Design of Experiments

for Engineers and Scientists

Jiju Antony

Preface xi

Acknowledgements xii

1 Introduction to industrial experimentation 1
1.1 Introduction 1
1.2 Some fundamental and practical issues in industrial experimentation 3
1.3 Summary 5
Exercises 5
References 5

2 Fundamentals of Design of Experiments 6
2.1 Introduction 6
2.2 Basic principles of Design of Experiments 7
2.2.1 Randomization 8
2.2.2 Replication 9
2.2.3 Blocking 10
2.3 Degrees of freedom 10
2.4 Confounding 11
2.5 Design resolution 12
2.6 Metrology considerations for industrial designed experiments 12
2.6.1 Measurement system capability 13
2.6.2 Some tips for the development of a measurement system 14
2.7 Selection of quality characteristics for industrial, experiments 15
Exercises 15
References 16

3 Understanding key interactions in processes 17
3.1 Introduction 17
3.2 Alternative method for calculating the two order interaction effect 20
3.3 Synergistic interaction vs antagonistic interaction 22
3.4 Scenario 1 23

3.5 Scenario 2 25
3.6 Summary 27
Exercises 27
References 28

4 A systematic methodology for Design of Experiments 29
4.1 Introduction 29
4.2 Barriers in the successful application of DOE 29
4.3 A practical methodology for DOE 31
4.3.1 Planning phase 31
4.3.2 Designing phase 33
4.3.3 Conducting phase 33
4.3.4 Analysing phase 34
4.4 Analytical tools of DOE 34
4.4.1 Main effects plot 34
4.4.2 Interactions plots 35
4.4.3 Cube plots 36
4.4.4 Pareto plot of factor effects 36
4.4.5 Normal Probability Plot of factor effects 36
4.4.6 Normal Probability Plot of residuals 37
4.4.7 Response surface plots and regression models 38
4.5 Model building for predicting response function 40
4.6 Confidence interval for the mean response 41
4.7 Summary 42
Exercises 42
References 43

5 Screening designs 44
5.1 Introduction 44
5.2 Geometric and non-geometric P–B designs 44
5.3 Summary 52
Exercises 53
References 53

6 Full factorial designs 54
6.1 Introduction 54
6.2 Example of a 2^2 full factorial design 54
6.2.1 Objective 1: Determination of main/interaction effects which influence mean plating thickness 55
6.2.2 Objective 2: Determination of main/interaction effects which influence variability in plating thickness 57
6.2.3 Objective 4: How to achieve a target plating thickness of 120 units? 58
6.3 Example of a 2^3 full factorial design 60
6.3.1 Objective 1: To identify the significant main/interaction effects which affect the process yield 61

6.3.2 Objective 2: To identify the significant main/interaction effects which affect the variability in process yield 63
6.3.3 Objective 3: What is the optimal process condition? 64
6.4 Example of a 2^4 full factorial design 65
6.4.1 Objective 1: Which of the main/interaction effects affect mean crack length? 66
6.4.2 Objective 2: Which of the main/interaction effects affect variability in crack length? 66
6.4.3 Objective 3: What is the optimal process condition to minimize mean crack length? 69
6.5 Summary 70
Exercises 71
References 72

7 Fractional factorial designs 73
7.1 Introduction 73
7.2 Construction of half-fractional factorial designs 73
7.3 Example of a $2^{(7-4)}$ factorial design 76
7.4 An application of 2-level fractional factorial design 80
7.5 Example of a $2^{(5-1)}$ factorial design 85
7.5.1 Objective 1: To identify the factors which influence the mean free height 86
7.5.2 Objective 2: To identify the factors which affect variability in the free height of leaf springs 87
7.5.3 How do we select the optimal factor settings to minimize variability in free height? 89
7.6 Summary 90
Exercises 90
References 92

8 Some useful and practical tips for making your industrial experiments successful 93
8.1 Introduction 93
8.1.1 Get a clear understanding of the problem 94
8.1.2 Project selection 94
8.1.3 Conduct exhaustive and detailed brainstorming session 95
8.1.4 Teamwork and selection of a team for experimentation 96
8.1.5 Select the continuous measurable quality characteristics or responses for the experiment 96
8.1.6 Choice of an appropriate Experimental Design 98
8.1.7 Iterative experimentation 98
8.1.8 Randomize the experimental trial order 99

8.1.9 Replicate to dampen the effect of noise or uncontrolled variation 99
8.1.10 Improve the efficiency of experimentation using blocking strategy 101
8.1.11 Understanding the confounding pattern of factor effects 101
8.1.12 Perform confirmatory runs/experiments 102
8.2 Summary 102
Exercises 103
References 103

9 Case studies 105
9.1 Introduction 105
9.2 Case studies 105
9.2.1 Optimization of a radiographic quality welding of cast iron 105
9.2.2 Reducing process variability using Experimental Design technique objective of the experiment 110
9.2.3 Slashing scrap rate using fractional factorial experiments 114
9.2.4 Optimizing the time of flight of a paper helicopter 117
9.2.5 Optimizing a wire bonding process using Design of Experiments 123
9.2.6 Training for Design of Experiments using a catapult 127
9.2.7 Optimization of core tube life using designed experiments 132
9.2.8 Optimization of a spot welding process using Design of Experiments 141
9.3 Summary 147
References 148

Index 149