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FINAL REPORT

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)

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Duration: February 1, 1980 - January 31, 1981

(Research under Richard E. Barlow)

Bayesian Reliability

A great deal of effort has gone into research and writing for the book INFERENCE AND DATA ANALYSIS FOR RELIABILITY AND LIFE TESTING. The first chapter INFERENCE FOR THE EXPONENTIAL LIFE DISTRIBUTION, ORC 79-16 has been again revised slightly due to the strong influence of an Air Force grant visitor, Professor Dennis Lindley. The role of failures and total time on test was elucidated in this report. Chapter 2, LIFE DISTRIBUTION MODELS AND INCOMPLETE DATA, ORC 80-20 has recently been completed. The role of stopping rules in statistical data analysis is now better understood. "Accelerated Life Tests and Information," ORC 80-14 is based on actual accelerated life test experiments still in progress. The use of entropy to quantify information is investigated. This paper is to be published in RADIATION RESEARCH in a special selection of papers concerned with radiation risk/analysis.

Chapter 3 on SAMPLING FROM PRODUCTION PROCESSES is in process. This work suggests simple Bayesian replacements for the classical control charts. The conceptual basis for control charts is reviewed in depth.

Professor Dennis Lindley visited Berkeley, Winter quarter 1980, and contributed substantially to our research program. He completed

a paper "The Bayesian Approach to Statistics," ORC 80-9. This will be published in a symposium proceedings. It explains Bayesian philosophy to scientists and engineers. He has also written another paper, "Scoring Rules and the Inevitability of Probability," ORC 81-1, January 1981. This is a very original piece of work which has inspired considerable additional research.

Under the Bayesian paradigm probability, measures must be subjectively assessed. This problem is addressed head-on in "Coherent Assessment of Subjective Probability," ORC 81-5. This work utilizes duality theory to show how incoherent probability assessments can be resolved using linear and nonlinear programming. This is a major problem in applying Bayesian inference procedures. The properties and use of scoring rules is being investigated at the present time and a report on this work will be issued this Fall.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A great deal of effort has gone into research and writing for the book, "Inference and Data Analysis for Reliability and Life Testing". The first chapter, "Inference for the Exponential Life Distribution", has been again revised slightly due to the strong influence of an Air Force grant visitor, Professor Dennis Lindley. The role of failures and total time on test was

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elucidated in this report. Chapter 2, "Life Distribution Models and Incomplete Data", has recently been completed. The role of stopping rules in statistical data analysis is now better understood. "Accelerated Life Tests and Information", is based on actual accelerated life test experiments still in progress. The use of entropy to quantify information is investigated. Chapter 3 on "Sampling From Production Processes" is in process. This work suggests simple Bayesian replacements for the classical control charts. The conceptual basis for control charts is reviewed in depth. Professor Lindley visited Berkeley, winter quarter 1980, and contributed substantially to the research program. He completed a paper entitled, "The Bayesian Approach to Statistics". It explains Bayesian philosophy to scientists and engineers. He has also written another paper, "Scoring Rules and the Inevitability of Probability". This is a very original piece of work which has inspired considerable additional research. Under the Bayesian paradigm probability, measures must be subjectively assessed. This problem is addressed head-on in "Coherent Assessment of Subjective Probability". This work utilizes duality theory to show how incoherent probability assessments can be resolved using linear and nonlinear programming. This is a major problem in applying Bayesian inference procedures. In reliability growth which occurs in discrete stages 1, 2, ..., it is usual to assume that the random parameters which reflect the failure rate during these stages obey a strict ordering. Following a suggestion by N. Singpurwalla, this assumption has been weakened to one in which the parameters are stochastically ordered. As shown in "Stochastically-Ordered Parameters in Bayesian Prediction", the problem now becomes an hierarchical Bayesian model, in which a sequence of strictly-ordered hyper-parameters are introduced that effect one's prior belief about the reliability growth. A generalized model for reliability growth has been under investigation in which the failure rate is assumed to be sum of two effects --- one depending upon the 'history' of failures since the start of testing, and the other depending upon the 'age' of the item under test. This quite general model incorporates many previously studied learning curve models, for example, those systems in which improvements are made only 'as produced', and those made continuously 'as operated'. Both of the models require the solution of two non-linear equations to find the maximum likelihood estimators of the growth and aging parameters. Numerical results reveal that, for a single system on test, the likelihood function is very broad; therefore, in a Bayesian formulation, this means that most of the prediction of ultimate performance would come from the prior. In other words, it now appears that reliability growth prediction requires the parallel testing of large numbers of items. Details will be given in "A General Framework for Learning-Curve Reliability Growth Models". Final scientific report, "Final Report, AFOSR-77-3179".

(Research under William S. Jewell)

Reliability Growth

In reliability growth which occurs in discrete stages 1,2, ..., it is usual to assume that the random parameters $\tilde{\theta}_1, \tilde{\theta}_i$, ... which reflect the failure rate during these stages obey a strict ordering

$$\tilde{\theta}_1 \geq \tilde{\theta}_2 \geq \cdots .$$

Following a suggestion by N. Singpurwalla, this assumption has been weakened to one in which the parameters are *stochastically ordered.* As shown in "Stochastically-Ordered Parameters in Bayesian Prediction," ORC 79-11, November 1980, the problem now becomes an hierarchical Bayesian model, in which a sequence of strictly-ordered *hyper-parameters* are introduced that effect one's prior belief about the reliability growth. Although the model is conceptually clear, the computational details are quite messy for realistic examples.

A generalized model for reliability growth has been under investigation since 1979, in which the failure rate is assumed to be sum of two effects--one depending upon the "history" of failures since the start of testing, and the other depending upon the "age" of the item under test. This quite general model incorporates many previously studied learning curve models, for example, those system in which improvements are made only "as produced", and those made continuously "as operated". Both of the models require the solution of two non-linear equations to find the maximum likelihood estimators of the growth and aging parameters. Numerical results reveal that, for a single system on test, the likelihood function is very broad; therefore, in a Bayesian formulation, this means that most of the prediction of ultimate performance would come from the prior. In other words, it now appears that reliability growth prediction requires the parallel testing of large numbers of items. Details will be given in "A General Framework for Learning-Curve Reliability Growth Models," ORC 79-11, the completion of which has been interrupted by the author's sabbatical leave.

Risk Models

At the invitation of the International Actuarical Association, the author prepared a survey paper on risk models for a plenary session of the 21st International Congress of Actuaries, entitiled "Models in Insurance: Paradigms, Puzzles, Communications, and Revolutions," ORC 80-10. Although the terminology is that of insurance, this paper should provide a useful survey of available models, with an extensive reference list, to anyone interested in individual and organizational financial risk.

Inverse Regression

In 1976, the author and R. Avenhaus (now at the Armed Forces Institute Munich) wrote a joint paper on a linearized Bayesian approach to inverse regression. With the help of E. Höpfinger (Nuclear Research Center, Jülich), this paper was expanded and distributed as "Approaches to Inverse Linear Regression," ORC 80-21.

Other Activities

In addition to the International Congress of Actuaries in Switzerland, June 1980, described above, Professor Jewell gave a survey of reliability growth models at the IMS Western Regional Meeting at Davis, California, June 1980.

From August 1980 until June 1981, Professor Jewell was on sabbatical leave at the Federal Institute of Technology, Zurich. His initial research activity was on the development of Bayesian techniques for the shaping of data subject to outliers. This and other research is described more fully in the research proposal for 1981-1982.

The following Operations Research Center reports were credited to Air Force Office of Scientific Research (AFSC) under Grant: AFOSR-77-3179

Willie, R. R., "Everyman's Guide to Times," ORC 77-2, January 1977.

Barlow, R. E., "Coherent Systems with Multi-State Components," ORC 77-5, January 1977.

Barlow, R. E., "Geometry of the Total Time on Test Transform," ORC 77-11, May 1977.

Jewell, W. S., "Bayesians Learn While Waiting," ORC 77-19, July 1977.

Barlow, R. E. and B. Davis, "Analysis of Time Between Failures for Repairable Components," ORC 77-20, July 1977.

Barlow, R. E. and T. Y. Liang, "Availability Analysis of the Superhilac Accelerator," ORC 77-21, July 1977.

Ben-Dov, Y., "Optimal Testing Procedures for Coherent Systems," ORC 77-23, September 1977.

Ben-Dov, Y., "Optimal State Detection Policies for Coherent Systems," ORC 77-30, November 1977.

Jewell, W. S., "'Reliability Growth' As an Artifact of Renewal Testing," ORC 78-9, June 1978.

Bühlmann, H. and W. S. Jewell, "Optimal Risk Exchanges," ORC 78-10, July 1978.

Jewell, W. S., "A Curious Renewal Process Average," ORC 78-12, July 1978.

Lindley, D. V., "Analysis of Life Tables with Grouping and Withdrawals," ORC 78-13, August 1978.

Willie, R. R., "Computer-Aided Fault Tree Analysis," ORC 78-14, August 1978.

Bühlmann, H. and W. S. Jewell, "Unicity of Fair Pareto Optimal Risk Exchanges," ORC 78-20, November 1978.

Barlow, R. E. and E. S. Hudes, "Asymptotic Measures of System Performance under Alternative Operating Rules, I," ORC 79-6, June 1979.

Barlow, R. E. and E. S. Hudes, "Asymptotic Measures of System Performance under Alternative Operating Rules, II," ORC 79-7, June 1979.

Jewell, W. S., "A General Framework for Learning Curve Reliability Growth Models," ORC 79-11, October 1979.

Jewell, W. S., "Stochastically-Ordered Parameters in Bayesian Prediction," ORC 79-12, October 1979.

Barlow, R. E. and F. Proschan, "Inference for the Exponential Life Distribution," ORC 79-16, December 1979.

Singpurwalla, N. D., "An Adaptive Bayesian Scheme for Estimating Relliability Growth under Exponential Failure Times," ORC 79-17, December 1979.

Lindley, D. V., "The Bayesian Approach to Statistics," ORC 80-9, May 1980.

Jewell, W. S., "Models in Insurance: Paradigms, Puzzles, Communications and Revolutions," ORC 80-10, June 1980.

Khalil, Z. S., "Availability of Series Systems with Components Subject to Various Shut-Off Rules," ORC 80-12, June 1980.

Barlow, R. E., "Accelerated LIfe Tests and Information," ORC 80-14, June 1980.

Barlow, R. E. and F. Proschan, "Life Distribution Models and Incomplete Data," ORC 80-20, September 1980.

Avenhaus, R., E. Höpfinger and W. S. Jewell, "Approaches to Inverse Linear Regression," ORC 80-21, October 1980.

Lindley, D. V., "Scoring Rules and the Inevitability of Probability," ORC 81-1, January 1981.

Nau, R. F., "Coherent Assessment of Subjective Proability," ORC 81-5, March 1981.