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**An Automated Tool for Developing Experimental Designs:
The Computer-Aided Design Reference for Experiments
(CADRE)**

by Robert C. Williges and Sam E. Middlebrooks

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An Automated Tool for Developing Experiments Designs: The Computer-Aided Design Reference for Experiments (CADRE)

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14. ABSTRACT Based on past problems with data collection in experiments, experimental designers need a tool to assist in establishing effective experiments in which the data collection method minimizes the amount of data required and the data collection effort while maximizing the effectiveness and power of the data. A desktop tool, the Computer-Aided Design Reference for Experiments (CADRE), was developed for this purpose. The CADRE tool includes over 850 pages of reference material covering 25 topics, divided into five major sections, including an introduction to experimental design; supplemental data collection design and analysis; basic analysis of variance (ANOVA) designs; advanced ANOVA designs; and empirical model building. In addition, the CADRE tool contains over 200 pages explaining 40 examples of statistical analyses covered in the reference material and is hyperlinked to version 9.1.3 of the SAS statistical analysis package. Designers can use the CADRE tool to choose experimental design procedures to interrogate and build empirical models in support of complex studies, such as future command and control (C2) systems computer simulations.					
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1. Introduction

Several statistical and experimental design and analysis textbooks cover basic and advanced experimental design techniques (Keppel and Wickens, 2004; Montgomery, 2008; Myers and Montgomery, 2002; Shadish, Cook, and Campbell, 2002; Winer, Brown, and Michels, 1991) as well as attempts at automated experimental design (Mills, Meyer, Rickels, and Hoyland, 1982). What they do not provide, and what is needed, is a computer-based reference (using modern hardware and software technologies) that incorporates an integrated subset of currently accepted basic and advanced experimental design approaches that human factors and ergonomics researchers can use in the complex system research environments they are investigating.

Procedural guidance and reference for experimental design and statistical analysis was often summarized in hard copy tables in the covers of textbooks (Siegel and Castellan, 1988). With the advent of hyperlink technology that can embed such information into machine independent Postscript Definition File (PDF) documents, modern computer technology provides the technical basis for the development of an interactive desktop tool to access a large reference resource to assist researchers in their quest for efficient and effective designs.

2. Description of the CADRE Tool

The research on command and control (C2) systems is a real case example of how the availability of an experimental design and analysis tool can significantly assist researchers in experimental design development and analysis of the results. Appropriate experimental designs for complex analyses can be overwhelming to complete, demanding to structure, and incomplete in their results if an ineffective experiment is followed. Considering the needs of this type of highly complex study provided the basis for developing procedures and processes to ease the burden of experimental design development and ensure that an effective design is selected that minimizes the data collection effort while maximizing the validity of the data.

In 2003 the U.S. Army Research Laboratory (ARL), in collaboration with the Virginia Polytechnic Institute and State University (Virginia Tech), sponsored the development of just such a tool, the Computer-Aided Design Reference for Experiments (CADRE). This three-year effort is now coming to fruition and the resulting interactive experimental design and statistical analysis reference resource provides a highly effective aid for researchers to quickly establish efficient experimental designs for their work.

2.1 CADRE Structure

The CADRE tool is as an interactive desktop computer tool designed to aid human factors and ergonomics researchers in experimental design and analysis. This tool, with the full documentation papers describing it, is on a CD accompanying this report. As the CADRE tool was developed with Government funding it is in the public domain and there are no distribution limitations associated with it.

The human factors experimental design and analysis reference material in CADRE is a compilation of two technical reports (Slater and Williges, 2006; Williges, 2006). The Williges report provides the primary reference material on experimental design in a PowerPoint presentation with accompanying notes. Over 850 pages of experimental design and analysis reference material for human factors researchers is provided in this report. The content of the reference material is presented in a numbered outline format on PowerPoint slides, and descriptive text together with appropriate reference citations are provided for the content of each slide. At the end of each topic presentation, references are provided to the current scientific literature for supplemental readings that are pertinent to the topic presented. The companion report by Slater and Williges is an appendix to Williges' report and provides over 200 pages in SAS of program files (SAS, 2004), output files, and explanations for 40 examples of statistical analyses covered by the 2006 Williges report.

The CADRE tool has several interactive features that can be used to rapidly locate reference material information. These features include extensive bookmarks within the PDF file; links between the reference material and the appendix for each example computational problem; and hyperlinks from the CADRE tool to the SAS desktop interactive statistical program for each example problem.

2.2 CADRE Topics

The CADRE reference material covers 25 topics, divided in to five major sections, including an introduction to experimental design; supplemental data collection design and analysis; basic analysis of variance (ANOVA) designs; advanced ANOVA designs; and empirical model building as shown in table 1.

Table 1. Major topics in CADRE.

Overview
Section 1. Introduction to Experimental Design
Topic 1. Research Design Process
Topic 2. Experimental Designs
Topic 3. Basic Statistical Concepts
Section 2. Supplemental Data Collection and Analysis
Topic 4. Supplemental Data Collection Methods
Topic 5. Analysis of Nominal Scale Data
Topic 6. Analysis of Ordinal Scale Data
Topic 7. Summary of Supplemental Data
Section 3. Basic Analysis of Variance (ANOVA) Design
Topic 8. Introduction to ANOVA
Topic 9. ANOVA Summary Table Components
Topic 10. Between-Subjects ANOVA Designs
Topic 11. Analysis of Comparisons and Interactions
Topic 12. Within-Subjects ANOVA Designs
Topic 13. Mixed-Factors ANOVA Designs
Topic 14. Summary of Basic ANOVA
Section 4. Advanced ANOVA Designs
Topic 15. Introduction to Advanced ANOVA
Topic 16. Hierarchical ANOVA Designs
Topic 17. Blocking ANOVA Designs
Topic 18. Fractional Factorial ANOVA Designs
Topic 19. Analysis of Covariance (ANCOVA)
Topic 20. Summary of Advanced ANOVA
Section 5. Empirical Model Building
Topic 21. Introduction to Empirical Models
Topic 22. Multiple Regression
Topic 23. Central-Composite Designs (CCDs)
Topic 24. Sequential Experimentation
Topic 25. Summary of Empirical Models

2.2.1 Topic 1. Research Design Process

Topic 1 presents the overall research design process. First, the various stages of research are shown in a flow diagram. Next, six critical aspects of this process are highlighted, from the research problem to research reports. As with all subsequent topics covered in the reference material, this topic concludes with a summary followed by suggestions for supplemental readings for in-depth coverage of the material covered in this topic.

2.2.2 Topic 2. Experimental Designs

Topic 2 is an introduction to experimental design. It begins with an overview of various conditions that can threaten the validity of the results of experiments and then offers a general notation for designating designs. Two general experimental design alternatives are presented, and the case is developed for always choosing randomized experimental designs, if possible.

2.2.3 Topic 3. Basic Statistical Concepts

Topic 3 summarizes basic statistical concepts that are fundamental to experimental design. This reference material is not a tutorial on basic statistics, but rather, the material highlights and summarizes key statistical concepts. It is assumed that users of this reference material already have a background in introductory descriptive and inferential statistics. Consequently, this topic is designed as a review of basic concepts without providing detailed descriptions or mathematical derivations. Users should refer to a textbook such as Walpole's latest edition on introductory statistics (Walpole, Myers, Myers, and Ye, 2002) for details on the concepts summarized in this topic if they are not familiar with them. The concepts of sampling distributions, the F-distribution, and statistical hypothesis testing are critical to understanding the experimental design topics covered in this reference.

2.2.4 Topic 4. Supplemental Data Collection Methods

Topic 4 deals with supplemental data collection that augments data from experimental designs. Quantitative supplemental data are very important for understanding and interpreting research results. Most supplemental data are analyzed by nonparametric analyses as opposed to the parametric analyses used on the major dependent variables manipulated in the experimental design. Several types of supplemental data collection techniques can be used. This reference concentrates on the graphical rating scales that are most often used to collect quantitative supplemental data in human factors research.

2.2.5 Topic 5. Analysis of Nominal Scale Data

Topic 5 deals with an overview of major supplemental data analysis alternatives that can be used with nominal scale data. Only a sample of nonparametric analyses covering the most common techniques used in human factors and ergonomics research is presented in this topic. Siegel (Siegel and Castellan, 1988) provides a detailed discussion of all of these techniques, and their formulae and notation are used throughout this topic for easy reference. The nonparametric techniques in this reference are organized around between-subjects and within-subjects techniques to facilitate an easy choice of nonparametric analysis procedures for nominal data.

2.2.6 Topic 6. Analysis of Ordinal Scale Data

Topic 6 deals with an overview of four nonparametric analysis alternatives that can be used with ordinal scale supplemental data. The four procedures described in this reference material are often used in human factors and ergonomics research. Once again, Siegel and Castellan (1988)

provide a detailed discussion of each of these techniques, and their formulae and notation are used throughout this topic for easy reference. Similar to the approach followed in the discussion on nominal data analysis, the presentation of this topic is organized around between-subjects and within-subjects techniques to facilitate choice of nonparametric analysis procedures for ordinal data.

2.2.7 Topic 7. Summary of Supplemental Data

Topic 7 summarizes the major points discussed in section 2 of the reference material dealing with supplemental data. First, supplemental data collection procedures dealing with self reports, questionnaires, and rating scales are reviewed. Second, supplemental data analysis techniques using common nominal and ordinal scale nonparametric procedures are reviewed. Third, a three-step process for dealing with supplemental data in experimental design is presented.

2.2.8 Topic 8. Introduction to ANOVA

Topic 8 introduces ANOVA designs by discussing their advantages, basic terms, and the three major categories of ANOVA designs used in human factors research. Next, procedures for specifying the underlying statistical model that describes the components of any ANOVA design are presented. The introduction ends with a discussion and example for using ANOVA for statistical hypothesis testing of the difference between two treatment means.

2.2.9 Topic 9. ANOVA Summary Table Components

Topic 9 provides an overview of the computational aspects of any between-subjects, within-subjects, and mixed-factors ANOVA design used in human factors research. The subsections are organized around the five major components of the ANOVA Summary Table used for listing the results of an ANOVA. Rather than derive formulae for calculating each component, computational procedures and algorithms are provided. First, each component of the summary table is discussed separately. Then conventions for stating the complete ANOVA summary table are presented for each of the three major categories of ANOVA experimental designs used in human factors research.

2.2.10 Topic 10. Between-Subjects ANOVA Designs

Topic 10 covers the construction and computational details of the first of the three major categories of ANOVA designs used in human factors and ergonomics research. Between-subjects designs are discussed in terms of one-factor, two-factor, and n-factor designs. The procedures for determining the sum of squares computational formulae for any ANOVA are presented in the discussion of one-factor designs. The concept of an interaction is presented in two-factor designs. Generalizations for constructing and analyzing any between-subjects ANOVA design are summarized under n-factor designs. Computational examples are provided for both a one-way and a two-way between-subjects design. A summary listing of all the ANOVA procedural rules and algorithms for conducting any ANOVA analysis in human factors research is provided at the end of this topic.

2.2.11 Topic 11. Analysis of Comparisons and Interactions

Topic 11 covers analytical techniques that can be used to isolate the form or nature of the main effects and interactions that are significant in the overall ANOVA. Basically, these procedures deal with multiple paired comparisons of various treatment means. First, this topic covers comparisons and provides examples of both planned and unplanned comparison procedures. Second, special analytical procedures in addition to paired comparisons are covered, and example computations are provided for the analysis of interactions. Although these procedures are demonstrated using between-subjects designs, these same techniques are appropriate for within-subjects and mixed-factors designs covered in the next two topics.

2.2.12 Topic 12. Within-Subjects ANOVA Designs

Topic 12 covers within-subjects ANOVA designs in which each subject receives every treatment condition in the human factors experiment. Basic configurations of one- and two-factor designs as well as generalizations to n-factor repeated measures designs are covered. The advantages of within-subjects designs are summarized as compared to between-subjects designs. Additional considerations in using repeated measures are discussed, including the homogeneity of covariance assumption, balancing techniques for controlling possible confounding effects of treatment orders, and the effect of differential transfer.

2.2.13 Topic 13. Mixed-Factors ANOVA Designs

Topic 13 covers the basic configuration and analytical procedures used in mixed-factors ANOVA designs, which comprise the third major category of ANOVA designs. Mixed-factors designs are composed of both between-subjects and within-subjects factors. This type of ANOVA design is often referred to as split-plot designs in scientific literature. These designs are used quite frequently in human factors and ergonomic research due to the nature of the independent variables being investigated in the experiment. Consider a training research study that investigates training methods and practice trials. The researcher must manipulate the training condition variable as a between-subjects variable because subjects cannot return to a beginning level of knowledge when provided with alternative training. On the other hand, practice trials in this training experiment must be manipulated as a within-subjects factor since each subject receives multiple trials. Consequently, a mixed-factors design is needed. This topic also provides a list of considerations that the research should address when using mixed-factors designs.

2.2.14 Topic 14. Summary of Basic ANOVA

Topic 14 provides a brief summary review and roadmap of basic ANOVA in terms of fundamental considerations, ANOVA design classification, ANOVA generalizations, and steps in the overall ANOVA design and data interpretation process. Details on these issues are provided in specific topics referenced.

2.2.15 Topic 15. Introduction to Advanced ANOVA

Topic 15 introduces topics in advanced ANOVA that expand upon the basic ANOVA procedures, rules, and algorithms already described in section 3 of the reference material. Two examples of extending basic ANOVA (i.e., Quasi-F ratios and Randomized Blocks Designs) are presented in detail. In addition, this introduction provides an overview of several special purpose ANOVA design and analysis procedures that satisfy various constraints present in human factors and ergonomics research. Detailed discussions of these procedures are presented in subsequent topics.

2.2.16 Topic 16. Hierarchical ANOVA Designs

Topic 16 covers hierarchical ANOVA designs that include nested factors of interest. This topic describes both the basic layout and the ANOVA computations involved in this class of experimental designs. These basic procedures can be generalized to higher-order hierarchical designs, and the use of hierarchical designs in human factors and ergonomics research is discussed. This topic ends with a general summary of the considerations of using hierarchical designs in human factors and ergonomics research.

2.2.17 Topic 17. Blocking ANOVA Designs

Topic 17 deals with ANOVA experimental designs that can be used to control nuisance variables that are confounded with the factors of interest in an experiment. These confounding factors may include the effect of repeated testing sessions or experimenter bias resulting from using several experimenters in data collection. Confounding is controlled through blocking designs where blocks represent the nuisance variables. Through the use of modular representation, the exact nature of the block confounding with specific treatment effects of interest can be determined by the experimenter in order to choose an experimental design to avoid confounding blocks with effects of major interest in a factorial ANOVA design. The use of blocking is demonstrated through 2^k factorial designs and extended to pseudo-factor blocking.

2.2.18 Topic 18. Fractional Factorial ANOVA Designs

Topic 18 deals with fractional replicates of full factorial ANOVA designs. When large-scale factorial designs are used in human factors and ergonomics research, constraints such as time, money, and equipment availability may make the complete factorial design unfeasible and data collection must be restricted to a portion of the design. Obviously, some effects in the full factorial design cannot be evaluated and some effects will be confounded with others if data are not collected on the entire design. The experimenter must select a subset of the complete design that yields the most useful data. Fractional-factorial designs are ANOVA designs in which only a fractional portion of the complete factorial designs are observed. Fractional replications of 2^k , 3^k , and 5^k designs can be constructed through modular representation. Most often 2^{k-p} fractional replicates are used in human factors research to avoid subsequent confounding of partial effects that are present in 3^k and 5^k designs. Alternatively, a subset of fractional-factorial designs, called

Latin Square designs, can be used to specify the subset of treatment conditions to observe when the experimenter is only interested in testing the main effects of three factors of interest. Consequently, this topic describes both 2^{k-p} fractional replicates and Latin Square designs.

2.2.19 Topic 19. Analysis of Covariance (ANCOVA)

Topic 19 deals with an analytical technique for reducing the effect of a covariate to increase the sensitivity of the F-test on effects of interest to the experiment. The covariate is correlated with the dependent variable and its effect is removed through simple linear regression. Both calculations of correlation and simple regression are described as the basic components of ANCOVA. Basic computations in ANCOVA and subsequent interpretations of results are described in this topic.

2.2.20 Topic 20. Summary of Advanced ANOVA

Topic 20 summarizes the advanced ANOVA techniques described in the reference material. This topic provides a summary of design constraints and describes a process for addressing them.

2.2.21 Topic 21. Introduction to Empirical Models

Topic 21 provides an overview of quantitative models with an emphasis on empirical model building developed through efficient experimental design. Empirical models are descriptive models of human behavior based on results obtained through one or more controlled experiments that can be used to predict human performance in complex systems. These empirical models can assist the human factors specialist in conducting design tradeoffs of critical interface parameters.

2.2.22 Topic 22. Multiple Regression

Topic 22 provides an overview of multiple regression procedures used to generate empirical models that involve more than one factor. First, multiple linear regression is described to demonstrate the calculations involved when considering more than one factor in the empirical model. Both classical and modern regression procedures for selecting the best multiple regression equation are described. Next, polynomial regression is discussed as the general form for stating empirical models in human factors research.

2.2.23 Topic 23. Central-Composite Designs (CCDs)

Topic 23 describes experimental designs that can be used to collect data for building second-order empirical models. Specifically, this topic focuses on CCDs that were developed to explore response surfaces using empirical models. The background, specification, analysis, and an example of a CCD along with a comparison to alternative second-order experimental designs are discussed in this topic.

2.2.24 Topic 24. Sequential Experimentation

Topic 24 incorporates the previous topics into an overall strategy for conducting research on complex systems often addressed in human factors and ergonomics research. Due to nature of complex research, the experimenter can conduct a series of small independent, but interrelated, experiments rather than one large complex study. This topic describes general strategies for conducting complex experiments and specifically draws upon considerations made in response surface methodology for conducting a series of small, interrelated studies. A general paradigm for conducting sequential research is presented along with a detailed example of using this paradigm in human factors research that resulted in a set of guidelines for sequential experimentation. The topic concludes with a description of combining sequential experiments into a common database that incorporates the results of several experiments. This database can then be interrogated to generate integrated empirical models across experiments.

2.2.25 Topic 25. Summary of Empirical Models

Finally, topic 25 summarizes the empirical model building techniques. The purpose and characteristics of empirical model building experiments are reviewed, the major components of empirical models are listed, and a sequential experimentation process for human factors research is provided.

2.3 CADRE Bookmarks

The PDF file in CADRE is heavily bookmarked around the nine expandable major bookmark tabs shown in table 2, which include over 500 bookmarks when fully expanded. The bookmarks were designed to provide the CADRE user with alternative paths for rapid location of information within the tool.

Table 2. Major bookmark tabs in CADRE.

Bookmark Tab 1. Forward
Bookmark Tab 2. List of Topics
Bookmark Tab 3. Notes on Computational Examples
Bookmark Tab 4. Experimental Design Procedures
Bookmark Tab 5. Statistical Analysis Procedures
Bookmark Tab 6. Appendix on SAS Examples
Bookmark Tab 7. Acknowledgements
Bookmark Tab 8. References/Supplemental Readings
Bookmark Tab 9. Subject Index

The first two major bookmark tabs shown in table 2 deal with selecting specific content in CADRE. Bookmark 1 is a single bookmark to an overview for using the CADRE tool. Bookmark tab 2 expands to provide immediate access to various subsections of the reference material for each topic in the table of contents listed in table 1.

Two major tab sections shown in table 2 expand to bookmarks that provide direct access to various experimental design and statistical analysis procedures described in the reference material. Experimental design procedures in bookmark tab 4 deal with issues such as research stages, critical research methods, basic and advanced ANOVA design selection, paradigms and guidelines for sequential experimentation, supplemental data collection, and components of research reports. Bookmark tab 5 deals with various statistical analysis procedures including basic statistics; various basic and advanced ANOVA computations; simple, multiple linear, and polynomial regression analysis; and empirical model building procedures.

Bookmark tabs 3 and 6 expand to the 40 computational examples provided throughout CADRE (see section 2.4). Bookmark tab 3 expands to a discussion of statistical computations for each example in the reference material. Alternatively, bookmark tab 6 provides immediate access to the SAS program appendix (Slater and Williges, 2006) that describes all the SAS (SAS, 2004) statistical analysis procedures used in CADRE.

The final three major bookmark tabs shown in table 2 deal with additional reference material. Bookmark tab 7 is a single bookmark to the tool acknowledgements. Bookmark tab 8 includes an alphabetical listing of all references used in the CADRE tool, and can be expanded to provide bookmarks to supplemental reading for book chapters and articles in the scientific literature to elaborate upon the reference material presented for each topic listed in table 1. Finally, Bookmark tab 9 expands to an extensive subject index arranged alphabetically for easy access to various topics in the reference material.

2.4 CADRE Links and Hyperlinks

The PDF file of CADRE also supports links between the computational descriptions of the examples in the reference material with the 40 examples in the Slater and Williges (2006) appendix, as shown in table 3. The reference material describes the various steps in the statistical calculation; whereas, the use of the SAS (2004) statistical package for conducting the analysis is described in the appendix. Each example in the appendix provides a problem description, a SAS input file, a SAS output file, and output explanation. Notes are provided throughout the appendix to describe tailored modifications when using various SAS procedures.

Table 3. Hyperlinked SAS examples in CADRE.

Example 1. Interval Estimation
Example 2. Single-Sample t-Test
Example 3. Between-Subjects t-Test
Example 4. Within-Subjects t-Test
Example 5. Chi-Square Goodness of Fit Test
Example 6. Chi-Square Test of Independence (2x2 Contingency Table)
Example 7. Chi-Square Test of Independence (RxC Contingency Table)
Example 8. Chi-Square Test of Independence (Two Additive 2x2 Partitions)
Example 9. McNemar Change Test
Example 10. Cochran Q Test
Example 11. Kolmogorov-Smirnov Tests
Example 12. Kruskal-Wallis One-Way ANOVA
Example 13. Wilcoxon Signed Ranks Test
Example 14. Friedman Two-Way ANOVA
Example 15. One-Factor, Between-Subjects ANOVA
Example 16. Two-Factor, Between-Subjects ANOVA
Example 17. Planned Comparisons
Example 18. Unplanned Comparisons
Example 19. Analysis of Interactions
Example 20. One-Factor, Within-Subjects ANOVA
Example 21. Two-Factor, Within-Subjects ANOVA
Example 22. Geisser-Greenhouse and Huynh-Feldt Corrections
Example 23. Testing Order Effects in Balanced Latin Squares
Example 24. Within-Subjects and Between-Subjects Design Comparison
Example 25. Two-Way, Mixed-Factors ANOVA
Example 26. Complete Hierarchical Between-Subjects Design
Example 27. Partial Hierarchical Between-Subjects Design
Example 28. Simple Blocking of 2^k Within-Subjects Design
Example 29. Complex Blocking of 2^k Within-Subjects Design
Example 30. One-Half Replicate of 2^4 Between-Subjects Design
Example 31. 4x4 Latin Square Designs
Example 32. Linear Correlation Coefficient
Example 33. Alternative Linear Correlations
Example 34. Simple Linear Regression
Example 35. Analysis of Covariance (ANCOVA) One-Way, Between-Subjects Design
Example 36. Multiple Linear Regression
Example 37. Best Regression Equation
Example 38. Polynomial Regression
Example 39. Orthogonal, Between-Subjects, Central-Composite Design
Example 40. Blocked, Within-Subjects, Central-Composite Design

Each of the 40 statistical examples in the Slater and Williges (2006) appendix is also hyperlinked to version 9.1.3 of the SAS (2004) statistical analysis package. If the SAS interactive statistical package is active on a user's computer, the CADRE tool can be directly linked to the SAS

program file for any example covered in the appendix. These programs also can be used as a guide for analyzing an experimenter's specific data set by simply modifying the names and numbers of independent variables and the specific data set of the dependent variables.

3. The Focus of CADRE

The major focus of CADRE is on understanding the various techniques and processes considered in applied experimental design by researchers who have a basic knowledge in statistics and experimental design. In order to conduct complex system research experiments, researchers must consider a variety of experimental design and analysis techniques. The CADRE tool features a review of the design construction, assumptions, and basic computations in a variety of experimental design techniques with an emphasis on ANOVA procedures and related designs. Rather than mathematical derivations, algorithms and guidelines are used to promote understanding. Saying that, references to the scientific literature are provided throughout CADRE for details on the various techniques and their use in complex applied research problems. Most researchers use statistical packages for analysis, so the focus is on the use and interpretation of SAS rather than hand calculations. Examples of hand calculations are provided in CADRE to promote a better understanding of the various experimental design techniques.

The process of choosing various techniques in applied experimental design is also a focus of CADRE. This includes considering the various stages in the research process; the supplemental data collection and analysis process; the process of empirical model building; and a process for conducting sequential experimentation.

CADRE represents one example of a computer-based desktop interactive tool that can assist researchers in conducting complex systems research. This tool can be expanded to incorporate additional experimental design procedures and additional statistical analyses packages that can hyperlinked to the reference material in CADRE. This tool needs to be widely available to the research community so that improvements based on usage can be made to both the content and interactive nature of CADRE.

In addition, the approach used in developing the CADRE tool can be extended to other desktop tools to assist the human factors researcher. CADRE can be considered the first prototype in a series of tools. Other computer-based tools addressing a variety of research methods (e.g., multivariate analysis, survey procedures, and cognitive task analysis), system design methods (e.g., focus groups, design guidelines, specifications, and requirements), and evaluation methods (e.g., usability assessment, operator workload evaluation, situation awareness, and crew resource management) can be added to this family of tools to be used by human factors professionals.

4. Conclusions

Research on Army C2 systems requires knowledge and use of complex experimental design and analysis. The CADRE tool can assist in designing effective experiments that allow data collection requiring minimum effort and maximum effectiveness of results. Sections 4 and 5 of CADRE deal specifically with fractional-factorial designs, polynomial regression, empirical model building, and sequential experimentation, which are particularly appropriate for investigating emerging C2 systems.

The studies that provided impetus to spawn the development of the CADRE tool were part of ongoing efforts to develop better understandings of how to structure socio-technical work environments. These conditions are characterized where teams function in a high stress, time dependent, decision-oriented work setting. In these situations, the goal is to optimize human cognitive performance in this type of work domain, such as can be found in military C2 systems. This work is especially relevant for studies of systems not yet in existence, such as the Future Combat System (FCS) and Objective Force Warrior (OFW).

5. References

- Keppel, G.; and Wickens, T. D. *Design and Analysis: A Researcher's Handbook*, 4 ed.; Prentice Hall: New Jersey, 2004.
- Middlebrooks, S. E.; Knapp, B. G.; Barnette, B. D.; Bird, C. A.; Johnson, J. M.; Kilduff, P. W.; Schipani, S. P.; Swoboda, J. C.; Wojciechowski, J. Q.; Tillman, B. W.; Ensing, A. R., Archer, S. G.; Archer, R. D.; Plott, B. M. CoHOST - Computer Simulation Models to Investigate Human Performance Task and Workload Conditions in a U.S. Army Heavy Maneuver Battalion Tactical Operations Center. In *Proceedings of the HFES 43rd Annual Meeting*, Human Factors and Ergonomics Society: Houston, TX, 1999, pp 242–246.
- Mills, R. G.; Meyer, E. G.; Rickels, W.; Hoyland, C.. *Introduction to Experimental Design and the User Assisted Automated Experimental (Test) Design Program (Aed): Version II. Volume I*; Technical Report TM-HU-567/001/00; Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, 1982.
- Montgomery, D. C. *Design and Analysis of Experiments*, 7 ed.; John Wiley and Sons, Inc.: New York, NY, 2008.
- Myers, R. H.; Montgomery, D. C. *Response Surface Methodology*, 2 ed.; John Wiley and Sons, Inc.: New York, NY, 2002.
- SAS System Version 9.1.3 for Windows and Online Documentation. The SAS Institute, Inc.: Cary, NC, 2004.
- Shadish, W. R.; Cook, T. D.; Campbell, D. T. *Experimental and Quasi-Experimental Designs for General Causal Inference*, Houghton Mifflin: New York, NY, 2002.
- Siegel, S.; Castellan, N. J., Jr. (1988). *Nonparametric Statistics for the Behavioral Sciences*, 2 ed.; McGraw-Hill: New York, NY, 1998.
- Slater, C. R.; Williges, R. C. *Appendix: SAS Examples for Human Factors Experimental Design and Analysis Reference*; Technical Report HFEEC-06-02; Virginia Polytechnic Institute and State University: Blacksburg, VA., 2006.
- Walpole, R. E.; Myers, R. H.; Myers, S. L.; Ye, K. *Probability and Statistics for Engineers and Scientists*, 7 ed.; Prentice Hall: New Jersey, 2002.
- Williges, R. C. *Human Factors Experimental Design and Analysis Reference*; Technical Report HFEEC-06-01; Virginia Polytechnic Institute and State University: Blacksburg, VA, 2006.

Williges, R. C. *Computer-Aided Design Reference for Experiments (Cadre): A Tool for Human Factors and Ergonomics Research*; Technical Report CD-ROM-07-01; Virginia Polytechnic Institute and State University: Blacksburg, VA, in press.

Winer, B. J.; Brown, D. R.; Michels, K. M. *Statistical Principles in Experimental Design*, 3 ed.; : McGraw-Hill, Inc.: New York, NY, 1991.

Acronyms and Abbreviations

ADA	Advanced Decision Architectures
ANCOVA	Analysis of Covariance
ANOVA	analysis of variance
ARL	U.S. Army Research Laboratory
C2	command and control
CADRE	Computer-Aided Design Reference for Experiments
CCD	Central-Composite Designs
FCS	Future Combat System
HRED	Human Research and Engineering Directorate
OFW	Objective Force Warrior
PDF	Postscript Definition File
Virginia Tech	Virginia Polytechnic Institute and State University

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