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Efficient V-B Block Designs for CDC Method 4

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I. Introduction

Orthogonal Latin squares are used for construction of Graeco Latin square, balanced incomplete block designs and square lattice designs. A set of p-1 orthogonal Latin square of side p can always be constructed if p is a positive prime or power of a positive prime.

If $p = 4t + 2$ and $t > 1$, then there exits pairs of mutually orthogonal Latin squares of order p (Bose, Shrikhande and Parker (1960)). From a practical view point, mutually orthogonal Latin squares are important and an exhaustive list of these squares is available in Fisher and Yates (1963). In this paper we use mutually orthogonal Latin squares in construction of mating designs for the diallel cross method 4 referred to Griffing (1956).

A diallel cross is a type of mating design used in plant breeding and animal breeding to study the genetic properties and potential of inbred lines or individuals. Let p denote the number of lines and let a cross between lines i and j be denoted by $i \times j$, where $i<j = 0, 1, \ldots, p$-1 and $p(p$-1)/2 possible crosses. Among the four types of diallel discussed by Griffing (1956), method 4 is the most commonly used diallel in plant breeding. This type of diallel crossing includes the genotypes of one set of F_1's means of the type $(i \times j) = (j \times i)$, but neither the parents nor the reciprocals with all possible v = $p(p$-1)/2 crosses. This is sometimes referred to as the modified diallel. We shall refer to it as a complete diallel cross (CDC).

The problem of finding optimal mating designs for complete diallel cross experiments has received attention in recent years; see Gupta and Kageyama (1994), Dey and Midha (1996) and Chai and Mukerjee (1999). Most of the results on optimal block designs for diallel crosses have been derived for the general combining ability (gca) under the assumptions that the model does not include parameters representing the specific combining ability (sca) Gupta and Kageyama (1994) and Dey and Midha (1996) but with few exceptions Chai and Mukerjee (1999) and Choi et al. (2002). The designs of these authors can be used to estimate specific combining ability (sca) but they demand more resources in terms of experimental units and experimental material. In such a situation there is need for designs which require minimum possible number of experimental units in conducting CDC experiments and are equally efficient in comparison to optimal block designs and randomized block designs when the model, in addition to the block effects and general combining ability, includes specific combining ability.

In the present paper we are proposing efficient variance balanced incomplete block designs for CDC experiments through mutually orthogonal Latin squares under the assumption that the model includes the parameter of specific combining ability.

II. Method of Design Construction

It is known that when p is a prime positive integer or a power of prime positive integer, it is possible to construct (p-1) orthogonal Latin squares in such a way that they differ only in a cyclical interchange of the rows from 2^{nd} to p^{th}. Such squares are taken for the construction of incomplete block designs for diallel crosses. For p =6, such squares cannot be constructed.

Assume that there are p inbred lines and it is desired to find an incomplete block design for a mating design involving p (p-1)/2 crosses. Out of (p-1) mutually orthogonal Latin square (MOLS), consider any two MOLS of semi-standard form of order p and superimposed one square over the other. We obtain one Graeco Latin square in which each cell contains ordered pairs of integers (i, j) taking values from 0 to p-1 . These ordered pairs of integers occur once in a square. From Graeco Latin square remove the pairs of the type with $i = j$ and considering other ordered pairs of integers as crosses between lines i and j and the columns as blocks. By doing so we get an incomplete block design d for diallel cross experiment method 4 with parameters v = p (p-1)/2, b = p, k = p-1, and r = 2. The total

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number of experimental units to be allotted to $v = p(p-1)/2$ is $n = p(p-1)$. Henceforth d (v, b, k) will denote the class of all block designs with v treatments, b blocks and block size k.

Example1:-

Let us consider the mating design for CDC experiment method 4 for $p = 5$ parents. Consider two mutually orthogonal Latin squares L_1 and L_2 of semi-standard form of order 5. Superimposing one over the other square we get Graeco Latin square.

L_1						L_2			
0	1	2	3	4	0	1	2	3	4
1	2	3	4	0	2	3	4	0	1
2	3	4	0	1	4	0	1	2	3
3	4	0	1	2	1	2	3	4	0
4	0	1	2	3	3	4	0	1	2

After superimposition L_2 over L_1 and removing cross of the type $i = j$ and considering columns as blocks, we obtain design d as given below:

Design d

B_1	B_2	B_3	B_4	B_5
1×2	2×3	3×4	4×0	0×1
2×4	3×0	4×1	0×2	1×3
3×1	4×2	0×3	1×4	2×0
4×3	0×4	1×0	2×1	3×2

III. Analysis

For the analysis of data obtained from design d, we will follow Singh and Hinkelmann- (1998) two stage procedures for estimating gca and sca effects. The first stage is to consider the proposed designs to estimate cross effects, say,

$\boldsymbol{\tau} = (\tau_{01}, \tau_{02}, \ldots, \tau_{(p-2)(p-1)/2})$ for design d by the following model.

$$\mathbf{y} = \mu \mathbf{1} + \mathbf{X}\boldsymbol{\tau} + \mathbf{D}\boldsymbol{\beta} + \mathbf{e} \tag{3.1}$$

Where $\mathbf{y}$ is an $n \times 1$ vector of observations, $\mathbf{1}$ is the $n \times 1$ vector of ones, $\mathbf{X}$ is the $n \times v$ design matrix for treatments and $\mathbf{D}$ is an $n \times b$ design matrix for blocks, that is, the $(h,u)^{th}$ $((h,l)^{th})$ element of $\mathbf{X}$ (respectively, of $\mathbf{D}$) is 1 if the h^{th} observation pertains to the u^{th} cross (to l^{th} block), and is zero otherwise ($h = 1, \ldots, n$; $u = 1, \ldots, v$; and $1, \ldots, b$), μ is a general mean, $\boldsymbol{\tau}$ is a $v \times 1$ vector of treatment parameters, $\boldsymbol{\beta}$ is a $b \times 1$ vector of block parameters and $\mathbf{e}$ is an $n \times 1$ vector of residuals. It is assumed that vector $\boldsymbol{\beta}$ is fixed and $\mathbf{e}$ is normally distributed with $E(\mathbf{e}) = \mathbf{0}$, $V(\mathbf{e}) = \sigma^2 \mathbf{I}$ and $\mathrm{Cov}(\boldsymbol{\beta}, \mathbf{e}') = (\mathbf{0})$, , where $\mathbf{I}$ is the identity matrix of conformable order.

Following Tocher (1952), Raghavarao (1971) and Dey (1986), the least square method for the analysis of a proposed designs leads to the following reduced normal equations for the model (3.1).

$$\mathbf{C}_d\boldsymbol{\tau} = \mathbf{Q}_d \tag{3.2}$$

Where $\mathbf{C}_d = \mathbf{r}^{\delta} - \mathbf{N}\,\mathbf{k}^{-1}\,\mathbf{N}'$ and $\mathbf{Q}_d = (Q_{1d}, \ldots, Q_{vd}) = \mathbf{T} - \mathbf{N}\,\mathbf{k}^{-\delta}\,\mathbf{B}$

In the above expressions above $\mathbf{r}^{\delta}$ and $\mathbf{k}^{\delta}$ are diagonal matrices of order $v \times v$ and $b \times b$ with elements 2 and p, respectively of design d. $\mathbf{N} = \mathbf{X}'\mathbf{D}$ is the $v \times b$ incidence matrix of the design d; $\mathbf{T} = \mathbf{X}'\,\mathbf{y}$ and $\mathbf{B} = \mathbf{D}'\,\mathbf{y}$ are vector of cross totals and block totals of order $v \times 1$ and $b \times 1$ for design d, respectively.

Hence a solutions to (3.2) is given by

$$\hat{\boldsymbol{\tau}} = \mathbf{C}_d^{-}\,\mathbf{Q}_d \tag{3.3}$$

Where $\mathbf{C}_d^{-}$ is a generalized inverses of $\mathbf{C}_d$ with property $\mathbf{C}\,\mathbf{C}^{-}\,\mathbf{C} = \mathbf{C}$. The sum of squares due to crosses are $\mathbf{Q}'_d\,\mathbf{C}_d^{-}\,\mathbf{Q}_d$ with degrees of freedom (d.f.) = rank $(\mathbf{C}_d)$ for design d and expectation and variance $\mathbf{Q}_d$ is as

$$E(\mathbf{Q}_d) = \mathbf{C}_d\,\boldsymbol{\tau} \text{ and } V(\mathbf{Q}_d) = \sigma^2\,\mathbf{C}_d \tag{3.4}$$

Now we will utilize the above equations to estimate the genetic parameters in the proposed design. The second stage is to utilize the fact that the cross effects can be expressed in terms of gca and sca effects. So we can write

$$\tau_{ij} = g_i + g_j + s_{ij} \tag{3.5}$$

Where g_i (g_j) is the gca for the i^{th} (j^{th}) parent, s_{ij} ($s_{ij} = s_{ji}$) is the sca for the cross between the i^{th} and the j^{th} parent ($i < j = 0, 1, \ldots, p-1$). In matrix notation equation (3.5) can be written as

$$\boldsymbol{\tau} = \mathbf{Z}\,\mathbf{g} + \mathbf{s} \tag{3.6}$$

Where $\mathbf{Z} = (z_{ui})$ ($u = 1, 2, \ldots, n$: $i = 0, 1, \ldots, p-1$) is the cross and gca relation matrix.

$z_{ui} = 2$, if the u^{th} cross has both parents i.

$= 1$, if the u^{th} cross has only one parent i.

$= 0$, otherwise.

Following the approach used in Kempthorne and Curnow (1961), equation (3.2) can then be written as

$$\mathbf{C}_d\,\boldsymbol{\tau} = \mathbf{C}_d\,\mathbf{Z}\,\mathbf{g} + \mathbf{C}_d\,\mathbf{s}$$
$$\text{or } E(\mathbf{Q}_d) = \mathbf{C}_d\,\mathbf{Z}\,\mathbf{g} + \mathbf{C}_d\,\mathbf{s} \tag{3.7}$$

Since the matrix $\mathbf{C}$ is singular, we use the unified theory of least square due to Rao (1973). So we get estimator of $\mathbf{g}$ as

$$\hat{\mathbf{g}} = (\mathbf{Z}'\,\mathbf{C}_d\,\mathbf{C}_d^{-}\,\mathbf{C}_d\,\mathbf{Z})^{-}\,\mathbf{Z}'\,\mathbf{Q}_d = (\mathbf{Z}'\,\mathbf{C}_d\,\mathbf{Z})^{-}\,\mathbf{Z}'\,\mathbf{Q}_d \tag{3.8}$$

Here the matrix $(\mathbf{Z}'\mathbf{C}_d\,\mathbf{Z}) = 2\,p\,(p-3)/(p-1)\,[\mathbf{I}_p - \frac{1}{p}\mathbf{1}_p\mathbf{1}'_p]$.

So $\hat{\mathbf{g}} = (Z' C_d Z)^- Z' C_d \boldsymbol{\tau}$ (3.9)

Hence $\hat{\mathbf{g}} = H_1 \boldsymbol{\tau}$, where $H_1 = (Z' C_d Z)^- Z' C_d$

Now $\mathrm{Cov}(\hat{\mathbf{g}}) = H_1 C_d H'_1 \sigma 2 = \sigma^2 (p-1)/2\, p\, (p-3)\, I_p$ (3.10)

Since the covariance matrix of $\hat{\mathbf{g}}$ is a constant times the identity matrix, therefore the proposed design d is variance-balanced for general combining ability effects. We thus have the following results.

Theorem

For a positive prime $p>3$, if there exits a mutually orthogonal Latin square of order p, then there always exist variance- balanced incomplete block design for CDC experiment method 4.

Now substituting the estimate of **g** in equation (3.6), we obtain the estimator of **s**.

$$\hat{\mathbf{s}} = (C_d^- - (p-1)/2\, p\, (p-3)\, Z Z')\, Q_d = (C_d^- - (p-1)/2\, p\, (p-3)\, Z Z')\, C_d \boldsymbol{\tau}$$
$$= H_2 \boldsymbol{\tau} \qquad (3.11)$$

Where
$$H_2 = (C_d^- - (p-1)/2\, p\, (p-3)\, Z Z')\, C_d$$
$$\mathrm{Var}(\hat{\mathbf{s}}) = H_2 C_d H'_2 \sigma^2 \qquad (3.12)$$

Since $H_1 1_v = 0$, $H_2 1_v = 0$, $H_1 H_2' = 0$, rank $(H_1) = p-1$ and rank $(H_2) = v-p$.

It follows that **g** and **s** represented by treatment contrasts that carry p-1 and v-p degrees of freedom respectively and that contrasts representing **g** are orthogonal to those representing **s**. It means the proposed design d allows for gca and sca effects to be estimated independently.

The sum of squares due to gca and sca for d are given by

$$\mathrm{SS\,(gca)} = Q'_d\, Z\, (Z' C_d Z)^- Z'\, Q_d \qquad (3.13)$$

$$\mathrm{SS\,(sca)} = Q_d' \,(C_d^- - (p-1)/2\, p\, (p-3)\, Z Z')\, Q_d \qquad (3.14)$$

The ANOVA is then given in Table 1.

Table 1 : Analysis of variance for design d

Source of variation	Degrees of Freedom	Sum of squares
Block	p-1	$B' B/p - G^2/p(p-1)$
Crosses (adjusted for blocks)	rank (C_d)	$Q'_d C_d^- Q_d$
gca	rank (H_1)	$Q'_d Z (Z' C_d Z)^- Z' Q_d$
sca	rank (H_2)	$Q_d' (C_d^- - (p-1)/2p(p-3) Z Z') Q_d$
Residual	(n-1) – rank (C_d) – rank (H_1) – rank (H_2)	$y'y - G^2/p(p-1) - B' B/p - Q'_d C_d^- Q_d$
Total	n-1	$y'y - G^2/p(p-1)$

G = grand total of all n observations

IV. Efficiency Factor

If instead of the proposed design d, one adopts a randomized complete block design with 2 blocks and each block contains p $(p-1)/2$ crosses, the C_R- matrix can easily shown to be

$$C_R = 2\,(p-2)\,(I_p - 1/p\, J_p) \qquad (4.1)$$

Where I_p is a identity matrix of order p and J_p is a matrix of 1's . So that the variance of best linear unbiased estimate (BLUE) of any elementary contrast among the gca effects is $\sigma_1^2/(p-2)$, where σ_1^2 is the per observation variance in the case of randomized block experiment. It is clear from (3.10) that using design d each BLUE of any elementary contrast among gca effects is estimated with variance $\sigma^2 (p-1)/p(p-3)$. . Hence efficiency factor E of design d as compared to randomized block design under the assumption of equal intra block variances is

$$E = (\sigma_1^2 = \sigma^2) \text{ is } p\,(p-3)/(p-1)\,(p-2) \qquad (4.2)$$

In Tables 2, 3, and 4 , we are presenting the efficiency factors of CDC by Gupta and Kageyama (1994) , universally optimal and efficient block designs reported by Dey and Midha (1996) and design d in relation to randomized block design, respectively.

Table 2 : Efficiency of GK designs and designs d in comparison to RBD

S.No.	p	n	r	2k	E_{GK}	E_d
1	4	6	3	4	1.00	0.66
2	5	10	4	4	0.83	0.83
3	7	21	6	6	0.93	0.93
4	8	28	7	8	1.00	0.95
5	8	28	7	4	0.66	0.95
6	9	36	8	8	0.96	0.96
7	9	36	8	6	0.85	0.96
8	10	45	9	10	1.00	0.98
9	10	45	9	6	0.83	0.98

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10	11	55	10	10	0.97	0.98
11	12	66	11	12	1.00	0.97
12	12	66	11	6	0.80	0.98
13	12	66	11	4	0.60	0.98
14	13	78	12	12	0.98	0.99
15	13	78	12	6	0.78	0.99
16	13	78	12	4	0.59	0.99
17	14	91	13	14	1.00	0.99
18	15	105	14	14	0.98	0.99
19	15	105	14	6	0.77	0.99

GK denotes Gupta and Kageyama

Table 3 : Efficiency of Optimal DM designs and designs d in comparison to RBD

S.No.	Ref. No.	p	n_1	E_{DM}	n_2	E_d
1	T2	5	30	0.83	20	0.83
2	T3	5	60	0.83	20	0.83
3	T4	5	90	0.83	20	0.83
4	T8	7	210	0.70	42	0.93
5	T22	7	210	0.93	42	0.93
6	T40	8	280	1.00	56	0.95
7	T41	9	252	0.96	72	0.96
8	T54	10	315	1.00	90	0.98

Table 4 : Efficiency of DM efficient designs and designs d in comparison to RBD

S.No.	Ref.	p	n_1	E_{DM}	n_2	E_d	S.No.	Ref	p	n_1	E_{DM}	n_2	E_d
1	T12	5	60	0.84	20	0.83	9	T58	5	60	0.84	20	0.83
2	T13	5	90	0.92	20	0.83	10	T60	5	60	0.97	20	0.83
3	T33	5	40	0.94	20	0.83	11	T94	7	210	0.84	42	0.93
4	T34	5	80	0.80	20	0.83	12	T95	7	210	0.91	42	0.93
5	T37	5	100	0.87	20	0.83	13	T77	8	196	0.98	56	0.95
6	T44	5	30	1.00	20	0.83	14	T85	9	252	1.00	72	0.96
7	T45	5	60	0.84	20	0.83	15	T91	10	405	0.92	90	0.98
8	T57	5	30	0.84	20	0.83							

DM denotes Dey and Midha , Ref means the design number reported by Dey and Midha(1996), n_1 and n_2 are number of experimental units required by Dey and Midha's designs and design d , respectively. E_{GK}, E_{DM} and E_d are the efficiencies of GK, DM and design d in comparison of RCBD, respectively.

V. Discussion

In Table 2, we find that for p = 4, 5, 8, 9, 10, 11, 12, 13, and 15 parental lines , the design d perform well in comparison to optimal diallel cross Gupta and Kageyama (1994). In Table 3, for p = 5, 7 and 9 the performance of design d is more or less same in comparison to optimal design Dey and Midha (1996). In Table 4, for p = 5, 7, 8 and 10 the design perform well in comparison to efficient designs. Since design d requires minimum possible experimental units, therefore, design d can be used in place of GK and DM designs for estimating gca and sca effects.

VI. Illustration

We show the essential steps of analysis of a diallel cross experiment, using an incomplete block design proposed in this paper. For this purpose, we take data from an unpublished experiment conducted by Dr. Terumi Mukai on *Drosophila melanogaster* Cockerham and Weir (1977) on page 203. For the purpose of illustration, we take data of relevant crosses from this experiment. Each cross is replicated twice. The layout and observations in parentheses are given below.

B_1	B_2	B_3	B_4	B_5
1×2 (21.0)	2×3 (16.8)	3×4 (13.8)	4×0 (18.8)	0×1 (16.5)
2×4 (15.2)	3×0 (16.2)	4×1 (12.2)	0×2 (31.8)	1×3 (13.0)
3×1 (11.4)	4×2 (15.4)	0×3 (17.8)	1×4 (13.6)	2×0 (30.4)
4×3 (15.2)	0×4 (14.6)	1×0 (15.4)	2×1 (23.0)	3×2 (16.3)

The following are the vector of treatment total, block total and adjusted treatment total, respectively.

T = (31.9, 62.2, 34.0, 33.4, 44.0, 24.4, 25.8, 33.10, 30.6, 29.0) ′

B = (62.8, 63.0, 59.2, 87.2, 76.2) ′

Q = (-1.95, 21.35, 3.45, -4.15, 6.50, -10.35, -10.80, -1.70, -0.85, -1.50) ′

ANOVA, estimates of gca, and sca along with their standard errors are shown in Tables 5, 6 and 7.

Table 5 : Analysis of variance of the data

Source	D.F	Sum of squares	Mean sum of square	F
Blocks	4	137.81		
Crosses	9	418.92	46.54	53.70
g.c.a	4	341.70	85.42	98.56
s.c.a	5	77.20	15.44	17.81
Intra block error	6	5.2	0.86	
Total	19	561.93		

Table 6 : Estimates of the general combining ability and their estimated standard error

Parent	Estimates of (gca)	± S E
0	-1.24	0.4147
1	-0.65	0.4147
2	-2.16	0.4147
3.	2.58	0.4147
4.	1.47	0.4147

Table 7 : Estimates of sca effects and their estimated standard error

SCA	Estimate of (sca)	± S E	SCA	Estimate of (sca)	± S E
s_{01}	-0.63	0.4818	s_{13}	-5.29	0.4818
s_{02}	8.65	0.4818	s_{14}	-5.61	0.4818
s_{03}	3.13	0.4818	s_{23}	-1.26	0.4818
s_{04}	-3.04	0.4818	s_{24}	0.52	0.4818
s_{12}	2.58	0.4818	s_{34}	0.95	0.4818

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