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Allocating factors to the columns of an orthogonal array when certain interactions are important

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Abstract

Fractional factorial plans represented by orthogonal arrays of strength two are known to be universally optimal under a model that includes the mean and all main effects, when all other factorial effects are assumed to be absent. However, if the number of factors in the experiment is smaller than the number of columns of a saturated or, tight orthogonal array and the experimenter is interested in estimating certain 2-factor interactions as well, one can possibly entertain these 2-factor interactions in the model apart from the mean and all main effects. The problem then is to allocate factors to the columns of the orthogonal array, so that the user-specified 2-factor interactions, in addition to the mean and the main effects, are optimally estimable. This problem is investigated in this paper with reference to the orthogonal array $OA(2^n, 2^n - 1, 2, 2)$, which exists for every integer $n \geq 2$. A method for the allocation of factors to factor representations is proposed that ensures the optimal estimation of the mean, all main effects and specified 2-factor interactions. The method is illustrated by considering in detail the cases $n = 3, 4$.

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1. Introduction

Two-level fractional factorial plans are used extensively in many diverse fields, notably in industrial experimentation and quality control work. Such fractional factorial plans when represented by orthogonal arrays have strong optimality properties. For instance, a fractional factorial plan represented by an orthogonal array of strength two is universally optimal in the sense of Kiefer (1975) and Sinha and Mukerjee (1982) for estimating the mean and all main effects when all interactions are assumed to be absent. Recall that a symmetric orthogonal array, denoted by $OA(N, n, m, g)$, with N rows (runs), n columns (factors), m symbols (levels) and strength g ($2 \leq g < n$) is an $N \times n$ matrix, with $m \geq 2$ distinct symbols in each column such that in any $N \times g$ submatrix, each possible combination of the symbols appears equally often as a row. For comprehensive accounts on orthogonal arrays and their applications in the context of fractional factorials, see Hedayat, Sloane and Stufken (1999) and Dey and Mukerjee (1999a).

For an integer $n \geq 2$, an orthogonal array $OA(2^n, 2^n - 1, 2, 2)$ of strength two exists and, can be constructed in the following manner: For $1 \leq i \leq n$, let $\boldsymbol{x}_i$ be a $2^n \times 1$ vector with entries 0 and 1, such that the rows of the $2^n \times n$ matrix formed by the n columns $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n$ are the all possible combinations of a 2^n factorial. Next, form $2^n - 1$ columns $k_1\boldsymbol{x}_1 + k_2\boldsymbol{x}_2 + \cdots + k_n\boldsymbol{x}_n$, where each k_i is either 0 or 1, not all k_i's are simultaneously zero and the elements in the sums are reduced modulo 2. Note that these $2^n - 1$ columns also include the (initial) columns $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n$. These $2^n - 1$ columns form an orthogonal array $OA(2^n, 2^n - 1, 2, 2)$. It follows then that no two columns in the set $\mathcal{S} = \{k_1\boldsymbol{x}_1 + k_2\boldsymbol{x}_2 + \cdots + k_n\boldsymbol{x}_n : \ k_i = 0, 1, \ (k_1, \ldots, k_n) \neq (0, \ldots, 0)\}$ are identical. We can represent the columns of the orthogonal array as (**1**, **2**, **12**, **3**, **13**, **23**, **123**, **4**,..., **1234...$\boldsymbol{n}$**), where the representation $\boldsymbol{i}$ stands for the column $\boldsymbol{x}_i$, $1 \leq i \leq n$, the representation $\boldsymbol{ij}$ stands for the column $\boldsymbol{x}_i + \boldsymbol{x}_j \pmod 2$, $i, j = 1, \ldots, n, i \neq j$, and so on. Such an array represents a 2^n-run fractional factorial plan for a 2-level experiment involving $2^n - 1$ factors. This plan is saturated and is universally optimal for estimating the mean and all main effects in the absence of 2-factor and higher order interactions. In view of this, fractional factorial plans represented by orthogonal arrays of strength two have traditionally been used for estimating main effects alone.

Restricting attention to the orthogonal array $OA(2^n, 2^n - 1, 2, 2)$, as described above, suppose the number of factors in the experiment is k $(< 2^n - 1)$, and, furthermore, the experimenter is interested in estimating some 2-factor interactions as well. Can one then entertain these 2-factor interactions in the model, along with the mean and the main effects of the k factors involved? This leads to the problem of allocating the k factors to the above "factor representations", so that the user-specified 2-factor interactions, in addition to the mean and the main effects, are optimally estimable. This problem is investigated in this paper. A method for the allocation of factors to factor representations is proposed that ensures the optimal estimation of the mean, all main effects and specified 2-factor interactions. However, there are a few occassions where the proposed method is unable to suggest an allocation ensuring optimal estimation. The method is illustrated by considering in detail the cases $n = 3, 4$.

The problem of estimating main effects and specified two-factor interactions via a fractional factorial plan has been studied earlier e.g., by Hedayat and Pesotan (1992, 1997), Wu and Chen (1992), Dey and Mukerjee (1999b) and Dey and Suen (2002). However, the problem addressed in this communication is slightly different from the ones considered hitherto in the literature.

For obtaining the optimal plans in this paper, we make use of a result of Dey and Mukerjee (1999b). For completeness, we state the result below in a form that is needed for this paper.

Theorem 1. *Let $\mathcal{D}$ be the class of all N-run fractional factorial plans for an arbitrary factorial experiment involving k factors, $F_1, \ldots, F_k$, such that each member of $\mathcal{D}$ allows the estimability of the mean, the main effects $F_1, \ldots, F_k$ and the t two-factor interactions $F_{i_1}F_{j_1}, \ldots, F_{i_t}F_{j_t}$,*

where $1 \le i_u \ne j_u \le k$ *for all* $u = 1, \ldots, t$. *A plan* $d \in \mathcal{D}$ *is universally optimal over* $\mathcal{D}$ *if all level combinations of the following sets of factors appear equally often in* d:
(a) $\{F_u, F_v\}$, $1 \le u < v \le k$;
(b) $\{F_u, F_{i_v}, F_{j_v}\}$, $1 \le u \le k$, $1 \le v \le t$;
(c) $\{F_{i_u}, F_{j_u}, F_{i_v}, F_{j_v}\}$, $1 \le u < v \le t$,
where a factor is counted only once if it is repeated in (b) or (c).

2. A method for allocation of factors

Throughout, we consider a fractional factorial plan represented by the orthogonal array $OA(2^n, 2^n - 1, 2, 2)$, as described in the previous section. Clearly, the addition of any two distinct columns of this array, each of which is a member of $\mathcal{S}$, gives rise to a different column belonging to $\mathcal{S}$. To begin with, we have the following result.

Lemma 1. *Let* $\boldsymbol{x}_{i_1}, \boldsymbol{x}_{i_2}, \boldsymbol{x}_{i_3}$ *be any three distinct columns of the orthogonal array* $OA(2^n, 2^n - 1, 2, 2)$, $n \ge 3$, *such that* $\boldsymbol{x}_{i_1} + \boldsymbol{x}_{i_2} + \boldsymbol{x}_{i_3} \ne \mathbf{0}$ (mod 2). *Then, the columns* $\boldsymbol{x}_{i_1}, \boldsymbol{x}_{i_2}, \boldsymbol{x}_{i_3}$ *form an orthogonal array of strength three.*

Proof. Let $f(u, v, w)$, $u, v, w = 0, 1$, denote the frequency of the ordered triplet (u, v, w) under the columns $\boldsymbol{x}_{i_1}, \boldsymbol{x}_{i_2}, \boldsymbol{x}_{i_3}$. Then, since $\boldsymbol{x}_{i_1}, \boldsymbol{x}_{i_2}, \boldsymbol{x}_{i_3}$ are three distinct columns of the orthogonal array $OA(2^n, 2^{n-1}, 2, 2)$ of strength two, we have

$$f(0,0,0) + f(0,0,1) = f(0,1,0) + f(0,1,1) = f(1,0,0) + f(1,0,1) = f(1,1,0) + f(1,1,1) = 2^{n-2},$$

$$f(0,0,0) + f(1,0,0) = f(0,0,1) + f(1,0,1) = f(0,1,0) + f(1,1,0) = f(0,1,1) + f(1,1,1) = 2^{n-2},$$

and

$$f(0,0,0) + f(0,1,0) = f(0,0,1) + f(0,1,1) = f(1,0,0) + f(1,1,0) = f(1,0,1) + f(1,1,1) = 2^{n-2}.$$

These yield

$$f(0,0,1) = f(1,0,0) = f(0,1,0) = f(1,1,1)$$

and

$$f(0,0,0) = f(1,0,1) = f(0,1,1) = f(1,1,0).$$

Since $\boldsymbol{x}_{i_1} + \boldsymbol{x}_{i_2} \ne \boldsymbol{x}_{i_3}$ (mod 2) and $\boldsymbol{x}_{i_1} + \boldsymbol{x}_{i_2} = \boldsymbol{x}_{i_4} \in \mathcal{S}$ for some $\boldsymbol{x}_{i_4} \ne \boldsymbol{x}_{i_3}$, and since $\boldsymbol{x}_{i_3}$ and $\boldsymbol{x}_{i_4}$ form an orthogonal array of strength two, we have

$$f(0,0,0) + f(1,1,0) = f(0,0,1) + f(1,1,1) = f(0,1,0) + f(1,0,0) = f(0,1,1) + f(1,0,1) = 2^{n-2}.$$

It follows then that $f(u, v, w) = 2^{n-3}$ for all $u, v, w = 0, 1$, completing the proof. □

For convenience, we henceforth represent the columns of the orthogonal array $OA(2^n, 2^n - 1, 2, 2)$ by an n-tuple $(k_1, k_2, \ldots, k_n)$, where for $1 \le i \le n$, $k_i = 0$ or 1 and $(k_1, k_2, \ldots, k_n) \ne (0, 0, \ldots, 0)$. Thus the representation **1** is now equivalently denoted by $(100\ldots0)$, **124** is equivalent to $(11010\ldots0)$, etc. We shall denote by Ω, the collection of all such $2^n - 1$ non-null binary vectors. It is not hard to see that the columns $\{\sum_{i=1}^{n} k_i \boldsymbol{x}_i\}$ are completely characterized by their respective binary representations, $(k_1, k_2, \ldots, k_n)$, i.e., by the elements of Ω. Clearly, the result of Lemma 1 holds when $\boldsymbol{x}_{i_j}$ is replaced by its binary representation. Henceforth, unless otherwise mentioned, we work with the n-tuples, $\{\boldsymbol{z}_i\}$ $1 \leq i \leq 2^n - 1$, each belonging to Ω, where $\boldsymbol{z}_i = (k_1, k_2, \ldots, k_n)$ and $i = \sum_{j=1}^{n} k_j 2^{n-j}$.

Now, suppose the number of factors involved in the experiment is k $(< 2^n - 1)$, but the experimenter can afford to make 2^n runs. Additionally, the experimenter is interested in estimating certain 2-factor interactions, along with the mean and the k main effects. The model postulated is one that includes the mean, k main effects and the specified 2-factor interactions. It is assumed that all interactions, not included in the model are absent. How should one assign the factors to the columns of the orthogonal array so that the mean, all main effects and the specified 2-factor interactions are optimally estimable?

To begin with, suppose the experiment involves $k < 2^n - 1$ factors and it is desired to estimate the mean, the k main effects and only *one* 2-factor interaction. Let the representation of the specified 2-factor interaction be $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$, where $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2} \in \Omega$ and let $\boldsymbol{z}_p = \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} \pmod 2$. Then from Lemma 1, all triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_j}\}$, $\boldsymbol{z}_{i_j} \in \Omega \setminus \{\boldsymbol{z}_p\}$, form an orthogonal array of strength three. Using Theorem 1 then, the design involving the columns of the orthogonal array represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \ldots, \boldsymbol{z}_{i_k}$, such that for $1 \leq u \leq k$, $\boldsymbol{z}_{i_u} \neq \boldsymbol{z}_p$, is universally optimal for estimating the mean, the k main effects and the interaction $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$.

Next, suppose the experiment involves $k < 2^n - 2$ factors and one is interested in estimating the mean, the main effects of the k factors and *two* 2-factor interactions. There are only two possible types of interactions that need to be considered, namely, (a) $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_3}\boldsymbol{z}_{i_4}$, (b) $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_3}$.

Case (a): The factorial effects involved here are the interactions of the type $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_3}\boldsymbol{z}_{i_4}$, in addition to the mean and main effects of k factors. Here, $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}$ and $\boldsymbol{z}_{i_4}$ are all distinct. Then, all triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_j}\}$, $\boldsymbol{z}_{i_j} \in \Omega \setminus \{\boldsymbol{z}_p\}$, form an orthogonal array of strength three. Similarly, all triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_j}\}, \boldsymbol{z}_{i_j} \in \Omega \setminus \{\boldsymbol{z}_q\}$, where $\boldsymbol{z}_q = \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} \pmod 2$, form an orthogonal array of strength three. Furthermore, arguing as in the proof of Lemma 1, it can be shown that the columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}\}$ form an orthogonal array of strength four, as long as $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} \neq \mathbf{0} \pmod 2$, i.e., as long as $\boldsymbol{z}_p \neq \boldsymbol{z}_q$. Now, invoking Theorem 1, we see that the design involving columns represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \ldots, \boldsymbol{z}_{i_k}$, such that none of these equal either $\boldsymbol{z}_p$ or $\boldsymbol{z}_q$ $(\neq \boldsymbol{z}_p)$, is universally optimal for estimating the mean, the k main effects and the interactions $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_3}\boldsymbol{z}_{i_4}$.

Case (b): In this case, we consider interactions of the type $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_3}$, apart from the mean and main effects of k factors, including $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}$, $3 \leq k \leq 2^n - 3$. The vectors $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}$ are distinct. Then, all triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_j}\}$, $\boldsymbol{z}_{i_j} \in \Omega \setminus \{\boldsymbol{z}_p\}$, form an orthogonal array of strength three. Similarly, if

$\boldsymbol{z}_s = \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3}$ (mod 2), then all triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_j}\}$, $\boldsymbol{z}_{i_j} \in \Omega \setminus \{\boldsymbol{z}_s\}$, form an orthogonal array of strength three. From Theorem 1, the design involving columns represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \ldots, \boldsymbol{z}_{i_k}$, such that none of these equal either $\boldsymbol{z}_p$ or $\boldsymbol{z}_s$, is universally optimal for estimating the mean, the k main effects and the interactions $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_2}$ and $\boldsymbol{z}_{i_1}\boldsymbol{z}_{i_3}$.

Finally, consider a general set up where there are k factors and one is interested in estimating the k main effects and t interactions, say $\boldsymbol{z}_{i_1}\boldsymbol{z}_{j_1}, \ldots, \boldsymbol{z}_{i_t}\boldsymbol{z}_{j_t}$, $1 \leq t < 2^n - k$. For $t \geq 2$, any two of these t interactions may or may not have a common factor, i.e., i_l could be equal to i_m or, j_m, for $l \neq m$.

For $1 \leq l \leq t$, let $\boldsymbol{z}_{i_l} + \boldsymbol{z}_{j_l} = \boldsymbol{z}_{u_l}$ (mod 2). Then, for $1 \leq l \leq t$, the triplets of columns of the orthogonal array represented by $\{\boldsymbol{z}_{i_l}, \boldsymbol{z}_{j_l}, \boldsymbol{z}_v\}$, $\boldsymbol{z}_v \neq \boldsymbol{z}_{u_l}$, $\boldsymbol{z}_v \in \Omega$, form an orthogonal array of strength three. Furthermore, consider four distinct vectors $\boldsymbol{z}_{i_\alpha}, \boldsymbol{z}_{j_\alpha}, \boldsymbol{z}_{i_\beta}, \boldsymbol{z}_{j_\beta}$, $1 \leq \alpha, \beta \leq t$. Then, the columns of the orthogonal array represented by these vectors form an orthogonal array of strength four, as long as $\boldsymbol{z}_{i_\alpha} + \boldsymbol{z}_{j_\alpha} + \boldsymbol{z}_{i_\beta} + \boldsymbol{z}_{j_\beta} \neq \mathbf{0}$ (mod 2), i.e., $\boldsymbol{z}_{u_\alpha} \neq \boldsymbol{z}_{u_\beta}$.

Then from Theorem 1, the design involving k columns of the orthogonal array represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{j_1}, \ldots, \boldsymbol{z}_{i_t}, \boldsymbol{z}_{j_t}$ in addition to other members of Ω , such that none of these equal the distinct vectors $\boldsymbol{z}_{u_1}$ or, $\boldsymbol{z}_{u_2}$,..., or, $\boldsymbol{z}_{u_t}$, is universally optimal for estimating the mean, the k main effects and the t interactions $\boldsymbol{z}_{i_1}\boldsymbol{z}_{j_1}, \ldots, \boldsymbol{z}_{i_t}\boldsymbol{z}_{j_t}$.

We illustrate these ideas by considering the 8- and 16-run plans in detail in the next two sections.

3. Eight run plans

For $n = 3$, one gets the array $OA(8, 7, 2, 2)$. The representations of the columns of this array are $\boldsymbol{z}_1 = (001), \boldsymbol{z}_2 = (010), \boldsymbol{z}_3 = (011), \boldsymbol{z}_4 = (100), \boldsymbol{z}_5 = (101), \boldsymbol{z}_6 = (110), \boldsymbol{z}_7 = (111)$. These representations are equivalent to the representations **3**, **2**, **23**, **1**, **13**, **12**, **123**. Suppose there are $k \leq 6$ factors involved and one is interested in estimating the 2-factor interaction $\boldsymbol{z}_{i_1}\boldsymbol{z}_{j_1}$ in addition to the mean and the k main effects. Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{j_1} = \boldsymbol{z}_{u_1}$ (mod 2). Then, the design with k factors represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{j_1}$ and an additional $k-2$ members of $\Omega \setminus \{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{j_1}, \boldsymbol{z}_{u_1}\}$, is universally optimal. To elaborate further, let there be $k = 6$ factors, denoted by $A, B, \ldots, F$ and, suppose one is interested in estimating the mean, the 6 main effects and an interaction AB (without loss of generality). Then we can assign factors $A, B, \ldots, F$ to the columns **1**, **2**, **3**, **13**, **23**, **123**, to arrive at the desired optimal design. An optimal design under a model that includes the mean, the interaction AB and main effects of fewer than 6 factors can be obtained by deleting an appropriate number of columns of the design with 6 factors.

Next, let there be $k = 4$ (or, $k = 5$) factors, denoted by A, B, C, D (or, $A, B, \ldots, E$, respectively) and, suppose one is interested in estimating the mean, the 4 (or, 5) main effects and two interactions, say AB and CD. Suppose the factors A, B, C, D have distinct representations $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}$ respectively. Furthermore, let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_5}$ (mod 2) and $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_6}$ (mod 2). Then, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_5} = \mathbf{0}$ (mod 2) and $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_6} = \mathbf{0}$ (mod 2).

This implies that the remaining one factor representation $\boldsymbol{z}_{i_7}$ must be equal to zero, which is impossible. It follows then that with only 8 runs, it is impossible to estimate the interactions AB and CD (i.e., a pair of interactions with no common factor) simultaneously.

This fact can also be observed by first constructing all possible distinct sets of triplets $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}\}$ such that $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_3} = \mathbf{0}$ (mod 2). These triplets indicate the column representations of two factors whose interaction is present and the column which is not to be considered as a factor. The sets of triplets are

$$\begin{array}{lcr} \{\mathbf{1} & \mathbf{2} & \mathbf{12}\} \\ \{\mathbf{1} & \mathbf{3} & \mathbf{13}\} \\ \{\mathbf{1} & \mathbf{23} & \mathbf{123}\} \\ \{\mathbf{2} & \mathbf{3} & \mathbf{23}\} \\ \{\mathbf{2} & \mathbf{13} & \mathbf{123}\} \\ \{\mathbf{3} & \mathbf{12} & \mathbf{123}\} \\ \{\mathbf{12} & \mathbf{13} & \mathbf{23}\} \end{array}$$

Treating the column representations as the 7 treatment symbols and the sets as blocks one gets a balanced incomplete block (BIB) design with 7 treatments and 7 blocks each of size 3. From a well known property of a symmetric BIB design, any two blocks has a common treatment. Thus, we cannot have 6 distinct symbols appearing in a pair of blocks. This leads us to the earlier observed fact that it is impossible to estimate simultaneously a pair of interactions with no common factor via the considered 8-run plan.

Next, we look at two or more 2-factor interactions such that any two interactions have a factor in common. Consider two interactions of the type AB and AC. Then we can assign factors $A, B, \ldots, E$ to the columns **1**, **2**, **3**, **23**, **123** to arrive at the desired optimal design. An optimal design with 4 factors can be obtained by deleting either of the columns **23** or **123**. When $t = 3$ interactions are of interest, the possible types of interactions are (i) AB, AC and AD, or (ii) AB, AC and BC. For each of these, we can assign factors A, B, C, D to the columns **1**, **2**, **3**, **123** leading to the desired optimal design.

4. Sixteen run plans

Consider the orthogonal array $OA(16, 15, 2, 2)$ as a special case of the array $OA(2^n, 2^n - 1, 2, 2)$ with $n = 4$. The representations of the columns of this array are $\boldsymbol{z}_1 = (0001), \boldsymbol{z}_2 = (0010), \boldsymbol{z}_3 = (0011), \boldsymbol{z}_4 = (0100), \boldsymbol{z}_5 = (0101), \boldsymbol{z}_6 = (0110), \boldsymbol{z}_7 = (0111), \boldsymbol{z}_8 = (1000), \boldsymbol{z}_9 = (1001), \boldsymbol{z}_{10} = (1010), \boldsymbol{z}_{11} = (1011), \boldsymbol{z}_{12} = (1100), \boldsymbol{z}_{13} = (1101), \boldsymbol{z}_{14} = (1110), \boldsymbol{z}_{15} = (1111)$. These representations are equivalent to the representations **4**, **3**, **34**, **2**, **24**, **23**, **234**, **1**, **14**, **13**, **134**, **12**, **124**, **123**, **1234**. Suppose there are $k \leq 14$ factors involved and one is interested in estimating the 2-factor interaction $\boldsymbol{z}_{i_1}\boldsymbol{z}_{j_1}$ in addition to the mean and the k main effects. Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{j_1} = \boldsymbol{z}_{u_1}$ (mod 2). Then, the design with k factors represented by $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{j_1}$ and an additional $k - 2$ members of $\Omega - \{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{j_1}, \boldsymbol{z}_{u_1}\}$, is universally optimal. To elaborate further, let there be $k = 14$ factors, denoted by $A, B, \ldots, N$ and, suppose one is interested in estimating the mean, the 14 main effects and an interaction AB (without loss of generality). Then we can assign factors $A, B, \ldots, N$ to the columns such that A and B are assigned to **1** and **2**, while the other factors are assigned to the remaining columns *except* column **12**. This gives us the desired optimal design. An optimal design with fewer than 14 factors can be obtained by deleting an appropriate number of columns of the design with 14 factors.

Next, let there be $k \leq 13$ factors, denoted by $A, B, \ldots, M$ and, suppose one is interested in estimating the mean, the k main effects and two interactions, say AB and CD. Suppose the factors A, B, C, D have distinct representations $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}$ respectively. Furthermore, let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_5} \pmod 2$ and $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_6} \pmod 2$. Then, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_5} = 0 \pmod 2$ and $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_6} = 0 \pmod 2$. This implies that we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_6}$ which satisfy the above two equations.

As in the case of 8-run plans, we now construct, for n=4, all possible distinct sets of triplets $\{\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}\}$ such that $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_3} = 0$. These triplets indicate the column representations of two factors whose interaction is present and the column which is not to be considered as a factor. These sets of triplets are

{**1** **2** **12**}	{**3** **4** **34**}	{**13** **24** **1234**}	{**14** **123** **234**}	{**23** **124** **134**}
{**1** **3** **13**}	{**2** **14** **124**}	{**4** **23** **234**}	{**12** **34** **1234**}	{**24** **123** **134**}
{**1** **4** **14**}	{**2** **134** **1234**}	{**3** **12** **123**}	{**13** **124** **234**}	{**23** **24** **34**}
{**1** **23** **123**}	{**2** **4** **24**}	{**3** **124** **1234**}	{**12** **134** **234**}	{**13** **14** **34**}
{**1** **24** **124**}	{**2** **34** **234**}	{**3** **14** **134**}	{**4** **123** **1234**}	{**12** **13** **23**}
{**1** **34** **134**}	{**2** **13** **123**}	{**3** **24** **234**}	{**4** **12** **124**}	{**14** **23** **1234**}
{**1** **234** **1234**}	{**2** **3** **23**}	{**4** **13** **134**}	{**12** **14** **24**}	{**34** **123** **124**}

As before, if we treat the column representations as the 15 treatment symbols, the above sets of triplets form a BIB design with 15 treatments and 35 blocks each of size 3. The above design is in fact a *resolvable BIB* design with 5 blocks in each row forming a complete replication. (Recall that a BIB design with v treatments, b blocks and replication number r is said to be resolvable if the b blocks can be partitioned into r sets of $m = b/r$ blocks such that each set contains every treatment exactly once.)

We can assign factors $A, B, \ldots, M$ to the columns such that A, B, C and D are assigned to **1**, **2**, **3** and **4** respectively. The other factors are assigned to the remaining columns *except* column **12** and column **34**. This gives us the desired optimal design. An optimal design with fewer than 13 factors can be obtained by deleting an appropriate number of columns of the design with 13 factors.

Under the above setup, in case the two interactions are, say AB and AC, then let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_4} \pmod 2$ and $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} = \boldsymbol{z}_{i_5} \pmod 2$. Then, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_4} = 0 \pmod 2$ and $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_5} = 0 \pmod 2$. This implies that we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}$ which satisfies the above two equations. We can assign factors $A, B, \ldots, M$ to the columns such that A, B and C are assigned to **1**, **2** and **3** respectively. The other factors are assigned to the remaining columns *except* column **12** and column **13**. This gives us the desired optimal design.

An optimal design with fewer than 13 factors can be obtained by deleting an appropriate number of columns of the design with 13 factors.

When $t = 3$, without loss of generality, there are four possible types of interactions: (i) AB, CD, EF; (ii) AB, AC, DE; (iii) AB, AC, AD; (iv) AB, AC, BC. For each of these cases, we can assign suitable columns to the factors, leading to the desired optimal design. The given resolvable BIB design is helpful in obtaining solutions to the equation sets that arise in each of the four cases. Suppose the factors A, B, C, D, E, F have distinct representations $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}$ respectively.

Case(i): Interactions AB, CD, EF
Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_7} \pmod 2$, $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_8} \pmod 2$, $\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} = \boldsymbol{z}_{i_9} \pmod 2$. Then, we have

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_7} = 0 \pmod 2; \ \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_8} = 0 \pmod 2, \ \boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} + \boldsymbol{z}_{i_9} = 0 \pmod 2.$$

Now we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_7}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_8}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}, \boldsymbol{z}_{i_9}$ which satisfy the above three equations. The answer lies in the 7 sets of the resolvable BIB design. Considering any one set, say the first set,

{**1** **2** **12**} {**3** **4** **34**} {**13** **24** **1234**} {**14** **123** **234**} {**23** **124** **134**}

and after selecting any three blocks, for each block, assigning the two interacting factors to any two (of the three) elements of the block, we get our desired allocation. In each of the three blocks, the element not assigned to any factor would be the column in the original orthogonal array, which is *not* to be allocated to any factor. The non-interacting $k-6$ factors are assigned the remaining columns. Thus, from the above set of 5 blocks, we can assign (for example) the k factors to the columns such that A, B, C, D, E and F are assigned to **1**, **2**, **3**, **4**, **13** and **24** respectively. The other factors are assigned to the remaining columns *except* columns **12**, **34** and **1234**. This gives us the desired optimal design.

Case(ii): Interactions AB, AC, DE
Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_6} \pmod 2$, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} = \boldsymbol{z}_{i_7} \pmod 2$, $\boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_5} = \boldsymbol{z}_{i_8} \pmod 2$. Then,

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_6} = 0 \pmod 2, \ \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_7} = 0 \pmod 2, \ \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_8} = 0 \pmod 2.$$

Now we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}, \boldsymbol{z}_{i_7}, \boldsymbol{z}_{i_8}$ which satisfy the above three equations. The answer lies in any two of the 7 sets of the resolvable BIB design. We can assign the k factors to the columns such that A, B, C, D and E are assigned to **1**, **2**, **3**, **14** and **123** respectively. The other factors are assigned to the remaining columns *except* columns **12**, **13** and **234**. This gives us the desired optimal design.

Case(iii): Interactions AB, AC, AD
Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_5} \pmod 2$, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} = \boldsymbol{z}_{i_6} \pmod 2$, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_7} \pmod 2$. Then it follows that

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_5} = 0 \pmod 2, \ \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_6} = 0 \pmod 2, \ \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_7} = 0 \pmod 2.$$

We need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}, \boldsymbol{z}_{i_7}$ which satisfy the above three equations. This time, the answer lies in any three of the 7 sets of the resolvable BIB design. We can assign the k factors to the columns such that A, B, C and D are assigned to **1**, **2**, **3** and **4** respectively. The other factors are assigned to the remaining columns *except* columns **12**, **13** and **14**. This gives us the desired optimal design.

Case(iv): Interactions AB, AC, BC
Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_4} \pmod 2$, $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} = \boldsymbol{z}_{i_5} \pmod 2$, $\boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_3} = \boldsymbol{z}_{i_6} \pmod 2$. It follows that

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_4} = 0 \pmod 2,\ \boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_5} = 0 \pmod 2,\ \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_6} = 0 \pmod 2.$$

Now we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}$ which satisfy the above three equations. Again, using the resolvable BIB design, we see that an allocation is to assign the k factors to the columns such that A, B and C are assigned to **1**, **2** and **3** respectively. The other factors are assigned to the remaining columns *except* columns **12**, **13** and **23**. This gives us the desired optimal design.

On lines similar to the case of $t = 3$, we are able to solve for possible situations for $t = 4$. For illustration, we consider a few cases. In what follows, we represent any assignment of a factor say, A to a column, say **1**, by $(A, \mathbf{1})$.

Case(i): Interactions AB, CD, EF, GH
The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4}), (E, \mathbf{13}), (F, \mathbf{24}), (G, \mathbf{14})$ and $(H, \mathbf{123})$. The columns that are not to be assigned any factors are **12**, **34**, **1234** and **234**. The other factors are assigned to the remaining columns.

Case(ii): Interactions AB, CD, EF, EG
The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4}), (E, \mathbf{13}), (F, \mathbf{24})$ and $(G, \mathbf{124})$. The columns that are not to be assigned any factors are **12**, **34**, **1234** and **234**. The other factors are assigned to the remaining columns.

Case(iii): Interactions AB, CD, CE, CF
The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4}), (E, \mathbf{124})$ and $(F, \mathbf{14})$. The columns that are not to be assigned any factors are **12**, **34**, **1234** and **134**. The other factors are assigned to the remaining columns.

Case(iv): Interactions AB, CD, CE, DE
The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4})$ and $(E, \mathbf{1234})$. The columns that are not to be assigned any factors are **12**, **34**, **124** and **123**. The other factors are assigned to the remaining columns.

Case(v): Interactions AB, AC, AD, AE
The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4})$ and $(E, \mathbf{23})$. The columns that are not to be assigned any factors are **12**, **13**, **14** and **123**. The other factors are assigned to the remaining columns.

Case(vi): Interactions AB, BC, CD, DA

The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3})$ and $(D, \mathbf{4})$. The columns that are not to be assigned any factors are **12**, **23**, **34** and **14**. The other factors are assigned to the remaining columns.

For $t = 5$, we come across some cases where inconsistent equations arise which do not allow one to solve for possible solutions. Again, for illustration, we consider a few cases.

Case(i): Interactions AB, CD, EF, GH, IJ

The assignments are: $(A, \mathbf{1}), (B, \mathbf{2}), (C, \mathbf{3}), (D, \mathbf{4}), (E, \mathbf{13}), (F, \mathbf{24}), (G, \mathbf{14}), (H, \mathbf{123})$, $(I, \mathbf{23})$ and $(J, \mathbf{124})$. The columns that are not to be assigned any factors are **12**, **34**, **1234**, **234** and **134**.

Case(ii): Interactions AB, CD, EF, GH, GI

Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_{10}}$ (mod 2), $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_{11}}$ (mod 2), $\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} = \boldsymbol{z}_{i_{12}}$ (mod 2), $\boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_8} = \boldsymbol{z}_{i_{13}}$ (mod 2), $\boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_9} = \boldsymbol{z}_{i_{14}}$ (mod 2). Then it follows that

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_{10}} = 0 \pmod 2, \ \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_{11}} = 0 \pmod 2, \ \boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} + \boldsymbol{z}_{i_{12}} = 0 \pmod 2,$$

$$\boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_8} + \boldsymbol{z}_{i_{13}} = 0 \pmod 2, \ \boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_9} + \boldsymbol{z}_{i_{14}} = 0 \pmod 2.$$

Now we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}, \boldsymbol{z}_{i_7}, \boldsymbol{z}_{i_8}, \boldsymbol{z}_{i_9}, \boldsymbol{z}_{i_{10}}, \boldsymbol{z}_{i_{11}}, \boldsymbol{z}_{i_{12}}, \boldsymbol{z}_{i_{13}}, \boldsymbol{z}_{i_{14}}$ which satisfy the above five equations. However, note that the above equations imply that $\boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_{15}} = 0$. This is impossible. Hence there exists no allocations of the columns to the factors which would enable one to have such an interaction set in the model.

Case(iii): Interactions AB, CD, EF, EG, EH

Let $\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} = \boldsymbol{z}_{i_9}$ (mod 2), $\boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} = \boldsymbol{z}_{i_{10}}$ (mod 2), $\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} = \boldsymbol{z}_{i_{11}}$ (mod 2), $\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_7} = \boldsymbol{z}_{i_{12}}$ (mod 2), $\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_8} = \boldsymbol{z}_{i_{13}}$ (mod 2). Then it follows that

$$\boldsymbol{z}_{i_1} + \boldsymbol{z}_{i_2} + \boldsymbol{z}_{i_9} = 0 \pmod 2, \ \boldsymbol{z}_{i_3} + \boldsymbol{z}_{i_4} + \boldsymbol{z}_{i_{10}} = 0 \pmod 2, \ \boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_6} + \boldsymbol{z}_{i_{11}} = 0 \pmod 2,$$

$$\boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_7} + \boldsymbol{z}_{i_{12}} = 0 \pmod 2, \boldsymbol{z}_{i_5} + \boldsymbol{z}_{i_8} + \boldsymbol{z}_{i_{13}} = 0 \pmod 2.$$

Now we need to identify distinct values of $\boldsymbol{z}_{i_1}, \boldsymbol{z}_{i_2}, \boldsymbol{z}_{i_3}, \boldsymbol{z}_{i_4}, \boldsymbol{z}_{i_5}, \boldsymbol{z}_{i_6}, \boldsymbol{z}_{i_7}, \boldsymbol{z}_{i_8}, \boldsymbol{z}_{i_9}, \boldsymbol{z}_{i_{10}}, \boldsymbol{z}_{i_{11}}, \boldsymbol{z}_{i_{12}}, \boldsymbol{z}_{i_{13}}$ which satisfy the above five equations. However, note that the above equations imply that $\boldsymbol{z}_{i_{14}} + \boldsymbol{z}_{i_{15}} = 0$. This is also impossible. Hence here too there exist no allocations of the columns to the factors which would enable one to have such an interaction set in the model.

Case(iv): Interactions AB, CD, CE, CF, CG

The assignments are: $(A, \mathbf{2}), (B, \mathbf{3}), (C, \mathbf{1}), (D, \mathbf{4}), (E, \mathbf{24}), (F, \mathbf{34})$ and $(G, \mathbf{234})$. The columns that are not to be assigned any factors are **23**, **14**, **124**, **134** and **1234**. The other $k - 7$ factors are assigned to the remaining columns.

The above ideas can, in principle, be extended to arrays with larger number of rows (runs), though the effort involved in larger arrays is obviously more. In general, an easy way to check the nonexistence of an allocation of the factors to the columns (leading to universally optimal designs) is to add (mod 2), all the equations that arise and then use the fact that $\sum_{j=1}^{2^n-1} \boldsymbol{z}_{i_j} = 0$. Nonexistence is implied in case this leads to one $\boldsymbol{z}_{i_j}$ or sum of two $\boldsymbol{z}_{i_j}$'s being equal to zero.

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