

## 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.

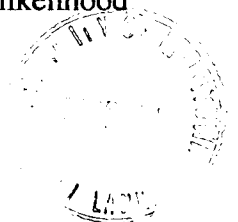
The RFLM used for modeling the computer simulation model has better prediction capability than RSM. These predictors can be used with several methods of optimization, a distinctive advantage over the optimization methods

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  $p = 2$  revealed that the predictor indeed is an interpolator that approximates to the multinomial function in the input variables for small values of  $\theta$ .

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  $\text{Var} [Y (x)] = \sigma^2 + \sigma_e^2$  where  $\sigma_e^2$  is the measurement error. The statistical model we used for computer experiments quantify uncertainty about the response where it is unobserved.

## Experimental Design



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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')

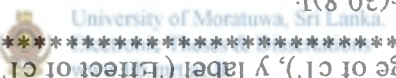
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% Scatter plot of observed values vs predicted
% values
% y vector of observed values
for i = 1:30
    py(i) = pred(t(i,:));
end
plot(y,py, x label ('observed response'),
      y label ('Predicted values'), title ('Predicted vs observed'))
% Q-Q plot
% 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'))

```



```

%*****
d4 = [zeros (30,4), s, zeros (30,5)];
for i = 1:30
g(i) = pred (d4 (i,:));
end
plot (s,g), x label ('Effect of R1'), y label ('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 ('Effect 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 ('Effect 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')
%*****
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')
%*****
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')

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```

%*****
% 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 = pi(r, c, j, m)
for i = 1: m
R(i, :) = [C(i,:), r(i,:), : ] ;
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 j = 1: 30
a(i, j) = sum((t(i, :) - t(j, :)).^2);
end
end
%*****
% Arrays for simulation study
%*****
load test
t = 10 (-2):.2: T1;
a = mal(t);
cr;
R4 = pi(r, c, 4, 10);
R5 = pi(r, c, 5, 10);

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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);
pe5 = st (rc5, 10, t, a);
pe6 = st (rc6, 10, t, a);
pe7 = st (rc7, 10, t, a);
pe8 = st (rc8, 10, t, a);
pe9 = st (rc9, 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)
c = 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);
h = [1.089 + (s' + .3891 * e') * m * (y' - 1.089 * e);

```



```

% *****
% Bayesian Prediction
% *****
function sb = sa (x, n, t, y)
for i = 1 : 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')

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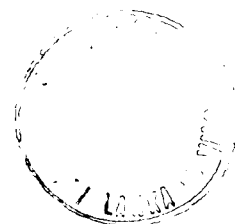
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