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# Optimization of Wheat Harvest

S. H. Kim, W. J. Kolaric

**Abstract**: Optimization was considered from three perspectives : minimum grain loss, minimum damaged grain loss, and minimum power consumption. Factors affecting combine performance were classified as control, adjustable, and environmental. Control and adjustable factors were optimized by the parameter design developed by Taguchi. Environmental factors were used as input for optimization. Optimum range for control and adjustable factors are presented. Parameter design was adequate to obtain the optimum levels of control factors and optimum range of adjustable factors.

**Keywords**: Optimization, Combine, Wheat, Parameter Design, Simulation

## Introduction

Many engineers have been concerned with the performance characteristics of combines and how design alternatives will change the machine performance (Goss, et al., 1958). However, performance evaluation of a combine is complicated by machine and crop variables. The comparisons of the performance of combines in different crop conditions are nearly impossible without fully understanding the relationship between variables. A physically based combine simulation model can help engineers evaluate machine performance prior to full prototype development. Unfortunately modern combines perform many functions at the same time so that a simple optimization analysis is not possible.

Off-line quality engineering technique can be introduced to solve optimization problems. The factors that cause variability in product quality functions are called factors of noise. There are three main types of noise : external noise, internal noise, and unit-to-unit noise (Taguchi, 1986). Assuring functional quality means finding techniques to reduce the effect of these three types of noise. The most important technique is optimal design which is an aspect of off-line quality control. A design quality assurance can be developed in three steps : system design, parameter design, and tolerance design. System design is the step in which one surveys the pertinent technology and asks, for example, what kind of combine cylinder type could be used to harvest corn. After the system design is settled, the optimum levels of the individual system parameters have to be determined. When the goal is to design a product with high stability and reliability, parameter design is the most important step. In parameter design we find the combination of parameter levels is sought that reduces the effect not just of internal noise, but of all noise. It is the central step in design research that produces high reliability under a wide range of conditions. After the system has been designed and the combination of parameter levels is sought that reduces the effect not just of internal noise, but of all noise. It is the central step in design research that produces high reliability under a wide range of conditions. After the system has been designed and the nominal mid-values of its parameters determined, the next step is to set the tolerances on the parameters. Environmental factors must be considered together with the system parameters. Narrow tolerances should be given to the noise factors with the greatest influence. Due to added expense narrow tolerances should be the weapon of last resort, to be used only when parameter design gives insufficient results.

The Robust Design method of quality engineering has application for complicated optimization problems with many variables such as the combine. Robust Design makes heavy use of orthogonal arrays proposed by Rao (Phadke, 1989) for planning experiments. Taguchi developed the foundations of Robust Design in the early 1960s. The method acts as an "amplifier"; it enables an making with a relatively small experimental effort.

Robust Design uses many ideas from statistical experimental design and adds a new dimension to it by explicitly addressing two major concerns faced by all product and process designers (Phadke, 1989 and Taguchi 1986) : a) Performance variation resulting from the diverse field environments under customer usage. b) Obtaining target performance levels at minimum cost.

The fundamental principle of Robust Design is to improve the quality of a product by minimizing the effect of the causes of variation without eliminating

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The author are **Sang Hun Kim**, Professor, Department of Agricultural Machinery, College of Agriculture, Kangwon National University, Korea, and **William J. Kolaric**, Professor, Dept. of Industrial Engineering, Texas Tech University, Texas, USA. **Corresponding author**: Sang Hun Kim, Professor, Department of Agricultural Machinery, College of Agriculture, Kangwon National University, Chunchon, Korea; e-mail:shkim@cc.kangwon.ac.kr.

the causes. This objective is achieved by optimizing the product and process designs to make the performance minimally sensitive to the various causes of variation, a process called parameter design. For the improvement of combine performance the cause of variation of grain losses and power consumption should be understood using a cause and effect diagram (Grant and Leaven Worth, 1988). Control and noise factors of combine performance can also be classified according to the grain losses and power consumption.

The objective of this study was to attempt to optimize the design and operations of a combine using Robust statistical techniques and the simulation model.

## Methods

There are as many as twenty two parameters that can affect combine performance. It is very difficult to find optimum levels for each parameter by a trial and error method because of the large number of parameters and also the many ways to define combine performance. Even if performance was defined only one way and if only three levels of each variable were used, an enormous number of combinations exist. A full factorial experiment for the combine performance would require $3^{22}$ or about $3.1 \times 10^{10}$ test runs or combinations.

Combine performance can be evaluated by grain quality like the amount of grain lost and grain damaged, and power consumption. Sometimes one factor shows an opposite response to the other two characteristics. For example, as concave length increases, quantity loss decreases, but power consumption increases.

The factors affecting combine performance can be classified in three categories : control, adjustable, and environmental factors. The control factors are set by the manufacturer. The adjustable factors can be changed by the operator during harvesting operations. The environmental factors can be considered as noise factors, the sensitivity of which should be minimized by machine design.

Parameter design was applied to a combine simulation model to find the optimum levels of control factors and optimum ranges of adjustable factors. The Texas tech. combine simulation program(Kim, 1990) was used for the combine simulation model.

### 1. Parameter Design for Grain Quality

Grain quality is sensitive to feed rate variation in the combine harvester. However, the feed rate cannot be controlled exactly or eliminated in a combine operation. Furthermore feed rate can change frequently and rapidly because of unexpected variation in plant height, cutterbar slope, grain yield, material distribution in the field, and so on. The input material to the straw walker and cleaning shoe also changes according to the feed rate variation and the unpredictable variation of operating conditions in the up-stream processes. Therefore, all the processes of the combine harvester are exposed to large feed rate variations. Previous experimental approaches, considering all factors as causes of variation, are not adequate for explaining factors such as feed rate. Therefore, in this research, a different approach entitled parameter design by Taguchi (Ross, 1988) was used to improve the quality of grain and power consumption in a combine. Parameter design was used without controlling or eliminating causes of variation. In other words, certain parameters of the combine process can be set to make the performance less sensitive to causes of variation. Signal to noise (S/N) ratios and other summary statistics (Phadke, 1989) are computed for each parameter design. In robust design analysis, the primary focus is on maximizing the S/N ratio.

### 2. Optimum Levels of Control Factors

### Control and Noise Factors

In this study, eleven control factors were selected for optimization. These factors and their three levels of variations are listed in table 1. Level 2 is the starting level chosen from the references (Kepner, et al., 1982 and Griffin, 1973). Level 1 is one-half the starting level, and level 3 is two times the starting level for all factors except E, F, G, and H factors. A wide range of values were used to increase the chance of capturing the nonlinearity of the relationship between the control factors and environmental factors. Tachugi has described a family of fractional factorial experimental matrices which can be utilized in various situations. In this situation, one possible matrix is the twenty-seven trial orthogonal array (OA), which is labeled the $L_{27}$ matrix. The $L_{27}$ orthogonal array (OA) is a good choice for studying eleven factors at three levels each. The $L_{27}$ OA is called the control orthogonal array (fig. 1). Obviously, many interactions

**Table 1 Control factors and their levels for optimum level test**

| Factors | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A. Cut width (m) | 2 | 4 | 8 |
| B. Cyliner width (m) | 0.5 | 1 | 2 |
| C. Concave length (m) | 0.15 | 0.3 | 0.6 |
| D. Cylinder dia. (m) | 0.25 | 0.5 | 1.0 |
| E. Cylinder bar | 6 | 8 | 10 |
| F. Sieve amplitude (cm) | 2.4 | 3.6 | 0.0 |
| G. Sieve inclination (deg.) | - 5 | 0 | 5 |
| H. Sieve projection angle (deg.) | 30 | 45 | 60 |
| I. Straw walker amplitude (cm) | 2.5 | 5 | 10 |
| J. Straw walker width (m) | 0.5 | 1 | 2 |
| K. Straw walker length (m) | 1.25 | 2.5 | 5 |

| Exp. No. | Column numbers and factor assignments | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 A | 2 B | 3 C | 4 D | 5 E | 6 F | 7 G | 8 H | 9 I | 10 J | 11 K | 12 e* | 13 e* |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 1 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 1 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 |

**Fig. 1 $L_{27}$ orthogonal array and factor assignments.**

are confounded with the main effects in the column headings this is the major compromise of using fractional factorial experiments to reduce the number of tests, some information must be surrendered. The linear graph for a $L_{27}$ helps establish the factor assignment to each column. As factors are added to a given OA, they should be placed in columns in which the lowest-order interaction is still of higher order than other columns. Taguchi views interactions as being unimportant because to obtain the interactive effect, the experimenter must control two main factors (Ross, 1988). Since one or more main effects usually need to be controlled for a product or process anyway, the interaction causes no additional complications. The experimenter needs to consider the interaction only to be ale to obtain the desired average response (Ross, 1988).

The noise (environmental) factors such as yield, plant height, and cutterbar slope are the primary noise factors for a combine harvester. The levels for the noise factors are shown in table 2. Since there were three factors with three levels, the $L_9$ OA was appropriate (fig. 2). The L9 OA is called the noise orthogonal array.

### Quality Characteristics and S/N Ratio

The grain loss, damaged grain, and power consumption were considered as quality characteristics which are continuous and nonnegative. They can take

**Table 2 Noise factors and their levels**

| Factor | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A. Yield (bu/acre) | 25 | 35 | 45 |
| B. Plant height (m) | 0.6 | 0.8 | 1.0 |
| C. Cutterbar slope (%) | 0 | 0.6 | 1.2 |

| Exp. No. | Column no. and factor assignments | | | |
|---|---|---|---|---|
| | 1<br>A | 2<br>B | 3<br>C | 4<br>e* |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

* empty column

**Fig. 2 L9 orthogonal array and factor assignments.**

any value from 0 to ∞. Their most desired value is zero. The S/N ratio was evaluated by using the procedure of a smaller-the-better type problem. the goal is to simply minimize the quality loss (Phadke, 1989). The quality loss is calculated with the following equation :

$$Q = k\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{2}\right] \qquad (1)$$

where Q = quality loss,
k = constant, and
$Y_i^2$ = quality characteristic.

Minimizing Q is equivalent to maximizing $\eta$ defined by the following equation :

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{2}\right] \qquad (2)$$

where $\eta$ = S/N ratio.

**Table 3 Adjustable factors and their levels for optimum range**

| Factor (Inner) | Level | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A. Cut height (m) | 0.1 | 0.2 | 0.3 |
| B. Machine speed (km/hr) | 2 | 4 | 6 |
| C. Concave clearance (cm) | 0.5 | 0.7 | 1.0 |
| D. Cylinder speed (rpm) | 800 | 1,000 | 1,200 |
| E. Sieve frequency (rpm) | 210 | 270 | 330 |
| F. Air velocity (m/s) | 5 | 7 | 8 |
| G. Louver-lip angle (°) | 20 | 30 | 40 |
| H. Straw walker frequency (rpm) | 170 | 210 | 250 |

**Table 4 Noise factors and their levels**

| Factor (Outer) | Level | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A. Cut height (m) | -5% | nominal | 5% |
| B. Machine speed (km/hr) | -5% | nominal | 5% |
| C. Concave clearance (cm) | -5% | nominal | 5% |
| D. Cylinder speed (rpm) | -5% | nominal | 5% |
| E. Sieve frequency (rpm) | -5% | nominal | 5% |
| F. Air velocity (m/s) | -5% | nominal | 5% |
| G. Louver-lip angle (° ) | -5% | nominal | 5% |
| H. Straw walker frequency (rpm) | -5% | nominal | 5% |

In this case the signal is constant, namely to make the quality characteristic equal to zero. Therefore the S/N ratio measures merely the effect of noise.

## 3. Optimum Range of Adjustable Factors

An optimum range of adjustable factor was determined by studying the robust characteristics of performance relative to the variation of the adjustable factors. During field operations, a nominal value of an adjustable factor is chosen by on operator. But, due to environmental variations, an optimum value can not be obtained exactly in every setting. Sometimes, the actual setting value is a little lower than nominal and sometimes a little higher. Which nominal is best to reduce sensitivity to quality loss from combine operation is the key to defining an optimum range for an adjustable factor. The nonlinear performance provides the opportunity to make the performance of combine process robust against noise factors.

### Adjustable and Noise Factors

With eight adjustable factors at three levels (table 3), an $L_{27}$ OA was used for the three level inner array with all of the primes indicating the nominal values for the factors to be investigated. As the noise factors, the outer three level array was used to designate the

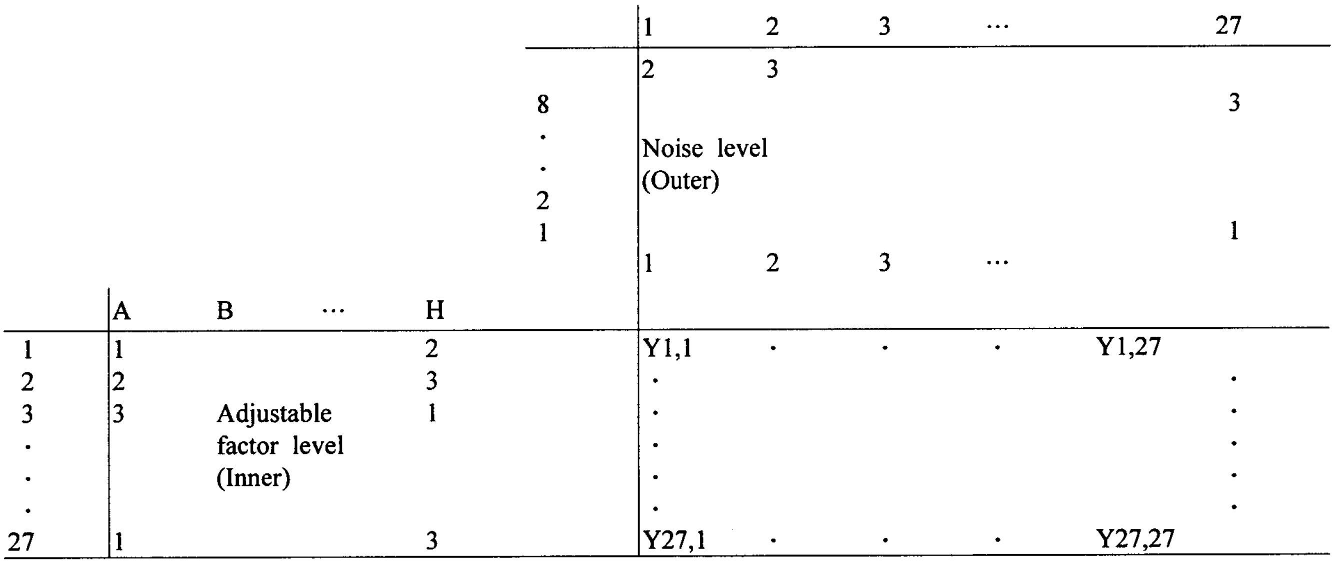


**Fig. 3 Inner and Outer array for optimum range of adjustable factor.**

**Table 5 Optimum level of control factors**

| Factor | Level | Value |
|---|---|---|
| A. Cut width (m) | 1 | 2 |
| B. Cylinder width (m) | 3 | 2 |
| C. Concave length (m) | 2 | 0.3 |
| D. Cylinder dia. (m) | 1 | 0.25 |
| E. Cylinder bar | 1 | 6 |
| F. Sieve amplitude (cm) | 1 | 2.4 |
| G. Sieve inclination (deg.) | 1 | - 5 |
| H. Sieve projection angle (deg.) | 1 | 30 |
| I. Straw walker amplitude (cm) | 2 | 5 |
| J. Straw walker width (m) | 3 | 2 |
| K. Straw walker length (m) | 2 | 2.5 |

**Table 6 Summarized results of verification experiment**

| Starting condition | | | Optimum | Improvement |
|---|---|---|---|---|
| Grain loss | % | 6.78 | 0.027 | |
| | $\eta$, dB | - 7.3 | 40.3 | 47.6 |
| Damaged grain loss | % | 0.97 | 0.005 | |
| | $\eta$, dB | 9.8 | 54.8 | 45.0 |
| Power consumption | % | 1.83 | 1.38 | |
| | $\eta$, dB | 4.1 | 6.6 | 2.5 |

variation around the nominal of the adjustable factors; level 1 was 5 percent below the nominal; level 2 was the actual nominal; and level 3 was 5 percent above the nominal (table 4). The inner/outer array arrangement is as shown in fig. 3.

**Quality Characteristics and S/N Ratio**

The operator adjustable factors can be optimized with the nominal-the-best type analysis. For these problems, scaling factors that can serve as adjustment factors are found for the system of variables. The objective function (Phadke 1989) to be used is

$$\eta = 10 \log_{10} \frac{\mu^2}{\sigma^2} \tag{3}$$

where $\mu = \frac{1}{n} \sum_{i=1}^{n} Y_i$, and

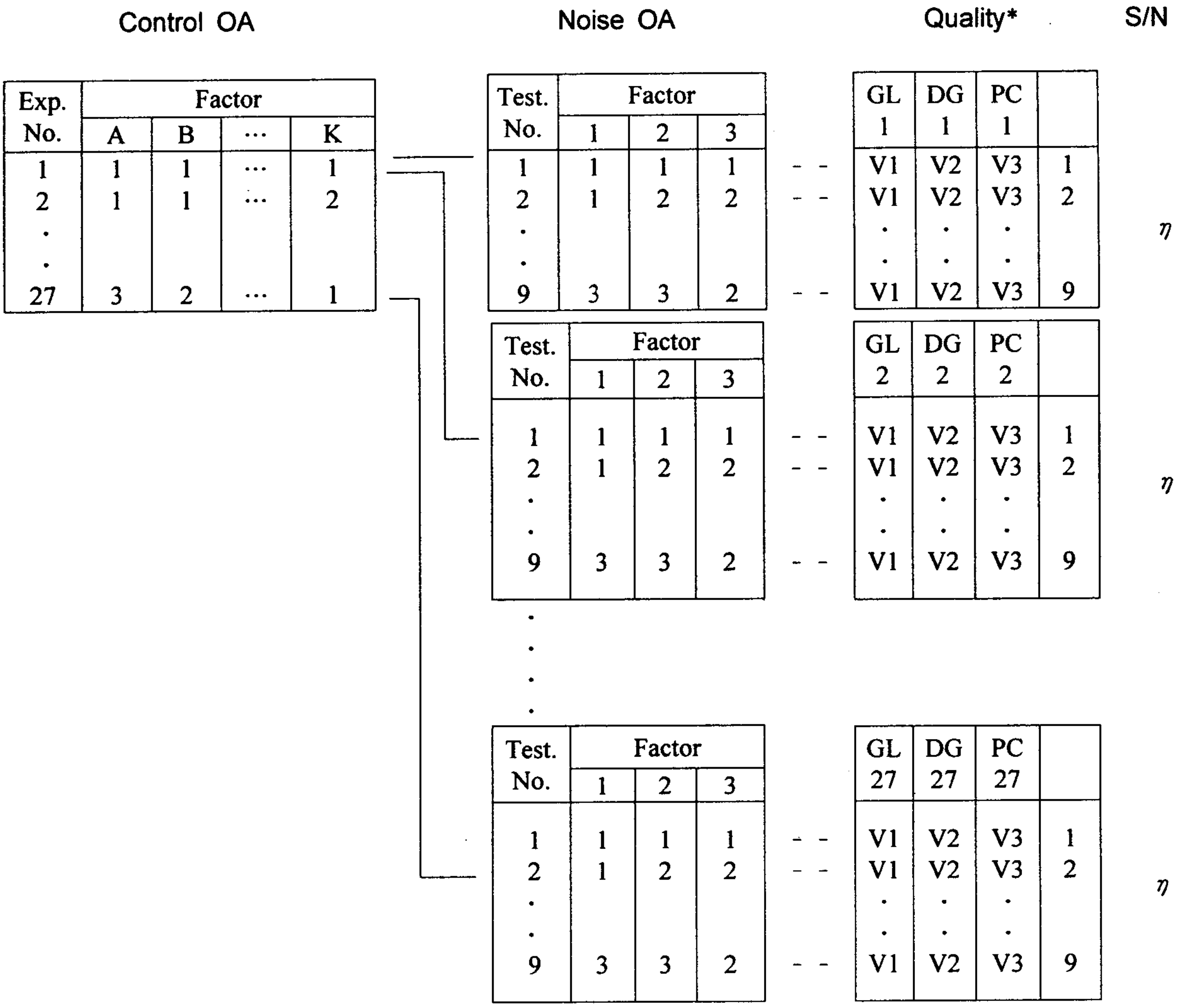
$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (Y_i - \mu)^2.$$

## Results and Discussion

### 1. Optimum Levels of Control Factors

Optimal levels of control factors were found by identifying the S/N ratio of the significant control factors of the system. The environmental factors in the noise matrix were changed when going from one row to the next row in the experiment. During the experiment, level 2 of the adjustable factors was selected based on the average combine operating condition in the field. Each row of the control orthogonal array represents a different trial design. For each trial design, the S/N ratio was evaluated by using equation 2. The simulation algorithm is graphically displayed in fig. 4.

The control orthogonal array (fig. 1) determined the control factor settings using table 1. The noise orthogonal array given in fig. 2 together with table 2 determined the 9 test condition that simulate the effect of the noise factors. For each row of the control factor setting, the combine simulation model was used



Control OA

| Exp. No. | Factor A | B | ··· | K |
|---|---|---|---|---|
| 1 | 1 | 1 | ··· | 1 |
| 2 | 1 | 1 | ··· | 2 |
| • | | | | |
| • | | | | |
| 27 | 3 | 2 | ··· | 1 |

Noise OA / Quality* / S/N (for each of the 27 control experiments)

| Test. No. | Factor 1 | 2 | 3 | GL 1 | DG 1 | PC 1 | | S/N |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | V1 | V2 | V3 | 1 | |
| 2 | 1 | 2 | 2 | V1 | V2 | V3 | 2 | η |
| • | | | | • | • | • | | |
| • | | | | • | • | • | | |
| 9 | 3 | 3 | 2 | V1 | V2 | V3 | 9 | |

| Test. No. | Factor 1 | 2 | 3 | GL 2 | DG 2 | PC 2 | | S/N |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | V1 | V2 | V3 | 1 | |
| 2 | 1 | 2 | 2 | V1 | V2 | V3 | 2 | η |
| • | | | | • | • | • | | |
| • | | | | • | • | • | | |
| 9 | 3 | 3 | 2 | V1 | V2 | V3 | 9 | |

•
•
•
•

| Test. No. | Factor 1 | 2 | 3 | GL 27 | DG 27 | PC 27 | | S/N |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | V1 | V2 | V3 | 1 | |
| 2 | 1 | 2 | 2 | V1 | V2 | V3 | 2 | η |
| • | | | | • | • | • | | |
| • | | | | • | • | • | | |
| 9 | 3 | 3 | 2 | V1 | V2 | V3 | 9 | |

**Fig. 4 Simulation algorithm for optimum levels of control factors (* GL : Grain Loss, DG : Damaged Grain, PC : Power Consumption).**

to calculate the S/N ratio and the mean value of the grain loss, damaged grain, and power consumption quality characteristics and the respective ANOVA were calculated. The factor effects are displayed graphically in fig. 5. Different levels of the same factor could be optimal for different quality characteristics. When different characteristics suggested different optimum levels, an appropriate trade-off was made using the quantitative knowledge of the effects.

Based on optimum levels of the control factors, sieve amplitude was found to have the largest effect on grain loss. By reducing the amplitude from 6 cm to 2.4 cm, the S/N ratio was improved by 27.6 db, which is equivalent to a 20-fold reduction in root mean square grain loss. The effects of sieve amplitude on damaged grain loss and power consumption are negligible.

Cylinder diameter also had a large effect on damaged grain loss. Reducing the diameter from 1 m to 0.25 m improved S/N ratio by 53.4 db (a 467-fold reduction in the root mean square damaged grain loss). A conflict between factor effects occurred on concave length. By increasing the concave length from 0.15 to 0.3 m, the S/N ratio of grain loss was improved 6.3 dB (a 2-fold reduction in root mean square), but the S/N ratio of power consumption was decreased 2.4 dB (a 1.3-fold increase in root mean square). There is, thus, a trade-off to be made between grain loss and power consumption. In this study, since grain loss was the key quality problem, concave length 0.3 m was chosen as an optimum level. The optimum levels of control factors are shown in table 5 based on fig. 5. The optimum combination chosen was $A_1B_3C_2D_1E_1$ $F_1G_1H_1I_2J_3K_2$. Using the previous calculation procedure, the S/N ratio for the optimum combination was improved 47.6 dB for grain loss, 45 dB for damaged grain loss, and 2.5 dB for power consumption (table 6). The improvement is measured relative to the mid-values originally selected from the literature.

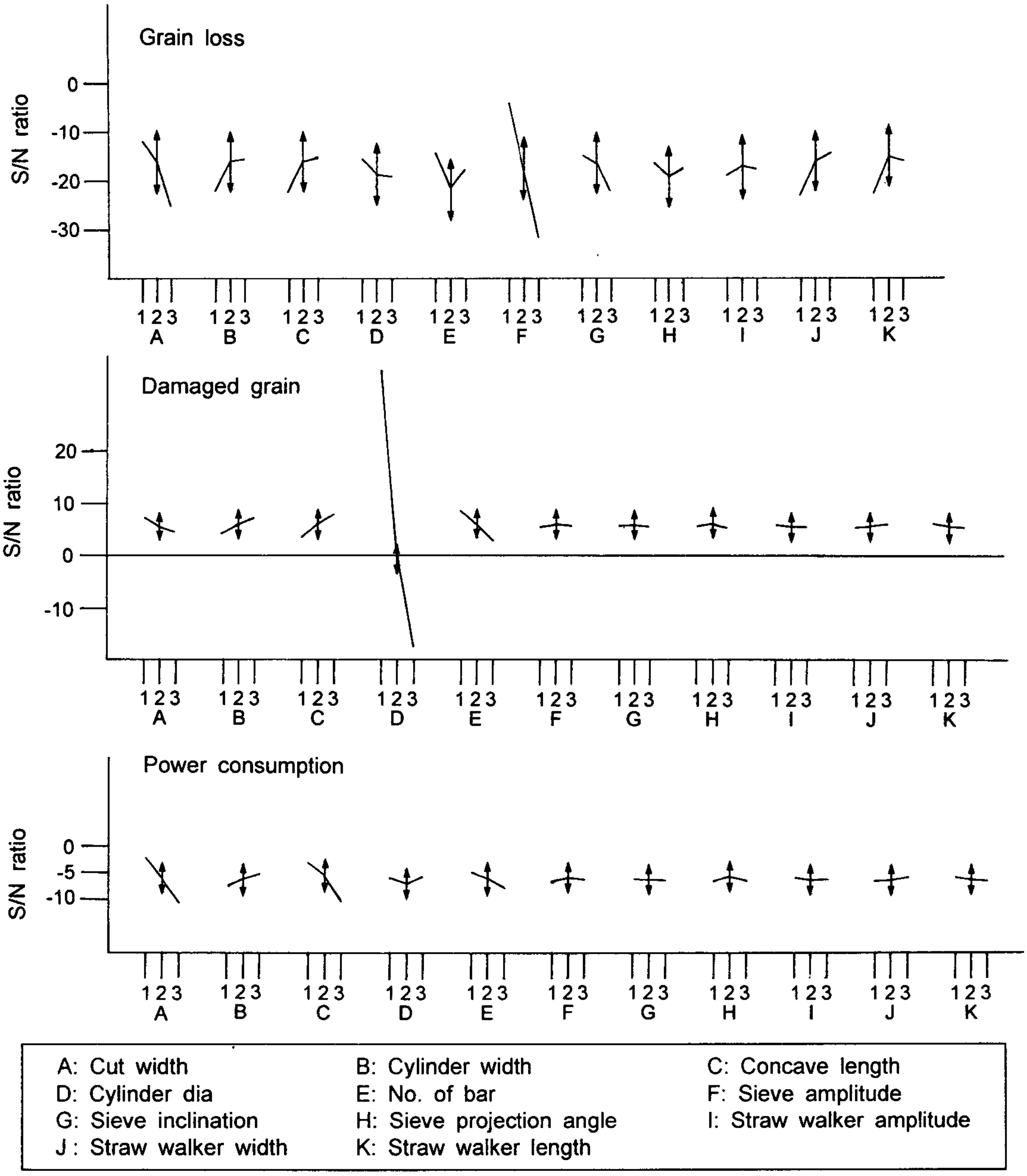


**Fig. 5 Effect of factors on quality characteristic.**

**2. Optimum Range of Control Factors**

Value of quality loss and power consumption were calculated for each of the 729 possible combination of inner and outer arrays. The values for the test of first row in the inner array and first row in the outer array were obtained by multiplication of values in the same columns of each array. The values are as follow: A=0.095, B=1.9, C=0.475, D=760, E=199.5, F=4.75, G=19, and H=161.5.

The S/N ratio was calculated to provide a measure of the variation caused by the noise levels. The ANOVA tables for S/N ratio and mean value of each quality characteristic are calculated. The effects of the various factors on S/N ratio are displayed for each of the three quality characteristics, respectively, in fig. 6. The 2-sigma confidence limits are also shown in fig. 6. A moderate improvement of S/N ratio is possible by increasing sieve frequency from 270 to 330 rpm and decreasing sieve louver-lip angle from 40° to 30°. For power consumption, the improvement of S/N ratio was possible by reducing combine machine speed from 4 to 2 km/hr and cylinder speed from 1,000 to 800 rpm, and by increasing concave clearance from 0.7 to 1 cm. For damaged grain loss, the S/N ratio was improved by reducing the cylinder speed from 1,000 to 800 rpm. The other factors have a negligible effect, because the adjustable factors have small effect on grain damage function except cylinder speed. The

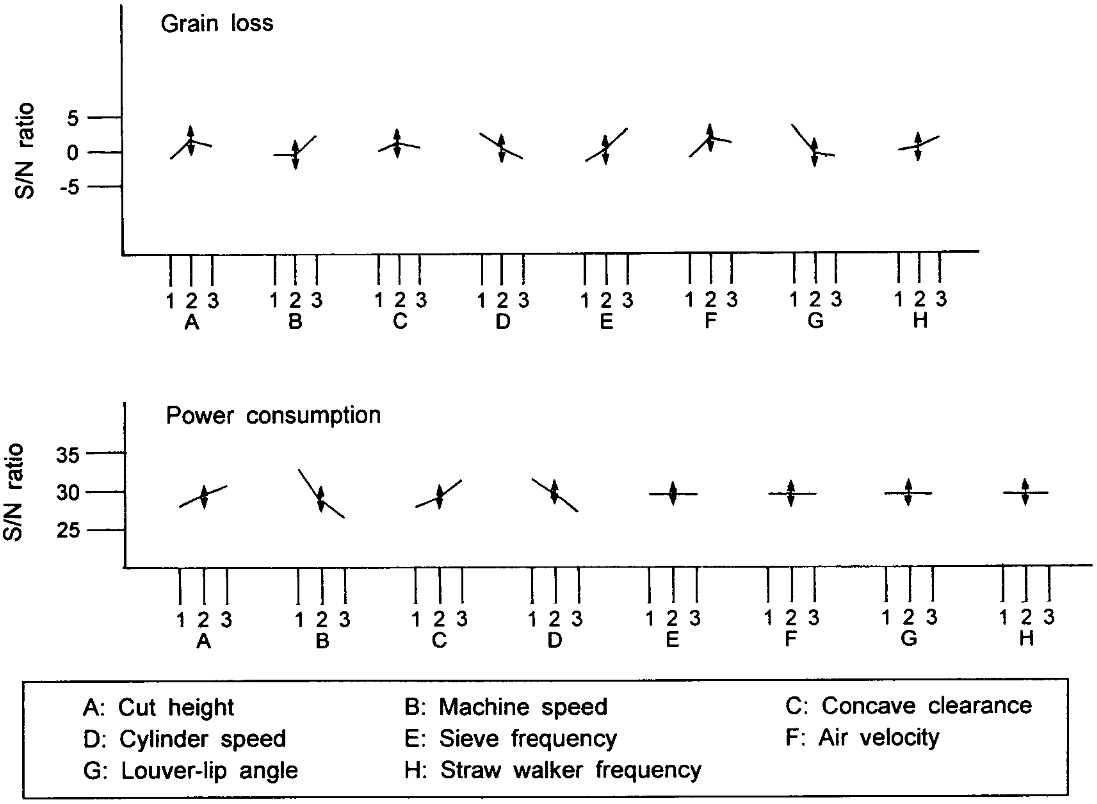


Fig. 6 Effect of adjustable factors on S/N ratios.

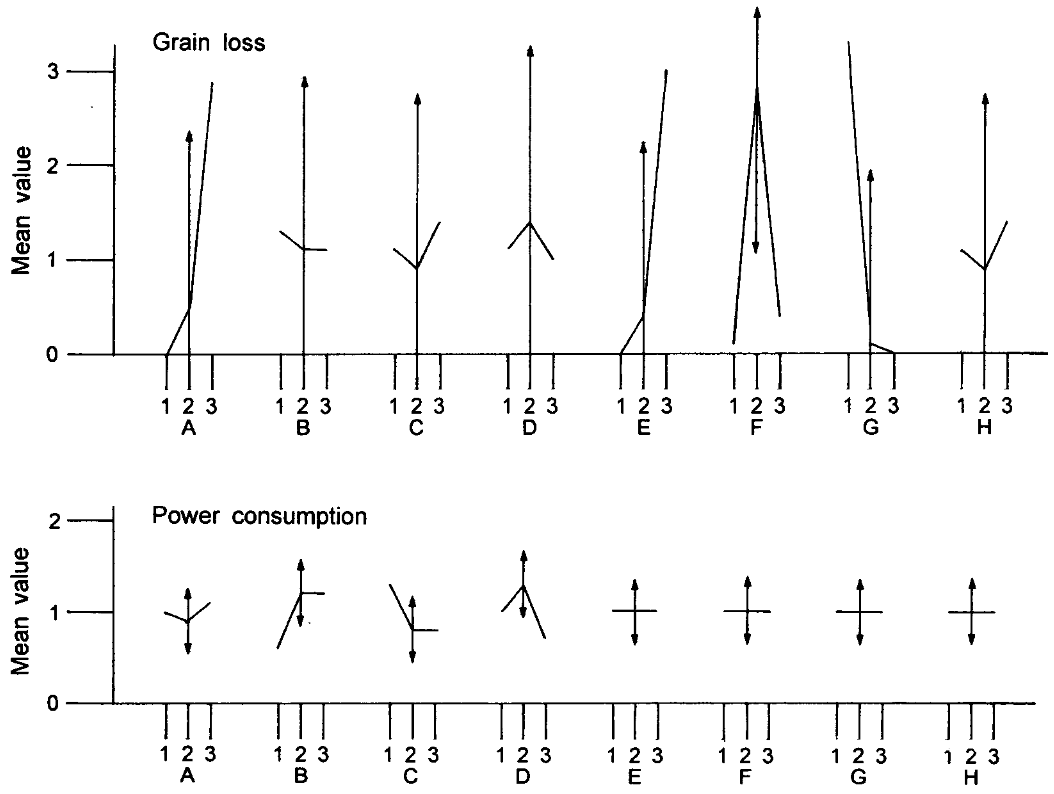


Fig. 7. Effect of adjustable factors on mean quality characteristic values.

results of the analysis of the average grain loss and power consumption are shown in fig. 7. Cut height and air velocity in the sieve have a great effect on the grain loss, but their effects on the S/N ratio are not large. These two factors could be used to adjust the grain loss. Sieve frequency and sieve louver-lip angle also have a large effect on the grain loss, but there is also a high variability associated with noise at the optimum range. For these two adjustable factors, a trade-off was considered for moderate sensitivity to noise and grain loss. Machine speed, concave clearance, and cylinder speed have an effect on the power consumption. Low sensitivity to the noise was shown at their optimum setting. Optimum ranges for adjustable factors are presented in table 7.

**Table 7 Optimum ranges of adjustable factors**

| Adjustable | Ranges | |
|---|---|---|
| A. Cut height (m) | 0.1 | 0.2* |
| B. Machine speed (km/hr) | 2* | 4 |
| C. Concave clearance (cm) | 0.7 | 1.0* |
| D. Cylinder speed (rpm) | 800* | 1,000 |
| E. Sieve frequency (rpm) | 210 | 270* |
| F. Air velocity (m/s) | 5* | 7 |
| G. Louver-lip angle (°) | 30* | 40 |
| H. Straw walker frequency (rpm) | 210* | 250 |

* preferred.

## Conclusions

The results obtained through the previously described optimization process seem reasonable. However the preceding optimization of a wheat harvesting must be viewed as a first-cut optimization. A sequence of follow-up experiments should be designed and run in both the simulation and physical domains. In any development activity, it is highly desirable that the conclusions continue to be valid when we advance to a new generation of technology. In the optimization of wheat harvest, this means that having developed the process in the simulation domain, we would want it to be valid when we change to the physical domain of combine operation factors. It appears that the parameter design used to optimize the system is a powerful tool for systems as complex as a combine. The combination of a physically based simulation program and the robust optimization procedure appears to provide a unique and possibly revolutionary tool for combine design.

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