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Preliminary Findings:
Design of Experiments
Contract No.: N61339-05-C-0127
University XXI (FY05)
Research and Support for the US Army

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Institute for Advanced Technology
The University of Texas at Austin

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14. ABSTRACT
The Design of Experiments project is developing recommendations for a new TOPM for applying DOE Techniques to the US Army's complex operational testing environment. These recommendations are being based upon evaluations of existing event design plans and testing reports. The focus has been primarily upon small- to medium-scale testing scenarios in order to provide recommendations that are easy to understand. The inherent complexity of large-scale testing events also increases the difficulty of making clear recommendations for improvements in testing. It is hoped that through the development of case studies and leveraging AFOTEC's work, we will develop recommendations that tailor DOE techniques and exploit their benefits for use by operation research analysts with USAOTC scenarios. These statistical techniques are expected to afford opportunities for substantial savings in resources for conduct of operational testing as well as accommodate testing of complex large systems.

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Preliminary Findings: Design of Experiments

Dr. J. Wesley Barnes, MAJ J. Whilden, and J. Toufic Chahin
Institute for Advanced Technology, The University of Texas at Austin

University XXI Background

The Institute for Advanced Technology (IAT), an Army University Affiliated Research Center (UARC) operating under US Army contract, was founded in 1990 as an autonomous research unit of The University of Texas at Austin (UT) under the Office of the Vice President for Research. The IAT has been in continuous operation since then, first as a Federally Funded Research and Development Center, and then as an Army UARC from 1993 to the present, conducting basic research in the areas of hypervelocity physics, electrodynamics, pulsed power, and technical education. The IAT research efforts include applied research through the University XXI (UXXI) program, which assists the military to address issues relating to digitization and military transformation.

As a part of the IAT, UXXI has access to world-class professors and graduate students at UT in order to conduct its projects. The faculty and staff comprise proven leaders whose knowledge covers a broad range of disciplines, from academic and industrial research to test, evaluation, and production. The IAT also offers a Secret facility clearance, with classified phone and fax, and extensive classified and unclassified computing facilities. This grants UXXI an ability to work on a number of projects that would otherwise be off limits to typical university level research facilities, including the work done on the Design of Experiments project.

Design of Experiments Project Background

As the United States faces accelerating military challenges, the US Army must make the best use of available resources. Narrow windows of time, limited troop availability, and limited funding present a special challenge for the US Army Operational Test Command (USAOTC). Existing test operating procedures and methodology (TOPM) do not incorporate design of experiment (DOE) techniques. These techniques are currently utilized by the US Air Force Operational Test & Evaluation Center (AFOTEC), resulting in better time utilization and cost savings. USAOTC tests with up to multiple battalions are substantially more complex than AFOTEC tests with pairs of planes, so a simple transfer of techniques will not completely address USAOTC needs. A solution tailored to US Army scenarios is needed.

The Design of Experiments project is developing recommendations for a new TOPM for applying DOE Techniques to the US Army's complex operational testing environment. These recommendations are being based upon evaluations of existing event design plans and testing reports. The focus has been primarily upon small- to medium-scale testing scenarios in order to provide recommendations that are easy to understand. The inherent complexity of large-scale testing events also increases the difficulty of making clear recommendations for improvements in testing. It is hoped that through the development of case studies and leveraging AFOTEC's work, we will develop recommendations that tailor DOE techniques and exploit their benefits for use by operation research analysts with USAOTC scenarios. These statistical techniques are expected to afford opportunities for substantial savings in resources for conduct of operational testing as well as accommodate testing of complex large systems. As we look to the testing of future complex systems of systems (SoS), these recommendations will offer a solution for low-cost, rapid-turnaround integrated testing.

Assessment of Current Practices

This document will serve as an interim summary of research to date on how the Army conducts testing on potential new or modified equipment for fielding to soldiers. This summary will not make any recommendations but will show what areas will be focused on for a research paper of much larger scope, to be delivered in April 2007. MAJ. John Whilden has been working directly with the Close Combat (CC) and the Aviation (AV) test directorates at Operational Test Command (OTC). Both the CC and AV directorates have provided him with additional documents for review. The Methodology and Analysis Division (MAD) at OTC continues to provide assistance as needed. The research has been expanded to include the evaluators at Army Test and Evaluation Command (ATEC).

There is a some resistance to change at OTC, an attitude found in many large institutions. Most of the civilian ORSAs and acquisition testers have predetermined methods of evaluating projects set before them. Many of the civilians know about DOE techniques but have yet to embrace them. There is a large push to embrace Lean Six Sigma (LSS) by the Army, including the test community. Part of LSS is process reduction. While MAJ. Whilden has received complete support at the upper personnel levels, there is some concern at the lower personnel levels.

The biggest issue voiced by testers at OTC is failure to follow the proper testing sequence as outlined by Army Regulation (AR) 73-1 and ATEC Pamphlet 73-1. It is routine that operational testing starts before an approved system evaluation plan (SEP) is in place, despite the SEP's being required by regulation. The SEP identifies the system being evaluated, the critical issues, and the system's proposed use in the hands of soldiers. It is this document that OTC uses to help formulate event design plan (EDP). When the SEP changes, it either delays testing or it introduces error into OTC testing, and it is not uncommon for testing to be underway when changes are made.

There is an unclear methodology to determine the appropriate experiment size and number of iterations. A common number of repetitions at OTC seems to be 30 runs using a dedicated company-sized element of troops. There does not seem to be any statistical basis for determining the size or number of repetitions for an experiment. The only software that the test directorates have available are Microsoft Excel and Microsoft Access. Although Excel does have statistical add-ins capable of creating summary statistics, it does not appear to have the capability to statistically determine an appropriate experiment size and proper number of iterations. DOE allows control over this by designing the experiment size based on an acceptable level of confidence and error.

It is clear that OTC does not use any method that allows for the interaction of variables. Whereas identifying interaction is a pronounced strength of DOE, most other methods—including the Taguchi method and one factor at a time (OFAT)—cannot calculate variable interactions. Variable interactions are statistically attributed as a main effect of a single variable that can introduce errors into the test. Stronger variable interactions lead to greater error using

OFAT or the Taguchi methods. OTC primarily uses Taguchi and OFAT type methods in its testing methods and designs.

A fundamental concept of DOE is determining which variables impact the process and designing an experiment that looks at the critical variables. Currently, OTC designs experiments without considering the impact of any variables. Tests center around critical performance issues and not the variables that impact the performance of the equipment. Once again, error is introduced in experiments when critical variables are ignored. If a system tested does poorly, it is difficult under current test design to determine why; likewise, if a system being tested performs well, the reasons remain unknown.

One difficult aspect for OTC is the fact that OTC is primarily concerned with the equipment in the hands of soldiers. Developmental Test Command (DTC) looks at actual laboratory-type data, such as muzzle velocity, and a shot group under ideal conditions that omit human error. A weapon could be fired by a computer on a mechanical rest. DTC conducts benchmark testing to ensure that the equipment performs to specification. DTC weighs ammunition fired and has accelerated-aging labs for testing durability to give two good examples. Whereas most of the data collected by DTC can be automated with extreme accuracy, most of OTC testing is much more subjective, relying on the input of soldiers.

The evaluation team at ATEC compiles all collected data from DTC and OTC and then runs statistical processes on the data to create findings. The responsibility of OTC is to provide packaged data that are accurate and in the form of spreadsheets and databases. OTC is required at times to provide a test report with summary statistics including graphs, means, quartiles, probable errors, etc., using Excel. The evaluation team at ATEC uses more powerful tools, such as SAS Jump, for statistical analysis. One further area of research will look at any problems created by not having the testers at OTC involved in the evaluation process to analyze data.

An OTC-Provided Scenario Amended to Use Design of Experiments

You are participating in a meeting of the ATEC System Team (AST) for the Long-Range Hunter reconnaissance system. This team has met before, and its members have provided their input, taking into account information from the test and evaluation working integrated process team (T&E WIPT). The SEP is complete, and it is time to provide the test designs for the various test events to detailed planning. One of these events is the nighttime maneuver portion of the initial operational test (IOT), which is the primary source for effectiveness data on target detection capabilities. This portion of the IOT is an instrumented field exercise performed under realistic conditions with typical user troops. Each field trial is four hours long, under specified conditions, and one field trial per night is planned using four Long-Range Hunters. The troop unit is available for 30 days. The Test Officer has prepared a draft test design for this event and furnished it to all AST members. This meeting is to consider any final changes that may be required before including this test design in the Test Plan for the IOT. The Test Officer is the AST Chair at this time, and will open the meeting.

Your responsibility is to make sure the test generates the needed data as planned in the data source matrix (DSM), is a sound and realistic tactical exercise, and is efficient and economical. You are the chair of this ATEC System Team, and you prepared this draft test design for review by the team. You feel that three field trials are the minimum needed in each set of conditions to generate adequate data. You have planned four subtests, each with an appropriate number of sets of three trials. Your design provides for at least three data trials for each test condition—for example, three trials with countermeasures and three without. And of course, there should be some extra trials for contingencies, such as having to re-run any trials that are not valid.

As far as you know, this design is acceptable to everyone on the AST, but you are open to suggestions for improvement. If anyone in the team sees any errors or opportunities for improvements, you will lead the effort to reach consensus. As chair, you will open this meeting with a call for comments on the draft design. This example also places each of the course attendees in a different role with different information. Appendix 4A has a list of all data, including role-play information.

The relevant section of the Long-Range Hunter SEP is Paragraph 4.7.7.3:

Subtest 1 - Types of Tactical Maneuver					
Conditions	Offense	Defense	Retrograde	Reinforcement	Total
Nr of Trials	3	3	3	3	12

Subtest 2 - Means of Long-Range Hunter Operation			
Conditions	Operated from Vehicle	Operated by Dismounted Personnel	Total
Nr of Trials	3	3	6

Subtest 3 - Range to Presented Targets			
Conditions	Long Range	Short Range	Total
Nr of Trials	3	3	6

Subtest 4 - Countermeasures			
Conditions	CM used by OPFOR	No CM used	Total
Nr of Trials	3	3	6

This test design needs 30 data record trials and includes six contingency trials.

A possible OTC course solution to the problem is:

	Countermeasures Present			No Countermeasures			
	Off	Def	Retro	Off	Def	Retro	
Veh	3	3	3	3	3	3	18
Dismt	3	3	3	3	3	3	18
	6	6	6	6	6	6	
	18			18			36

The OTC solution suggests that the improved design increases the number of trials (sample size) for each of the two countermeasure conditions from three to 18, increases the sample size for each of the two mounting conditions from three to 18, and increases the sample size for each of the three maneuver conditions from three to 12, for a total of 36 trials overall. (Range is not shown in the matrix because it is a tactically varied factor.) Contingency trials are not needed because each condition has either 12 or 18 trials and could lose several of them and still have far more than the required number of trials.

Comments on the OTC solution to the problem:

- There has to be a statistical analysis of this problem. The test as written does not use statistical means to determine the correct number of iterations required to obtain different acceptable levels of α and β error with a calculated level of confidence.
- This solution does not show the process flow of the Long-Range Hunter problem to achieve test results that can accurately conclude the effectiveness of the Long-Range Hunter system. The process flow diagram helps to show what is actually critical to the success of the Long-Range Hunter.
- The most critical variable (range) is left off the solution. It is perhaps the best single variable to determine the actual effectiveness of the Long-Range Hunter. The purpose of the Long-Range Hunter is to provide a picture of enemy layout on a battlefield. A Long-Range Hunter must detect the enemy before being detected by the enemy.
- The solution indicates the use of one factor at a time (OFAT) in the test experiment. DOE allows testing to look at the interactions of variables. A key interaction that would be present would be the interaction of range variables and countermeasure variables. The interaction would show the effectiveness of enemy countermeasures to prevent detection by friendly forces.

More detail in applying DOE methods to the Long-Range Hunter example problem will follow. There will first be a formulation of the problem using the four-step DOE method. Statistical methods will be used to determine the appropriate number of iterations per variable. DOE will also help to determine the appropriate variables to test. Once the test is designed, a fictitious database of test results will be analyzed using the 2^k model. Problem formulation using DOE methods will use the same factors and constraints as the TEBC course solution considered.

The process flow diagram will take the Long-Range Hunter and sculpt an experimental design. The process flow diagram should help to generate a process flow of how the experiment will test the Long-Range Hunter, and it should generate a potential list of measures of performance (MOPs) that testers can screen to determine the most critical variables.

Figure 1 is a sample of what a process flow diagram (PFD) could look like. Depending on the actual mission of the Long-Range Hunter, you could develop a number of different PFDs. This PFD indicates that the most critical aspect of the Long-Range Hunter is its ability to detect the enemy before being detected. This critical concept would drive the development of MOPs that would be critical to determine if a system meets required mission capabilities and specifications.

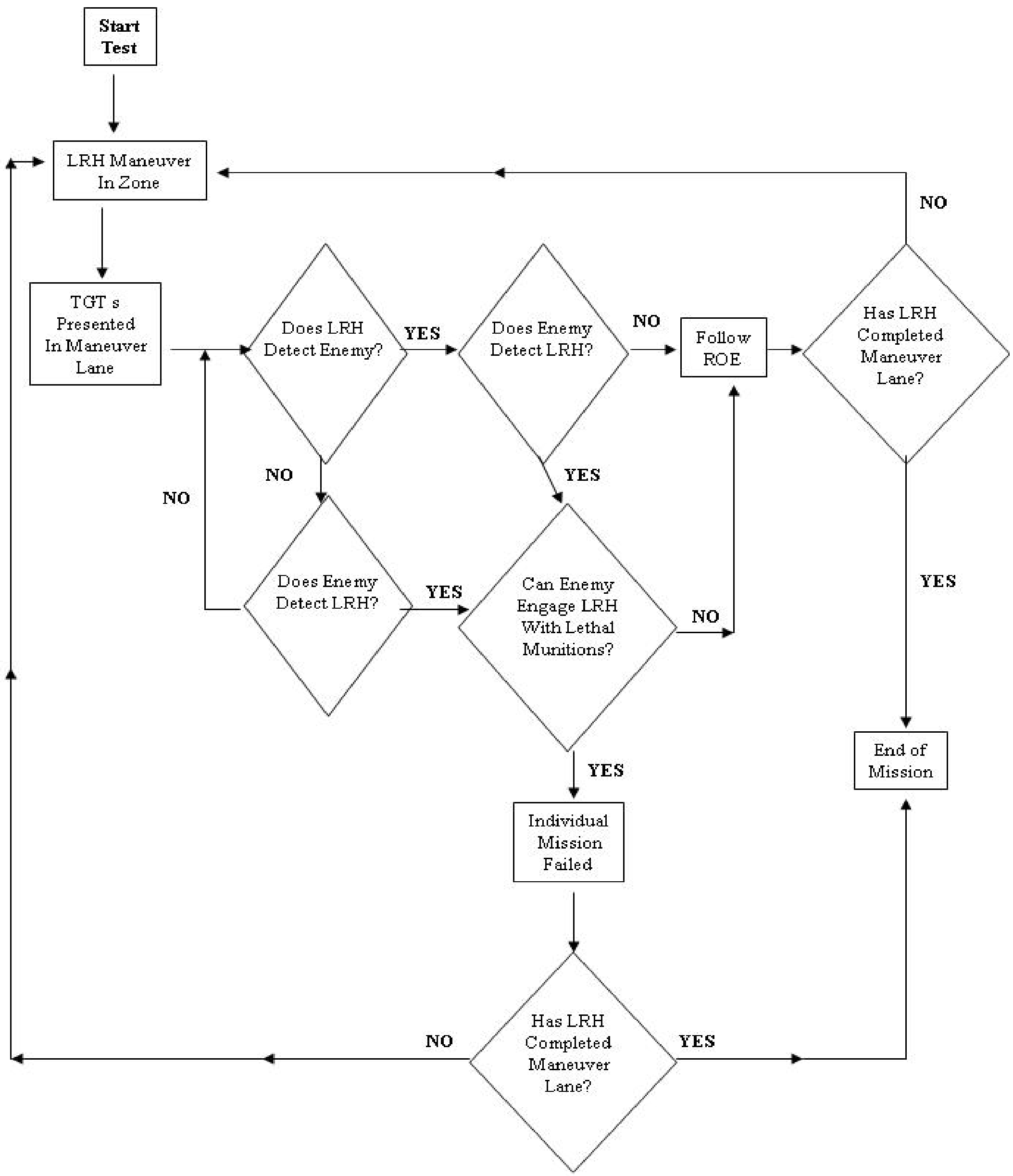

Figure 1. Sample process flow diagram (PFD).

In this PFD, the Long-Range Hunter starts at a predetermined point and proceeds down a specified maneuver lane. In this test, enemy targets are either stationary in a defensive posture or maneuvering in an offensive or screening posture. The key for the Long-Range Hunter, as the yes/no questions show, is its ability to detect the enemy before being detected. The PFD allows for several different situations, including the following:

1. The Long-Range Hunter detects the enemy before being detected.
2. The Long-Range Hunter and enemy detect each other near simultaneously.
3. The enemy detects the Long-Range Hunter before it detects the enemy.
4. Neither the enemy nor Long-Range Hunter detect each other.

Each scenario represents different problems that the test should discern. The MOPs help to recognize the overall effectiveness of a system. This PFD also shows that the Long-Range Hunter can pass parts of the test and fail others. Failure of one event on a test does not terminate the test.

The following table is a list of sample MOPs that testing could use to determine the overall effectiveness of the Long-Range Hunter as a system. These potential MOPs all look at performance aspects of the Long-Range Hunter. They do not look at other factors, such as maintenance and supportability of the Long-Range Hunter, which would also be very important (although secondary to actual mission performance).

N	MOP	Units	Range	Priority	Data Elem	Source
1	Detection Distance of Enemy by LRH	M	0-5000	H		Range Instr / OCs
2	Detection Distance of LRH by Enemy	M	0-5000	H		Range Instr / OCs
3	Maximum Scan Distance of LRH	M	0-5000	H		OCs / LRH Crew
4	Time to engage Enemy once Detected	S	0-180	M		Radio / OCs
5	Target Damage	%	0-100	M		MILES Report
6	Survivability against Enemy Fire	%	0-100	M		MILES Report
7	Time of LRH to break Contact	S	0-?	M		Radio / OCs
8	Detection Angle of TGT from LRH	°	0-360	M		OCs

Units: M = Meters S = Seconds % = Percentage ° = Degrees
Priority: H = High M = Medium L = Low

Again, understand that there could be any number of MOPs, depending on the requirements of the tested system. These MOPs can be prioritized in any way deemed appropriate. However, if everything is high priority, then nothing is. Data for these MOPs could come from any number of available sources. Obviously the more automated a collection method is, the less human error can creep into the test results.

Variable construction becomes critical, as it drives the overall design of the LRH experiment. DOE would lay out variable construction as shown in Figure 2.

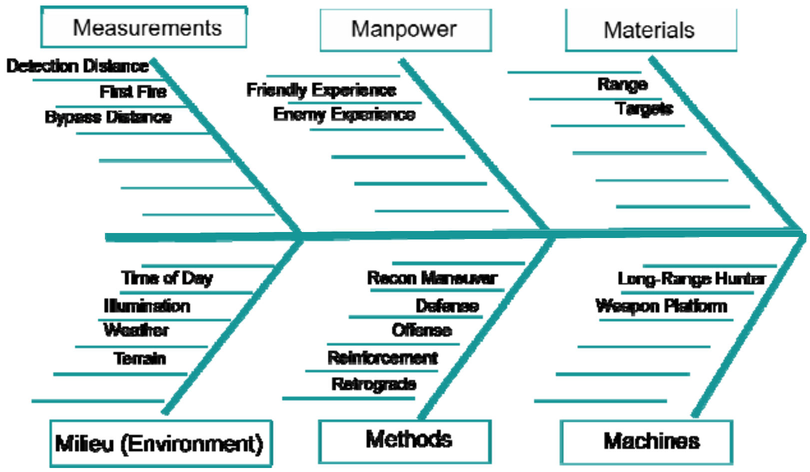

Figure 2. A sample of possible variables.

While Figure 2 presents possible variables, a refined list of tested variables could look as follows:

<u>**Tested Variables**</u>			
1	TGT Presentation	2000M	500M
2	Mission Type	Offense	Defense
3	Operation Mode	Mounted	Dismounted
4	Enemy Countermeasures	Yes	No
5	Enemy Force	Light (INF)	HVY (Mech)

These variables are the basis for DOE construction. The OTC construction of variables does not give the testers any way to know which variables cause the success or failure of the experiment. This construction of variables does. Another issue with the OTC solution is the lack of detail. There is a big difference between presenting targets at 300 m and 1000 m. The OTC model does not capture this. The OTC model ignores weather, terrain, time of day, illumination, etc. These variables are critical to determining the success of the Long-Range Hunter. Under DOE, choose to control them. Use the most difficult but common conditions soldiers could face—such as night, offense, open and wooded terrain, etc. DOE would expect control of these types of variables. A test run at night and a test run during daylight would have completely different results. A test run with 50% illumination at night will yield different results than a test run at night with 5% illumination. Failure to control these types of variables will introduce error into an experiment. Using these five tested variables yields the following table of unique runs:

Case	TGT Pres	Mission Type	OP Mode	Enemy CMs	Enemy Force
1	Long	Offense	Mount	Yes	Light
2	Short	Offense	Mount	Yes	Light
3	Long	Defense	Mount	Yes	Light
4	Short	Defense	Mount	Yes	Light
5	Long	Offense	Dismount	Yes	Light
6	Short	Offense	Dismount	Yes	Light
7	Long	Defense	Dismount	Yes	Light
8	Short	Defense	Dismount	Yes	Light
9	Long	Offense	Mount	No	Light
10	Short	Offense	Mount	No	Light
11	Long	Defense	Mount	No	Light
12	Short	Defense	Mount	No	Light
13	Long	Offense	Dismount	No	Light
14	Short	Offense	Dismount	No	Light
15	Long	Defense	Dismount	No	Light
16	Short	Defense	Dismount	No	Light
17	Long	Offense	Mount	Yes	Heavy
18	Short	Offense	Mount	Yes	Heavy
19	Long	Defense	Mount	Yes	Heavy
20	Short	Defense	Mount	Yes	Heavy
21	Long	Offense	Dismount	Yes	Heavy
22	Short	Offense	Dismount	Yes	Heavy
23	Long	Defense	Dismount	Yes	Heavy
24	Short	Defense	Dismount	Yes	Heavy
25	Long	Offense	Mount	No	Heavy
26	Short	Offense	Mount	No	Heavy
27	Long	Defense	Mount	No	Heavy
28	Short	Defense	Mount	No	Heavy
29	Long	Offense	Dismount	No	Heavy
30	Short	Offense	Dismount	No	Heavy
31	Long	Defense	Dismount	No	Heavy
32	Short	Defense	Dismount	No	Heavy

There are 32 unique runs considering these five two-level variables. These 32 runs yield much more complete data than the suggested 36 runs by the OTC example. DOE also offers the capability to construct a partial fractural. If the enemy force variable is blocked and essentially controlled, the number of unique runs can be reduced to 16 from 32. If enemy countermeasures are further blocked, the number of unique runs can be reduced to 8. Blocking might assume that a heavy enemy force was used and that there would always be enemy countermeasures, which would be the worst case. A partial fractural DOE design would allow you to reduce the number of field days from 30 to 15. Statistics and resources would drive which DOE model was used. Blocking the variables would confound them and could introduce error.

Projected Focus of In-Depth Report

It is projected that MAJ. Whilden's overall master's thesis will be 60 pages in length. This will cover all informational topics such as the structure of ATEC, applicable regulations, and all topics in this summary report. The final submission is still set for the last week of April 2007.

This report will hinge upon a fictional example called the Long-Range Hunter. This fictional example is used by OTC to train newly assigned personnel on basic test design methods. The next section will briefly demonstrate the efficiencies gained by using DOE.

Future research will focus on:

1. Showing how the Army can implement DOE principles to reduce error in experiments, thereby reducing required assets.
2. Researching the impacts of testing sequence when timing problems occur.
3. Showing the impacts of not using a DOE method that allows interactions of variables.
4. Showing how DOE can help to statistically determine sample size and the proper number of iterations to generate test results at a predetermined acceptable error and confidence level.
5. Researching which tools and structure OTC needs to conduct valid and accurate testing.
6. Looking at a recommended implementation plan to help OTC adopt and use DOE principles.

The final report will expand upon all these principles and use sample fictional databases to derive statistical inferences.

Participants

J. Wesley Barnes, Cullen Trust for Higher Education Endowed Professor in Engineering, The University of Texas at Austin

Dr. Barnes joined The University of Texas at Austin in 1974. A past coordinator of the Graduate Program in Operations Research and Industrial Engineering, Professor Barnes is currently graduate advisor and chair of the Graduate Studies Committee. Under Dr. Barnes's guidance, the Operations Research and Industrial Engineering Graduate Program has grown to about 80 full-time graduate students.

The author of several books, including a winner of the Institute of Industrial Engineers Book-of-the-Year Award, Dr. Barnes has recently become one of the world's leaders in applying direct search optimization techniques to problems of production scheduling, manufacturing processes, vehicle routing, and military logistics. Dr. Barnes is the author of over 100 technical articles and reports and has supervised 20 PhD students and 40 MS students. In the last sixyears, Dr. Barnes has obtained over $1,000,000 in sole-principal-investigator research grants to support his investigations into metaheuristic approaches to complex logistics, routing, and service systems problems.

Dr. Barnes is currently director of a research consortium joining The University of Texas at Austin, the Air Force Institute of Technology, and the Air Force Air Mobility Command. He was recently appointed adjunct professor with the Department of Operational Sciences at the Air Force Institute of Technology. The research consortium, in its fourth year of activities, is funded by the Air Force Office of Sponsored Research to perform “advanced air mobility command operational airlift analyses using group theoretic metaheuristics.”

Major John N. Whilden, Graduate Student, The University of Texas at Austin

MAJ. Whilden hails from Grand Prairie, Texas. He was commissioned a Second Lieutenant in December 1990 and has served in the Army in the United States, Korea, and Kuwait. His education includes a Bachelor of Business Administration with a specialty in management information systems from Texas Tech University, a Master of Science in logistics management from The Florida Institute of Technology, and he will complete a Master of Science in operations research and industrial engineering from The University of Texas at Austin in May 2007. He is a graduate of the Chemical Officer Basic Course, The Combined Logistics Officer Advanced Course, The Combined Arms and Staff Services School, and The Petroleum Officers Course.

His awards and decorations include the Meritorious Unit Citation, two awards of the Meritorious Service Medal, two awards of the Army Commendation Medal, the Army Achievement Medal, the Army Reserve Component Achievement Medal, two awards of the National Defense Medal, the Global War on Terrorism Expeditionary Medal, the Global War on Terrorism Service Medal, the Korean Defense Service Medal, the Army Service Ribbon, and the Overseas Service Ribbon.

J. Toufic Chahin, Research Engineer, The University of Texas at Austin

Mr. Chahin is a research engineer for the University XXI team. He recently joined the team after filling positions as research director at *WIRED* magazine and analyst at Stanford Research Institute Consulting and Business Intelligence. Mr. Chahin earned an MS in science and technology commercialization while attending the IC2 Institute in 2002, and a BA in mathematics in 2000, both from The University of Texas at Austin. He is the project lead for Design of Experiments, which is a University XXI project in support of the Army’s Operational Test Command (OTC).