CHAPTER - 08

CONCLUSIONS AND FURTHER RESEARCH

The study of the different methods used for robust engineering design has led to the investigations of a number of statistical topics as well as others such as interpolation and optimization. The main interest in this study was in the application of robust engineering to computer simulation models. To help in the development of robust engineering method and to compare the different methods, thorough understanding of the different methods developed both for experimental designs and statistical analysis and the underlying statistical and probabilistic concepts are necessary. The conclusions in this study could be roughly stated under robust parameter design, random field linear model and experimental design.

Robust Parameter Design

Taguchi developed statistical methods and experimental designs for improving quality in designed products to make performance insensitive to many types of variability. The methods developed by Taguchi and his coworkers had many important concepts and quality philosophy behind them but were not particularly efficient and have some deficiencies from a statistical point of view. The investigations of the loss model approach and RSM approach that were developed in the late 80's and 90's show that the RSM method has more flexibility than the LM approach in the choice of experimental designs, the associated analysis, in the choice of different probability models for the distributions of noise factors and provides more opportunity for experimentation with different noise distributions.

There are several other areas in statistical modeling that can be used for robust engineering designs. For example Generalized Additive Models are useful for modeling both static and dynamic parameter design problems and the extensions of these models for spatial modeling is a useful area of research as these methods could be easily used with computer simulation models when the observations are from the exponential family of distributions. We have proposed a method for binary-input, binary output problem in Section 2.7. In general, satisfactory statistical and probabilistic models built for the computer simulation models could help enormously in understanding behaviour of the complex computer codes and also in engineering design optimization methods.

Random Field Linear Model

The approach used in this thesis for robust parameter design is the modeling approach. The random field linear model of Chapter 3 was used to predict the responses of circuit simulation model. The predictions were accurate enough, so the predictor was used for optimization and for data analysis.

The RFLM used for modeling the computer simulation model has better prediction capability than RSM. These predictors can be used with several methods of optimization, a distinctive advantage over the optimization methods used in LM, for robust engineering methods. The RFLM predictors can play a large role in multiple objective optimization procedures due to the graphical outputs RFLM provides when used with Latin Hypercube Sampling design. Unlike the RSM's which are local approximations of the response functions in the factor space, the RFLM is valid over a wider region of the factor space and does not need an initial nominal value for the optimization procedure.

Software for the fitting of the model graphical outputs and optimization was prepared using MATLAB. We found working with MATLAB code easier for developing software, especially due to the ease with which MATLAB handles matrices. For RFLM to be used widely it is necessary to have softwares available. More refined, software for RFLM prediction is another useful tool that could be added to the engineers' tool boxes for design optimization.

A closer look at the predictor with the covariance function with þ = 2 revealed that the predictor indeed is an interpolator that approximates to the multinomial function in the input variables for small values of θ.

Usually RFLM is applied to two or three dimensions in spatial statistical literature. The applications of RFLM for modeling computer simulation models in 90's led to the extension of this model to higher dimensions. The study of this model for prediction is a fast growing field with many opportunities for further research. The covariance function used in this thesis needs further research on a theoretical basis. The computation of maximum likelihood estimates caused some problems. This could possibly be due to the structure of the correlation matrix. The study of modality of maximum likelihood, investigations on the robustness of the parameters for prediction, consistency of maximum likelihood estimates in small samples will be useful.

Although we have used RFLM for deterministic observations, the methodology can be extended to settings where systematic and random error are both important, the covariance function can be adapted so that Var [Y (x)] = $\sigma^2 + \sigma_\varepsilon^2$ where σ_ε^2 is the measurement error. The statistical model we used for computer experiments quantify uncertainty about the response where it is unobserved.

Experimental Design

We used the Latin Hypercube Sampling design for sampling design points. The applications of traditional designs for parameter design experiments were well researched. The recent interests are in the use of LHS for modeling, estimation and simulation studies in parameter design problems when the observations are created using a computer simulation model. LHS design is easy to construct. It is a random design, and was developed for designing experiments for high dimensional computer experiments. Earlier work has shown that Latin hypercube sampling design is asymptotically more efficient than simple random sampling or stratified random sampling for the estimation of multi-dimensional integrals. The structure of the design could be improved to improve the prediction capability as well as for computing estimates of multi-dimensional integrals using Monte-Carlo simulation. The use of LHS design with computer simulation experiments eases the search for important factors in the design space.

There are several theoretical properties of this design that deserve further study with relevance to its use as sampling design to fit RFLM. The best linear predictor is an interpolator. The RFLM and LHS designs had been used previously to construct optimal designs for Bayesian interpolation. It will be useful to compare the interpolation schemes produced by this design with RFLM with methods of interpolation schemes in the numerical analysis literature.

APPENDIX
MATLAB PROGRAMS.

```
%*********************************************************************
% Log likelihood.
%*********************************************************************
function L =lik (x)
aaa
E = ones (30,1);
C = exp ((-1)*x.*a);
G = inv (C );
F = E' * G;
B1= F * E;
B= (B1 )^ (-1) * F * y ' ;
H = y ' - B. * E ;
S = .1. * (H' * (G * H) );
L = - .5 *((-30 * log (S)) + log (det(C)));
%*********************************************************************
% Prediction
%*********************************************************************
Function yp = pred (u)
aaa ;
E = ones (30,1);
C = exp ((-1) * .50. * a);
G = inv (C );
F = E' * G;
B1= F * E;
B2= (B1)^(-1);
B = B2 * F * y';
H = y'- B. * E;
V1= ones (30,1) * u;
V2= V1- t;
V3= V2. * V2;
V4= (sum(V3'))';
r = exp ((-.50. * V4));
yp = B+(r' * G) * (H);
%*********************************************************************
% Two-dimensional projection of the experimental design
%*********************************************************************
u = t(:,1); % first column
v = t(:,6); % sixth column
plot (u,v);x label ('column 1'),y label ('column 6'),
%*********************************************************************
% Log likelihood plot
%*********************************************************************
lik;
x = .47: .05: .5;
plot (x,L),x label('theta'),y label('log-likelihood')
title('loglikelihood vs theta')
```

```
%**********************************************************************
% Scalter plot of observed values vs predicted
%values
%**********************************************************************
% y vector of observed values
for i =1:30
py (i) = pred (t (i,:));
end
plot (y,py), x label ('observed response'),
y label ('Predicted values'), title ('Predicted vs observed')
%**********************************************************************
%Q-Q plot
%**********************************************************************
% r standardized residuals
% q Gaussian quantiles
  plot (r, q), x label('Gaussian quantiles'),y label('standardized residuals'),title('Q-Q plot standardized residuals against standard normal quantiles')
%**********************************************************************
% main effect plots
%**********************************************************************
s = t(:,1) ;
d = [s, zeros (30,9) ];
for i=1:30
b(i) = pred (d (i,:) ;
end
plot (s,b), x label ('Range of c1'), y label ('Effect of c1'), title ('Effect of c1')
%**********************************************************************
d1=[zeros (30,1),s,zeros(30,8)];
for i=1:30
c(i) = pred (d1(i,:) );
end
plot (s,c), x label ('Range of c2'), y label ('Effect of c2'), title ('Effect of c2')
%**********************************************************************
d2=[zeros(30,2), s, zeros(30,7)];
for i=1:30
e(i)=pred (d2(i,:) );
end
plot (s,e), x label ('Range of c3'), y label ('Effect of c3')
%**********************************************************************
d3=[zeros (30,3), s, zeros (30,6)];
for i=1:30
f(i)=pred (d3 (i,:) );
end
plot (s,f), x label ('Range of c4'), y label ('Effect of c4'), title ('Effect of c4')
```

```
%************************************************************************
d4 = [zeros (30,4), s, zeros (30,5)];
for i =1:30
g(i) = pred (d4 (i,:) );
end
plot (s,g), x label ('Range of R1'), y label ('Effect of R1'), title ('Effect of R1')
%************************************************************************
d5 = [zeros (30,5), s, zeros (30,4)];
for i =1:30
h(i) = pred (d5 (i,:) );
end
plot (s,h), x label ('Range of R2'), y label ('Effect of R2')
%************************************************************************
d6 = [zero(30,6), s, zeros (30,3)];
for i =1:30
k(i) = pred (d6 (i,:) );
end
plot (s,k), x label ('Range of R3'), y label ('Effect of R3')
%************************************************************************
d7 = [zeros (30,7), s, zeros (30,2) ];
for i =1:30
l(i) = pred (d7(i,:) );
end
plot (s,l), x label ('Range of R4'), y label ('Effect of R4'), title ('Effect of R4')
%************************************************************************
d8 = [zeros (30,8), s, zeros (30,1)];
for i = 1:30
m(i) = pred (d8(i,: ) );
end
plot (s,m), x label ('Range of R5'), y label ('Effect of R5'),title ('Eff ect of R5')
%************************************************************************
d9=[zeros (30,9), s]
for i = 1:30
n(i) = pred (d9(i,:) );
end
plot (s,n), x label ('Range of R6'), y label ('Effect of R6'), title ('Effect of R6')
```

```
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
% Initial set of control and noise arrays, cr
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C1 = rand (10,1) * .1 + .35;
C2 = rand (10,1) * .1 + .25;
C3 = rand (10,1) * .05 + .45;
C4 = zeros (10,1);
C = [ C1,C2,C3,C4];
r1 = rand (10,1) * - .1 + .4;
r2 = rand (10,1) *   .1  - (.5);
r3 = rand (10,1) * .1 +.4;
r4 = rand (10,1) * .1 + .4;
r5 = rand (10,1) * .. .1 – (.5);
r6 = rand (10,1) * .1 + .4;
r = [r1, r2, r3, r4, r5, r6];
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
% Cross over
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
function R = rr (r, c, j, m)
for i = 1: m
R (i, :) = [C (i,:), r(j, : ) ] ;
end
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
% Classical prediction
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
function yp = st (x, n, t, a, y)
for i = 1 : n
    s = x (i , :);
    yp (i , :) = pred (s, t, a, y);
end
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
function a = mal (t)
for i = 1 : 30
for i = 1 : 30
a (i , j) = sum ((t (i , :) – t (j , :)^ .2;
end
end
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
% Arrays for simulation study
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
load test
t = 10 ^ (-2). * T1;
a = mal (t);
cr;
R4 = rr (r, c, 4, 10);
R5 = rr (r, c, 5, 10);
```

```
R6 = rr (r, c, 6, 10);
R7 = rr (r, c, 7, 10);
R8 = rr (r, c, 8, 10);
R9 = rr (r, c, 9, 10);
rc4 = R4 + randn (10 , 10) * .1;
rc5 = R5 + randn (10 , 10) * .1;
rc6 = R6 + randn (10 , 10) * .1;
rc7 = R7 + randn (10 , 10) * .1;
rc8 = R8 + randn (10 , 10) * .1;
rc9 = R9 + randn (10 , 10) * .1;
pe4 = st (rc4, 10, t, a);
pc5 = st (re5, 10, t, a);
pc6 = st (re6, 10, t, a);
pc7 = st (re7, 10, t, a);
pe8 = st (re8, 10, t, a);
pe9 = st (re9, 10, t, a);
%**********************************************
%**********************************************
% Estimation of prior means and variances
%**********************************************
function [b2, b, s] = pm (t , y)
a = mal (t);
e = ones (15 , 1);
d = exp ((-1) * .8 . * a);
g = inv (d);
f = e' * g;
b1 = f * e;
b2 = (b1)^(-1);
b = (b2) * f * y';
h = y' – b . * e;
s = (1/15) . * h' * (g * h);
%**********************************************
% Posterior mean
%**********************************************
function b = pb (u, t, y)
e = ones (15 , 1);
a = mal (t);
d = exp ((-1) * .8 . * a);
v1 = repmat (u, [15 , 1] );
v2 = v1 – t;
v3 = v2 . * v2;
v4 = (sum (v3'))';
s = exp (-.8 . * v4);
n = d + .3891 * e * e ';
m = inv (n);
b = 1.089 + (s' + .3891 * e' ) * m * (y' – 1.089 . * e);
```

```
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
% Bayesian Prediction
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
function sb = sa (x, n, t, y)
for i = i : n
    s = x (i , :);
    sb (i , :) = pb (s, t, y);
end
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  * * * * * * * * * * * * * * *
[b2, b, s1] = pm (d1 , v1');
[b3, b4, s2] = pm (d2 , v2');
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  * * * * * *
% Main effect plots with calssical predictor
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  * * * * * *
s = t (: , 1);
t5 = [s, zeros (30,5)];
t6 = [zeros (30 , 1), s, zeros (30 , 4)];
t7 = [zeros (30 , 2), s, zeros (30 , 3)];
t8 = [zeros (30 , 3), s, zeros (30 , 2)];
t9 = [zeros (30 , 4), s, zeros (30 , 1)];
t10 = [zeros (30 , 5), s];
a = mal (t3);
z5 = st (t5, 30, d1, a, u1');
z6 = st (t6, 30, d1, a, u1');
z7 = st (t7, 30, d1, a, u1');
z8 = st (t8, 30, d1, a, u1');
z9 = st (t9, 30, d1, a, u1');
z10 = st (t10, 30, d1, a, u1');
hold
plot (s, z5, ' . ' )
plot (s, z6, ' + ')
plot (s, z7, ' x ')
plot (s, z8, ' 0 ')
plot (s, z9, ' : ')
plot (s, z10, ' * ')
x label ( ' Range'), y label ( ' Main effects '),
title (' Main effects ')
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  * * * * * *
% Main effect plots with Bayesian predictor
%* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  * * * * * *
y5 = sa (t5 , 30, d2, u2');
y6 = sa (t6 , 30, d2, u2');
y7 = sa (t7 , 30, d2, u2');
y8 = sa (t8 , 30, d2, u2');
y9 = sa (t9 , 30, d2, u2');
y10 = sa (t10 , 30, d2, u2');
```

```
hold
plot (s , y5, ' + ')
plot (s , y6, ' o ')
plot (s , y7)
plot (s , y8, ' * ')
plot (s , y9, ' . ')
plot (s, y10, ' : ')
x label (' Range'), y label (' Main effects), title (' Main effects')
%*********************************************** ******
% Joint effect plot
%*********************************************** ******
s = t (: , 1);
u = s
for i = 1 : 30
for j = 1 : 30
l = [ 0 0 0 , t (i ,1), o, t (i , 1)];
z (i , j) = pred (l);
end
end
contour (s,u,z), x label (' Range of t4'),
y label ('Range of t6'), title ('Joint effect of t4 and t6')
```

BIBLIOGRAPHY

1. Adams, B.M. and Woodall, W.H., (1989) "An analysis of Taguchi's on-line process control procedure under a random walk model." *Technometrics*, 31, 401-414.

2. Akin, J.E. (1994) *Finite Elements for Analysis and Designs.* Academic Press Limited. 24-28 Oval Road, London NWI 7DX.

3. Alvarez, A.R., Abdi, B.L., Young, D.L., Weed, H.D., Teplik, J. and Herald, E.R., (1988) "Application of statistical design and response surface methods to computer-aided VLSI device design." *IEEE Transactions on Computer Aided Design*, 7, 272-288.

4. Anderson, D.A., and Aitkin, M., (1985) "Variance component models with binary response interviewer variability." *J.R. Statist. Soc. B*, 47, 203-210.

5. Aslett, R., Buck, R.J., Duvall, S.G., Sacks, J., and Welch, W.J., (1998) "Circuit optimization via sequential computer experiments design of an output buffer." *Appl. Statist.* 47, Part I, 31-48.

6. Atkinson, A.C. and Donev, A.N. (1992) *Optimum Experimental Designs* Oxford; Oxford University Press.

7. Atkinson, A.C. and Cook, R.D. (1995) "D-optimum designs for hetroscedastic linear models." *J. Am. Statist. Ass.*, 90, 204-212.

8. Atkinson, A.C., (1996) "Usefulness of optimum experimental designs (with discussion)" *J.R. Statist. Soc.* B, 58, 59-76. Discussion 95-111.

9. Atkinson, A.C. and Cook, R.D. (1997) "Designing for a response transformation parameter." *J.R. Statist. Soc.* B, 59, 111-124.

10. Barnard. G.A., (1986) "Rescuing our manufacturing industry." *The Statistician.* 35, 3-16.

11. Baskerville, J.C., and Toogood, J.H. (1982) "Guided regression modelling for prcdiction and cxploration of structurc with many cxplanatory variables." *Technometrics,* Vol 24, No.1, 9-17.

12. Bates, R.A., Buck, R.J., Riccomagno, E. and Wynn, H.P. (1996) "Experimental design and observation for large systems. (with discussion)" *J.R. Statist. Soc.* B, 58, 77-94. Discussion 95-111.

13. Beckman, R.J. and Mckay, M.D., (1987) "Monte-Carlo estimation under different distribution using the same simulation." *Technometrics* 29, 153-160.

14. Bernado, M.C., Buck, R, Liu, L., Nazaret, W.A., Sacks, J., and Welch, W.J., (1992) "Integrated circuit design optimization using a sequential strategy." *IEEE Transactions on Computer-Aided Design.* 11, 361-372.

15. Bisgaard, S. (1996) "A comparativc analysis of thc pcrformancc of Taguchi's linear graphs for the design of two-level fractional factorials." *Appl. Statist.* 45, No.3, 311-322.

16. Bisgarrd, S., and Steinberg, D.M., (1997) "The design and analysis of 2^{k-p} prototype experiments." *Technometrics,* 39, No.1, 52-62.

17. Bohachevsky, I.O., Johnson, M.E., Stein, M.L. (1986) "Generalized simulated annealing for function optimization." *Technometrics,* 28, 209-217.

18. Boning, D.S., and Mozunder, P.K., (1994) "DOE/Opt: A system for design of experiments, Response surface modeling and optimization using process and device simulation." *IEEE Transactions on Semi-Conductor Manufacturing* Vol.7, No.2, 233-244.

19. Borkowski, J.J., and Lucas, J.M. (1997) "Designs of mixed resolution for process robustness studies." *Technometrics*. Vol.59, No.1, 52-70.

20. Box, G.E.P. and Hunter, J.S. (1957) "Multi-factor experimental design for exploring response surfaces." *The Annals of Mathematical Statistics*. 28, 195-241.

21. Box, G.E.P. and Draper, N.R. (1963) "The choice of a second order rotatable design." *Biometrika*, 50, 335-352.

22. Box, G.E.P. and Draper, N.R, (1982) "Measures of lack of fit for response surface designs and predictor variable transformations." *Technometrics*. Vol.24, No.1, 1-8.

23. Box, G.E.P. and Meyer, R.D. (1986) "An analysis of unreplicated fractional factorials." *Technometrics*, 28, 11-18.

24. Box, G.E.P. and Meyer, R.D. (1986) "Dispersion effects from fractional designs." *Technometrics*, 28, 19-27.

25. Box, G.E.P. (1988) "Signal to noise ratios, performance criteria and transformations (with discussion)." *Technometrics*, 30, 1-40.

26. Box, G.E.P., (1992) in "Taguchi parameter design, a panel discussion." Ed. Nair V.N. *Technometrics*, 34, 127-161.

27. Box, G.E.P. and Jones S(1992) in "Taguchi's parameter design, a panel discussion." Ed. Nair V.N. *Technometrics*, 34, 127-161.

28. Box, G.E.P. (1994) "Statistics and quality improvement." *J.R. Statist. Soc.* A. 157, Part II, 209-229.

29. Brayton, R., Director, S. and Hatchell G. (1980) "Yield maximization and worst-case design with arbitrary statistical distributions." *IEEE Transactions on Circuit Systems*. No.9, 756-764.

30. Brayton, R, Hachtel, G. and Sangiovanni Vincentelli, A.L. (1981) "A survey of optimization techniques for integrated-circuit design." *Proceedings of the IEEE*, 69, 1334-1362.

31. Brinkley, P.A., Meyer, K.P. and Lu, J.C. (1996) "Combined generalized linear modeling - Non-linear programming approach to robust process design - A case - study in circuit board quality improvement" *Appl. Statist.* 45, No.1, 99-110.

32. Carroll, R.J. and Ruppert, D., (1987) "Diagnostics and robust estimation when transforming the regression model and the response." *Technometrics* Vol.29, No.3, 287-299.

33. Carroll, R.J. and Ruppert D. (1988) *Transformation and weighting in regression* Chapman and Hall.

34. Chao, P.Y., and Hwang, Y.D. (1997) "An improved Taguchi's method in designing experiments for CFRP composite." *Int. J. Prod. Res.* Vol. 35, No.1, 51-66.

35. Cheng, C.S. (1989) "Some orthogonal main effects plans for asymmetrical factorials." *Technometrics* 31, 475-478.

36. Cheng, C.S. and Li, C.C. (1993) "Constructing orthogonal fractional factorial designs when certain factor-level combinations are debarred." *Technometrics 35,* 277-283.

37. Christensen, R. (1987), *Plane Amswers to Complex Questions. The Theory of Linear Models.* Springer-Verlay New York inc.

38. Christensen, R., Johnson, W. and Pearson, L.M. (1992) "Prediction diagnostics for spatial linear models." *Biometrika* 79, 583-592.

39. Cook, R.D. and Weisberg, S. (1982) *Residuals and Influence in Regression*, London. Chapman and Hall.

40. Cook, R.D. and Weisberg. S. (1983) "Diagnostic for hetroscedasticity in regression" Biometrika, 70, 1-10.

41. Cook, R.D. and Nachtsheim, C.J. (1989) "Computer-aided blocking of factorial and response surface designs." *Technometrics* 31, 339-346.

42. Cox, D.R. (1984) "Present position and potential developments: some personal views, design of experiments and regression." *J.R. Statist. Soc* A 147, Part 2, 306-315.

43. Cressie, N.A.C. (1993) *Statistics for Spatial Data*, John Wiley and Sons inc.

44. Currin, C., Mitchell, T. Morris, M. and Ylvisaker, D. (1991) " Bayesian prediction of deterministic functions with application to the design and analysis of computer experiments." *J. Am. Statist. Ass.* 86, 953-963.

45. Curnow, R.N. and Dayananda R.A. (1991) "The use of Prior and Experimental Information in Setting Process Control Variables." Dept. of Statistics, University of Reading.

46. Davidian, M. and Carroll, R.J. (1987) "Variance function estimation." *J. Am. Statist. Ass.* 82, 1079-1091.

47. Davies, O.L. (1967) *Design and Analysis of Industrial experiments* Oliver and Boyd.

48. Dayananda, R.A. (1992) "Fifty years of quality technology." *Vidyodaya J. of Sci*, Vol.4, No.1, 1-31.

49. De Feo, P. and Myers R.H. (1992) "A new look at experimental design robustness." *Biometrika*, 79, 375-381.

50. D' Errico, J.R. and Zaino, N.A. (1988) "Statistical tolerancing using a modification of Taguchi's method." *Technometrics*, 30, 397-405.

51. Dietrich, C.R., (1991) "Modality of the restricted maximum likelihood for spatial Gaussian random fields." *Biometrika*, 78, 833-840.

52. Diggle, P.J., Tawn, J.A., and Moyeed, R.A., "Model-based geostatistics", *Appl. Statist.* 47, Part 3, 299-350.

53. Dobson, A.J. (1990) *An Introduction to Generalized Linear Models.* Chapman and Hall.

54. Downing, D.J., Gardiner, R.H., and Hoffman, F.O. (1985) "An examination of response surface methodology for uncertainty analysis in assessment models." *Technometrics*, 27, 151-163.

55. Draper, N.R. and Hunter, W.G. (1966) "Design of experiments for parameter estimation in multi-response situation." *Biometrika*, 53, 525-533.

56. Draper, N.R. (1985) "Small composite designs." *Technometrics*, 27, 173-180.

57. Draper, N.R. and Lawrence (1965) "Designs which minimize model inadequacies: cuboidal regions of interest", *Biometrika*, 52, 111-118.

58. Draper, N.R. and Lin, D.K.J., (1990) "Small response surface designs." *Technometrics*, 32, 187-194.

59. Elseyed, E.A., and Chen, A., (1993) "Optimal levels of process parameters for products with multiple characteristics." *Int. J. Prod. Res.* Vol.31, 5, 1117-1132.

60. Engel, T., (1992) "Modeling variation in industrial experiments." *Appl. Statist.* 41, 579-594.

61. Fearn, T., (1992) "Box-Cox transformations and the Taguchi method: an alternative analysis of a Taguchi case study." *Appl. Statist*, 41, 553-559.

62. Fogel, D.B., (1994) "An introduction to simulated evolutionary optimization." IEEE Transactions on Neural Networks, Vol. 5, No. 1, 3-14.

63. Ford, I., Kitosis, C.P., and Titterington, D.M., (1989) "Recent advances in non-linear experimental design." *Technometrics*, 31, 49-60.

64. Franklin, M.F., and Bailey, R.A., (1977) "Selection of defining contrasts and confounded effects in two-level experiments." *J.R. Statist. Soc. C*, 26, 321-326.

65. Franklin, M.F., (1985) "Selecting defining contrasts and confounded effects in p^{n-m} factorial experiments." *Technometrics*, 27, 165-172.

66. Fries, A., and Hunter, W.G., (1980) "Minimum aberration 2^{k-p} designs." *Technometrics*, 22, 601-608.

67. Galil and Keifer, J. (1980) "Time and space-saving computer methods related to Mitchell's DETMAX. for finding D-optimum Designs." *Technometrics*, 22, 301-313.

68. Gao, F., Sacks, J., and Welch, W.J, (1996) "Predicting urban ozone levels and trends with semiparametric modeling." *Journal of Agricultural, Biological and Environmental Statistics*, Vol.1, No.4, 404-425.

69. Giovannitti - Jensen, A., and Myers, R.H., (1989) "Graphical assessment of the prediction capability of response surface designs." *Technometrics*, 31, 159-171.

70. Gotway. C.A., and Hartford, A.H., (1996) "Geostatistical method for incorporating auxiliary information in the prediction of spatial variables." *Journal of Agricultural, Biological and Environmental Statistics*, Vo.1, No.1, 17-39.

71. Hahn, G.J., and Dershowitz, A.F., (1974) "Evolutionary operation today - some survey results and observations." *Appl. Statist.*, 23, 214-218.

72. Handcock, M.S., and Wallis, J.R., (1994) "An approach to statistical spatial temporal modeling of meteorological field" (with comments). *J. Am. Statist. Ass.* 89, No.426, 368-390.

73. Handcock, M.S., and Stein, M.L., (1993) "A Bayesian analysis of kriging." *Technometrics*, 35, 403-410.

74. Harville, D.A., and Jeseke, D.R., (1992) "Mean squared error of estimation or prediction under a general linear model." *J. Am. Statist. Ass.* 87, 724-731.

75. Haslett, J., and Heyes, K., (1998) "Residuals for the linear model with general covariance structure." *J.R. Statist. Soc.* B, 60, Part I, 201-215.

76. Hastie, T., and Tibshirani, R., (1993) "Varying - coefficient models" (with discussion). *J.R. Statist. Soc.* B, 55, No.4, 757-796.

77. Hedayat, A., and Wallis, W.D., (1978) "Hardamard matrices and their applications." *The Annals of Statistics.* Vol.6, 1184-1235.

78. Heines, M.L., (1987) "The application of the annealing algorithm to the construction of exact optimal designs for linear-regression models." *Technometrics*, Vol.29, No.4, 439-446.

79. Hunter W.G., (1981) "The practice of statistics. The real world in an idea whose time has come." *The American Statistician*, 35, 72-76.

80. Hunter, J.S., (1985) "Statistical design applied to product design." *Journal of Quality Technology*, 17, 210-221.

81. Hussey, J.R., Myers, R.H., and Houck, E.C. (1987) "Correlated simulation experiments in first-order response surface design." *Operations Research*, Vol.35, No.5, 744-758.

82. Iman, R.L., and Conover, W.J., (1987) "A measure of top-down correlation." *Technometrics*, Vo.29, No.3, 351-357.

83. Jensen, A.G., and Myers, R.H., (1989) "Graphical assessment of the prediction capability of response surface designs." *Technometrics*, Vol.31, No.2, 159-171.

84. Johnson, M.E., and Nachtsheim., C.J., (1983) "Some guidelines for constructing exact D-optimal convex design spaces." *Technometrics*, Vol.25, No.3, 271-277.

85. Juran, J.M., *Quality Control Handbook*, Third edition, McGraw Hill, New York.

86. Kacker, R.N., (1985) "Off-line quality control, parameter design and the Taguchi method (with discussion)." *Journal of Quality Technology*, 17, 176-209.

87. Kacker, R.N., and Shoemaker, A.C., (1986) "Robust design a cost effective method for improving manufacturing process." *A T & T Technical Journal*, 65, 39-50.

88. Kacker, R.N. and Tsui, K.L., (1990) "Interaction graphs: graphical aids for planning experiments." *Journal of Quality Technology*, 22, 1-14.

89. Kang, G., and Bates, D.M., (1990) "Approximate inferences in multiresponse regression analysis." *Biometrika*, 77, 2, 321-331.

90. Kapur, J.N. (1973) "Twenty five years of maximum entropy principle" *Journal of Mathematical and Physical Sciences.* 103-156.

91. Keisall, J.E., and Diggle, P.J., (1998) "Spatial variation in risk of disease: a non-parametric binary regression approach." *Appl. Statist.* 47, Part 4, 559-573.

92. Khuri A.I. (1992) "Response surface models with random block effects." *Technometrics,* Vo.34, No.1, 26-36.

93. Kirmani, S.N.U.A., and Peddada, S.D., (1993) "Stochastic ordering approach to off-line quality control." *Appl. Statist.* 42, No.2, 271-281.

94. Kotz. S., Pearn, W.L. and Johnson, N.L. (1993) "Some process capability indices are more reliable than one might think." *Appl. Statist.* (1993) 42, No.1, 55-62.

95. Kunert, J. (1997) "On the use of the factor-sparsity assumption to get an estimate of the variance in saturated designs." *Technometrics,* Vol.39, No,1, 81-90.

96. Laslett, G.M., (1994) "Kriging and splines an empirical comparison of their predictive performance in some application (with discussion)." *J. Am. Statist. Ass.,* 89, 391-409.

97. Le Blanc, M., and Tibshirani, R., (1994) "Adaptive principal surfaces." *J. Am. Statist. Ass.* Vol.89, No.425, 53-64.

98. Leon, R.V., Shoemaker, A.C., Kacker, R.N., (1987) "Performance Measure Independent of Adjustment. (with discussion)" *Technometrics,* 29, 253-282.

99. Lenth, R.V., (1989) "Quick and easy anlaysis of unreplicated factorials." *Technometrics,* 31, 469-474.

100. Lin, D.K.J., and Draper, N.R. (1992) "Projection properties of Plackett and Burman designs." *Technometrics*, Vol.34, No.1, 423-428.

101. Lindley, D.V., and Smith, A.F.M., (1972) "Bayes estimates for the linear model (with discussion)." *J.R. Statist. Soc.* B, 1, 1-41.

102. Liu, L., Nazaret, U.A., and Beale, R.G. (1990) "Computer - Aided Design for Quality (CADQ)." *AT&T Technical Journal*, 47-60.

103. Logethetis, N., (1990) "Box-Cox transformations and the Taguchi Method." *Appl. Statist*, 39, 31-48

104. Logethetis. N., (1990) "Managing the component tolerances." *Total Quality Management*, Vol.1, No.1, 75-84.

105. Lowe, C.W., (1974) "Evolutionary operation in action." *Appl. Statist.* 23, 218-226.

106. Lucas, J.M., (1976) "Which response surface design is best." *Technometrics*, 18, No.4, 411-417.

107. Mak, T.K., (1992) "Estimation of parameters in hetroscedastic linear models." *J.R. Statist. Soc. B.* 54, 649-655.

108. Mardia, K.V., and Marshall, R.J., (1984) "Maximum likelihood estimation of models for residual covariance in spatial regression." *Bometrika*, 71, 135-146.

109. Mardia, K.V., and Watkins, A.J., (1989) "On multimodality of the likelihood in the spatial linear model." *Biometrika*, 76, 289-295.

110. Mauro, C.A., and Smith, D.E., (1982) "The performance of two-stage group screening in factor screening experiments." *Technometrics*, Vol.24, No.4, 325-328.

111. McCaskey, S.D. and Tsui, K.L. (1997) "Analysis of dynamic robust design experiments." *Int., J. Prod. Res.* Vol.35, No.6, 1561-1574.

112. McCullagh, P. (1983) "Quasi-likelihood functions." *The Annals of Statistics*, Vol.11, No.1, 59-67.

113. McCullagh, P. and Nelder, J.A. (1989) *Generalized Linear Models*, 2nd ed, London: Chapman and Hall.

114. McPherson, G. (1989) "The scientists view of Statistics - A neglected area (with comments)." *J.R. Statist. Soc.* A, 152, 221-240.

115. Mead, R. (1990) "The non-orthogonal design of experiments (with discussion)." *J.R. Statist, Soc.* A, 153, 151-202.

116. Miller and Wu (1992) in "Taguchi's parameter design, a panel discussion." Ed. Nair V.N. *Technometrics*, 34, 127-161.

117. Mitchell, T.J. (1974) "Computer construction of D-optimal first-order designs." *Technometrics*, 16, 211-220.

118. Morris, M.D. and Mitchell, T.J. (1983) "Two-level multifactor designs for detecting the presence of interaction." *Technometrics*, 25, 345-355.

119. Morris, M.D., Mitchell, T.J. and Ylvisaker, D. (1993) "Bayesian design and analysis of computer experiments: use of derivatives in surface prediction." Technometrics Vol.35, 243-255.

120. Myers, R.H., Khuri, A.L. and Carter, W.H. (1989) "Response surface methodology: 1966:1988." *Technometrics*, 31, 137-157.

121. Myers, R.H., Khuri, A.I. and Vining, G. (1992) "Response surface alternatives to Taguchi robust parameter design approach." *The American Statistician*, Vol.46, No.2, 131-139.

122. Myers, R.H. (1976) *Response surface methodology,* Department of Statistics, Virginia Polytechnic Institute and State University, Blacksburg V.A.

123. Nair, V.N. ana Pregibon, D., (1986) "A data analysis stratcgy for quality engineering experiments." *AT&T Technical Journal,* 65, 73-84.

124. Nair, V.N. and Pregibon D. (1988) "Analyzing dispersion effects from replicated factorial experiments." *Technometrics,* 30, 247-257.

125. Nair, V.N. (ed) (1992) "Taguchi's parameter design - A panel discussion." *Technometrics,* 34, 127-161.

126. Nelder, J.A. and Pregibon D., (1987) "An Extended Quasi Likelihood Function." *Biometrika,* 74, 221-232.

127. Nelder J.A. and Lee, Y. (1992). "Likelihood Quasi-Likelihood and Pseudo-Likelihood: Some Comparisons." *J.R. Statist. Soc.* B., 54, 273-284.

128. Nelder, J.A. (1992) in "Taguchi's parameter design: a panel discussion." ed. Nair V.N. *Technometrics,* 34, 127-161.

129. Nigam, A.K. and Gupta, V.K. (1985) "Construction of orthogonal main-effect plans using Hardamard matrices." *Technometrics.* Vol.27, No.1, 37-40.

130. O'Hagan, A., (1978) "Curve fitting and optimal design for prediction (with discussion)." *J.R. Statist. Soc. B.* 40, 1-42.

131. Owen, A.B., (1992) "A central limit theorem for Latin Hypercube Sampling." *J.R. Statist. Soc.* B, 54, 541-552.

132. Owen, A.B. (1994) "Controlling correlation in Latin Hypercube Samples." *J. Am. Statist. Ass.* Vol.89, No. 428, 1517-1521.

133. Patterson, H.D. (1954) "The errors of lattice sampling." *J.R. Statist. Soc. B.* 16, 140-149.

134. Patterson, H.D. (1976) "Generation of factorial designs." *J.R. Statist. Soc. B.* 38, 175-179.

135. Phadke, M.S. Kacker, R.N., Speeney D.V., and Grieco M.S.,(1983) "Off-line quality control in integrated circuit fabrication using experimental design. *The Bell System Technical Journal*, Vol.1. No.5, 1273-1309.

136. Phadke, M.S. (1986) "Design optimization case studies." *AT&T Technical Journal*, 65, 51-68.

137. Pothoff, R.P. and Roy, S.N. (1964) "A generalized multivariate analysis of variance model useful especially for growth curve problems." *Biometrika*, 51, 313-326.

138. Ripley, B.D., (1977) "Modeling spatial pattern (with discussion)." *J.R. Statist. Soc. B.* 39, 172-212.

139. Rosenbaum, P.R. (1994) "Dispersion effects from fractional factorials in Taguchi's method for quality design." *J.R. Statist. Soc. B.* 56, No.4, 641-652.

140. Sacks, J. Schiller, S.B. and Welch. W.J. (1989) "Design for computer experiments." *Technometrics*, 31, 41-47.

141. Sacks, J., Welch, W.J., Mitchell, R.J. and Wynn, H.P. (1989) "Design and analysis of computer experiments." *Statistical Science*, 4, 409-435.

142. Sacks, J, and Welch, W.J. (1992) in "Taguchi's parameter design: a panel discussion." ed. Nair V.N. *Technometrics*, 34, 127-161.

143. Sampson P.D. and Guttorp P. (1992) "Non parametric estimation of non-stationary spatial covariance structure." *J. Am. Statist. Ass.* 87, 108-119.

144. Shannon. C.E. (1948) "A mathematical theory of communication." *The Bell System Technical Journal*, 27, 3, 379-423, 623-656.

145. Shoemaker, A.C. and Kacker, R.N. (1988) "A methodology for planning experiments in robust product and process design." *Quality and Reliability Engineering International*, 4, 95-103.

146. Silvey (1980) *Optimum Design*, London, Chapman and Hall.

147. Simpson T.W. Peplinski, J., Koch, P.N. and Allen, J.K. (1997) "On the use of statistics for deterministic computer experiments." ASME Design Engineering Technical Conferences, Sept. 14-17, 1997, Sacramento, California.

148. Song, A.A., Mathur, A.M., Pattipathi, K.P. (1995) "Design of process parameters using robust design techniques and multiple criteria optimization." *IEEE Transactions on Systems, Man and Cybernatics*, Vol.25, No.11, 1437-1446.

149. Stein, A. and Corsten, L.C.A. (1991) "Universal kriging and cokriging as a regression procedure." *Biometrics*, 47, 575-588.

150. Stein, M. (1987) "Large sample properties of simulations using Latin Hypercube Sampling." *Technometrics*, 29, 143-151.

151. Steinberg, D.M. and Hunter, W.G. (1984) "Experimental design, review and comment (with discussion)." *Technometrics*, 26, 71-130.

152. Steinberg, D.M. (1985) "Model robust response surface designs: Scaling two-level factorials." *Biometrika*, 72, 513-526.

153. Stigler, C.M. (1977) "Do robust estimators work with real data?" *The Annals of Statistics*. Vol.5, No.6, 1055-1098.

154. Taguchi, G. (1990) *Introduction to Quality Engineering*, Asian Productivity Organization, Tokyo.

155. Tang, B. (1993) "Orthogonal array-based Latin hypercubes." *J. Am. Statist. Ass.* 88, 424, 1392-1397.

156. Tsui, K.L. (1988) "Strategies for planning experiments using orthogonal array and confounding tables." *Quality and Reliability Engineering International*, 4, 113-122.

157. Tsui, K.L. (1999) "Robust design optimization for multiple characteristic problems" Int. J. Prod. Res., Vol.37, No.2, 433-445.

158. Vecchia, A.V., (1988) "Estimation and model identification for continuous spatial process." *J.R. Statist. Soc B.* 50, 297-312.

159. Vecchia, A.V. (1992) "A new method of prediction for spatial regresion models." *J.R. Statist. Ser* B, 54, 813-830.

160. Vining, G.G. and Myers, R.H. (1990) "Combining Taguchi and response surfacc philosophics, A dual rcsponsc approach." *Journal of Quality Technology*, 22, 38-45.

161. Vining. G.G. and Myers R.H. (1991) "A graphical approach for evaluating response surface designs in terms of the mean squared error of prediction." *Technometrics*, 33, 315-326.

162. Wald, A. (1943) "On the efficient design of statistical investigations." *The Annals of Statistics*, 134-140.

163. Wang, J.C. and Wu, C.F.J. (1991) "An approach to the construction of asymmetrical orthogonal arrays." *J. Am. Statist. Ass.* 86, 450-456.

164. Wang, J.C. and Wu, C.F.J. (1992) "Nearly orthogonal arrays with mixed levels and small runs." *Technometrics*, 34, 409-422.

165. Warnes, J.J. and Ripley, B.D. (1987) "Problems with likelihood estimation of covariance functions of spatial Gaussian processes." *Biometrika*, 74, 640-642.

166. Welch W.J. (1982) "Branch-and-bound search for experimental designs based on D-optimality and other criteria." *Technometrics*, 24, 41-48.

167. Welch, W.J., (1983) "A mean squared error criterion for the design of experiments." *Biometrika*, 70, 205-213.

168. Welch W.J., Yu, Tat-Kuan, Kang, S.M. and Sacks, J. (1990) "Computer experiments for quality control by parameter design." *Journal of Quality Technology*, 22, 15-22.

169. Welch, W.J, Buck, R.J., Sacks, J., Wynn, H.P., Mitchell, T.J., and Morris, M.D. (1992) "Screening, Predicting and Computer Experiments." *Technometrics*, 34, 15-25.

170. Whittle, (1954) "Stationary processes in the plane." *Biometrika*, 41, 434-449.

171. Wu, C.F.J., and Chen, Y. (1992) "A graph-aided method for planning two-level experiments when certain interactions are important." *Technometrics*, 34, 162-175.

172. Wynn, H.P. (1984) "Jack Kiefer's contributions to experimental design." *The Annals of Statistcs*, Vol.12, No.2, 416-423.

173. Yakowvitz, S.J. and Szidarovsky. F. (1985) "A comparison of kriging with non parametric regression methods." *Journal of Multivariate Analysis*, 16, 21-53.

174. Ylvisaker, D, (1975) "Designs on random fields." *A survey of statistical designs and linear models*, ed. Srivastava J.N. Holland Publishing Company.

175. Ylvisaker, D. (1987) "Prediction and Design." *The Annals of Statistics*, 15, 1-19.

176. Zimmerman, D.L. and Harville, D.A. (1991) "A random field approach to the analysis of field plot experiments and other spatial experiments." *Biometrics*, 47, 223-239.