ADMISSIBILITY AND OPTIMALITY OF EXPERIMENTAL DESIGNS

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1. INTRODUCTION

In this paper we study the relation between admissiblity and optimality of experimental designs. While it is standard decision theoretic reasoning that a statistical procedure which is uniquely optimal will necessarily be admissible, we here prove a converse to the effect that an admissible design is uniquely optimal with respect to the E-criterion and a specific choice of the parameter system of interest. The general equivalence theory may then be employed to obtain necessary conditions for admissibility.

As usual we choose the experimental conditions from a compact k-dimensional *experimental domain* $\mathcal{X} \subset \mathbb{R}^k$. We assume that under experimental conditions $x \in \mathcal{X}$ the real observation $Y(x)$ follows a linear model

$$Y(x) = x'\theta + \sigma e(x)$$

with uncorrelated errors $e(x)$ of unit variance. A *design* ξ is a probability distribution with finite support on the experimental domain $\mathcal{X}$, determining allocation and proportion of the experimental conditions.

The performance of a design ξ is determined through its $k \times k$ *moment matrix*

$$M(\xi) = \int_{\mathcal{X}} xx'd\xi.$$

Let $\mathcal{M}$ be the *feasible set* of moment matrices, assumed to be a convex and compact subset of nonnegative definite $k \times k$ matrices.

We shall study admissibility of a candidate matrix M in the set $\mathcal{M}$. It is illuminating to first discuss the case when the full parameter θ is of interest (Section 2). Before turning to the more general case of an s-dimensional parameter system $K'\theta$ (Section 4) we derive some intermediate results on information matrices (Section 3).

2. ADMISSIBILITY FOR THE FULL PARAMETER SET

Suppose $M \in \mathcal{M}$ is a moment matrix whose admissibility properties we wish to investigate. We call M *admissible for* θ *in* $\mathcal{M}$ when no moment matrix $A \in \mathcal{M}$ satisfies $A \geq M$ and $A \neq M$, relative to the Löwner ordering $\geq$. To avoid trivialities we assume $M \neq 0$.

We shall show that every admissible moment matrix is E-optimal, i.e. it maximizes the minimum eigenvalue of an appropriate information matrix. However, the parameter system for which E-optimality is obtained is related to the candidate matrix M in an intrinsic manner: We choose the system $H'\theta$ from a full rank decomposition

$$M = HH',$$

where with $r = \operatorname{rank} M$ the $k \times r$ matrix H has full column rank r. An E-optimal moment matrix for $H'\theta$ in $\mathcal{M}$ is one which maximizes $\lambda_{\min}(C_H(A))$ over $A \in \mathcal{M} \cap \mathcal{A}(H)$, where $\mathcal{A}(H)$ is the convex cone of all nonnegative definite $k \times k$ matrices whose range contains the range of H, and

$$C_H(A) = (H'A^- H)^{-1} \qquad \text{for } A \in \mathcal{A}(\cancel{K}H).$$

We need an auxiliary lemma before turning to admissibility.

Lemma 1. *Let $A \in \mathcal{M}$ be a competing moment matrix. If A is E-optimal for $H'\theta$ in $\mathcal{M}$ then $A \geq M$.*

Proof. By construction the range of M contains (actually coincides with) the range of H, and we have

$$C_H(M) = (H'M^- H)^{-1} = (H'(HH')^- H)^{-1} = I_r.$$

Optimality of A yields $1 = \lambda_{\min}(C_H(M)) \leq \lambda_{\min}(C_H(A))$. Therefore $I_r \leq C_H(A)$, and pre- and postmultiplication with H and H' gives

$$M = HH' \leq HC_H(A)H' \leq A,$$

where the last inequality may be found for instance in Pukelsheim & Styan (1983, p. 147). □

We are now in a position to establish the relation between admissibility and unique E-optimality as announced above.

Theorem 1. *The moment matrix M is admissible for θ in $\mathcal{M}$ if and only if M is uniquely E-optimal for $H'\theta$ in $\mathcal{M}$.*

Proof. Suppose M is admissible. From Theorem 2 in Pukelsheim (1980, p. 344) we know that there exists an E-optimal moment matrix A for $H'\theta$ in $\mathcal{M}$. By Lemma 1 we have $A \geq M$, and admissibility of M forces $A = M$. This establishes unique E-optimality of M.

Conversely suppose M is uniquely E-optimal. Let A be a competing moment matrix satisfying $A \geq M$. Due to monotonicity A will also be E-optimal. But then uniqueness forces $A = M$, i.e. admissibility of M. □

Lemma 1 and Theorem 1 are closely related to Corollary 8.4 of Pukelsheim (1980, p. 359). Next we turn to the classical Theorem 7.1 on admissibility of Karlin & Studden (1966, p. 808), investigating the existence of a nonnegative definite matrix $N \neq 0$ or a positive definite matrix N satisfying the system of *normality inequalities*

$$\operatorname{trace}(AN) \leq \operatorname{trace}(MN) \qquad \text{for all } A \in \mathcal{M}.$$

Employing customary notions of convex analysis we shall call a matrix N which satisfies this system of inequalities to be *normal to $\mathcal{M}$ at M*.

Theorem 2. *(i) If M is admissible for θ in $\mathcal{M}$ then there exists a nonnegative definite $k \times k$ matrix $N \neq 0$ which is normal to $\mathcal{M}$ at M.*
(ii) If there exists a positive definite $k \times k$ matrix N which is normal to $\mathcal{M}$ at M then M is admissible for θ in $\mathcal{M}$.

Proof. (i) From Theorem 1 we know that M is E-optimal for $H'\theta$ in $\mathcal{M}$. The general equivalence theory provides a necessary and sufficient condition of optimality in the following form, see Theorem 8 of Pukelsheim (1980, p. 356). Optimality holds if and only if for all $A \in \mathcal{M}$

$$\operatorname{trace}(H'GAG'HE) \leq \lambda_{\max}(H'M^{-}H) = 1/\lambda_{\min}(C_H(M)),$$

for some generalized inverse G of M and some matrix $E \in \operatorname{conv} S$. Here $\operatorname{conv} S$ denotes the convex hull of all $r \times r$ matrices of the form zz' such that z is a normalized eigenvector of $C_H(M)$ corresponding to $\lambda_{\min}(C_H(M))$. However, we have seen above that $C_H(M)) = I_r$, and so E actually is an arbitrary nonnegative definite $r \times r$ matrix with trace equal to 1.

Define the nonnegative definite matrix $N = G'HEH'G$. Then

$$\operatorname{trace} AN \leq 1 = \operatorname{trace} MN \quad \text{for all } A \in \mathcal{M}.$$

Hence N cannot be 0, and it satisfies the normality inequalities.
(ii) Let A be a competing moment matrix satisfying $A \geq M$. Then $0 \leq \operatorname{trace}\{(A-M)N\}$. On the other hand the normality inequalities yield $\operatorname{trace}\{(A-M)N\} \leq 0$. Therefore $\operatorname{trace}\{(A-M)N\} = 0$, and positive definiteness of N forces $A = M$. Thus admissibility is established. □

Our proof provides the additional information that in Theorem 2(i) we can choose N so as to satisfy $1 \leq \operatorname{rank} N \leq r = \operatorname{rank} M$.

Note that rank 1 matrices $M = cc'$ may well be admissible for the k-dimensional parameter θ. By Theorem 1 admissibility then holds if and only if M is uniquely optimal for $c'\theta$ in $\mathcal{M}$, and then Theorem 2(i) admits a rank 1 choice $N = dd'$.

Admissibility for a subset of the full parameter system admits a similar development, with slightly more technical input concerning information matrices.

3. INFORMATION MATRICES

Consider a fixed s-dimensional parameter system $K'\theta$ given by some $k \times s$ matrix K of full comlumn rank s. Admissibility for $K'\theta$ concentrates on the $s \times s$ information matrix for $K'\theta$ which, if $A \in \mathcal{A}(K)$ with $\mathcal{A}(K)$ defined as in the preceeding section, is given by

$$C_K(A) = (K'A^{-}K)^{-1}.$$

Recall that for the full parameter case a rank deficient moment matrix M may be admissible. Similarly a rank deficient information matrix $C_K(A)$ may prove admissible for $K'\theta$, provided we exercise some care when extending the matrix function C_K from $\mathcal{A}(K)$ to the convex cone $NND(k)$ of all nonnegative definite $k \times k$ matrices. The appropriate definition for an arbitrary matrix $A \in NND(k)$ is

$$C_K(A) = \lim_{\epsilon \downarrow 0}(K'(A + \epsilon I)^{-1}K)^{-1}.$$

Then $C_K(A)$ is nonsingular if and only if $A \in \mathcal{A}(K)$ and in this case

$$C_K(A) = (K'A^-K)^{-1},$$

see Lemma 2 in Müller-Funk, Pukelsheim & Witting (1985, p. 23). Another representation of the extended matrix function C_K was used in Gaffke (1987), namely

$$C_K(A) = \min_{L_K} L_K A L_K',$$

where the minimum is taken over all left inverses L_K of K (i.e. $L_K K = I_s$) and is carried out relative to the Löwner matrix ordering. That the minimum exists is a consequence of the Theorem in Krafft (1983). It can also be seen using the Gauss-Markov Theorem, as follows.

Consider a linear model with expectation $K\beta$ and dispersion matrix A, where $\beta \in \mathbb{R}^s$ is the unknown parameter vector. The set $\{L_K\}$ of left inverses of K defines the set of linear unbiased estimators for β, and the BLUE for β corresponds to a particular member L_K such that $L_K A L_K'$ is a minimum. We will call such a matrix L_K a left inverse of K *minimizing for* A, i.e.

$$L_K K = I_s \qquad \text{and } C_K(A) = L_K A L_K'.$$

Equivalently one could say that L_K' is a minimum A-seminorm generalized inverse of K', see Rao & Mitra (1971, p. 46).

Both expressions for $C_K(A)$ coincide, as shown next.

Lemma 2. *For all nonnegative definite $k \times k$ matrices A we have*

$$\lim_{\epsilon \downarrow 0}(K'(A+\epsilon I)^{-1}K)^{-1} = \min_{L_K} L_K A L_K'.$$

Proof. Since for $\epsilon > 0$ the matrix $A + \epsilon I$ is positive definite, we know from the Gauss-Markov Theorem that

$$\min_{L_K} L_K(A+\epsilon I)L_K' = (K'(A+\epsilon I)^{-1}K)^{-1}.$$

Let L_K^* be a left inverse of K minimizing for A. Then

$$\min_{L_K} L_K A L_K' \leq \min_{L_K} L_K(A+\epsilon I)L_K' \leq L_K^*(A+\epsilon I)L_K^{*\prime},$$

and letting $\epsilon \to 0$ the assertion follows. □

With the extended definition of C_K a moment matrix $M \in \mathcal{M}$ is called admissible for $K'\theta$ in $\mathcal{M}$ when no moment matrix $A \in \mathcal{M}$ satisfies $C_K(A) \geq C_K(M)$ and $C_K(A) \neq C_K(M)$.

Again we wish to study a fixed moment matrix $M \in \mathcal{M}$. However, we now choose a full rank decomposition of its information matrix (which we assume to be nonzero)

$$C_K(M) = HH',$$

where with $t = \operatorname{rank} C_K(M)$ the $s \times t$ matrix H has full column rank t.

We shall have to investigate the parameter system $H'K'\theta$. The information matrices relative to the representations $(KH)'\theta$ and $H'(K'\theta)$ satisfy the following decomposition rule. The matrix functions C_{KH} and C_H are defined as above with KH and H instead of K and with domains $NND(k)$ and $NND(s)$, respectively.

Lemma 3. *For all nonnegative definite $k \times k$ matrices A we have*

$$C_{KH}(A) = C_H(C_K(A)).$$

Proof. When A is positive definite then

$$C_{KH}(A) = (H'K'A^{-1}KH)^{-1} = C_H((K'A^{-1}K)^{-1}) = C_H(C_K(A)).$$

Now take a nonnegative definite matrix A. For $\epsilon > 0$ then $C_K(A) \leq C_K(A+\epsilon I)$. Since $A + \epsilon I$ is positive definite we obtain $C_H(C_K(A)) \leq C_{KH}(A+\epsilon I)$. The right hand side becomes $C_{KH}(A)$ when $\epsilon \to 0$.

For the converse inequality let L_H be a left inverse of H minimizing for $C_K(A)$, and L_K be a left inverse of K minimizing for A. Obviously $L_H L_K$ is a left inverse of KH, and by Lemma 2

$$C_{KH}(A) \leq L_H L_K A L'_K L'_H = L_H C_K(A) L'_H = C_H(C_K(A)).$$

The two inequalities force equality, and the proof is complete. □

An analoguous decomposition rule holds for left inverses of KH minimizing for A.

Lemma 4. *A left inverse L_{KH} of KH is minimizing for A if and only if $L_{KH} = L_H L_K$ for some left inverse L_K of K minimizing for A and some left inverse L_H of H minimizing for $C_K(A)$.*

Proof. We first note that if L_K is a given left inverse of K, then the set of all left inverses of K is the linear manifold $L_K + B$ where B may be any $s \times k$ matrix with $BK = 0$. From this it is easy to see that L_K is minimizing for A if and only if $L_K A Q_K = 0$, where Q_K denotes the orthogonal projector onto the nullspace of K'. Similarly a left inverse L_{KH} of KH is minimizing for A if and only if $L_{KH} A Q_{KH} = 0$, where Q_{KH} is the orthogonal projector onto the nullspace of $(KH)'$.

To prove the direct part of the lemma let L_{KH} be a left inverse of KH minimizing for A. Consider the matrix equations

$$L_{KH} K X = L_{KH}, \quad \text{and} \quad X \cdot [K,\, AQ_K] = [I_s,\, 0].$$

Obvioulsy each of them separately has a solution. Moreover they have a common solution for X, by Theorem 2.3.3 in Rao & Mitra (1971, p. 25). In order to apply this theorem we must verify $L_{KH} K [I_s, 0] = L_{KH}[K, AQ_K]$, but this holds true in view of $L_{KH} A Q_{KH} = 0$ and $Q_K = Q_{KH} Q_K$. Setting $L_K = X$ and $L_H = L_{KH} K$, we have a left inverse L_K of K minimizing for A, a left inverse L_H of H, and $L_H L_K = L_{KH}$. In fact, L_H is minimizing for $C_K(A)$ since by Lemma 3

$$L_H C_K(A) L'_H = L_H L_K A L'_K L'_H = L_{KH} A L'_{KH} = C_{KH}(A) = C_H(C_K(A)).$$

The converse part is immediate: Evidently $L_H L_K$ is a left inverse of KH, and $L_H L_K A L'_K L'_H = L_H C_K(A) L'_H = C_H(C_K(A)) = C_{KH}(A)$. □

We shall now use these intermediate results for our discussion of admissibility and optimality.

4. ADMISSIBILITY FOR PARAMETER SUBSETS

Let $M \in \mathcal{M}$ be a fixed moment matrix. We resume the discussion of M being admissible for $K'\theta$ in $\mathcal{M}$. Assume that $C_K(M) \neq 0$ and choose a full rank decomposition $C_K(M) = HH'$ as in Section 3. We first present a result similar to Lemma 1.

Lemma 5. *Let $A \in \mathcal{M}$ be a competing moment matrix. If A is E-optimal for $H'K'\theta$ in $\mathcal{M}$ then $C_K(A) \geq C_K(M)$.*

Proof. By construction the range of $C_K(M)$ contains the range of H. Applying Lemma 3 we obtain

$$C_{KH}(M) = (H'C_K(M)^- H)^{-1} = (H'(HH')^- H)^{-1} = I_t.$$

Optimality of A yields $1 = \lambda_{\min}(C_{KH}(M)) \leq \lambda_{\min}(C_{KH}(A))$. Therefore $I_t \leq C_{KH}(A)$, and pre- and postmultiplication with H and H' yields

$$C_K(M) = HH' \leq HC_H(C_K(A))H' \leq C_K(A).$$

Note that $C_H(C_K(A)) = C_{KH}(A)$ is nonsingular and hence $C_K(A) \in \mathcal{A}(H)$. □

The following theorem on admissibility and E-optimality parallels Theorem 1.

Theorem 3. *The moment matrix M is admissible for $K'\theta$ in $\mathcal{M}$ if and only if M is E-optimal for $H'K'\theta$ in $\mathcal{M}$ and for any other E-optimal moment matrix $A \in \mathcal{M}$ for $H'K'\theta$ in $\mathcal{M}$ we have $C_K(A) = C_K(M)$.*

Proof. Follow the proof of Theorem 1, with Lemma 1 replaced by Lemma 5. Use Lemma 3 for the converse part. □

We are now in a position to present our main result: A proof based on E-optimality of Theorem 2 of Gaffke (1987).

Theorem 4. *(i) If M is admissible for $K'\theta$ in $\mathcal{M}$ then there exists a nonnegative definite $s \times s$ matrix $D \neq 0$ and there exists a left inverse L_K of K minimizing for M such that $L_K' D L_K$ is normal to $\mathcal{M}$ at M.*
(ii) If there exists a positive definite $s \times s$ matrix D and a left inverse L_K of K minimizing for M such that $L_K' D L_K$ is normal to $\mathcal{M}$ at M then M is admissible for $K'\theta$ in $\mathcal{M}$.

Proof. (i) By Theorem 3 the moment matrix M is E-optimal for $H'K'\theta$ in $\mathcal{M}$, and as shown above $C_{KH}(M) = I_t$. The general equivalence theory tells us that

$$\operatorname{trace}(H'K'GAG'KHE) \leq 1 \quad \text{for all } A \in \mathcal{M},$$

for some generalized inverse G of M and some nonnegative definite $t \times t$ matrix E with trace equal to 1. Define the matrix $N = G'KHEH'K'G$. Then

$$\operatorname{trace}(AN) \leq 1 = \operatorname{trace}(MN) \quad \text{for all } A \in \mathcal{M},$$

and $1 \leq \operatorname{rank} N \leq t$. The matrix $L_{KH} = H'K'G$ satisfies $L_{KH}KH = H'K'GKH = (C_{KH}(M))^{-1} = I_t$ and $L_{KH}ML_{KH}' = H'K'GMG'KH = I_t = C_{KH}(M)$, and thus is a left inverse of KH minimizing for M. Lemma 4 then ensures that $L_{KH} = L_H L_K$ where L_K is a left inverse of K minimizing for M. Setting $D = L_H' E L_H$ we obtain the desired representation

$$N = L_{KH}' E L_{KH} = L_K' L_H' E L_H L_K = L_K' D L_K.$$

(ii) Let A be a competing moment matrix satisfying $C_K(A) \geq C_K(M)$. Then

$$\begin{aligned} 0 &\leq \operatorname{trace}\{(C_K(A) - C_K(M))D\} \\ &\leq \operatorname{trace}\{(L_K A L_K' - L_K M L_K')D\} \\ &= \operatorname{trace}\{(A - M) L_K' D L_K\} \leq 0, \end{aligned}$$

and because of positive definiteness of D therefore $C_K(A) = C_K(M)$. □

The proof gives the aditional information that in Theorem 4(i) we can choose the $s \times s$ matrix D so as to satisfy $1 \leq \operatorname{rank} D \leq t = \operatorname{rank} C_K(M)$.

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