclusion, our approach provides country elevator managers with an operational tool for optimizing the characteristics of grain batches. This approach can be used in addition to other methods proposed by agronomists for improving wheat quality like nitrogen fertilization management (Meynard et al., 1997) or the use of information on cultivar characteristics (Heintz, 1994, Le Bail, 1997). In many cases, these methods were not found to be sufficient to guarantee a satisfactory batch grain protein content because of the interaction between environment, genotype and farmers' practices. We think that the model-based approach presented in this paper can be particularly useful for collecting areas including a high number of fields. In this case, an effective information system can make the management of the field characteristics easier. Recent development of traceability systems (Møller Hansen et al., 1999) could give new opportunities to build up

cropping system databases in which our segregating programs could provide precious information for quality management at the level of the collecting area. Our next objective is to improve the performances of LP models by using more sophisticated crop models for yield and grain protein content without increasing too much the cost of the information.

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