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101 WAYS TO DESIGN AN EXPERIMENT, OR SOME IDEAS ABOUT TEACHING DESIGN OF EXPERIMENTS

by

William G. Hunter

The University of Wisconsin-Madison

I want to share some ideas about teaching design of experiments. They are related to something I have often wondered about: whether it is possible to let students experience first-hand all the steps involved in an experimental investigation-thinking of the problem, deciding what experiments might shed light on the problem, planning the runs to be made, carrying them out, analyzing the results, and writing a report summarizing the work. One curiosity about most courses on experimental designing, it seems to me, is that students get no practice <u>designing</u> realistic experiments although, from homework assignments, they do get practice <u>analyzing</u> data. Clearly, however, because of limitations of time and money, if students are to design experiments and actually carry them out, they cannot be involved with elaborate investigations. Therefore, the key question is this: Is it feasible for students to devise their own simple experiments and carry them through to completion and, if so, is it of any educational value to have them do so? I believe the answer to both parts of the question issues, and the purpose of this paper is to explain why.

Background

The particular design course I have taught most often is a one-semester course that includes these standard statistical techniques: t-tests (paired and unpaired), analysis of variance (primarily for one-way and two-way layouts), factorial and fractional factorial designs (emphasis given to two-level designs), the method of least squares (for linear and nonlinear models), and response surface methodology. The value of randomization and blocking is stressed. Special attention is given to these questions: What are the assumptions being made? What if they are violated? What common pitfalls are encountered in practice? What precautions can be taken to avoid these pitfalls? In analyzing data how can one determine whether the model is adequate? Homework problems provide ample opportunity for carefully examining residuals, especially by plotting them. The material for this course is discussed in the context of the iterative nature of experimental investigations.

Most of those who have taken this course have been graduate students, principally in engineering (chemical, civil, mechanical, industrial, agricultural) but also in a variety of other fields including statistics, food science, forestry, chemistry, and biology. There is a prerequisite of a one-semester introductory statistics course, but this requirement is customarily waived for graduate students with the understanding that they do a little extra work to catch up.

Simulated Data

One possibility is to use simulated data, and the scope here is wide, especially with the availability of computers. At times I have given assignments of this kind, especially response surface problems. Each student receives his or her own sets of data based upon the designs he or she chooses.

The problem might be set up as one involving a chemist who wishes to find the best settings of these five variables-temperature, concentration, pH, stirring rate, and amount of catalyst-and to determine the local geography of the response surface(s) near the optimum. To define the region of operability, ranges are specified for each of these variables. Perhaps more than one response can be measured, for instance, yield and cost. The student is given a certain budget, either in terms of runs or money, the latter being appropriate if there is an option provided for different types of experiments which have different costs. The student can ask for data in, say, three stages. Between these stages the accumulated data can be analyzed so that future experiments can be planned on the basis of all available information.

In generating the data, which contains experimental error, there are many possibilities. Different models can be used for each student, the models not necessarily being the usual simple first-order or second-order linear models. Not all variables need to be important, that is, some may be dummy variables (different ones for different students). Time trends and other abnormalities can be deliberately introduced into the data provided to the students.

The student prepares a report including a summary of the most important facts discovered about his or her system and perhaps containing a contour map of the response surface(s) for the two most important variables (if three of the five variables are dummies, this map should correspond to the true surface from which the data were generated). It is instructive then to compare each student's findings with the corresponding true situation.

Students enjoy games of this type and learn a considerable amount from them. For many it is the first time they realize just how frustrating the presence of an appreciable amount of experimental error can be. The typical prearranged undergraduate laboratory experiments in physics and chemistry, of course, have all important known sources of experimental error removed (typically the data are supposed to fall on a straight line-exactly-or else).

Real Data

A few years ago I asked each student taking the course to perform an experiment of his or her own devising, thereby diving rise to real rather than simulated data. The students were given three weeks to complete this assignment and hand in a detailed report describing what they had done and what they had learned. The students obviously enjoyed the project and derived quite a bit from it. Consequently, I have repeated the assignment every semester I have taught the course since then.

One's first reaction might be that there are not enough possibilities for experiments of this kind. But this is incorrect, as is illustrated by Table 1, which lists some of the experiments reported by the students. Experiments number 1-63 are of the home type and experiments number 64-101 are of the laboratory type. Note the variety of studies done. To save space, for most variables the levels used are not given. Anyway, they are not essential for our purposes here. Most of these experiments were 2^3 factorial designs. Let us look briefly at the first two home experiments and the first two laboratory experiments.

Bicycle Experiment

In experiment number 1 the student, Norman Miller, using a 2^3 factorial design with all points replicated, studied the effects of three variables-seat height (26, 30 inches), light generator (on or off), and tire pressure (40, 55 psi)-on two responses-time required to ride his bicycle over a particular course and his pulse rate at the finish of each run (pulse rate at the start was virtually constant). To him the most surprising result was how much he was slowed down by having the generator on. The average time for each run was approximately 50 seconds. He discovered that raising the seat reduced the time by about 10 seconds, having the generator on increased it by about one-third that amount and inflating the tires to 55 psi reduced the time by about the same amount that the generator increased it. He planned further experiments.

Popcorn Experiment

In experiment number 2 the student, Karen Vlasek, using a 2^3 factorial design with four replicated center points, determined the effects of three variables on the amount of popcorn produced. She found, for example, that although double the yield was obtained with the gourmet popcorn, it cost three times as much as the regular popcorn. By using this experimental design she discovered approximately what combination of variables gave her best results. She noted that it differed from those recommended by the manufacturer of her popcorn popper and both suppliers of popcorn.

Dilution experiment

In experiment number 64 the student, Dean Hafeman, studied a routine laboratory procedure (a dilution) that was performed many times each day where he worked-almost on a mass production basis. The manufacturer of the equipment used for this work emphasized that the key operations, the raising and lowering of two plungers, had to be done slowly for good results. The student wondered what difference it would make if these operations were done quickly. He set up a 2^4 factorial design in which the variables were the raising and lowering of plunger A and the raising and lowering of plunger B. The two levels of each variable were slow and fast. To his surprise, he found that none of the variables had any measurable effect on the readings. This conclusion had important practical implications in his laboratory because it meant that good results could be obtained even if the plungers were moved quickly; consequently a considerable amount of time could be saved in doing this routing work.

Trouble-shooting Experiment

In experiment number 65 the student, Rodger Melton, solved a trouble-shooting problem that he encountered in his research work. In one piece of his apparatus an extremely small quantity of a certain chemical was distilled to be collected in a second piece of the apparatus. Unfortunately, some of this material condensed prematurely in the line between these two pieces of apparatus. Was there a way to prevent this? By using a 2^3 factorial design the problem was solved, it being discovered that by suitably adjusting the voltage and using a J-tube none of the material condensed prematurely. The column temperature, which was discovered to be minor consequence as far as premature condensation was concerned (a surprise), could be set to maximize throughput.

Most Popular Experiments

The most popular home experiments have concerned cooking since recipes lend themselves so readily to variations. What to measure for the response has sometimes created a problem. Usually a quality characteristic such as taste has been determined (preferably independently by a number of judges) on a 1-5 or 1-10 scale. Growing seeds has also been an easy and popular experiment. In the laboratory experiments, sensitivity or robustness tests have been the most common (the dilution experiment, number 65, discussed above is of this type). Typically the experimenter varies the conditions for a standard analytical procedure (for example, for the measurement of chemical oxygen demand, COD) to see how much the measured value is affected. That is, if the standard procedure calls for the addition of 20 ml. of a particular chemical, 18 ml. and 22 ml. might be tried. Results from such tests are revealing no matter which way they turn out. One student, for example, concluded "The results sort of speak for themselves. The test is not very robust." Another student, who studied a different test, reported "The results of the Yates analysis show that the COD test is indeed robust."

Structuring the Assignment

I have always made these assignments completely open, saying that they could study anything that interested them. I have tended to favor home rather than laboratory experiments. I have suggested they choose something they care about, preferably something they've wondered about. Such projects seem to turn out better than those picked for no particularly good reason. Here is how a few of the reports began: "Ever since we came to Madison my family has experienced difficulty in making bread that will rise properly." "Since moving to Madison, my green thumb has turned black. Every plant I have tried to grow has died." (Nothing works in Madison?) "This experiment deals with how best to prepare pancakes to satisfy the group of four of us living together." "I rent an efficiency on the second floor of an apartment building which has cooking facilities on the first floor only. When I cook rice, my staple food,I have to make one to three visits to the kitchen to make sure it is ready to be served and not burned. Because of this inconvenience, I wanted to study the effects of certain variables on the cooking time of rice." "My wife and I were wondering if our oldest daughter had a favorite toy." "For the home brewer, a small kitchen blender does a good job of grinding malt, provided the right levels of speed, batch size and time are used. This is the basis of the experimental design." "During my career as a beer drinker, various questions have arisen." "I do much of the maintenance and repair work around my home, and some of the repairs require the use of epoxy glue. I was curious about some of the factors affecting its performance." "My wife and I are interested in indoor plants, and often we like to give them as gifts. We usually select a cutting from one of our fifty or so plants, put it in a glass of water until it develops roots, and then pot it. We have observed that sometimes the cutting roots quickly and sometimes it roots slowly, so we decided to experiment with several factors that we thought might be important in this process." "I chose to find out how my shotguns were firing.

I reload my own shells with powders that were recommended to me, one for short range shooting and one for long range shooting. I had my doubts if the recommendations were valid."

What Did the Students Learn?

The conclusion reached in this last experiment was: "As it looks now, I should use my Gun A with powder C for close range shooting, such as for grouse and woodcock. I should use gun B and powder D for longer range shooting as for ducks and geese." As is illustrated by this example and the first four discussed above, the students sometimes learned things that were directly useful to them. Some other examples: "Spending $70 extra to buy tape deck 2 is not justified as the difference in sound is better with the other, or probably there is no difference. The synthesizer appears not to affect the quality of the sound." In operating my calculator I can anticipate increasing operation time by an additional 15 minutes and 23 seconds on the average by charging 60 minutes instead of 30 minutes." "In conclusion, the Chinese dumplings turned out very pretty and very delicious, especially the ones with thin skins. I think this was a successful experiment.

Naturally, not all experiments were successful. "A better way to have run the experiment would have been to..." Various troubles arose. "The reason that there is only one observation for the eighth row is that one of the cups was knocked over by a curious cat." "One observation made during the experiment was that the child's posture may have affected the duration of the ride. Mark (13 pounds) leaned back, thus distributing his weight more evenly. On the other hand, Mike (22 pounds) preferred to sit forward, which may have made the restoring action of the spring more difficult." (The trouble here was that the variable the student wanted to study was weight, not posture.) Another student, who was studying factors that affected how fast snow melted on sidewalks, had some of his data destroyed because the sun came out brightly (and unexpectedly) one day near the end of his experiment and melted all the snow.

Because of such troubles these simple experiments have served as useful vehicles for discussing important practical points that arise in more serious scientific investigations. Excellent questions for this purpose have arisen from these studies. "Do I really need to use a completely randomized experiment? It will take much longer to do that way?" There have been good examples that illustrate the sequential nature of experimentation and show how carefully conceived experimental designs can help in solving problems."...This must have been the main reason why the first experiment completely failed. I decided to try another factorial design. Synchronization of the flash unit and camera still bothered me. I decided to experiment with..." some other factors.

As a result of these projects students seem to get a much better appreciation of the efficiency and beauty of experimental designs. For example, in this last experiment the student concluded: "The factorial design proved to be efficient in solving the problem. I did get off on the wrong track initially, but the information learned concerning synchronization is quite valuable." Another student: "It is interesting to see how a few experiments can give so much information."

There is another point, and it is not the least important. Most of the students had fun with these projects. And I did, too. Just looking through Table 1 suggests why this is so, I think. One report ended simply: "This experiment was really fun!" Many students have reported that this was the best part of the course.

There is a tendency sometimes for experimenters to discount what they have learned, this being true not only for students in this class, but also for experimenters in general. That is, they learn more than they realize. Hindsight is the culprit. On pondering a certain conclusion, one is prone to say "Oh yes, that makes sense. Yes, that's the way it should be. That's what I would have expected." While this reaction is often correct, one is sometimes just fooling oneself, that is, interrogation at the outset would have produced exactly the opposite opinion. So that students could more accurately gauge what they learned from their simple experiments, I tried the following and it seemed to work: after having decided on the experimental runs to perform, the student guessed what his or her major conclusions would be and wrote them down. Upon completion of the assignment, these guesses were checked against the actual results, which immediately provided a clear picture of what was learned (the surprises) [1] and what was confirmed (the non-surprises).

Pedagogy

I now tend to spend much more time introducing each new topic than I used to. Providing appropriate motivation is extremely important. For classes I have had the privilege of teaching-whether in universities or elsewhere-I have found that it has been better to use concrete examples followed by the general theory rather than the reverse. I now try to describe a particular problem in some detail, preferably a real one with which I am familiar, and then pose the question: What would YOU do? I find it helpful to resist

[1] Incidentally, the way our educational system works students rarely have the opportunity to be surprised. But yet isn't that an important part of learning?

the temptation to move on too quickly to the prepared lecture so that there is ample time for students to consider this question seriously, to discuss it, to ask questions of clarification, to express ideas they have, and ultimately (and this really the object of the exercise) to realize that a genuine problem exists and they do not know how to solve it. They are then eager to learn. And after we have finished with that particular topic they know they have learned something of value. (I realize as I write this that I have been strongly influenced by George Barnard, who masterfully conducted a seminar in this manner at Imperial College, London, in 1964-65, which I was fortunate to have attended.)

Current examples are well-received, especially controversies (for example, weather modification experiments). Some useful sources are court cases, advertisements, TV and radio commercials, and "Consumer Reports". An older controversy still of considerable interest from a pedagogical point of view is the AD-X2 battery additive case. Gosset's comments on the Lanarkshire Milk Experiment are still illuminating. Sometimes trying to get the data that support a particular TV commercial or the facts from both parties of a dispute has made an interesting side project to carry along through a semester.

Summary

Having each student exercise his or her own initiative in thinking up an experiment and carrying it through to completion has turned out successfully. Using games involving simulated data has also been useful. I have incorporated such projects, principally of the former type, into courses I have taught, and I urge others to consider doing the same. Why?

First of all, it's fun. The students have generally welcomed the opportunity to learn something about a particular question they have wondered about. I have been fascinated to see what they have chosen to study and what conclusions they have reached, so it has been fun for me, too. The students and I have certainly learned interesting things we did not know before. Why doesn't my bread rise? Why don't my flowers grow? Is this analytical procedure robust? Will carrying a crutch make it easier for me to get a ride hitchhiking? (Incidentally, it made it harder.)

Secondly, the students have gotten a lot out of such experiences. There is a definite deepening of understanding that comes from having been through a study from start to finish-deciding on a problem, the variables, the ranges of the variables, and how to measure the response(s), actually running the experiment and collecting the data, analyzing the results, learning what the practical consequences are, and finally writing a report. Being veterans, not of the war certainly but of a minor skirmish at least, the students seem more comfortable and confident with the entire subject of the design of experiments, especially as they share their experiences with one another.

Thirdly, I have found it particularly worthwhile to discuss with them in class some of the practical questions that naturally emerge from these studies. "What can I do about missing data?" "These first three readings are questionable because I think I didn't have my technique perfected then-What should I do?" "A most unusual thing happened during this run, so should I analyze this result with all the others or leave it out?" They are genuinely interested in such questions because they have actually encountered them, not just read about them in a textbook. Sometimes there is no simple answer, and lively and valuable discussions then occur. Such discussions, I hope, help them understand that, when they confront real problems later on which refuse to look like those in the textbooks no matter how they are viewed, there are alternatives to pretending they do and charging ahead regardless or forgetting about them in hopes they will go away or adopting a "non-statistical" approach-in a word, there are alternatives to panic.

Table 1. List of some studies done by students in an experimental design course.

1. variables: seat height (26, 30 inches), generator (off,on), tire pressure (40, 55 psi)

   responses: time to complete fixed course on bicycle and pulse rate at finish

2. variables: brand of popcorn (ordinary, gourmet), size of batch (1/3,2/3 cup), popcorn to oil ratio (low, high)

   responses: yield of popcorn

3. variables: amount of yeast, amount of sugar, liquid (milk, water), rise temperature, rise time

   responses: quality of bread, especially the total rise

4. variables: number of pills, amount of cough syrup, use of vaporizer

   responses: how well twins, who had colds, slept during the night

5. variables: speed of film, light (normal, diffused), shutter speed

   responses: quality of slides made close up with flash attachment on camera

6. variables: hours of illumination, water temperature, specific gravity of water

   responses: growth rate of algae in salt water aquarium

7. variables: temperature, amount of sugar, food prior to drink (water, salted popcorn)

   responses: taste of Koolaid

8. variables: direction in which radio is facing, antenna angle, antenna slant

   responses: strength of radio signal from particular AM station in Chicago

9. variables: blending speed, amount of water, temperature of water, soaking time before blending

   responses: blending time for soy beans

10. variables: charge time, digits fixed, number of calculations performed

    responses: operation time for pocket calculator

11. variables: clothes dryer (A,B), temperature setting, load

    responses: time until dryer stops

12. variables: pan (aluminum, iron), burner on stove, cover for pan (no, yes)

    responses: time to boil water

13. variables: aspirin buffered? (no, yes) dose, water temperature

    responses: hours of relief from migraine headache

14. variables: amount of milk powder added to milk, heating temperature, incubation temperature

    responses: taste comparison of homemade yogurt and commercial brand

15. variables: pack on back (no, yes), footwear (tennis shoes, boots), run (7, 14 flights of steps)

    responses: time required to run up steps and heartbeat at top

16. variables: width to height ratio of sheet of balsa wood, slant angle, dihedral angle, weight added, thickness of wood

responses: length of flight of model airplane

17. variables: level of coffee in cup, devices (nothing, spoon placed across top of cup facing up), speed of walking

    responses: how much coffee spilled while walking

18. variables: type of stitch, yarn gauge, needle size

    responses: cost of knitting scarf, dollars per square foot

19. variables: type of drink (beer, rum), number of drinks, rate of drinking, hours after last meal

    responses: time to get steel ball through a maze

20. variables: size of order, time of day, sex of server

    responses: cost of order of french fries, in cents per ounce

21. variables: brand of gasoline, driving speed, temperature

    responses: gas mileage for car

22. variables: stamp (first class, air mail), zip code (used, not used), time of day when letter mailed

    responses: number of days required for letter to be delivered to another city

23. variables: side of face (left, right), beard history (shaved once in two years0-sideburns, shaved over 600 times in two years-just below sideburns)

    responses: length of whiskers 3 days after shaving

24. variables: eyes used (both, right), location of observer, distance

    responses: number of times (out of 15) that correct gender of passerby was determined by experimenter with poor eyesight wearing no glasses

25. variables: distance to target, guns (A,B), powders(C,D)

    responses: number of shot that penetrated a one foot diameter circle on the target

26. variables: oven temperature, length of heating, amount of water

    responses: height of cake

27. variables: strength of developer, temperature, degree of agitation

    responses: density of photographic film

28. variables: brand of rubber band, size, temperature

    responses: length of rubber band before it broke

29. variables: viscosity of oil, type of pick-up shoes, number of teeth in gear

    responses: speed of H.O. scale slot racers

30. variables: type of tire, brand of gas, driver (A,B)

    responses: time for car to cover one-quarter mile

31. variables: temperature, stirring rate, amount of solvent

    responses: time to dissolve table salt

32. variables: amounts of cooking wine, oyster sauce,sesame oil

    responses: taste of stewed chicken

33. variables: type of surface, object (slide rule, ruler, silver dollar), pushed? (no,yes)

    responses: angle necessary to make object slide

34. variables: ambient temperature, choke setting, number of charges

    responses: number of kicks necessary to start motorcycle

35. variables: temperature, location in oven, biscuits covered while baking? (no,yes)

    responses: time to bake biscuits

36. variables: temperature of water, amount of grease, amount of water conditioner

    responses: quantity of suds produced in kitchen blender

37. variables: person putting daughter to bed (mother, father), bed time, place (home, grandparents)

    responses: toys child chose to sleep with

38. variables: amount of light in room, type of music played, volume

responses: correct answers on simple arithmetic test, time required to complete test, words remembered (from list of 15)

39. variables: amounts of added Turkish, Latakia, and Perique tobaccos

    responses: bite, smoking characteristics, aroma, and taste of tobacco mixture

40. variables: temperature, humidity, rock salt

    responses: time to melt ice

41. variables: number of cards dealt at one time, position of picker relative to the dealer

    responses: points in games of sheepshead, a card game

42. variables: marijuana (no, yes),tequila (no, yes),sauna (no, yes)

    responses: pleasure experienced in subsequent sexual intercourse

43. variables: amounts of flour, eggs, milk

    responses: taste of pancakes, consensus of group of four living together

44. variables: brand of suntan lotion, altitude, skier

    responses: time to get sun burned

45. variables: amount of sleep the night before, substantial exercise during the day? (no, yes), eat right before going to bed? (no, yes)

    responses: soundness of sleep, average reading from five persons

46. variables: brand of tape deck used for playing music, bass level, treble level, synthesizer? (no, yes)

    responses: clearness and quality of sound, and absence of noise

47. variables: type of filter paper, beverage to be filtered, volume of beverage

    responses: time to filter

48. variables: type of ski, temperature, type of wax

    responses: time to go down ski slope

49. variables: ambient temperature for dough when rising, amount of vegetable oil, number of onions

    responses: four quality characteristics of pizza

50. variables: amount of fertilizer, location of seeds (3 x 3 Latin square)

    responses: time for seeds to germinate

51. variables: speed of kitchen blender, batch size of malt, blending time

    responses: quality of ground malt for brewing beer

52. variables: soft drink (A,B), container (can, bottle), sugar free? (no, yes)

    responses: taste of drink from paper cup

53. variables: child's weight (13, 22 pounds),spring tension (4, 8 cranks), swing orientation (level, tilted)

    responses: number of swings and duration of these swings obtained from an automatic infant swing

54. variables: orientation of football, kick (ordinary, soccer style),steps taken before kick, shoe (soft, hard)

    responses: distance football was kicked

55. variables: weight of bowling ball, spin, bowling lane (A, B)

    responses: bowling pins knocked down

56. variables: distance from basket type of shot, location on floor

    responses: number of shots made (out of 10) with basketball

57. variables: temperature, position of glass when pouring soft drink, amount of sugar added

    responses: amount of foam produced when pouring soft drink into glass

58. variables: brand of epoxy glue, ratio of hardener to resin, thickness of application, smoothness of surface, curing time

    responses: strength of bond between two strips of aluminum

59. variables: amount of plant hormone, water (direct from tap, stood out for 24 hours), window in which plant was put

responses: root lengths of cuttings from purple passion vine after 21 days

60. variables: amount of detergent (1/4, 1/2 cup), bleach (none, 1 cup), fabric softener (not used, used)

    responses: ability to remove oil and grape juice stains

61. variables: skin thickness, water temperature, amount of salt

    responses: time to cook Chinese meat dumpling

62. variables: appearance (with and without a crutch), location, time

    responses: time to get a ride hitchhiking and number of cars that passed before getting a ride

63. variables: frequency of watering plants, use of plant food (no, yes), temperature of water

    responses: growth rate of house plants

64. variables: plunger A up (slow, fast),plunger A down (slow, fast), plunger B up (slow, fast) plunger B down (slow, fast)

    responses: reproducibility of automatic diluter, optical density readings made with spectrophotometer

65. variables: temperature of gas chromatograph column, tube type (U, J), voltage

    responses: size of unwanted droplet

66. variables: temperature, gas pressure, welding speed

    responses: strength of polypropylene weld,manual operation

67. variables: concentration of lysozyme, pH, ionic strength, temperature

    responses: rate of chemical reaction

68. variables: anhydrous barium peroxide powder,sulfur,charcoal dust

    responses: length of time fuse powder burned and the evenness of burning

69. variables: air velocity, air temperature, rice bed depth

    responses: time to dry wild rice

70. variables: concentration of lactose crystal, crystal size, rate of agitation

    responses: spread ability of caramel candy

71. variables: positions of coating chamber, distribution plate, and lower chamber

    responses: number of particles caught in a fluidized bed collector

72. variables: proportional band, manual reset, regulator pressure

    responses: sensitivity of a pneumatic valve control system for a heat exchanger

73. variables: chloride concentration, phase ratio, total amine concentration, amount of preservative added

    responses: degree of separation of zinc from copper accomplished by extraction

74. variables: temperature, nitrate concentration, amount of preservative added

    responses: measured nitrate concentration in sewage, comparison of three different methods

75. variables: solar radiation collector size, ratio of storage capacity to collector size, extent of short-term intermittency of radiation, average daily radiation on three successive days

    responses: efficiency of solar space-heating system, a computer simulation

76. variables: pH, dissolved oxygen content of water, temperature

    responses: extent of corrosion of iron

77. variables: amount of sulfuric acid, time of shaking milk-acid mixture, time of final tempering

    responses: measurement of butterfat content of milk

78. variables: mode (batch, time-sharing), job size, system utilization (low, high)

    responses: time to complete job on computer

79. variables: flow rate of carrier gas, polarity of stationary liquid phase, temperature

responses: two different measures of efficiency of operation of gas chromatograph

80. variables: pH of assay buffer, incubation time, concentration of binder

responses: measured cortisol level in human blood plasma

81. variables: aluminum, boron, cooling time

responses: extent of rock candy fracture of cast steel

82. variables: magnification, read out system (micrometer, electronic), stage light

responses: measurement of angle with photogrammetric instrument

83. variables: riser height, mold hardness, carbon equivalent

responses: changes in height, width, and length dimensions of cast metal

84. variables: amperage, contact tube height, travel speed, edge preparation

responses: quality of weld made by submerged arc welding process

85. variables: time, amount of magnesium oxide, amount of alloy

responses: recovery of material by steam distillation

86. variables: pH, depth, time

responses: final moisture content of alfalfa protein

87. variables: deodorant, concentration of chemical, incubation time

responses: odor produced by material isolated from decaying manure, after treatment

88. variables: temperature variation, concentration of cupric sulfate concentration of sulfuric acid

responses: limiting currents on totaling disk electrode

89. variables: air flow, diameter of bead, heat shield (no, yes)

responses: measured temperature of a heated plate

90. variables: voltage, warm-up procedure, bulb age

    responses: sensitivity of micro densitometer

91. variables: pressure, amount of ferric chloride added, amount of lime added

    responses: efficiency of vacuum filtration of sludge

92. variables: longitudinal feed rate, transverse feed rate, depth of cut

    responses: longitudinal and thrust forces for surface grinding operation

93. variables: time between preparation of sample and refluxing, reflux time, time between end of reflux and start of titrating

    responses: chemical oxygen demand of samples with same amount of waste (acetanilide)

94. variables: speed of rotation, thrust load, method of lubrication

    responses: torque of taper roller bearings

95. variables: type of activated carbon, amount of carbon, pH

    responses: adsorption characteristics of activated carbon used with municipal waste water

96. variables: amounts of nickel, manganese, carbon

    responses: impact strength of steel alloy

97. variables: form (broth, gravy), added broth (no, yes), added fat (no, yes), type of meat (lamb, beef)

    responses: percentage of panelists correctly identifying which samples were lamb

98. variables: well (A, B), depth of probe, method of analysis (peak height, planimeter)

    responses: methane concentration in completed sanitary landfill

99. variables: paste (A, B), preparation of skin (no, yes), site (sternum, forearm)

    responses: electrocardiogram reading

100. variables: lime dosage, time of flocculation, mixing speed

responses: removal of turbidity and hardness from water

101. variables: temperature difference between surface and bottom waters, thickness of surface layer, jet distance to thermocline, velocity of jet, temperature difference between jet and bottom waters

responses: mixing time for an initially thermally stratified tank of water