**Final Report for Period:** 06/2008 - 05/2009 **Submitted on:** 08/31/2009
**Principal Investigator:** Kim, Seong-Hee . **Award ID:** 0400260
**Organization:** GA Tech Res Corp - GIT
**Submitted By:**
Kim, Seong-Hee - Principal Investigator

**Title:**
GOALI: Efficient Simulation Techniques for Comparing Constrained Systems

## Project Participants

### Senior Personnel

**Name:** Kim, Seong-Hee
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**
She has worked on developing new variance estimators with better statistical properties --- which is critical to ensure good performance of selection procedures. She also developed a selection procedure with a tighter elimination boundary for finding the best among a number of simulated systems. She is currently working with Drs. Andradottir and Goldsman as well as Ph.D. students on the problem of finding the best alternative simulated system in the presence of a stochastic constraint and estimating the variance parameter of output data from steady-state simulations.

**Name:** Goldsman, David
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**
He has been working on improvements over existing variance estimators --- which is critical to ensure good performance of statistical selection procedures --- and developing efficient selection procedures for the problem of finding the best alternative simulated system among a number of simulated systems with or without constraints.

**Name:** Andradottir, Sigrun
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**
She has conducted research on efficient statistical selection procedures for selecting the best among a number of simulated systems in the presence of stochastic constraints. She also has been working on developing improved variance estimation techniques and stopping rules for steady-state simulations.

**Name:** Diamond, Bob
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**
Bob Diamond is a co-PI from an industrial company for discrete-event simulation software packages, which is located in San Diego, California. This project started June, 2004 and the three PI's from academia who reside in Atlanta have been working on developing variance estimation techniques with better statistical properties and efficient algorithms for finding the best among a number of simulated systems with/without stochastic constraints. Since Winter 2005, we have communicated with Bob Diamond and David Krahl (the Director of Technical Services) via email and phone in order to discuss which statistical procedure to implement into their simulation software package, Extend. We also arranged a summer internship position in his company for one of our Ph.D. students in 2006. We started regular conference call meetings with them last summer and will continue until next summer for knowledge transfer from academia to industry.

**Name:** Tsui, Kwok-Leung
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**
He works with two PIs (David Goldsman and Seong-Hee Kim) on problems related to new variance estimators for correlated data.

### Post-doc

**Graduate Student**

**Name:** Batur, Demet

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Demet Batur is a Ph.D. student of Drs. David Goldsman and Seong-Hee Kim. She has been working on developing new variance estimators and new selection procedures. She finished her Ph.D. in May, 2006.

**Name:** Gupta, Vivek

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

He is an advisee of Drs. Sigrun Andradottir and David Goldsman and has been working on this project since January 2005. His research concerns estimating the variance parameter of output data from steady-state simulations.

**Name:** Healey, Christopher

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

He is a Ph.D. student of Drs. Sigrun Andradottir, David Goldsman, and Seong-Hee Kim. He works on problems involving the performance of ranking and selection procedures in the presence of constraints.

**Name:** Aktaran-Kalayci, Tuba

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

She worked on developing overlapping standardized time series variance estimators. She was Dr. David Goldsman's Ph.D. student and graduated in 2006.

**Name:** Antonini, Claudia

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Claudia Antonini worked on developing variance estimators for simulation using folded standardized time series.

**Name:** Meterelliyoz, Melike

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Melike Meterelliyoz worked on variance parameter estimation methods with reuse of data.

**Undergraduate Student**

**Technician, Programmer**

**Name:** Krahl, David

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Mr. David Krahl is Lead Engineer and the Director of Technical Services at Imagine That, Inc. As he is responsible for block development of Extend, we have worked closely with him to develop a tool for optimization based on ranking and selection.

**Other Participant**

**Research Experience for Undergraduates**

## Organizational Partners

## Other Collaborators or Contacts

We have written papers with numerous other co-authors, as detailed in the findings and contributions sections of this report.

## Activities and Findings

**Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

Research and education activities are described in the attached PDF version at the end of the report.

**Findings: (See PDF version submitted by PI at the end of the report)**

Findings are described in the attached PDF version at the end of the report.

**Training and Development:**

The results related to variance estimators and constrained ranking and selection procedures have been introduced to students in our Masters and Ph.D. simulation courses. Also, the results have been introduced to the research community through tutorial papers and tutorial presentations at the Winter Simulation Conference and the INFORMS Conference.

Close collaboration with our GOALI partners Bob Diamond and David Krahl is currently ongoing to implement our procedures in the optimization tools of Extend, a real-world discrete-event computer simulation software package.

**Outreach Activities:**

The results were presented in a number of conferences, including the annual IIE Conference, the annual INFORMS Conference, the Winter Simulation Conference, and the NSF Grantees Conference.

`Fully Sequential Procedures for Comparing Constrained Systems via Simulaion,' Sigrun Andradottir, David Goldsman and Seong-Hee Kim (presenter). INFORMS Conference, Denver, Colorado, 2004.

`Fully Sequential Procedures with a Parabolic Boundary,' Demet Batur (presenter), David Goldsman and Seong-Hee Kim. INFORMS Conference, Denver, Colorado, 2004.

`Overlapping Overlapping Batch Means -- Something More for Nothing?' David Goldsman, Tuba Aktaran (presenter), Bruce Schmeiser and Wheyming Song, INFORMS Conference, Denver, Colorado, 2004.

`Overlapping Variance Estimators for Simulation,' Christos Alexopoulos, Nilay T. Argon, David Goldsman and Gamze Tokol. 2004 Winter Simulation Conference, Washington D.C., 2004.

`Steady-State Simulation Analysis Using ASAP3,' Natalie M. Steiger, James R. Wilson, Jeffrey A. Joines, Emily K. Lada, Christos Alexopoulos and David Goldsman. 2004 Winter Simulation Conference, Washington D.C., 2004.

`GOALI: Efficient Simulation Techniques for Comparing Constrained Systems,' Seong-Hee Kim, Sigrun Andradottir (presenter), Bob Diamond and David Goldsman. 2005 NSF Grantees Conference, Scottsdale, Arizona, 2005.

`Linear Combinations of Overlapping Variance Estimators for Simulations,' Tuba Aktaran-Kalayci (presenter) and David Goldsman. INFORMS Conference, San Francisco, California, 2005.

`Finding Feasible Systems When the Number of Systems or

Constraints is Large,' Demet Batur (presenter) and Seong-Hee Kim. INFORMS Conference, San Francisco, California, 2005.

`Fully Sequential Procedures for Bernoulli Selection,' Gwendolyn J. Malone, Seong-Hee Kim, David Goldsman and Demet Batur (presenter). INFORMS Conference, San Francisco, California, 2005.

`Fully Sequential Procedures for Bernoulli Selection,' IIE Annual Conference, Gwendolyn J. Malone, Seong-Hee Kim, David Goldsman and Demet Batur (presenter). Atlanta, Georgia. 2005.

`Linear Combinations of Overlapping Variance Estimators for Simulations,' Tuba Aktaran-Kalayci (presenter) and David Goldsman. 2005 Winter Simulation Conference, Orlando, Florida, 2005.

`Finding the Best in the Presence of a Stochastic Constraint,' Sigrun Andradottir, David Goldsman and Seong-Hee Kim (presenter). 2005 Winter Simulation Conference, Orlando, Florida, 2005.

`Finding the Set of Feasible Systems When the Number of Systems or Constraints is Large,' Demet Batur (presenter) and Seong-Hee Kim. 2005 Winter Simulation Conference, Orlando, Florida, 2005.

`Performance of Variance Updating Ranking and Selection Procedures,' Gwendolyn J. Malone (presenter), Seong-Hee Kim, David Goldsman and Demet Batur. 2005 Winter Simulation Conference, Orlando, Florida, 2005.

`Exact Expected Values of Variance Estimators for Simulation,' David Goldsman, Bogazici University (Istanbul, Turkey), March and May 2006.

`Exact Expected Values of Variance Estimators for Simulation,' David Goldsman, INSEAD (Paris, France), May 2006.

`Exact Expected Values of Variance Estimators for Simulation,' David Goldsman, Koc University (Istanbul, Turkey), June 2006.

`Exact Expected Values of Variance Estimators for Simulation,' David Goldsman, Middle East Technical University (Ankara, Turkey), December 2006.

`GOALI: Efficient Simulation Techniques for Comparing Constrained Systems,' Seong-Hee Kim (presenter), Sigrun Andradottir, Bob Diamond and David Goldsman. 2006 NSF Grantees Conference, St. Louis, Missouri, 2006.

`Linear Combinations of Variance Estimators of the Sample Mean,' Wenchi Chiu, David Goldsman (presenter), and Wheyming Song. 2006 36th International Conference on Computers and Industrial Engineering, Taipei, Taiwan, R.O.C., 2006.

`Overlapping Folded Variance Estimators for Stationary Simulation Output,' Melike Meterelliyoz, Christos Alexopoulos, and David Goldsman, INFORMS Conference, Pittsburgh, PA, 2006.

`The Role of Simulation in Humanitarian Logistics' (Keynote

Address), David Goldsman, June 2006 36th International Conference on Computers and Industrial Engineering, Taipei, Taiwan, R.O.C, 2006.

`Variance Estimation in Steady-Sate Simulations Using Linear Regression,' Sigrun Andradottir, David Goldsman, and Vivek Gupta, INFORMS Conference, Pittsburgh, PA, 2006.

`Improving Ranking and Selection Techniques with Overlapping Variance Estimators,' David Goldsman, Christopher M. Healey, and Seong-Hee Kim, International Workshop in Sequential Methodologies, Auburn, AL, 2007.

`Ranking and Selection Techniques with Overlapping Variance Estimators,' Christopher M. Healey, David Goldsman, and Seong-Hee Kim, INFORMS Conference, Seattle, WA, 2007.

`A Distribution-Free Tabular CUSUM Chart for Correlated Data with Automated Variance Estimation,' Joongsup Lee, Christos Alexopoulos, David Goldsman, Seong-Hee Kim, Kwok-Leung Tsui, and James R. Wilson, INFORMS Conference, Seattle, WA, 2007.

`Ranking and Selection Techniques with Overlapping Variance Estimators,' Christopher M. Healey, David Goldsman, and Seong-Hee Kim, 2007 Winter Simulation Conference, Washington D.C., 2007.

`Recent Advances in Ranking and Selection,' Seong-Hee Kim and Barry L. Nelson. 2007 Winter Simulation Conference, Washington D.C., 2007.

`Confidence Interval Estimation Using Linear Combinations of Overlapping Variance Estimators,' Tuba Aktaran-Kalayci, David Goldsman, and James R. Wilson,
2007 Winter Simulation Conference, Washington D.C., 2007.

`Replicated Batch Means for Steady-State Simulations with Initial Transients,' Christos Alexopoulos, Sigrun Andradottir, Nilay Tanik Argon, and David Goldsman,
2007 Winter Simulation Conference, Washington D.C., 2007.

`Folded Standardized Time Series Area Variance Estimators for Simulation,' Claudia Antonini, Christos Alexopoulos, David Goldsman, and James R. Wilson,
2007 Winter Simulation Conference, Washington D.C., 2007.

`Improving Efficiency of Selection Procedures,' Sigrun Andradottir, Bob Diamond, David Goldsman, and Seong-Hee Kim, NSF Engineering Research and Innovation Conference, Knoxville, Tennessee, 2008.

`Fully Sequential Procedures with Dormancy for Comparing Constrained Systems,' Christopher M. Healey, Sigrun Andradottir, and Seong-Hee Kim, INFORMS Conference, Washington D.C., 2008.

`Variance Estimators for Simulation Based on Data Re-use,' Christos Alexopoulos, Claudia Antonini, David Goldsman, Melike Meterelliyoz, and James R. Wilson, INFORMS Conference, Washington

D.C., 2008.

## Journal Publications

Christos Alexopoulos and David Goldsman, "To Batch Or Not To Batch?", ACM Transactions on Modeling and Computer Simulation, p. 76, vol. 14, (2004). Published,

Natalie M. Steiger, Emily K. Lada, James R. Wilson, Jeffrey A. Joines,Christos Alexopoulos, and David Goldsman, "ASAP3: A Batch Means Procedure for Steady-State Simulation Analysis", ACM Transactions on Modeling and Computer Simulation, p. 39, vol. 15, (2005). Published,

Seong-Hee Kim, Barry L. Nelson, and James R. Wilson, "Some Almost-Sure Convergence Properties Useful in Sequential Analysis", Sequential Analysis, p. 411, vol. 24, (2005). Published,

Seong-Hee Kim, "Comparison with a Standard via Fully Sequential Procedures", ACM Transactions on Modeling and Computer Simulation, p. 155, vol. 15, (2005). Published,

Goldsman, D; Kang, KB; Kim, SH; Seila, AF; Tokol, G, "Combining standardized time series area and Cramer-von Mises variance estimators", NAVAL RESEARCH LOGISTICS, p. 384, vol. 54, (2007). Published, 10.1002/nav.2021

Batur, D; Kim, SH, "Fully sequential selection procedures with a parabolic boundary", IIE TRANSACTIONS, p. 749, vol. 38, (2006). Published, 10.1080/0740817050053910

Aktaran-Kalayci, T; Alexopoulos, C; Argon, NT; Goldsman, D; Wilson, JR, "Exact expected values of variance estimators for simulation", NAVAL RESEARCH LOGISTICS, p. 397, vol. 54, (2007). Published, 10.1002/nav.2021

Sigrun Andradottir and Seong-Hee Kim, "Fully Sequential Procedures for Comparing Constrained Systems", Naval Research Logistics, p. , vol. , (2007). Submitted,

Demet Batur and Seong-Hee Kim, "Finding Feasible Systems in the Presence of Constraints on Multiple Performance Measures", ACM Transactions on Modeling and Computer Simulation, p. , vol. , (2009). Accepted,

Wenchi Chiu, David Goldsman, and Wheyming Tina Song, "Bias-Aware Linear Combinations of Variance Estimators", WSEAS Transactions on Electronics, p. 167, vol. 4, (2007). Published,

Healey, C., D. Goldsman, and S.-H. Kim, "Ranking and Selection Techniques with Overlapping Variance Estimators", Sequential Analysis, p. , vol. , (2009). Accepted,

Batur, D; Goldsman, D; Kim, SH, "An improved standardized time series Durbin-Watson variance estimator for steady-state simulation", OPERATIONS RESEARCH LETTERS, p. 285, vol. 37, (2009). Published, 10.1016/j.orl.2009.01.01

Antonini, C; Alexopoulos, C; Goldsman, D; Wilson, JR, "Area variance estimators for simulation using folded standardized time series", IIE TRANSACTIONS, p. 134, vol. 41, (2009). Published, 10.1080/0740817080233126

Alexopoulos, C; Argon, NT; Goldsman, D; Tokol, G; Wilson, JR, "Overlapping variance estimators for simulation", OPERATIONS RESEARCH, p. 1090, vol. 55, (2007). Published, 10.1287/opre.1070.047

Alexopoulos, C; Argon, NT; Goldsman, D; Steiger, NM; Tokol, G; Wilson, JR, "Efficient computation of overlapping variance estimators for simulation", INFORMS JOURNAL ON COMPUTING, p. 314, vol. 19, (2007). Published, 10.12

Aktaran-Kalayci, T; Goldsman, D; Wilson, JR, "Linear combinations of overlapping variance estimators for simulation", OPERATIONS RESEARCH LETTERS, p. 439, vol. 35, (2007). Published, 10.1016/j.orl.2006.08.00

Alexopoulos, C; Andradottir, S; Argon, NT; Goldsman, D, "Replicated batch means variance estimators in the presence of an initial transient", ACM TRANSACTIONS ON MODELING AND COMPUTER SIMULATION, p. 317, vol. 16, (2006). Published,

Argon, NT; Andradottir, S, "Replicated batch means for steady-state simulations", NAVAL RESEARCH LOGISTICS, p. 508, vol. 53, (2006). Published, 10.1002/nav.2015

Alexopous C; Chang BY; Goldsman D; Lee S; Marshall WS, "Overcoming Negativity Problems for Cramer--von Mises Variance Estimators", International Journal of Simulation and Process Modeling, p. 1, vol. 4, (2006). Published,

Kim, SH; Alexopoulos, C; Tsui, KL; Wilson, JR, "A distribution-free tabular CUSUM chart for autocorrelated data", IIE TRANSACTIONS, p. 317, vol. 39, (2007). Published, 10.1080/0740817060074394

Lee, J; Alexopoulos, C; Goldsman, D.; Kim, S.-H.; Tsui, K.-L; Wilson, JR, "A Distribution-Free Tabular CUSUM Chart for Correlated Data with Automated Variance Estimation", IIE Transactions, p. , vol. , (2009). Accepted,

Alexopoulos, C; Antonini, C; Goldsman, D; Meterelliyoz, M, "Performance of Folded Variance Estimators for Simulation", ACM Transactions on Modeling and Computer Simulation, p. , vol. , (2009). Accepted,

## Books or Other One-time Publications

Gwendolyn J. Malone, "Ranking and Selection Procedures for Bernoulli and Multinomial Data", (2005). Thesis, Published
Bibliography: Doctoral Dissertation, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Seong-Hee Kim and Barry L. Nelson, "Selecting the Best System", (2006). Book, Published
Editor(s): S.G. Henderson and B.L. Nelson
Collection: Handbooks in Operations Research and Management Science: Simulation
Bibliography: Elsevier, Oxford, UK

Christos Alexopoulos, David Goldsman, and Richard Serfozo, "Stationary Processes: Statistical Estimation", (2006). Book, Published
Editor(s): C. Read, N. Balakrishnan, and B. Vidakovic
Collection: Encyclopedia of Statistical Sciences
Bibliography: 2nd Edition, John Wiley and Sons, New York

David Goldsman and Barry L. Nelson, "Correlation-Based Methods for Output Analysis", (2006). Book, Published
Editor(s): S.G. Henderson and B.L. Nelson
Collection: Handbooks in Operations Research and Management Science: Simulation
Bibliography: Elsevier, Oxford, UK

Demet Batur, "Variance Estimation in Steady-State Simulation, Selecting the Best System, and Determining a Set of Feasible Systems via Simulation", (2006). Thesis, Published
Bibliography: Doctoral Dissertation, H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Tuba Aktaran-Kalayci, "Steady-state Analyses: Variance Estimation in Simulations and Dynamic Pricing in Service Systems", (2006). Thesis, Published
Bibliography: Doctoral dissertation, H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Melike Meterelliyoz, "Variance Parameter Estimation Methods with Re-Use of Data", (2007). Thesis, Published
Bibliography: Doctoral Dissertation, H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Tuba Aktaran-Kalayci, Christos Alexopoulos, David Goldsman, and James R. Wilson, "Optimal Linear Combinations of Overlapping Variance Estimators for Steady-State Simulation", (2009). Book, Published
Editor(s): C. Alexopoulos, D. Goldsman, and J. R. Wilson
Collection: Advancing the Frontiers of Simulation: A Festschrift in Honor of George Samuel Fishman
Bibliography: Springer, Heidelberg, Germany

## Web/Internet Site

## Other Specific Products

**Product Type:**

**Software (or netware)**

**Product Description:**

This software is to implement overlapping standardized time series variance estimators due to Alexopoulos, Argon, Goldsman, Tokol and Wilson (2006) and Alexopoulos, Argon, Goldsman, Steiger, Tokol and Wilson (2006) in an easy way for general use. User's manual is also available.

**Sharing Information:**

The user's manual and software are accessible via ftp://ftp.eos.ncsu.edu/pub/jwilson/ovesie-online-supp.pdf and ftp://ftp.eos.ncsu.edu/pub/jwilson/ovesie-soft.exe.

## Contributions

**Contributions within Discipline:**

Here we summarize contributions of our work.

1. From the 1st Year

Christos Alexopoulos and David Goldsman} (2004). ``To Batch Or Not To Batch?" ACM Transactions on Modeling and Computer Simulation, 14:76--114. [This paper won the 2007 INFORMS Simulation Society Outstanding Simulation Publication Award.]

Contributions: The paper systematically investigates the two most popular methods used in simulation output analysis. It gives explicit conditions under which the method of batch means is superior to that of independent replications.

Nilay Tanik Argon and Sigrun Andradottir (2006). ``Replicated Batch Means for Steady-State Simulations," Naval Research Logistics, 53:508--524.

Contributions: The paper introduces the new idea of combining the multiple replications and batch means methods for output analysis in steady-state simulation.

Demet Batur and Seong-Hee Kim (2006). ``Fully Sequential Selection Procedures with Parabolic Boundary." IIE Transactions, 38:749--764.

Contributions: This paper extends work due to Zhu et al. (2004) by accounting for (i) unknown and unequal variances and (ii) correlation across systems due to, e.g., the use of common random numbers.

David Goldsman, Keebom Kang, Seong-Hee Kim, Andrew F. Seila, and Gamze Tokol (2007). ``Combining Standardized Time Series Area and Cramer--von Mises Variance Estimators,'' Naval Research Logistics, 54:384--396.

Contributions: The new estimators developed in the paper allow for more efficient estimation of the variance of the sample mean, a quantity that ought to be reported as part of any study involving estimation of the underlying population mean.

Seong-Hee Kim (2005). ``Comparison with a Standard via Fully Sequential Procedures.'' ACM Transactions on Modeling and Computer Simulation, 15:155--174.

Contributions: This paper provides state-of-the-art procedures for the comparison-with-a-standard problem popular in simulation. In addition, the procedures can be further extended to check the feasibility of simulated systems in the presence of stochastic constraints on some secondary performance measures.

Seong-Hee Kim, Barry L. Nelson, and James R. Wilson (2005). ``Some Almost-Sure Convergence Properties Useful in Sequential Analysis.'' Sequential Analysis, 24:411--419.

Contributions: The findings in this paper can be adapted to study the asymptotic behavior of a number of sequential ranking-and-selection procedures involving continuation regions of various shapes. Specifically, our work provides tools to help in the development of asymptotically valid selection procedures for steady-state simulations.

Natalie M. Steiger, Emily K. Lada, James R. Wilson, Jeffrey A. Joines, Christos Alexopoulos, and David Goldsman (2005). ``ASAP3: A Batch Means Procedure for Steady-State Simulation Analysis,'' ACM Transactions on Modeling and Computer Simulation, 15:39--73.

Contributions: On the theory side of things, we believe that this is the most efficient and stable sequential confidence interval procedure in the literature. On the applied side, we provide pseudo-code for the algorithm, as well as executable code so that users can run the algorithm easily on their own.

2. From the 2nd Year

Tuba Aktaran-Kalayci and David Goldsman (2005). ``Linear

Combinations of Overlapping Variance Estimators for Simulations," Proceedings of the 2005 Winter Simulation Conference (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 756--762, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This paper generalizes standardized time series estimators that have been proposed in the literature. The estimators proposed in the paper exploit a great deal of the possible information they can get from a given data set and, therefore, are (to date) the most efficient standardized time series estimators based on batching.

Christos Alexopoulos, Nilay Tanik Argon, David Goldsman, Gamze Tokol, and James R. Wilson (2007). ``Overlapping Variance Estimators for Simulation," Operations Research 55:1090--1103.

Contributions: The idea of using overlapping batches is applied to standardized time series estimators.

Christos Alexopoulos, Nilay Tanik Argon, David Goldsman, Natalie M. Steiger, Gamze Tokol, and James R. Wilson} (2007). ``Efficient Computation of Overlapping Variance Estimators for Simulation," INFORMS Journal on Computing 19:314--327.

Contributions: Efficient algorithms to avoid heavy additional computational efforts in computing overlapping standardized time series estimators are proposed. Software and a user's manual for general and easy use are made available via the web. In addition, the paper shows how to use standardized time series estimates in constructing certain confidence intervals.

Sigrun Andradottir, David Goldsman, and Seong-Hee Kim (2005). ``Finding the Best in the Presence of a Stochastic Constraint." Proceedings of the 2005 Winter Simulation Conference (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 732--738, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: We present statistically valid selection procedures that can handle a general stochastic constraint. This is the first work in this area that has been done in the literature.

Demet Batur and Seong-Hee Kim (2005). ``Procedures for Feasibility Detection in the Presence of Multiple Constraints." Proceedings of the 2005 Winter Simulation Conference (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 692--698, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: Procedures presented in the paper will serve as a critical step to move from optimization with one stochastic constraint to optimization with multiple stochastic constraints, which is the ultimate goal of this ongoing grant.

Gwen J. Malone, Seong-Hee Kim, David Goldsman, and Demet Batur (2005). ``Performance of Variance Updating Ranking and Selection Procedures." Proceedings of the 2005 Winter Simulation Conference (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 825--832, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: The paper shows that the idea of variance updating can be very useful --- even in the context of ranking and selection problems involving terminating simulations --- with little loss in the probability of correct selection.

3. From the 3rd Year

Tuba Aktaran-Kalayci, Christos Alexopoulos, Nilay Tanik Argon, David Goldsman, and James R. Wilson (2007). ``Exact Expected Values of Variance Estimators for Simulation," Naval Research Logistics 54:397--410.

Contributions: For a wide variety of cases, the exact expected values of variance estimators for steady-state simulation can be calculated for any sample size.

Tuba Aktaran-Kalayci, David Goldsman, and James R. Wilson (2007). ``Linear Combinations of Overlapping Variance Estimators for Simulation," Operations Research Letters 35:439--477.

Contributions: The variance parameter estimators proposed in the paper exploit more information from a given data set than other estimators proposed in the simulation literature. The result is a class of new estimators with low bias and low variance.

Christos Alexopoulos, Sigrun Andradottir, Nilay Tanik Argon, and David Goldsman (2006). ``Replicated Batch Means Variance Estimators in the Presence of an Initial Transient," ACM Transactions on Modeling and Computer Simulation 16:317--328.

Contributions: Our expressions explicitly show how a simulation's transient mean function affects variance estimator performance. In some cases, the replicated batch means estimator is a good compromise choice with respect to bias and variance. However, care must be taken to avoid an excessive number of replications when the transient function is pervasive.

Christos Alexopoulos, Byeong-Yun Chang, David Goldsman, Sungjoo Lee, and William S. Marshall (2006). ``Overcoming Negativity Problems for Cramer--von Mises Variance Estimators." International Journal of Simulation and Process Modelling 4:1--6.

Contributions: By providing a way to avoid negative values of Cramer-von Mises (CvM) variance estimators, one can use CvM estimators safely in many applications, including estimating variance parameters in ranking and selection procedures.

4. From the 4th Year

Tuba Aktaran-Kalayci, David Goldsman, and James R. Wilson (2007). ``Confidence Interval Estimation Using Linear Combinations of Overlapping Variance Estimators," Proceedings of the 2007 Winter Simulation Conference (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 448--454, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This proceedings paper expands on the earlier results from our Aktaran-Kalayci et al. (2007) Operations Research Letters article (listed in the Contributions from the 3rd Year).

Christos Alexopoulos, Sigrun Andradottir, Nilay Tanik Argon, and David Goldsman (2007). ``Replicated Batch Means for Steady-State Simulations with Initial Transients," Proceedings of the 2007 Winter Simulation Conference (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 308--312, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This proceedings paper gives some additional results above and beyond those in the Alexopoulos, et al. (2006) ACM TOMACS paper. Specifically, we obtain performance properties of replicated batch means under more general assumptions than heretofore considered.

Sigrun Andradottir and Seong-Hee Kim (2006). ``Fully Sequential Procedures for Comparing Constrained Systems via Simulation," submitted to Naval Research Logistics.

Contributions: This paper defines a new problem, namely, constrained ranking and selection and provides creative and new approaches to solve the problem.

Claudia Antonini, Christos Alexopoulos, David Goldsman, and James R. Wilson (2009). ``Area Variance Estimators for Simulation Using Folded Standardized Time Series." IIE Transactions 41:134--144.

Contributions: We look at an entirely new class of variance parameter estimators that effectively re-use data from simulations. The new estimators are asymptotically more efficient than benchmark estimators such as batch means or certain standardized time series estimators.

Claudia Antonini, Christos Alexopoulos, David Goldsman, and James R. Wilson (2007). ``Folded Standardized Time Series Area Variance Estimators for Simulation,'' Proceedings of the 2007 Winter Simulation Conference (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 455--462, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This paper is the proceedings version of the Antonini et al. (2008) IIE Transactions paper on the same subject.

Wenchi Chiu, David Goldsman, and Wheyming Tina Song (2007). ``Bias-Aware Linear Combinations of Variance Estimators,'' WSEAS Transactions on Electronics 4:167--173.

Contributions: This paper proposes a novel approach to variance estimation for computer simulation output. Namely, we attempt to minimize the variance of a linear combination of estimators subject to a bias constraint.

Christopher M. Healey, Seong-Hee Kim, and David Goldsman (2007). ``Ranking and Selection Techniques with Overlapping Variance Estimators,'' Proceedings of the 2007 Winter Simulation Conference (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 522--529, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This paper is the proceedings version of the Healey, Kim, and Goldsman (2009) listed in the contributions from the 5th year.

Seong-Hee Kim and Barry L. Nelson (2007). ``Recent Advances in Ranking and Selection,'' Proceedings of the 2007 Winter Simulation Conference (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 162--172, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

Contributions: This tutorial provides directions of future research in ranking and selection and explains the importance of our research dealing with constrained ranking and selection.

5. From the 5th Year

Demet Batur, David Goldsman, and Seong-Hee Kim (2009). ``An Improved Standardized Time Series Durbin--Watson Variance Estimator for Steady-State Simulation.'' Operations Research Letters 37:285--289.

Contributions: With a little extra computational work, we can obtain a variance estimator with better statistical properties than standardized time series area or Cramer--von Mises estimators.

Demet Batur and Seong-Hee Kim (2009). ``Finding Feasible Systems in the Presence of Constraints on Multiple Performance Measures," To appear in ACM Transactions on Modeling and Computer Simulation.

Contributions: This paper provides statistical procedures for feasibility detection when the number of constraints on a secondary performance measure is larger than one.

Christopher M. Healey, David Goldsman, and Seong-Hee Kim (2009). ``Ranking and Selection Techniques with Overlapping Variance Estimators." To appear in Sequential Analysis.

Contributions: This paper studies (i) the significance of statistical properties of estimators for the asymptotic variance parameter in steady-state simulation and (ii) why research involving variance estimators for steady-state simulations needs to be continued.

Christos Alexopoulos, Claudia Antonini, David Goldsman, and Melike Meterelliyoz} (2009). ``Performance of Folded Variance Estimators for Simulation."  To appear in ACM Transactions on Modeling and Computer Simulation.

Contributions: We provide fine-tuned expected value and variance results for a new class of folded estimators; and we show that the new folded estimators perform as advertised by theory.

Tuba Aktaran-Kalayci, Christos Alexopoulos, David Goldsman, and James R. Wilson (2009). ``Optimal Linear Combinations of Overlapping Variance Estimators for Steady-State Simulation." In Advancing the Frontiers of Simulation: A Festschrift in Honor of George Samuel Fishman (ed. C. Alexopoulos, D. Goldsman, and J. R. Wilson), 291--328, Springer, Heidelberg, Germany.

Contributions:  We derive optimal linear combinations of a large class of variance parameter estimators. We show that these estimators outperform others in the literature with only minor additional computational costs.

**Contributions to Other Disciplines:**

New variance estimators for autocorrelated data from our work further alleviate the difficulties in obtaining a good variance estimate prior to performing any statistical process control procedure in quality control.

In addition to the first two papers published last year, the third paper was submitted to IIE Transactions in 2008:

1. Kim, S.-H., C. Alexopoulos, K.-L. Tsui, and J. R. Wilson. 2006. A Distribution-Free Tabular CUSUM Chart for Autocorrelated Data, IIE Transactions, 39:317-330.

2. Kim, S.-H., C. Alexopoulous, D. Goldsman, and K.-L. Tsui. 2006. A New Model-Free CuSum Chart for Autocorrelated Processes. Technical Report.

3. Lee, J, C. Alexopoulos, D. Goldsman, S.-H. Kim, K.-L. Tsui, and J. R. Wilson. 2009. A Distribution-Free Tabular CUSUM Chart for Correlated Data with Automated Variance Estimation, IIE Transactions, accepted.

**Contributions to Human Resource Development:**

Four female PhD students were graduated: one is currently an assistant professor at a university, two are post-docs in universities, and one is a former assistant professor and currently in industry. These women have certainly helped bolster underrepresented groups in education and industry. Dr. Goldsman also gave numerous lectures to high school math teachers for probability and statistics and is helping to develop a new OR-based 12th grade math course for the state of Georgia.

**Contributions to Resources for Research and Education:**

Free software for variance estimators for steady-state simulation has been developed, and it is accessible on the internet for any researchers or educators.
This will help researchers and educators understand the implementation and performance of variance estimators for stationary autocorrelated data.

**Contributions Beyond Science and Engineering:**

Our procedures for constrained ranking and selection can provide more practically meaningful solutions for a complicated decision-making process, including environmental management.
For example, one PI is collaborating with researchers in environmental engineering and they show that uncertainty should be considered in determining the most cost-effective design of a seawater desalination plant; and constrained ranking and selection procedures could provide a useful decision-making tool to find the most cost-effective design.

## Conference Proceedings

Alexopoulos, C;Andradottir, S;Argon, NT;Goldsman, D, Replicated batch means for steady-state simulations with initial transients, "DEC 09-12, 2007", PROCEEDINGS OF THE 2007 WINTER SIMULATION CONFERENCE, VOLS 1-5, : 296-300 2007

Aktaran-Kalayci, T;Goldsman, D;Wilson, JR, Confidence interval estimation using linear combinations of overlapping variance estimators, "DEC 09-12, 2007", PROCEEDINGS OF THE 2007 WINTER SIMULATION CONFERENCE, VOLS 1-5, : 427-433 2007

Antonini, C;Alexopoulos, C;Goldsman, D;Wilson, JR, Folded standardized time series area variance estimators for simulation, "DEC 09-12, 2007", PROCEEDINGS OF THE 2007 WINTER SIMULATION CONFERENCE, VOLS 1-5, : 434-441 2007

Healey, C;Goldsman, D;Kim, SH, Ranking and selection techniques with overlapping variance estimators, "DEC 09-12, 2007", PROCEEDINGS OF THE 2007 WINTER SIMULATION CONFERENCE, VOLS 1-5, : 501-508 2007

Benson, KC;Goldsman, D;Pritchett, AR, Ranking and selection procedures for simulation, "DEC 03-06, 2006", Proceedings of the 2006 Winter Simulation Conference, Vols 1-5, : 179-185 2006

Malone, GJ;Kim, SH;Goldsman, D;Batur, D, Performance of variance updating ranking and selection procedures, "DEC 04-07, 2005", Proceedings of the 2005 Winter Simulation Conference, Vols 1-4, : 825-832 2005

Aktaran-Kalayci, T;Goldsman, D, Linear combinations of overlapping variance estimators for simulations, "DEC 04-07, 2005", Proceedings of the 2005 Winter Simulation Conference, Vols 1-4, : 756-762 2005

Kim, SH;Nelson, BL, Recent advances in ranking and selection, "DEC 09-12, 2007", PROCEEDINGS OF THE 2007 WINTER SIMULATION CONFERENCE, VOLS 1-5, : 150-160 2007

Batur, D;Kim, SH, Procedures for feasibility detection in the presence of multiple constraints, "DEC 04-07, 2005", Proceedings of the 2005 Winter Simulation Conference, Vols 1-4, : 692-698 2005

Andradottir, S;Goldsman, D;Kim, SH, Finding the best in the presence of a stochastic constraint, "DEC 04-07, 2005", Proceedings of the 2005 Winter Simulation Conference, Vols 1-4, : 732-738 2005

Goldsman, D;Kim, SH;Nelson, BL, Statistical selection of the best system, "DEC 04-07, 2005", Proceedings of the 2005 Winter Simulation Conference, Vols 1-4, : 178-187 2005

**Categories for which nothing is reported:**

Organizational Partners

Any Web/Internet Site

# Activities

The performance of statistical selection procedures, especially for steady-state simulation, depends highly on the quality of variance estimates. The three co-PIs have worked on improvements of existing variance estimators, to produce estimators with better statistical properties — that is, low bias and low variance — for output data from steady-state simulations. In particular, we have investigated:

1. the method of replicated batch means — whether it is better to conduct one long run, or multiple smaller runs, or a compromise between the two extremes;
2. ASAP3, a new sequential procedure for confidence interval estimation;
3. new "overlapping" estimators based on standardized time series for the variance parameter of a stationary stochastic process;
4. analysis of the computational effort to produce overlapping standardized time series estimators and the use of their asymptotic distribution to construct confidence intervals via those estimators;
5. linear combinations of nonoverlapping standardized time series area estimators;
6. linear combinations of overlapping standardized time series area estimators;
7. combining nonoverlapping standardized time series area and Cramér–von MIses variance estimators — resulting in Durbin–Watson type variance estimators — to achieve low bias and low variance;
8. improved jackknifed versions of Durbin–Watson type estimators for the asymptotic variance parameter;
9. linear combinations of overlapping standardized time series area and Cramér–von Mises estimators;
10. overlapping versions of the jackknifed version of the Durbin–Watson estimator for the asymptotic variance parameter;
11. new "folded" standardized time series area and Cramér–von Mises estimators for the asymptotic variance parameter;
12. (ongoing) linear regression of various variance estimators to produce a new linear combination estimator having lower bias and variance;
13. (ongoing) the connection between standardized time series and spectral estimators; and
14. (ongoing) the determination of a warm-up period in steady-state simulation using spectral estimators.

In addition, variance estimators feed into the main problem under study, namely, the development of new selection procedures in the presence of stochastic constraints. To this end, we have investigated

1. a selection procedure for comparing a number of alternative simulated systems with a standard, which can be extended to checking the feasibility of systems;

2. new selection procedures using a parabolic elimination boundary;
3. a new procedure to check feasibility in the presence of a stochastic constraint;
4. the performance of a procedure with variance updates on independent and identically distributed data with normal or Bernoulli marginals;
5. new procedures that find a set of feasible or near-feasible systems and then choose the best among those systems in the set in the presence of one stochastic constraint;
6. procedures that find a set of feasible or near-feasible systems among a finite number of simulated systems in the presence of multiple stochastic constraints;
7. the performance of ranking and selection procedures specially designed for steady-state simulation with new variance estimators;
8. developing procedures to check feasibility in the presence of multiple stochastic constraints;
9. (ongoing) presenting the idea of dormancy for constrained ranking and selection procedures, where a system becomes dormant (pausing sampling) when it is found to be inferior to a system whose feasibility is not known yet and the system turns back to competition when the superior system turns out to be infeasible; and
10. (ongoing) developing procedures for constrained ranking and selection in the presence of multiple stochastic constraints with the use of common random numbers.

One Ph.D. student finished her Ph.D. in 2004 with a thesis titled "Ranking and Selection Procedures for Bernoulli and Multinomial Data" and two Ph.D. students finished in 2006 with theses titled "Variance Estimation in Steady-State Simulation, Selecting the Best System, and Determining a Set of Feasible Systems via Simulation" and "Steady-state Analyses: Variance Estimation in Simulations and Dynamic Pricing in Service Systems". One Ph.D. student finished in 2007 with a thesis titled "Variance Parameter Estimation Methods with Re-Use of Data". Two Ph.D. students (Vivek Gupta and Christopher Healey) are currently working on topics related to this project.

## Findings

### From the 1st Year

- CHRISTOS ALEXOPOULOS AND DAVID GOLDSMAN (2004). "To Batch Or Not To Batch?" *ACM Transactions on Modeling and Computer Simulation* **14**, 76–114. [This paper won the 2007 INFORMS Simulation Society Outstanding Simulation Publication Award.]

  Findings: In this paper, we compare the method of batch means to that of independent replications in the context of steady-state simulation output analysis. In particular, is it better to conduct one long run (and use batch means) or to conduct multiple smaller runs (independent replications)? We find that independent replications performs well when the underlying observations are, indeed, in steady-state. Unfortunately, independent replications falls apart in the presence of a mild transient in the output stream. Therefore, we recommend the use of batch means in most practical applications in which steady-state analysis is deemed appropriate.

- NILAY TANIK ARGON AND SIGRÚN ANDRADÓTTIR (2006). "Replicated Batch Means for Steady-State Simulations," *Naval Research Logistics* **53**, 508–524.

  Findings: We present and analyze a new output analysis method for steady-state simulation called the replicated batch means method that combines two well known output analysis techniques, namely the multiple replications and batch means methods. We also present new methods for initializing the replications in steady-state simulation. Numerical results show that the replicated batch means method, implemented with a good initialization technique and number of replications, is a promising method for steady-state simulation output analysis.

- DEMET BATUR AND SEONG-HEE KIM (2006). "Fully Sequential Selection Procedures with Parabolic Boundary." *IIE Transactions* **38**, 749–764.

  Findings: This paper extends findings from Zhu et al. 2004. In particular, we generalize selection procedures with a parabolic boundary; and we consider the more-realistic case involving unknown variances. Selection procedures with a parabolic elimination boundary show better performance over existing selection procedures with a triangular boundary, especially when the number of systems is large and common random numbers are employed. Therefore, when the number of systems is very large — which is the case of interest for this grant — the new procedures seem preferable.

- DAVID GOLDSMAN, KEEBOM KANG, SEONG-HEE KIM, ANDREW F. SEILA, AND GAMZE TOKOL (2007). "Combining Standardized Time Series Area and Cramér–von Mises Variance Estimators," *Naval Research Logistics* **54**, 384–396.

  Findings: We study estimators for the variance of the sample mean from a stationary stochastic process. In particular, we combine two different estimators arising from the method of standardized time series — namely, the so-called area and Cramér–von Mises estimators. We find that the combined estimators have the same low bias as their constituents, but lower variance. We demonstrate the efficacy of the new estimators using exact and Monte Carlo examples.

- SEONG-HEE KIM (2005). "Comparison with a Standard via Fully Sequential Procedures." *ACM Transactions on Modeling and Computer Simulation* **15**, 155–174.

  Findings: We develop statistically valid fully sequential procedures for the problem of finding systems whose expected performance measures are larger or smaller than a single system —

referred to as a standard — and, if there are any, finding the one with the largest or smallest performance. The procedures are appropriate for use in the simulation environment since they account for (i) unknown/unequal variances and (ii) dependence across systems due to, e.g., the use of techniques such as common random numbers. We find that the new procedures are a great deal more efficient than existing procedures.

- SEONG-HEE KIM, BARRY L. NELSON, AND JAMES R. WILSON (2005). "Some Almost-Sure Convergence Properties Useful in Sequential Analysis." *Sequential Analysis* **24**, 411–419.

  Findings: Given a sequence of functions converging to a realization of the relevant Brownian motion process on the unit interval, we show that the corresponding sequence of boundary-hitting points converges almost surely to the boundary-hitting point for the Brownian motion process.

- NATALIE M. STEIGER, EMILY K. LADA, JAMES R. WILSON, JEFFREY A. JOINES, CHRISTOS ALEXOPOULOS, AND DAVID GOLDSMAN (2005). "ASAP3: A Batch Means Procedure for Steady-State Simulation Analysis," *ACM Transactions on Modeling and Computer Simulation* **15**, 39–73.

  Findings: This paper gives an efficient sequential method for computing confidence intervals for the mean of a steady-state simulation process. The technique is based on the method of batch means, and we find that it outperforms other sequential procedures on a variety of stochastic processes.

### From the 2nd Year

- TÛBA AKTARAN-KALAYCI AND DAVID GOLDSMAN (2005). "Linear Combinations of Overlapping Variance Estimators for Simulations," *Proceedings of the 2005 Winter Simulation Conference* (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 756–762, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: The paper examines properties of linear combinations of overlapping standardized time series area estimators for the variance parameter of a stationary stochastic process. The paper shows that the linear combination estimators have lower bias and variance than their overlapping constituents and nonoverlapping counterparts.

- CHRISTOS ALEXOPOULOS, NILAY TANIK ARGON, DAVID GOLDSMAN, GAMZE TOKOL, AND JAMES R. WILSON (2007). "Overlapping Variance Estimators for Simulation," *Operations Research* **55**, 1090–1103.

  Findings: The paper studies estimators for the variance parameter of a stationary stochastic process that are calculated from a set of overlapping batches. In particular, we present general theory for overlapping variance estimators based on standardized time series area and Cramér–von Mises estimators. The new estimators have the same bias as, but substantially lower variance than, their nonoverlapping counterparts.

- CHRISTOS ALEXOPOULOS, NILAY TANIK ARGON, DAVID GOLDSMAN, NATALIE M. STEIGER, GAMZE TOKOL, AND JAMES R. WILSON (2007). "Efficient Computation of Overlapping Variance Estimators for Simulation," *INFORMS Journal on Computing* **19**, 314–327.

  Findings: The paper presents algorithms that require order-of-sample-size work to calculate overlapping versions of standardized time series estimators. Also, the paper shows that the asymptotic distribution of each overlapping variance estimator is closely approximated by that of a rescaled chi-squared random variable whose scaling factor and degrees of freedom are set to match the mean and variance of the target asymptotic distribution.

- Sigrún Andradóttir, David Goldsman, and Seong-Hee Kim (2005). "Finding the Best in the Presence of a Stochastic Constraint." *Proceedings of the 2005 Winter Simulation Conference* (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 732–738, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: The paper provides a solution to the problem of finding the best among a finite number of simulated systems in the presence of a stochastic constraint on a secondary performance measure. We first find a set that contains feasible or near-feasible systems (Phase I) and then choose the best among those systems in the set (Phase II). The paper contains a procedure for Phase I and another procedure that performs Phases I and II sequentially to find the best feasible system.

- Demet Batur and Seong-Hee Kim (2005). "Procedures for Feasibility Detection in the Presence of Multiple Constraints." *Proceedings of the 2005 Winter Simulation Conference* (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 692–698, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: The paper solves the problem of finding a set of feasible or near-feasible systems among a finite number of simulated systems in the presence of a number of stochastic constraints. The paper extends a procedure for Phase I presented by Andradóttir, Goldsman, and Kim (2005) to the case of multiple constraints by the use of the Bonferroni inequality. Moreover, to accelerate the efficiency of the resulting procedure, a procedure is presented that applies screening to linear combinations of the collected observations across stochastic constraints as well as raw observations from each stochastic constraint.

- Gwen J. Malone, Seong-Hee Kim, David Goldsman, and Demet Batur (2005). "Performance of Variance Updating Ranking and Selection Procedures." *Proceedings of the 2005 Winter Simulation Conference* (ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines), 825–832, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: The paper considers a procedure called $\mathcal{KN}$++ that updates a variance estimate as more observations become available. The procedure is specially designed for a steady-state simulation and proven to be asymptotically valid when common random numbers (CRN) are not employed. The paper presents a modification of $\mathcal{KN}$++ that is asymptotically valid with the use of CRN. The modified $\mathcal{KN}$++ is tested when data are obtained from a terminating simulation (not a steady-state simulation), possibly with the use of CRN. Specific applications include the finding-the-best problem when (i) the data are normal, and (ii) the data are Bernoulli. Experimental results show that the modified $\mathcal{KN}$++ is significantly more efficient than a statistically valid fully sequential procedure without variance update for independent and identically normally distributed data with only slight degradation in the probability of correct selection. For Bernoulli data, it works better than other competitors under some configurations.

## From the 3rd Year

- Tûba Aktaran-Kalayci, Christos Alexopoulos, Nilay Tanik Argon, David Goldsman, and James R. Wilson (2007). "Exact Expected Values of Variance Estimators for Simulation," *Naval Research Logistics* **54**, 397–410.

Findings: We formulate exact expressions for the expected values of selected estimators of the variance of the sample mean arising from a steady-state simulation output process. Given in terms of the autocovariance function of the process, these expressions are derived for variance estimators based on the methods of nonoverlapping batch means, overlapping batch means, and standardized time series. Comparing estimator performance in a first-order autoregressive process and the M/M/1 queue-waiting-time process, we find that certain standardized time series estimators outperform their competitors as the sample size becomes large.

- Tûba Aktaran-Kalayci, David Goldsman, and James R. Wilson (2007). "Linear Combinations of Overlapping Variance Estimators for Simulation," *Operations Research Letters* **35**, 439–477.

  Findings: The paper examines properties of linear combinations of overlapping standardized time series area estimators for the variance parameter of a stationary stochastic process. In addition to materials covered in our paper in *the Proceedings of the 2005 Winter Simulation Conference*, this paper provides more details of the results including theorems, proofs, and experimental results.

- Christos Alexopoulos, Sigrún Andradóttir, Nilay Tanik Argon, and David Goldsman (2006). "Replicated Batch Means Variance Estimators in the Presence of an Initial Transient," *ACM Transactions on Modeling and Computer Simulation* **16**, 317–328.

  Findings: The simulation output analysis method of replicated batch means (RBM) combines good characteristics of the methods of independent replications and batch means. This article gives analytical results for the mean and variance of the RBM estimator for the variance of the sample mean for a class of processes having initial transients with an additive form. We provide succinct complementary extensions of some of the results in the literature. Our expressions explicitly show how the transient function affects estimator performance and suggest that in some cases, the RBM estimator is a good compromise choice with respect to bias and variance. However, care must be taken to avoid an excessive number of replications when the transient function is pervasive.

- Christos Alexopoulos, Byeong-Yun Chang, David Goldsman, Sungjoo Lee, and William S. Marshall (2006). "Overcoming Negativity Problems for Cramér–von Mises Variance Estimators." *International Journal of Simulation and Process Modelling* **4**, 1–6.

  Findings: It is known that Cramér–von Mises estimators for the variance of the sample mean can sometimes produce negative values. We found that this problem can be overcome by taking batches of observations, forming a variance estimator from each batch, and then averaging. In fact, for all practical purposes, the negativity problem goes away completely after just a few batches.

### From the 4th Year

- Tûba Aktaran-Kalayci, David Goldsman, and James R. Wilson (2007). "Confidence Interval Estimation Using Linear Combinations of Overlapping Variance Estimators," *Proceedings of the 2007 Winter Simulation Conference* (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 448–454, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: This proceedings paper expands on the earlier results from our Aktaran-Kalaycı et al. (2007) *Operations Research Letters* article (listed in the Findings from the 3rd Year).

- Christos Alexopoulos, Sigrún Andradóttir, Nilay Tanik Argon, and David Goldsman (2007). "Replicated Batch Means for Steady-State Simulations with Initial Transients," *Proceedings of the 2007 Winter Simulation Conference* (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 308–312, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: This proceedings paper gives some additional results above and beyond those in the Alexopoulos, et al. (2006) *ACM TOMACS* paper. Specifically, we look at the performance of replicated batch means under more general assumptions than heretofore considered.

- Sigrún Andradóttir and Seong-Hee Kim (2006). "Fully Sequential Procedures for Comparing Constrained Systems via Simulation," submitted to *Naval Research Logistics*.

  Findings: The paper investigates how to correctly select the best feasible system when there is one constraint on a secondary performance measure. Solving this problem requires the identification and removal from consideration of infeasible systems (Phase I) and of systems whose primary performance measure is dominated by that of other feasible systems (Phase II). The authors consider two approaches, namely, carrying out Phases I and II sequentially and carrying out Phases I and II simultaneously, and provides specific example procedures of each type.

- Claudia Antonini, Christos Alexopoulos, David Goldsman, and James R. Wilson (2009). "Area Variance Estimators for Simulation Using Folded Standardized Time Series." *IIE Transactions* **41**, 134–144.

  Findings: We estimate the variance parameter of a stationary simulation process using "folded" versions of standardized time series area estimators. Asymptotically as the sample size increases, different folding levels yield unbiased estimators that are independent scaled chi-squared variates, each with one degree of freedom. We exploit this result to formulate improved variance estimators based on the combination of multiple levels as well as the use of batching. The improved estimators preserve the asymptotic bias properties of their predecessors, but have substantially lower asymptotic variances.

- Claudia Antonini, Christos Alexopoulos, David Goldsman, and James R. Wilson (2007). "Folded Standardized Time Series Area Variance Estimators for Simulation," *Proceedings of the 2007 Winter Simulation Conference* (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 455–462, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: This paper is the proceedings version of the Antonini et al. (2008) *IIE Transactions* paper on the same subject.

- Wenchi Chiu, David Goldsman, and Wheyming Tina Song (2007). "Bias-Aware Linear Combinations of Variance Estimators," *WSEAS Transactions on Electronics* **4**, 167–173.

  Findings: In this paper, we attempt to minimize the variance of an estimator subject to a bias constraint — a goal that differs from that of minimizing mean squared error, in which case there would be no explicit bias constraint. We propose a *bias-aware* mechanism to achieve our goal. Specifically, we use linear combinations of estimators based on different batch sizes to approximately satisfy the bias constraint; and then we minimize the variance by choosing appropriate linear combination weights.

- Christopher M. Healey, Seong-Hee Kim, and David Goldsman (2007). "Ranking and Selection Techniques with Overlapping Variance Estimators," *Proceedings of the 2007 Winter Simulation Conference* (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 522–529, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: The experimental study of the paper shows that the performance of ranking and selection procedures can be improved over other procedures in the literature by the use of better variance estimators with good statistical properties.

- Seong-Hee Kim and Barry L. Nelson (2007). "Recent Advances in Ranking and Selection," *Proceedings of the 2007 Winter Simulation Conference* (ed. S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton), 162–172, Institute of Electrical and Electronics Engineers, Piscataway, NJ. (refereed)

  Findings: This tutorial provides an overview on recent advances made in ranking and selection for selecting the best simulated system and discusses challenges that still exist in the field.

### From the 5th Year

- Demet Batur, David Goldsman, and Seong-Hee Kim (2009). "An Improved Standardized Time Series Durbin–Watson Variance Estimator for Steady-State Simulation." *Operations Research Letters* **37**, 285–289.

  Findings: The paper presents an improved jackknifed version of Durbin-Watson type estimators for the asymptotic variance parameter from a steady-state simulation. These new estimators are based on combinations of standardized time series area and Cramér-von Mises estimators. Analytical and empirical examples demonstrate their efficacy in terms of bias and variance.

- Demet Batur and Seong-Hee Kim (2009). "Finding Feasible Systems in the Presence of Constraints on Multiple Performance Measures." To appear in *ACM Transactions on Modeling and Computer Simulation*.

  Findings: The paper studies how to find a set of feasible systems in the presence of multiple constraints. It shows that the Bonferroni inequality can be used to extend procedures for a single constraint to multiple constraints; furthermore, it shows that aggregation and variance updates can help improve the efficiency of the procedures.

- Christopher M. Healey, David Goldsman, and Seong-Hee Kim (2009). "Ranking and Selection Techniques with Overlapping Variance Estimators." To appear in *Sequential Analysis*.

  Findings: The paper studies the effects of variance estimators with good statistical properties on the performance of ranking and selection procedures for steady-state simulations. The paper also gives a recommendation for the best variance estimator.

- Christos Alexopoulos, Claudia Antonini, David Goldsman, and Melike Meterelliyoz (2009). "Performance of Folded Variance Estimators for Simulation." To appear in *ACM Transactions on Modeling and Computer Simulation*.

  Findings: We extend and analyze the class of folded estimators for the variance parameter of a steady-state simulation output process (originally discussed in Antonini et al. 2009 from the 4th year findings). In particular, we derive the asymptotic distributional properties of the various estimators as the run length increases, as well as their bias, variance, and mean squared error. We also study linear combinations of these estimators, and we show that such combinations yield estimators with lower variance than their constituents. Finally, we consider the consequences of batching, and we see that the batched versions of the new estimators compare favorably to benchmark estimators such as the nonoverlapping batch means estimator.

- Tûba Aktaran-Kalayci, Christos Alexopoulos, David Goldsman, and James R. Wilson (2009). "Optimal Linear Combinations of Overlapping Variance Estimators for Steady-State Simulation." In *Advancing the Frontiers of Simulation: A Festschrift in Honor of George Samuel Fishman* (ed. C. Alexopoulos, D. Goldsman, and J. R. Wilson), 291–328, Springer, Heidelberg, Germany.

  Findings: We formulate an optimal linear combination of overlapping variance estimators (OLCOVE) to estimate the variance parameter of a steady-state simulation output process. Each variance estimator is computed from the same data set using one of the following methods: (i) overlapping batch means (OBM); or (ii) standardized time series (STS) applied to overlapping batches separately and then averaged over all such batches. Each estimators batch size is a fixed real multiple (at least unity) of a base batch size, appropriately rounded. The overall sample size is a fixed integral multiple of the base batch size. Exploiting the control-variates method, we assign OLCOVE coefficients so as to yield a minimum-variance estimator. We establish asymptotic properties of the bias and variance of OLCOVEs computed from OBM or STS variance estimators as the base batch size increases. Finally, we use OLCOVEs to construct confidence intervals for both the mean and the variance parameter of the target process. An experimental performance evaluation reveals the potential benefits of using OLCOVEs for steady-state simulation analysis.