Fractional Factorial and Related Designs: An Annotated Bibliography of Applications Papers

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Abstract

In this paper we provide an annotated bibliography of about 140 papers which have appeared in journals in a variety of areas in the last 5 years and in which a fractional factorial design or related design has been used. For each reference we have indicated the design or designs used and whether or not the responses are given in the paper. The level of detail given in these papers makes them suitable sources for examples in a course on the design and analysis of experiments.

Introduction

Factorial designs were introduced in the agricultural area by Fisher [6] in the 1920s and taken up enthusiastically both there and in the manufacturing and engineering areas, partly due to the efforts of Tippett [13]. More recently, Taguchi [12] is credited with being responsible for the extensive use of fractional factorial designs in industry in both Japan and the US. Bisgaard [1] gives an eclectic history of factorial designs and their use in industry. Theoretical developments, notably the construction of fractional factorial designs, may be found in Kempthorne [8], McLean and Anderson [9] and Montgomery [10].

Despite the large number of fractional factorial designs that are used in industry at the moment, most undergraduate textbooks on experimental design continue to present examples from the 1940's and 1950's. The list of case studies provided in Bisgaard [1] goes some way to alleviating this problem but of the 131 case studies that he cites, the latest ones were published in 1975 and only 10 are from the 1970's at all. By choice, all his examples are industrial. Some detailed recent case studies can be found in Czitrom and Spagon [4]. Most textbooks make no mention of the fact that fractional factorial designs are also used in investigations in areas as diverse as law, marketing and medicine. Examples of the areas in which we have found fractional factorial designs used may be found in Table 1.

In this paper we give an annotated bibliography of around 140 papers in a variety of application areas, as tabulated in Table 1. With the exception of about 20 papers, chosen because there were few in that application area, all the papers given have the original responses given. About 30% of the papers we originally reviewed did not have the raw data. Many papers do not mention the statistical software used to perform the analyses, but of those that do Statgraphics and SAS proved to be the most popular.

The bibliography is divided into five sections depending on the type of design that was used. Thus we have listed separately those papers that used two (or more) distinct designs and those which used a Box-Behnken, central composite or Plackett-Burman design and the remainder of the papers are in a section called simply *fractional factorial designs.*

In the next section we recall the definitions of the designs that we have chosen to include in this paper.

	Design			
Area	BBD	CCD	FFD	PBD
Agriculture			94	
Aviation			93	
Biochemistry			37	
Biology		60		
Biotechnology	13, 19, 33	6, 10, 13, 14, 16, 17, 19, 28, 33, 65, 78	6, 11, 38, 83, 88, 92, 127	9, 16, 20, 131, 137, 139, 141
Chemical Engineering	40, 41, 42, 43, 46. 47, 49	31, 34, 61, 67, 68, 80	29, 34, 37, 38, 83, 98, 100, 104, 123, 126	29, 132, 133, 135
Chemistry	41, 42, 43	34, 36, 56, 57, 69, 72, 77	2, 29, 34, 36, 84, 85, 102, 108, 110, 112, 113, 118, 124, 125, 128	8, 21, 29, 136
Chromatography	18	1, 5, 24, 69, 79	1, 5, 24, 35, 87, 92, 102, 106, 115, 120	1, 4, 129, 138, 143
Engineering		7, 66	30, 32, 89, 121, 90, 93, 101	7, 8, 130, 142
Environment	47	59, 77	86, 96, 98, 103, 123, 126	21, 136
Food Technology	13, 45, 50	3, 13, 25, 55, 58, 62, 71	3, 25, 95, 97, 106, 116, 117	
Genetics			11	
Law			119	
Manufacturing	54	7, 34	34, 91, 111	7
Marketing			94, 107, 114	
Materials		7, 22	22	7
Medical		73	12, 99, 122	
Microbiology		16, 27, 59, 74	88, 96	16, 23, 137, 140
Pharmacy	18, 39, 42, 43, 44, 48, 51, 52, 53	15, 63, 64, 70, 75, 76, 79, 81	15, 26, 82, 105, 109	15, 134

Table 1: The areas in which we have found fractional factorial designs used. BBD = Box-Behnken design; CCD = central-composite design; FFD = fractional factorial design; PBD = Plackett-Burman design.

Some definitions

A *factor* is any attribute of the experimental units which may affect the response observed in the experiment. Those factors which are applied by the experimenter are called *treatment factors* and any factors which are inherent attributes of the units are called *block factors*. The possible values that a factor can take are called the *levels* of the factor.

Each of the possible combinations of the treatment factor levels is called a *treatment combination*. A *complete factorial design* (FD) is one in which each of the treatment combinations appears an equal number of times. If all the treatment factors have 2 levels then we talk about a 2^k design. A *fractional factorial design* (FFD) is one in which only a subset of the treatment combinations appear. We use 2^{k-p} to denote a $1/2^p$ fraction of a 2^k design.

A *foldover* design is a 2^{k-p} FFD which has been doubled in size by including the complementary treatment combinations; that is, the treatment combinations obtained by changing all 1's to 0's and 0's to 1's.

A *balanced incomplete block design* (BIBD) with parameters (v, b, r, k, λ) consists of b blocks each of size k. The number of treatments in the design is v, all treatments are replicated r times and every pair of treatments appears in λ blocks. Thus some restrictions are placed on the values of v, b, r, k, and λ. In particular, counting the occurrences of treatments, $vr = bk$ and by counting pairs of treatments, $\lambda(v-1) = r(k-1)$. Because of these relationships we usually talk about a (v, k, λ) BIBD.

A v factor *Box-Behnken design* (BBD) is formed from the $v \times b$ incidence matrix of a BIBD and a complete 2^k design written with the factors as rows. The first 1 in each block in the incidence matrix is replaced by the levels of the first factor in the 2^k design, the second 1 in each block is replaced by the levels of the second factor in the 2^k design and so on. Each zero in the incidence matrix is replaced by a row of k zeroes. Centre points may also be added. These designs were introduced by Box and Behnken [2].

1	1	0
1	0	1
0	1	1

BIBD

1	1	-1	-1
1	-1	1	-1

2^2 design

1	1	-1	-1	1	1	-1	-1	0	0	0	0
1	-1	1	-1	0	0	0	0	1	1	-1	-1
0	0	0	0	1	-1	1	-1	1	-1	1	-1

Box-Behnken design

Table 2: A Box-Behnken design with $v = 3, k = 2$

A FFD in which all of the main effects can be estimated independently of any interaction terms is said to be of *resolution III*. A FFD in which all of the two-factor interactions can be estimated independently of main effects and other two factor interactions is said to be of *resolution V*. The foldover of a FFD of resolution III is of resolution IV. In general a FFD is of resolution R if no p factor interaction is aliased with another interaction containing less than $R - p$ factors.

A *central composite design* (CCD) has three parts. The first is a resolution V FFD, the second is points on the axes of each of the factors, located equidistant from the origin, and the third is some points at the origin. The points on the axes are called the *star points* or the *axial points*. A CCD for three factors with axial points at distance 1.6 from the origin and 2 centre points appears in Table 3.

Factor																
A	1	1	1	1	-1	-1	-1	-1	1.6	-1.6	0	0	0	0	0	0
B	1	1	-1	-1	1	1	-1	-1	0	0	1.6	-1.6	0	0	0	0
C	1	-1	1	-1	1	-1	1	-1	0	0	0	0	1.6	-1.6	0	0

Table 3: A central composite design for three factors

Plackett and Burman [11] introduced symmetric designs with factors with 2, 3, 5 or 7 levels in which main effects could be estimated if interactions are ignored. The two-level designs with N runs, where N is not a power of two, are the designs that are commonly referred to when the phrase *Plackett-Burman design* is used but Rogan, Altira and Goodall[138] uses a three level PBD. The aliasing structure of these designs can get complicated; see Hamada and Wu [7] and Box and Draper [3]. The design in Table 4 is a twelve run PBD.

1	1	-1	1	1	1	-1	-1	-1	1	-1
-1	1	1	-1	1	1	1	-1	-1	-1	1
1	-1	1	1	-1	1	1	1	-1	-1	-1
-1	1	-1	1	1	-1	1	1	1	-1	-1
-1	-1	1	-1	1	1	-1	1	1	1	-1
-1	-1	-1	1	-1	1	1	-1	1	1	1
1	-1	-1	-1	1	-1	1	1	-1	1	1
1	1	-1	-1	-1	1	-1	1	1	-1	1
1	1	1	-1	-1	-1	1	-1	1	1	-1
-1	1	1	1	-1	-1	-1	1	-1	1	1
1	-1	1	1	1	-1	-1	-1	1	-1	1
1	1	1	1	1	1	1	1	1	1	1

Table 4: A twelve run Plackett-Burman design

A *screening design* is a design used to determine which of a set of factors are active. A *response surface design* is one used to estimate the quantitaive parameters of a surface modelling the response given the factors studied. Five of the papers use the *Doehlert uniform shell design* (Doehlert [5]). These designs have $d^2 + d + 1$ points for d factors: one at the origin and the other points on a sphere centered at the origin.

In Table 5 the main uses of each of the designs described in this paper are indicated.

Design Type	Screening	Optimization	Response Surface	Interaction studies
BBD	No	Yes	Yes	Selected
CCD	No	Yes	Yes	Selected
FD	Yes	Yes	Yes	All
FFD	Yes	No	Yes	Selected
PBD	Yes	No	Yes	Selected

Table 5: A table showing the main uses of each of the designs discussed in this paper

Acknowledgements

The authors thank Dr R.J. Ritchie for helping to classify the papers by area. D.J. Street gratefully acknowledges support from a UTS Incentive Grant.

References

1. S. Bisgaard (1992). Industrial use of statistically desgined experiments: Case study references and some historical anecdotes, *Quality Engineering* **4**, 547-562.

2. G.E.P. Box and D.W. Behnken (1960). Some new three level designs for the study of quantitative variables, *Technometrics* **2**, 455-475.

3. G.E.P. Box and N.R. Draper (1987). *Empirical model building and response surfaces*, John Wiley, New York.

4. V. Czitrom and P. Spagon (1997). *Statistical case studies for industrial process improvement*, American Statistical Association and Society of Industrial and Applied Mathematics.

5. D.H. Doehlert (1970). Uniform shell designs, *Applied Statistics* **19**, 231-239.

6. R.A.Fisher (1926). The arrangement of field experiments, *Journal of Ministry for Agriculture* **33**, 503-513.

7. M. Hamada and C.F.J. Wu (1992).Analysis of designed experiments with complex aliasing, *Journal of Quality Technology* **24**, 130-137.

8. O. Kempthorne (1952). *The design and analysis of experiments*, John Wiley, New York.

9. R. A. McLean and V. L. Anderson (1984). *Applied fractional factorial designs*, Marcel Dekker, New York.

10. D. C. Montgomery (1991). *Design and analysis of experiments*, John Wiley, New York.

11. R.L. Plackett and J.P. Burman (1946). The design of optimum multifactorial experiments, *Biometrika* **33**, 305-325 and 328-332.

12. G. Taguchi (1987). *System of experimental design*, UNIPUB/ Kraus International Publications, New York.

13. L.H.C. Tippett (1934). *Applications of statistical methods to the control of quality in industrial production*, Manchester Statistical Society.

Annotated Bibliography

Two or More Designs Used

1. Altria, K.D., Clark, B.J., Filbey, S.D., Kelly, M.A. and Rudd, D.R. (1995). Application of chemometric experimental designs in capillary electrophoresis: A review. *Electrophoresis* **16**, 2143-2148.
This is a brief review paper of the use of FD, FFD, PBD and CCD in capillary electrophoresis. No data sets are given, but references to some are given.

2. Andersson, P.M., Lundstedt, T. and Abramo, L. (1996). Synthesis and optimization of 1-pyrrolemethane sulfonate by means of experimental design. (1996). *Journal of Chemometrics* **10**, 379-384.
Responses from a 2^{5-2}_{III} with two centre points used as a screening experiment are given. As the results were not conclusive the design was expanded to a 2^{5-1}_{IV} with three centre points design by foldover and the responses are given. Two active factors were used in a Doehlert design. Data also given for this experiment.

3. Arbaisah, S.M., Asbi, B.A., Junainah, A.H. and Jamilah, B. (1996) Determination of optimum conditions for pectinesterase extraction from soursop fruit (*Anona muricata*) using response surface methodology. *Food Chemistry* **55**, 289-292.
One response variable from a 2^{5-2} design and from a two factor CCD with 5 centre points are given.

4. Arnoldsson, K.C. and Kaufmann, P. (1994). Lipid class analysis by normal phase high performance liquid chromatography, development and optimization using multivariate methods. *Chromatographia* **38**, 317-324.
The responses from a blocked, four-factor 8 run PBD are given. Optimisation steps, involving a 2^3 design with centre point and a 3^2 design, are described but no responses for these are given.

5. Beijersten, I. and Westerlund, D. (1995). Derivatization Of Dipeptides With 4-Fluoro-7-Nitro-2,1,3-Benzoxadiazole For Laser-Induced Fluorescence And Separation By Micellar Electrokinetic Chromatography. *Journal of Chromatography* **716**, 389-399.
One response variable from a 2^{5-1} FFD and from a three factor CCD with 4 centre points are given.

6. Boleda, M.D., Briones, P., Farres, J. and Tyfield, L. Pi R. (1996). Experimental Design - A Useful Tool For PCR Optimization. *Biotechniques* **21**, 134-140.
Tutorial-type presentation of both FFD and polymerase chain reaction (PCR). One response variable from a 2^{5-2} FFD and from a two factor CCD with 3 centre points are given. Some references to applications of FFD in various areas.

7. Bucher, R.A. and Loos, A.C. (1994). Parametric statistical analysis of electrostatic powder prepregging. *Journal of Advanced Materials* **25**, 44-50.
One response from a three-factor 12 run PBD is given. The three active factors are used in a face-centred CCD with 6 centre points. The estimated equations and several response surfaces are given.

8. Bzik, T.J., Henderson, P.B. and Hobbs, J.P. (1998). Increasing the precision and accuracy of top-loading balances: Application of experimental design. *Analytical Chemistry* **70**, 58-63.
This paper compares PBDs and 'one-at-a-time' weighing schemes. Results for both schemes are given.

9. Carlson, A.D. Hofer, J.D. and Riggin, R.M. (1997). Development of an optimized peptide map for recombinant activated human protein c by means of an experimental design strategy. *Analytica Chimica Acta* **352**, 221-230.
A 12-run PBD was used to screen seven factors for their effect on the relative peak height this being given for 19 peptide fragments. A 2^3 design was then used to determine significant main and interaction effects and the relative peak height was given for 12 peptide fragments.

10. Chen, H.C. (1996). Optimizing the concentrations of carbon, nitrogen and phosphorus in a citric acid fermentation with response surface method. *Food Biotechnology* **10**, 13-27.
The response variables from a replicated 2^3 experiment, a series of experiments along the path of steepest ascent, and a CCD experiment are given. Estimated coefficients, and graphs of the response surface are also given.

11. De Meo, M., Laget, M., Digiorgio, C., Guiraud, H., Botta, A., Castegnaro, M. and Dumenil, G. (1996). Optimization of the salmonella/mammalian microsome assay for urine mutagenesis by experimental designs. *Mutation Research: Reviews in Genetic Toxicology* **340**, 51-65.
One response variable from two different 2^{3-1} FFDs and from a Doehlert design are given.

12. Dyvik, K., Dyrstad, K. and Tronstad, A. (1995). Relationship between viscosity and determined injection pressure in angiography catheters for common roentgen contrast media. *Acta Radiologica* **36**, 43-49.
For each of 8 contrast media, a 2^2 FD with 3 centre points and a 2^{5-1} FFD with 3 centre points were conducted. Estimated equations and graphs of the results are given.

13. Embuscado, M.E., Marks, J.S. and BeMiller, J.N. (1994). Bacterial cellulose. 2. Optimization of cellulose production by *Acetobacter-xylinum* through response surface methodology. *Food Hydrocolloids* **8**, 419-430.
The response variable from a seven factor BBD used as a screening design and a four factor CCD with 7 centre points are given. Various contour plots and response surfaces are also given. The predicted values at the optimum settings were verified by experiment.

14. Gomes, D.J., Gomes, J. and Steiner, W. (1994). Production of highly thermostable xylanase by a wild strain of thermophilicfungus. *Thermoascus aurantiacus* and partial characterization of the enzyme. *Journal of Biotechnology* **37**, 11-22.
Responses from a 2^3 design, along a path of steepest ascent and for a 3^2 design are given.

15. Gratteri, P. Furlanetto, S., Laporta, E., Pinzauti, S. and Leardi, R. (1996). Development and set-up of drug electroanalysis by experimental design: A survey. *Farmaco* **51**, 231-246.
This paper discusses three applications of sequential exerpimental design. The first uses a PBD, a FFD and a Doehlert design. The second uses a PBD, D-optimal design and a FD. The third example uses a three-quarter FFD and a CCD. Results are given for all designs as well as estimated effects, and some plots.

16. Haltrich, D., Laussamayer, B. and Steiner, W. (1994). Xylanase formation by *Sclerotium rolfsii*: effect of growth substrates and development of a culture medium using statistically designed experiments. *Applied Microbiology and Biotechnology* **42**, 522-530.
One response from a folded seven factor, 12 run PBD with one centre point are given. Then a 2^4 design was used to determine whether further reductions in the number of active factors could be achieved (response not given). Finally the responses from a two factor CCD with two centre points are given. The accuracy of the model was then investigated

17. Haltrich, D., Preiss, M. and Steiner, W. (1993). Optimization of a culture medium for increased xylanase production by a wild strain of *Schizophyllum-commune*. *Enzyme & Microbial Technology* **15**, 854-860.
Responses from a 2^3 design, along a path of steepest ascent and for a three factor orthogonal CCD with 2 centre points are given. The equation and some graphical representations are also given.

18. Hows, M.E.P., Perrett, D. and Kay, J. (1997). Optimisation of a simultaneous separation of sulphonamides, dihydrofolate reductase inhibitors and β-lactam antibiotics by capillary electrophoresis. *Journal of Chromatography* **768**, 97-104.
One response variable from a three factor BBD with three centre points is given as is the corresponding estimated equation. Some contour plots are given and as well as a comparison of the predicted and observed response at the optimum setting. At the same time as the BBD was carried out, the experimenters carried out a trial and error optimisation which they note took 45 runs to arrive at a sensible setting.

19. Junqua, M., Duran, R., Gancet, C. and Goulas, P. (1997). Optimization of microbial transglutaminase production using experimental designs. *Applied Microbiology & Biotechnology* **48**, 730-734.
A 2^5 design with five centre points was used to determine the active factors for each of two response variables. A four factor BBD with six centre points was used to calculate "the optimum concentrations that might be more relevant for other experimental domains". A two factor CCD with 5 centre points was used to optimise one of the response variables.

20. Kern, M., Nidetzky, B., Kulbe, K.D. and Haltrich, D. (1998). Effect of nitrogen sources on the levels of aldose reductase and xylitol dehydrogenase activities in the xylose-fermenting yeast *Candida tenuis*. *Journal of Fermentation & Bioengineering* **85**, 196-202.
A seven-factor 26 run folded PB design with two centre points was used as a screening design. The factor levels and standardised effects are given for this experiment. The results of a follow-up complete 2^3 experiment are given, as well as a discussion of the results of this experiment.

21. Koch, I., Harrington, C.F., Reimer, K.J. and Cullen, W.R. (1997). Simplex optimisation of conditions for the determination of antimony in environmental samples by using electrothermal atomic absorption spectrometry. *Talanta* **44**, 771-780.
An eight factor, 12 run PBD and a five factor, 8 run PBD were used to determine the four factors that effected the response. The levels of these factors were then optimised using the composite modified simplex optimisation method. Responses for this third experiment only are given.

22. Lumpkin, N.E., King, W. and Tansley, T.L. (1996). Refinement of Low-Resistance Ni-Ge-Au Ohmic Contacts to n^+ GaAs using screening and response surface experiments. *Journal of Materials Research* **11**, 1238-1243.
One response variable from a 2^{7-3} and a three factor CCD with 2 centre points are given. Confirmatory runs were made and the results presented.

23. Masson, F., Lebert, A., Talon, R. and Montel, M.C. (1997). Effects of physico-chemical factors influencing tyramine production by *Carnobacterium divergens*. *Journal of Applied Microbiology* **83**, 36-42.
A Doehlert uniform-shell design was used to determine the levels of three factors. For each combination in the Doehlert design, a two factor, four run PBD was carried out. Estimated coefficients are given, as are some response surfaces.

24. Morris, V.M., Hargreaves, C., Overall, K., Marriott, P.J. and Hughes, J.G., (1997). Optimization of the capillary electrophoresis separation of ranitidine and related compounds. *Journal of Chromatography* **766**, 245-254.

After a discussion of the results from two screening designs, both FFDs, responses from a three factor CCD and from a two factor CCD are given. Reproducibility of the system was looked at.

25. Pagliarini, E., Peri, C., Zanoni, B. and Ghizzardi, M. (1996). Optimization of olive paste expression - maximizing yield by central composite design approach. *Journal of the Science of Food & Agriculture* **71**, 470-474.
One response variable from a 2^4 FD used as a screening design, and from a three factor CCD with four centre points are given. Some response surfaces are plotted.

26. Pean, J.M., Venierjulienne, M.C., Filmon, R., Sergent, M., Phantanluu, R. and Benoit, J.P. (1998). Optimization of HSA and NGF encapsulation yields in PLGA microparticles. *International Journal of Pharmaceutics.* **166**, 105-115.
Two response variables from a 2^{10-6} design are given. For the two most significant factors a Doehlert design was used in the optimization step and the data are given.

27. Pham, P.L., Taillandier, P., Delmas, M. and Strehaiano, P. (1998). Optimization of a culture medium for xylanase production by. *Bacillus* sp. using statistical experimental designs. *World Journal of Microbiology & Biotechnology* **14**, 185-190.
One response variable from a 2^3 design augmented with 5 centre points, from the points on a path of steepest ascent and from a two factor CCD with 5 centre points are given. Some contour plots are given.

28. Pizarro, C., Fernandeztorroba, M.A., Benito, C. and Gonzalezsaiz, J.M. (1997). Optimization by experimental design of polyzcrylamide gel composition as support for enzyme immobilization by entrapment. *Biotechnology & Bioengineering* **53**, 497-506.
One response variable from a two factor CCD with five centre points, three replicates of a 2^2 design with four centre points and three replicates of a two factor CCD with 3 centre points are given, together with estimated response surface equations and response surface plots.

29. Rodriguez, L.C., Garcia, R.B., Campana, A.M.G. and Sendra, J.M.B. (1998). A new approach to a complete robustness test of experimental nominal conditions of chemical testing procedures for internal analytical quality assessment. *Chemometrics & Intelligent Laboratory Systems* **41**, 57-68.
The paper advocates the use of PBDs to study the topic of the title. Responses for a seven-factor, 8 run PBD, two 1/3 replicates of a 3^3 designs,and two three-factor, 4 run PBDs are given, as is the analysis of them.

30. Rowlands, H. and Pham, D.T. (1995). Application of the taguchi method to the design of a robot sensor. *Robotica* **13**, 607-617.
A comparison of the information obtained from 2^5, 2^{5-1} and 2^{5-2} experiments in this area. Good diagram of the experimental set-up. Results are presented as sums of squares and graphically.

31. Sanchez, N., Martinez, M. and Aracil, J. (1997). Selective esterification of glycerine to 1-glycerol monooleate. 2. Optimization studies. *Industrial & Engineering Chemistry Research* **36**, 1529-1534.
Longitudinal data of four response variables from a blocked 2^2 design with four centre points are given. Because a significant curvature effect was found for each response, the design was extended to a blocked two factor CCD with four centre points. The estimated second-order response surface is given for each of the four responses.

32. Shumate, D.A. and Montgomery, D.C. (1996). Development of a TIW plasma etch process using a mixture experiment and response surface optimization. *IEEE Transactions on Semiconductor Manufacturing* **9**, 335-343.
Describes a 2^{5-1} experiment, a mixture experiment and response surface design on three factors. Responses are given for the mixture experiment only. Discussion of the first design and parameter estimates from the third are included.

33. Srinivas, D., Rao, KJ., Theodore, K. and Panda, T. (1995). Direct conversion of cellulosic material to ethanol by the intergeneric fusant *Trichoderma reesei* QM 9414/*Saccharomyces cerevisiae* NCIM 3288. *Enzyme & Microbial Technology* **17**, 418-423.
One response variable from a three factor BBD with 6 centre points, and the estimated equation, are given. A two factor CCD with 5 centre points was then used to optimize pH and temperature and the responses are given as is the estimated equation.

34. Taylor, R.W., Barren, J.P., Nick, R.J. and Cawse, J.N. (1997). Nonlinear effects on yield and color for an intermediate in an industrial process. *Polymer Testing* **16**, 75-89.
One response variable from a 2^{6-1} design with 5 centre points used as a screening design is given. Based on this analysis a three factor CCD was run and the results of this design are also given.

35. Thorsteinsdottir, M., Westerlund, D., Andersson, G. and Kaufmann, P. (1997). Multivariate evaluation of the separation performance in micellar electrokinetic capillary chromatography of peptides - experimental screening. *Chromatographia* **46**, 545-554.
One response variable from a 2^{9-5} design and from a D-optimal design that was used subsequently to investigate the interactions of some of the factors are given.

36. Tsirk, A., Gronowitz, S. and Hornfeldt, A.B. (1998). Multivariate optimization and mechanistic considerations of the amine induced ring-opening reaction of 2-alkyl-3-bromo-5-methylthiophene-1,1-dioxides. *Tetrahedron* **54**, 1817-1834.
Three responses from 15 experiments consisting of 8 factorial points, 4 axial points and 3 centre points are given, as is the response surface equation. Then some responses are given along the path of steepest ascent and from a two factor CCD with two centre points and a half-replicate.

37. Veglio, F. (1996). The optimization of manganese dioxide bioleaching media by fractional factorial experiments. *Process Biochemistry* **31**, 773-785.
One response variable from a 2^{7-3}, a 2^{5-1} (at two time points), and a replicated 2^3 design (the validation study), are given.

38. Veglio, F., Beolchini, F. and Ubaldini, S. (1998). Empirical models for oxygen mass transfer - a comparison between shake flask and lab-scale fermenter and application to manganiferous ore bioleaching. *Process Biochemistry* **33**, 367-376.
Results of a 3^3 factorial design are given. Since interactions were not significant, six further 3^{3-1} FFDs on other factors were carried out and the data given. The data for six 2^2 with one centre point factorial designs are given also.

Box Behnken Designs

39. Bodea, A. and Leucuta, S.E. (1998). Optimization of propranolol hydrochloride sustained-release pellets using Box-Behnken design and desirability function. *Drug Development & Industrial Pharmacy* **24**, 145-155.
Four response variables from a three factor BBD with three centre points and the estimated equations are given. Some contour plots are given as is a table comparing the predicted and observed responses at the optimum settings.

40. Chen, H.C. (1994). Response-surface methodology for optimizing citric acid fermentation by *Aspergillus foetidus*. *Process Biochemistry* **29**, 399-405.
Two response variables from a three factor BBD with three centre points and the estimated equations are given. Some contour plots are given as is a table comparing the predicted and observed responses at the optimum settings.

41. Degroot, J.A., Doughty, A.T., Stewart, K.B. and Patel, R.M. (1994). Effects of cast film fabrication variables on structure development and key stretch film properties. *Journal of Applied Polymer Science* **52**, 365-376.
Five response variables from a three factor BBD with three centre points are given, as well as the estimated equations obtained from three of these variables. Some contour plots are given.

42. de la Maza, A., Manich, A.M., Coderch, L., Bosch, P. and Parra, J.L. (1995). The formation of liposomes *in vitro* by mixtures of lipids modeling the composition of the stratum corneum. *Colloids & Surfaces A-Physicochemical & Engineering Aspects* **101**, 9-19.
Three response variables from a three factor BBD with three centre points and the estimated equations are given. Some contour plots are given.

43. de la Maza, A., Manich, A.M., Coderch, L., Baucells, J. and Parra, J.L. (1996). Lipid composition influence on the surfactant-induced release of the contents in liposomes formed by lipids modelling the stratum corneum. *Colloids & Surfaces A-Physicochemical & Engineering Aspects* **113**, 259-267.
One response variable from a three factor BBD with three centre points is given, as well as the corresponding estimated equation. Some contour plots are given.

44. Goskonda, S.R., Hileman, G.A. and Upadrashta, S.M. (1994). Controlled release pellets by extrusion-spheronization. *International Journal of Pharmaceutics* **111**, 89-97.
Two response variables, one collected at 4 time points, from a four factor BBD are given, as well as the estimated equations obtained. Two additional points were run to test for lack of fit and two batches were made at the optimal setting.

45. Guerrero, S. , Alzamora, S.M. and Gerschenson, L.N. (1996). Optimization of a combined factors technology for preserving banana puree to minimize colour changes using the response surface methodology. *Journal of Food Engineering* **28**, 307-322.
One response variable from a three factor BBD with three centre points at each of five time points is given, as well as the estimated equation obtained at each time point. Some contour plots are given.

46. Gulrajani, M.L. and Sinha, S. (1993). Studies in degumming of silk with aliphatic amines. *Journal of the Society of Dyers & Colourists* **109**, 256-260.
Eight response variables collected from a three factor BBD with three centre points are given, as well as the corresponding estimated equations. Some contour plots are given as are the results of experiments performed at the optimum values.

47. Hierlemann, A., Weimar, U., Kraus, G., Schweizerberberich, M. and Gopel W. (1995). Polymer-based sensor arrays and multicomponent analysis for the detection of hazardous organic vapours in the environment. *Sensors & Actuators B-Chemical* **26**, 126-134.
This paper compares a full factorial, a BBD and an artificial neural network for dealing with the problem in the title. They conclude that a BBD can reduce the calibration time by 90% with no reduction in resolution. No data are given.

48. Khan, M.A., Dib, J. and Reddy, I.K. (1996). Statistical optimization of ketoprofen-Eudragit(r) S100 coprecipitates to obtain controlled-release tablets. *Drug Development & Industrial Pharmacy* **22**, 135-141.
Three response variables from a three factor BBD with three centre points are given as is one of the estimated equations obtained. Some contour plots are given and there is a comparison of the predicted and observed responses at the optimum settings.

49. Patel, R.M., Butler, T.I., Walton, K.L. and Knight, G.W. (1994). Investigation of processing-structure-properties relationships in polyethylene blown films. *Polymer Engineering & Science* **34**, 1506-1514.
One response variable from a three factor BBD with no centre points are given as is the corresponding estimated equation. Some contour plots are given

50. Raghavan, C.V., Babu, R.S., Chand, N. and Rao, P.N.S. (1996). Response surface analysis of power consumption of dough sheeting as a function of gap, reduction ratio, water, salt and fat. *Journal of Food Science & Technology-Mysore* **33**, 313-321.
Two response variables from each of five three factor BBD with three centre points are given, as well as the estimated equations obtained by combining the 75 observations for each response variable. Various contour plots are given.

51. Sastry, S.V., Reddy, I.K. and Khan, M.A. (1997). Atenolol gastrointestinal therapeutic system: Optimization of formulation variables using response surface methodology. *Journal of Controlled Release* **45**, 121-130.
Five response variables from a three factor BBD with three centre points are given as are the corresponding estimated equations. Some contour plots are given as well as the observed values at the calculated optimal setting.

52. Shah, R.D., Kabadi, M., Pope, D.G. and Augsburger, L.L. (1995). Physico-mechanical characterization of the extrusion-spheronization process. Part II: Rheological determinants for successful extrusion and spheronization. *Pharmaceutical Research* **12**, 496-507.
Four response variables from a three factor BBD with three centre points are given. The estimated equation from one of these is given.

53. Singh, S.K., Dodge, J., Durrani, M.J. and Khan, M.A. (1995). Optimization and characterization of controlled release pellets coated with an experimental latex. I. Anionic drug. *International Journal of Pharmaceutics* **125**, 243-255.
Three response variables from a three factor BBD with three centre points are given as are the corresponding estimated equations. Some contour plots are given.

54. Wesling, P. and Emamjomeh, A. (1994). TAB Inner-lead bond process characterization for single-point laser bonding. *IEEE Transactions on Components Packaging & Manufacturing Technology Part A* **17**, 142-148.
A three factor BBD was used to fabricate four sets of experimental samples that were used for as-fabricated testing, high-temperature aging and thermal cycling. Only as-fabricated results were reported (including second order response surface coefficients).

Central Composite Designs

55. Abdullah, B., Gardini, F., Paparella, A. and Guerzoni, M.E. (1994). Growth modelling of the predominant microbial groups in hamburgers in relation to the modulation of atmosphere composition, storage temperature, and diameter of meat particle. *Meat Science* **38**, 511-526.
Twenty replicates of each of the combinations of a three factor CCD with 6 centre points were prepared and analysed at various times. The maximum numbers obtained after fitting a Gompertz equation to this longitudinal data are given and analysed using a regression model. Several contour plots are given.

56. Altesor, C., Corbi, P., Dol, I. and Knochen, M. (1993). Application of experimental design to the development of a multicomponent derivative spectrophotometric method: Simultaneous determination of sulfamethoxazole and trimethoprim. *Analyst* **118**, 1549-1553.
Two response variables from a three factor CCD with one centre point are given. Second order response surfaces are discussed in the text but never given explicitly. Lastly, the accuracy and precision of analytical determinations was investigated.

57. Barnabas, I.J., Dean, J.R., Tomlinson, W.R. and Owen S.P. (1995). Experimental design approach for the extraction of polycyclic aromatic hydrocarbons from soil using supercritical carbon dioxide. *Analytical Chemistry* **67**, 2064-2069.
One response variable from a blocked four factor CCD with six centre points are given. Statistics on lack of fit for linear, quadratic and cubic response surfaces are given, as are the coefficients for the quadratic model fitted.

58. Bautista, D.A., Sylvester, N., Barbut, S. and Griffiths, MW. (1997). The determination of efficacy of antimicrobial rinses on turkey carcasses using response surface designs. *International Journal of Food Microbiology* **34**, 279-292.
Responses from three two factor CCDs, the equations obtained, and the corresponding response surfaces are given.

59. Bergman, I., Svensson, B.H. and Nilsson, M. (1998). Regulation of methane production in a Swedish acid mire by pH, temperature and substrate. *Soil Biology & Biochemistry* **30**, 729-741.
The effects of three factors on methane production for the upper and lower levels of three samples (6 scenarios) are measured where the factors were varied according to a CCD with the number of runs varying from 14 to 18. Significant regression coefficients are given for each of the scenarios. No designs or data are given.

60. Brown-Brandl, T.M. Beck, M.M., Schulte, D.D., Parkhurst, A.M. and Deshazer, J.A. (1997). Physiological responses of tom turkeys to temperature and humidity change with age. *Journal of Thermal*

Biology **22**, 43-52.
Results from a three factor uniform- precision, rotatable CCD are discussed. The estimated equations are presented, as are some graphs of responses but the original responses are not given.

61. Chaair, H., Heughebaert, J.C., Heughebaert, M. and Vaillant, M. (1994). Statistical analysis of apatitic tricalcium phosphate preparation. *Journal of Materials Chemistry* **4**, 765-770.
Three response variables from a six factor CCD with 3 centre points and using a half replicate are given. The coefficients of second order response surface for one of the responses are given.

62. Collar, C. and Martinez, C.S. (1993). Amino acid profiles of fermenting wheat sour doughs. *Journal of Food Science* **58**, 1324-1328.
For each of two conditions (yeast present and absent) a three factor CCD with 1 centre point was carried out and the amino acid profile, consisting of information on 23 amino acids, is given for each run. These profiles are compared using factor analysis. Plots summarising the findings are given.

63. Dredan, J., Zelko, R., Antal, I., Bihari, E. and Racz, I. (1998). Effect of particle size and coating level on the diffuse reflectance of wax matrices. *Journal of Pharmacy & Pharmacology* **50**, 139-142.
The response variable from a two factor, face-centred CCD and the corresponding estimated equation are given. A plot of the response is given.

64. Fedina, L.T., Zelko, R., Fedina, L.I., Szabados, Z.S., Szanto, M. and Vakulya G. (1997). The effect of surfactant and suspending agent concentration on the effective particle size of metered-dose inhalers. *Journal of Pharmacy & Pharmacology* **49**, 1175-1177.
The response variable from a two factor, face-centred CCD is given, as is the estimated second-order response surface. The surface is plotted.

65. Haltrich, D., Laussamayer, B., Steiner, W., Nidetzky, B. and Kulbe, K.D., (1994). Cellulolytic and hemicellulolytic enzymes of *Sclerotium rolfsii*: optimization of the culture medium and enzymatic hydrolysis of lignocellulosic material. *Bioresource Technology* **50**, 43-50.
Two replicates of one response variable from a two factor CCD with two centre points are given. A graph of the fitted response surface design is given, together with the predicted equation. The optimum conditions were verified by experiment.

66. Hasnat, K., Murtaza, S. and Tasch A.F. (1994). A Manufacturing sensitivity analysis of 0.35 μm LDD MOSFET's. *IEEE Transactions on Semiconductor Manufacturing* **7**, 53-59.
A half fraction of a seven factor rotatable CCD with 1 centre point was used but the experimental data are not given. Second order response surface equations are given for six electrical responses. The statistical distribution of electrical parameters was predicted via a Monte Carlo approach using these response surface equations.

67. Jimenez, L., Delatorre, M.J., Maestre, F., Ferrer, J.L. and Perez, I. (1997). Organosolv pulping of wheat straw by use of phenol. *Bioresource Technology* **60**, 199-205.
Six response variables from a three factor CCD with one centre point are given. The analysis and a discussion are included.

68. Jimenez, L., Maestre, F., Delatorre, M. and Perez I. (1997). Organosolv pulping of wheat straw by use of methano-water mixtures. *TAPPI Journal* **80**, 148-154.
Five response variables from a three factor CCD with no centre points are given. The analysis and a discussion are included.

69. Jimidar, M., Hamoir, T., Degezelle, W., Massart, D.L., Soykenc, S. and Vandewinkel, P. (1993). Method development and optimization for the determination of rare earth metal ions by capillary zone electrophoresis. *Analytica Chimica Acta* **284**, 217-225.
Three response variables from a two factor CCD with 1 centre point are given. Quadratic response surface equations and some graphical displays of them are presented.

70. Kleinebudde, P. and Lindner, H. (1993). Experiments with an instrumented twin-screw extruder using a single-step granulation/extrusion process. *International Journal of Pharmaceutics* **94**, 49-58.
Five response variables from two replicates of a two factor CCD with one centre point are given, as are the fitted equations and some response surface plots.

71. Liadakis, G.N., Tzia, C., Oreopoulou, V. and Thomopoulos, C.D. (1998). Isolation of tomato seed meal proteins with salt solutions. *Journal of Food Science* **63**, 450-453.
Four response variables from a two factor CCD with 5 centre points,and a full discussion, are given.

72. Llompart, M.P., Lorenzo, R.A., Cela, R. and Pare, J.R.J. (1997). Optimization of a microwave-assisted extraction method for phenol and methylphenol isomers in soil samples using a central composite design. *Analyst* **122**, 133-137.
Four response variables from a three-factor, face-centered CCD with three centre points are given. Some coding errors appear to have been made in the CCD.Contour plots are given.

73. Mager, P.P. (1997). How design statistics concepts can improve experimentation in medicinal chemistry. *Medicinal Research Reviews* **17**, 453-475.
This is a tutorial paper with some applications and is suitable as supplementary material in a post-graduate experimental design course (honours or above). Some designs and actual data from medicinal chemistry are given for illustrative purposes.

74. Oh, S., Rheem, S., Sim, J., Kim, S. and Baek, Y. (1995) Optimizing conditions for the growth of *Lactobacillus casei* YIT 9018 in tryptone-yeast extract-glucose medium by using response surface methodology. *Applied & Environmental Microbiology* **61**, 3809-3814.
One response variable from a five factor CCD with 8 centre points in two blocks is given. The estimated equation for an adequate model is given. Partial response surface plots are given.

75. Ostberg, T. and Graffner, C. (1994). Calcium alginate matrices for oral multiple unit administration 3. Influence of calcium concentration, amount of drug added and alginate characteristics on drug release. *International Journal of Pharmaceutics* **111**, 271-282.
Eight response variables from a two factor uniform precision CCD with five centre points are given, as are the estimated equations and some response surface graphs. Three combinations of levels not used in the experiment were used to confirm the predictive capabilities of the model.

76. Ruchatz, F., Kleinebudde, P. and Muller, B.W. (1997). Residual solvents in biodegradable microparticles. influence of process parameters on the residual solvent in microparticles produced by the aerosol solvent extraction system (ASES) process. *Journal of Pharmaceutical Sciences* **86**, 101-105.
Six responses from a two factor CCD with 2 centre points and the axial points replicated twice are given. For each response the response surface coefficients are given, as are some appropriate plots.

77. Saim, N., Dean, J.R., Abdullah, M.P. and Zakaria, Z. (1998). An experimental design approach for the determination of polycyclic aromatic hydrocarbons from highly contaminated soil using accelerated solvent extraction. *Analytical Chemistry* **70**, 420-424.
Seventeen respons variables from a three factor CCD with 2 centre points are given, along with the estimated response surface coefficients.

78. Sen, R. and Swaminathan, T. (1997). Application of response-surface methodology to evaluate the optimum environmental conditions for the enhanced production of surfactin. *Applied Microbiology & Biotechnology* **47**, 358-363.
One response variable from a four factor CCD with 6 centre points, the estimated equation and contour plots are given.

79. Varesio, E., Gauvrit, J.Y., Longeray, R., Lanteri, P. and Veuthey, J.L., (1998). Central composite design in the chiral analysis of amphetamines by capillary electrophoresis. *Electrophoresis* **18**, 931-937.
Four response variables from a face-centred five factor CCD with two centre points and using a hlaf-replicate are given. The second-order response surface coefficients and plots for each of the four responses are given

80. Zaman, A.A. and Fricke, A.L. (1996) Effect of pulping variables on enthalpy of kraft black liquors: Empirical predictive models. *Industrial & Engineering Chemistry Research* **35**, 2438-2443.
Two response variables from a four factor CCD with 1 centre point are given but are missing for two of the axial points. The coefficients for two second-order response surfaces and some contour plots are given.

81. Zeng, X.M., Martin, G.P. and Marriott, C. (1994). Tetrandrine delivery to the lung: The optimisation of albumin microsphere preparation by central composite design. *International Journal of Pharmaceutics* **109**, 135-145.
Average responses from a three factor CCD with 6 centre points, the fitted equation and several response surface plots are given.

Fractional Factorial Designs

82. Abuzarur-Aloul, R., Gjellan, K., Sjolund, M. and Graffner, C. (1998). Critical dissolution tests of oral systems based on statistically designed experiments. II. In vitro optimization of screened variables on ER-coated spheres for the establishment of an in vitro/in vivo correlation. *Drug Development and Industrial Pharmacy* **24**, 203-212.
A 2^{4-1}_{IV} + 4 centre points design was used to gain knowledge about "how a solid system releases its drug content in the gastrointestinal tract". Percent dissolved remoxipride was measured for each experiment at 30, 60, 120, 360, and 720 minutes but is not given. The observed dissolution profiles in vitro and in vivo are presented. Lastly an in vitro/in vivo correlation was established.

83. Alves, L.A., Felipe, M.G.A., Silva, J.B.A.E., Silva, S.S. and Prata, A.M.R., (1998). Pretreatment of sugarcane bagasse hemicellulose hydrolysate for xylitol production by Candida Guilliermondii. *Applied Biochemistry and Biotechnology* **70**, 89-98.
Average responses of two replicates of a 2^{5-1} design are given. The two active factors were used in a 2^2 design with a centre face and three replicates at the centre point, and the data are given. Coefficients for response surfaces are given along with their plots.

84. Araujo, P.W. and Brereton, R.G., (1996). Experimental Design .1. Screening. *TRAC-Trends In Analytical Chemistry* **15**, 26-31.
A general introduction written for chemists with references to uses of designs in chemical experiments in the literature. Includes the results of one 2^{7-3} design.

85. Bafna, S.S. and Beall, A.M. (1997). A design of experiments study on the factors affecting variability in the melt index measurement. *Journal of Applied Polymer Science* **65**, 277-288.
Responses from a 2^{6-2}_{IV} design with three replicates, one for High Melt Index and one for Low Melt Index are given.

86. Bauer, C. and Rombke, J. (1997). Factors influencing the toxicity of two pesticides on three lumbricid species in laboratory tests. *Soil Biology and Biochemistry* **29**, 705-708.
For each of 9 scenarios, a 2^{5-1} design was used and three response variables observed but are not given. Some plots on % difference to initial weight are given. No ANOVAs or equations are given. Tests were done at day 14 and day 28.

87. Cestari, A.R., Bruns, R.E. and Airoldi, C. (1996). A fractional factorial design applied to organofunctionalized silicas for adsorption optimization. *Colloids and Surfaces A-Physicochemical and Engineering Aspects* **117**, 7-13.
Results of two replicates of a 2^{4-1} design are presented, as well as a discussion of how the levels for the factors were determined.

88. Chen, G.Q. and Gouaux, E. (1997). Overexpression of a glutamate receptor (GluR2) ligand binding domain in *Escherichia coli*: Application of a novel protein folding screen. *Proceedings of The National Academy of Sciences of The United States of America* **94**, 13431-13436.
Three response variables from a 2^{12-8}_{III} FFD are given, together with plots of response curves for each run.

89. Chien, T.W., Lin, C.H. and Sphicas, G. (1997). A systematic approach to determine the optimal maintenance policy for an automated manufacturing system. *Quality and Reliability Engineering International* **13**, 225-233.
A thorough discussion of the steps involved in determining the factors and levels for a FFD. The results of a 2^{5-1} design are presented and discussed.

90. Choueiki, M.H., Mountcampbell, C.A. and Ahalt, S.C. (1997). Building a quasi optimal neural network to solve the short-term load forecasting problem. *IEEE Transactions on Power Systems* **12**, 1432-1439.
A 'quasi optimal' neural network was built from the analysis of a 2^{10-4}_{IV} design used to solve the aforementioned problem. Only significant effects and their estimates are reported.

91. Cohen, D. (1997). Influence of filament winding parameters on composite vessel quality and strength. *Composites. Part A, Applied science and manufacturing* **28**, 1035-1047.
Seven response variables from a 2^{5-2} design with one replicated run are given. Excellent discussion of all phases of the experiment.

92. Dauneau, P. and Perezmartinez, G. (1997). Fractional factorial design and multiple linear regression to optimise extraction of volatiles from a lactobacillus plantarum bacterial suspension using purge and trap. *Journal of Chromatography* **775**, 225-230.
One response variable from a 2^{4-1} design with 3 centre points are given and discussed.

93. Davis, BL., Cavanagh, P.R., Sommer, H.J. and Wu, G. (1996). Ground reaction forces during locomotion in simulated microgravity. *Aviation Space and Environmental Medicine* **67**, 235-242.
Describes a $4 \times 3 \times 3 \times 2$ fractionated design. Results are given as averages or graphically.

94. Donahue, D.W., Sowell, R.S. and Bengtson, N.M. (1996). Simulation of alternative agricultural marketing systems. *Agricultural Systems* **51**, 395-406.
Several marketing systems were developed and the effect of a number of factors on the systems was determined using a FFD. Neither responses nor parameter estimates are given.

95. Eilamo, M., Kinnunen, A., Latvakala, K. and Ahvenainen, R. (1998). Effects of packaging and storage conditions on volatile compounds in gas-packed poultry meat. *Food Additives and Contaminants* **15**, 217-228.
Ten response variables from a $2^1 \times 3^{6-4}$ FFD are given. Seven replicate samples were packed for each experiment. "Two of these were tested for microbial content, three for sensory quality and the other two for volatiles contents after the storage interval determined by the experimental design."

96. Ekblad, A., Wallander, H., Carlsson, R. and Huss-danell, K. (1995). Fungal biomass in roots and extramatrical mycelium in relation to macronutrients and plant biomass of ectomycorrhizal *Pinus sylvestris* and *Alnus incana*. *New Phytologist* **131**, 443-451.
Six macronutrients were arranged in a 2^{6-2} FFD in pots and each combination replicated 12 times. Half of the pots were non-mycorrhizal and half inoculated with *P. involutus*. The pots were paired and arranged in a climate chamber in randomised blocks. Results are presented graphically.

97. Ellekjaer, M.R., Ilseng, M.A. and Naes, T. (1996). A case study of the use of experimental design and multivariate analysis in product improvement. *Food Quality and Preference* **7**, 29-36.
Compares design results to results of a principal components analysis on the same data set. The FFD was a 2^{7-2} and some centre points and reference samples were also included. Results are given in normal plots and in tables indicating significant effects. Plots of scores and loading are also given.

98. Fallman, A.M. (1997). Performance and design of the availability test for measurement of potentially leachable amounts from waste materials. *Environmental Science and Technology* **31**, 735-744.
A 2^{6-3}_{III} design was initially used but a foldover to a 2^{6-2}_{IV} design was necessary. Forty-four different response variables were evaluated in these experiments. Evaluations were based on a multiplicative model and the models parameters are given. Normality was assumed. The data are not given.

99. Feldman, H.A., McKinlay, J.B., Potter, D.A., Freund, K.M., Burns, R.B., Moskowitz, M.A. and Kasten, L.E. (1997). Nonmedical influences on medical decision making: An experimental technique using videotapes, factorial design and survey sampling. *Health Services Research* **32**, 343-366.
Sixty-four videos were made according to a 2^{8-2} FFD and then paired to be shown to physicians who were asked to say what further diagnostic evaluation they would recommend and what options they would offer to the patients. Results are given in other papers.

100. Garea, A., Fernandez, I., Viguri, J.R., Ortiz, M.I. Fernandez, J., Renedo, M.J. and Irabien J.A. (1997). Fly-ash calcium hydroxide mixtures for SO_2 removal: structural properties and maximum yield. *Chemical Engineering Journal* **66**, 171-179.
Three response variables from a 2^{5-1} design with 5 centre points are given.

101. Gates, T.K. and Alzahrani, M.A. (1996). Spatiotemporal stochastic open-channel flow.2. Simulation experiments. *Journal of Hydraulic Engineering* **122**, 652-661.
Discusses the use of a 2^{9-2} FFD in doing Monte Carlo simulation experiments. Results are discussed and some parameter estimates given.

102. Glaser, .R.A. and Shulman, S.A. (1996). Study of variables affecting extraction of organic solvents from solid sorbent sampling media using supercritical carbon dioxide. *Chromatographia* **42**, 665-674.
Some responses for a non-orthogonal FFD where collection was limited by instrument are given, as well as parameter estimates for some of the fitted polynomials.

103. Henderson-Sellers, B. and Henderson-Sellers, A. (1996). Sensitivity evaluation of environmental models using fractional factorial experimentation. *Ecological Modelling* **86**, 291-295.
Discusses the benefits of FFD over the designs traditionally used for sensitivity testing. Includes three references to earlier studies.

104. Joo, H.K., Hool, J.N. and Curtis, C.W.. (1998). ANOVA Analysis of two-stage coprocessing of low-density polyethylene, coal, and petroleum resid. *Energy and Fuels* **12**, 704-714.
A $3 \times 2^{3-1}$ design was used to evaluate reaction parameters used in two-stage co-processing. A 3^{3-1} design with duplication after one week for four of the experiments was used to determine the effect of H_2 pressure and coal content. The aliasing structure was given for both designs. Data are given along with some of the ANOVAs for a subset of the response variables measured.

105. Khundker, S., Dean, J.R. and Jones, P. (1995). A comparison between solid phase extraction and supercritical fluid extraction for the determination of fluconazole from animal feed. *Journal of Pharmaceutical and Biomedical Analysis.* **13**, 1441-1447.
Results and discussion of two 2^{4-1} FFDs.

106. Kinoshita, E., Sugimoto, T., Ozawa, Y. and Aishima, T. (1998). Differentiation of soy sauce produced from whole soybeans and defatted soybeans by pattern recognition analysis of HPLC Profiles. *Journal of Agricultural and Food Chemistry* **46**, 877-883.
Results from a 2^{5-1} design with 3 replicates of one point are given. Principal components were calculated separately for the two soy sauce data sets. Cluster analysis was performed on the HPLC profiles.

107. Lenk, P.J., Desarbo, W.S., Green, P.E. and Young, M.R. (1996). Hierarchical Bayes conjoint analysis: Recovery of partworth heterogeneity from reduced experimental designs. *Marketing Science* **15**, 173-191.
This paper compares the estimates obtained from a main effects design and a subset of such a design. Parameter estimates are given for two sets of data.

108. Loukas, Y.L. (1997). $2^{(K-P)}$ Fractional Factorial Design via Fold Over: Application to Optimization of novel multicomponent vesicular systems. *Analyst* **122**, 1023-1027.
Two response variables from a 2_{IV}^{6-2} design are given. An additive linear model in the main effects was fitted for both sets of data. Diagnostic plots of residuals and Pareto charts of effects are presented.

109. Loukas, Y.L. (1998). A computer-based expert system designs and analyzes a $2^{(k-p)}$ fractional factorial design for the formulation optimization of novel multicomponent liposomes. *Journal of Pharmaceutical and Biomedical Analysis* **17**, 133-140.
Two response variables from a 2_{IV}^{4-1} FFD are given. Main effects are estimated and coefficients for the linear equations fitted to the two responses are given.

110. Loukas, Y.L. (1998). Experimental studies for screening the factors that influence the effectiveness of new multicomponent and protective liposomes. *Analytica Chimica Acta* **361**, 241-251.

One response variable from a 2^{6-3} FFD and its foldover are given. A discussion of the choice of factors and factor levels is given and an analysis and discussion of the results is presented.

111. Moon, H.S. and Na, S.J. (1997). Optimum design based on mathematical model and neural network to predict weld parameters for fillet joints. *Journal of Manufacturing Systems* **16**, 13-23.
Five responses from a 2^{5-1} design are given. On the basis of the results, a system was developed to estimate the welding process variables' "effect on the fillet welded joint shape using the neural network and optimum design."

112. Nascimento, I.C., Deoliveira, A.E. and Bruns, R.E.,(1998). A statistical approach of density functional effects on the vibrational frequencies and infrared intensities of CH_3F. *Spectrochimica Acta. Part A, Molecular and Biomolecular Spectroscopy* **54**, 831-841.
Six response variables from a 2^{5-1} FFD are given and used to determine more accurate wave functions. Results obtained for all frequency and intensity values were analysed using principal components analysis.

113. Oles, P.J. (1998). Fractional factorial experimental design as a teaching tool for quantitative analysis. *Journal of Chemical Education* **75**, 357-359.
The application presented is gravimetric determination of chloride by precipitation with Ag^+ ion and results from a 2^{5-2} design are given.

114. Oppewal, H., Louviere, J.J. and Timmermans, J.P. (1994). Modeling hierarchical conjoint processes with integrated choice experiments. *Journal of Marketing Research* **31**, 92-105.
This paper describes the use of fractional factorial designs to describe travel options and shopping centre options to consumers, and hence to establish the effect of each of various factors on their choices.

115. Osborne, L.M. and Miyakawa, T.W.,(1997). Use of experimental design in the optimization of HPLC methodology for the separation of stereoisomers. *Journal of Liquid Chromatography and Related Technologies* **20**, 501-509.
Four response variables from a 2^{4-1} design with 3 centrepoints are given.

116. Renard, C.M.G.C., Lemeunier, C. and Thibault, J.F. (1995). Alkaline extraction of xyloglucan from depectinised apple pomace - optimisation and characterisation. *Carbohydrate Polymers* **28**, 209-216.
Gives the results of a 2^{5-2} design with 2 centre points. A discussion of why a fraction was needed is included.

117. Rustom, I.Y.S., Foda, M.I. and Lopezleiva, M.H. (1998). Formation of oligosaccharides from whey UF-permeate by enzymatic hydrolysis - analysis of factors. *Food Chemistry* **62**, 141-147.
Four response variables from a 2^{4-1} design for each of three different enzymes are given.

118. Slaveykova, V.I. and Hoenig, M. (1997). Electrothermal atomic absorption spectrometric determination of lead and tin in slurries. Optimization study. *Analyst* **122**, 337-343.
Four response variables from a 2^{7-3} design are given. Some interaction diagrams are presented for confounded terms and estimated effects also given.

119. Smith, B.C., Penrod, S.D., Otto, A.L. and Park, R.C. (1996). Jurors use of probabilistic evidence. *Law and Human Behavior* **20**, 49-82.
Sixteen videos of a simulated rape trial were made according to a 2^{7-3} design although one factor could not be orthogonally confounded. The responses were mock jurors' assessment of the guilt of the defendent at five time points. Raw results are not available but analyses at each time point and across the time points are given.

120. Thorsteinsdottir, M., Westerlund, D., Andersson, G. and Kaufmann, P. (1998). Chemometric evaluation of the band broadening in micellar electrokinetic chromatography of peptides. *Journal of Chromatography A* **809**, 191-201.
One response variable from each of three 2^{5-2} FFD with centre points, as well as various estimated parameters and response surface plots, are given.

121. Vepa, T.S. and George, K.P. (1997). Deflection response models for cracked rigid pavements. *Journal of Transportation Engineering-ASCE* **123**, 377-384.
This paper discusses the development of a model for describing the deflection of cracked rigid pavements. Eight factors are identified as being important and a $2^{4-3} \times 3^4$ design is used to determine a database of results from which a regression model is developed. The results from the regression model are then compared with actual results from two test pavements. The estimated parameters are given as are graphs which indicate the agreement between the predicted and observed deflections.

122. Woodside, A.G., Breaux, R. and Briguglio, E. (1998). Testing care-giver acceptance of new syringe technologies. *IJTM Special Issue on Management of Technology in Health Care* 446-457.
This paper describes the use of fractional factorial designs to establish options to present to care-givers to establish which syringe types they prefer.

123. Yang, G.C.C. and Tsai, C.M. (1998). A study on heavy metal extractability and subsequent recovery by electrolysis for a municipal incinerator fly ash. *Journal of Hazardous Materials* **58**, 103-120.
One response variable from a 2^{4-1} design and from a 2^{3-1} design are given. Effect estimates, normal probability plots and some results plots are all given.

124. Yang, H.J. and Yang, C.H. (1998). Statistical experimental strategies approach to emulsion copolymerization of styrene and n-butyl acrylate. *Journal of Applied Polymer Science* **69**, 551-563.
Six response variables from a 2^{5-1} experiment are given. Univariate analyses of each response are given and discussed.

125. Zhang, H., Lunsford, S.K., Marawi, I., Rubinson, J.F. and Mark, H.B. (1997). Optimization of preparation of poly(3-Methylthiophene)-modified pt microelectrodes for detection of catecholamines. *Journal of Electroanalytical Chemistry* **424**,101-111.
A 2^{5-1} design was used for two different experiments and the data are given. Each experiment has two response variables, one being dichotomous.

126. Zhang, S. and Forssberg, E. (1998). Optimization of electrodynamic separation for metals recovery from electronic scrap. *Resources Conservation and Recycling* **22**, 143-162.
One response variable from a 2^{8-4}_{IV} design is given. The ambiguity of one significant interaction effect was clarified by conducting 4 additional runs.

127. Zhu, Y., Knol, W., Smits, J. P. and Bol, J. (1996). Medium optimization for nuclease P1 production by penicillium citrinum in solid-state fermentation using polyurethane foam as inert carrier. *Enzyme and Microbial Technology* **18**, 108-112.
One response variable from each of two 2^{7-4} experiments are given. The second experiment uses different levels, based on the results of the first experiment.

128. Zipper, P., Janosi, A., Wrentschur, E., Geymayer, W., Ingolic, E. Friesenbichler, W. and Eigl, F. (1997). Wide-angle X-Ray, densitometric and microscopical studies on injection molded polypropylene disks. *International Polymer Processing* **12**, 192-199.
One response variable from a 2^{5-3} design is given.

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129. Boonkerd, S., Detaevernier, M.R., Heyden, Y.V., Vindevogel, J. and Michotte, Y. (1996). Determination of the enantiomeric purity of dexfenfluramine by capillary electrophoresis: Use of a Plackett-Burman design for the optimization of the separation. *Journal of Chromatography* **736**, 281-289.
Four responses from 2 five-factor, 8 run PBDs are given, as well as the estimated effects. The repeatability of the optimal settings was determined.

130. Bullington, R.G., Lovin, S., Miller, D.M. and Woodall, W.H. (1993). Improvement of an industrial thermostat using designed experiments. *Journal of Quality Technology* **25**, 262-270.

This is a case study of an eleven-factor, 12 run PBD. The responses are given and some possible analyses discussed.

131. Castro, P.M.L., Ison, A.P., Hayter, P.M. and Bull, A.T. (1996). CHO cell growth and recombinant interferon-γ production: Effects of BSA, Pluronic and lipids. *Cytotechnology* **19**, 27-36.
A four-factor 8 run PBD was used to construct 8 culture media. To each of these culture media different combinations of a lipid mixture and Pluronic F68 was added. The responses for these media are given.

132. Chehbouni, A., Chaouki, J., Guy, C. and Klvana, D. (1995). Effects of different parameters on the onset of fluidization in a turbulent regime [French]. *Canadian Journal of Chemical Engineering* **73**, 41-50.
One response from a four-factor 8 run PBD, and the corresponding analysis, are given. The authors compare the model that they have developed with other published models.

133. Dung, N.V. (1995). Factors affecting product yields and oil quality during retorting of Stuart oil shale with recycled shale: A screening study. *Fuel* **74**, 623-627.
Seven response variables from a seven-factor, 8 run PB design are given. It is clear from the paper that some of the factors can not be held at exactly the levels determined and the actual levels observed are given. The significant factors for each of the responses are identified.

134. Durig, T. and Fassihi, A.R. (1993). Identification of stabilizing and destabilizing effects of excipient-drug interactions in solid dosage form design. *International Journal of Pharmaceutics* **97**, 161-170.
Thirteen factors were investigated using a 24 run PB design. Responses are given as well as the estimated factor effects.

135. Irvine, G.M. Clark, N.B. and Recupero, C. (1996). Extended delignification of mature and plantation eucalypt wood Part 2: The effects of chip impregnation factors. *Appita Journal* **49**, 347-352.
One response from a 14 factor, 16-run PBD is given.

136. Lavilla, I., Perez-Cid, B. and Bendicho, C. (1998). Optimization of digestion methods for sewage sludge using the Plackett-Burman saturated design. *Fresenius Journal of Analytical Chemistry* **361**, 164-167.
Five responses for three experiments, a six-factor, a five-factor and a four-factor, PBD are given, as are the estimated effects. The accuracy of the method was confirmed using a sample of known composition.

137. Poorna, V. and Kulkarni, P.R. (1995). A study of inulinase production in *Aspergillus niger* using fractional factorial design. *Bioresource Technology* **54**, 315-320.
One response variable from a 15 factor, 16 run PBD are given.

138. Rogan, M.M., Altria, K.D. and Goodall, D.M. (1994). Plackett-Burman experimental design in chiral analysis using capillary electrophoresis. *Chromatographia* **38**, 723-729.
Three response variables from a four-factor, three-level, 15 run PBD are given, as are the estimated percentage main effects for each of the responses.

139. Srinivas, M.R.S., Chand, N. and Lonsane, B.K. (1994). Use of Plackett-Burman design for rapid screening of several nitrogen sources, growth product promoters, minerals and enzyme inducers for the production of alpha-galactosidase by *Aspergillus niger* MRSS-234 in solid state fermentation system. *Bioprocess Engineering* **10**, 139-144.
Longitudinal results for three responses from a nineteen-factor, 20 run PBD are presented. The estimated coefficients for one of the responses, at each of four times, are given.

140. Stevens, T.O. (1995). Optimization of media for enumeration and isolation of aerobic heterotrophic bacteria from the deep terrestrial subsurface. *Journal of Microbiological Methods* **21**, 293-303.
A twelve-factor 16 run PBD was used and the estimated effects of each of the factors, for each of 10 samples, are given.

141. Taillandier, P., Gilis, F., Portugal, F.R., Laforce, P. and Strehaiano, P. (1996). Influence of medium composition, pH and temperature on the growth and viability of *Lactobacillus acidophilus*. *Biotechnology Letters* **18**, 775-780.

Three response variables from a seven-factor 8 run PBD, augmented with 4 centre points, are given. Estimated equations are given, as well as Pareto charts for each response variable.

142. Van Driessche, I., Persyn, F., Fiermans, L. and Hoste, S. (1996). A statistical Plackett-Burman design of the thermal process in the synthesis of the Bi-2223 HTSC. *Superconductor Science & Technology* **9**, 843-848.
Four response varaibles from a 10 factor, 16-run PBD are given. Large values for some dummy factors suggest significant two factor interactions so a larger design was used but only summary results for this are given.

143. Veress, T. (1993). Study of the extraction of LSD from illicit blotters for HPLC determination. *Journal of Forensic Sciences* **38**, 1105-1110.
One response variable from a four factor, 8 run PBD is given.