15:18:34 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 08/12/91

Active

Project #: E-24-622 Cost share #: E-24-319 Rev #: 2
Center # : 10/24-6-R7048-0A0 Center shr #: 10/22-1-F7048-0A0 OCA file #:
Work type : RES
Contract#: DDM-9007532 Mod #: AMENDMENT 01 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: 47.041
Main project #: PE #: N/A

Project unit: ISYE Unit code: 02.010.124
Project director(s):
SERFOZO R F ISYE (404)894-2305

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 900901 to 930228 (performance) 930531 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	130,000.00
Funded	60,000.00	130,000.00
Cost sharing amount		6,500.00

Does subcontracting plan apply ?: N

Title: STOCHASTIC NETWORK PROCESSES

PROJECT ADMINISTRATION DATA

OCA contact: Mildred S. Heyser 894-4820

Sponsor technical contact	Sponsor issuing office
DONALD GROSS	MARTIN V. GEARY
(202)357-5167	(202)357-9602
NSF	NATIONAL SCIENCE FOUNDATION
1800 G STREET, N.W.	1800 G STREET,N.W.
WASHINGTON, D.C. 20550	WASHINGTON,D.C. 20550

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
AMENDMENT 1 ADDS $60K. GRANT IS NOW FULLY FUNDED._ALL OTHER TERMS AND CONDITIONS REMAIN UNCHANGED.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 06/11/93

Project No. E-24-622 Center No. 10/24-6-R7048-0A0

Project Director SERFOZO R F School/Lab ISYE

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-9007532 Contract Entity GTRC

Prime Contract No.

Title STOCHASTIC NETWORK PROCESSES

Effective Completion Date 930228 (Performance) 930531 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsEFFECTIVE DATE 9-1-90. CONTRACT VALUE $130,000.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other CARL BAXTER-FMD	Y
FRED CAIN-OOD	Y

E-24-622

May 27, 1991

Mrs. Carol Guido, Administrative Officer
DDM, Room 1128
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

Dear Mrs. Guido:

I would like to request that NSF continue my grant DDM-900-7532 for the 1991 fiscal year. I plan to use the budget in my original proposal and so I am not including a revised one.

Sincerely,

Richard F. Serfozo

Abstract of Activities on NSF Grant DDM-900-7532

Stochastic Network Processes

By

Richard F. Serfozo, Georgia Institute of Technology

The aim is to develop stochastic network processes for modeling manufacturing and computer networks. What are likely bottlenecks, machine busy periods, throughput rates, travel times etc.? The focus is on networks with dependent nodes (parallel processing or regulating service rates to avoid extremes in queues), batch processing, concurrent movements, and routing to avoid congestion. The current theory is for one-at-a-time movements and independent nodes and routings. The main activities are: (a) Solve the long-standing problem of characterizing travel times in networks. (b) Find appropriate Markovian partial-balances for representing dependent nodes. (c) Find a way to represent batch processing and concurrent movements. (d) Develop Monte Carlo procedures for computing certain parameters in equilibrium distributions of networks.

E24-622

GEORGIA TECH 1885-1985

DESIGNING TOMORROW TODAY

Georgia Institute of Technology
School of Industrial and Systems Engineering
Atlanta, Georgia 30332-0205
(404) 894-2300

June 12, 1992

Dr. F. Hank Grant, Program Director
Operations Research and Production Systems
National Science Foundation
1800 G. Street, N.W.
Washington, DC 20550

Dear Hank:

Enclosed is my yearly status report on my NSF Grant DDM-9007532. The focus here is only on results that we have documented.

Sincerely,

Richard F. Serfozo

Status Report on NSF Project DDM-9007532 Stochastic Network Processes

Richard F. Serfozo
Georgia Institute of Technology

June 10, 1992

The general theme of our research has been to develop stochastic network processes for modeling the movement of discrete units in networks. Primary examples are the movement of parts and supplies in manufacturing plants and in distribution systems and the movement of data packets and telephone calls in computer and telecommunications networks. The distinguishing feature of our research is the emphasis on the next generation of *intelligent* networks that will be the backbone of our manufacturing and computer systems. In these networks, the processing of units at the nodes and the routing of units typically depend dynamically on the actual network congestion, and units move concurrently (e.g. batch processing). Most of the present theory of stochastic network processes is for unintelligent networks in which the nodes operate independently, the routes of units are independent, and the units move one-at-a-time. Our goal is to provide an understanding of these more complex intelligent networks by describing their stochastic behavior. The following is a summary of the papers we have written for this project during the last two years. .

1 Optimal Routing and Servicing in Dependent, Parallel Processing Systems by R. Menich and the PI. *Queueing Systems* , 9, 403-418, 1991.
In a system of independent, identical parallel processing service stations, customers are typically routed to the shortest queue. And any auxiliary

mobile server is typically assigned to serve the longest queue. When are these dynamic control policies optimal for *dependent* parallel processing stations? We show they are optimal for a wide class of Markovian systems in which the arrival and service rates at the stations (which may depend on the numbers of customers at *all* the stations) satisfy certain symmetry and monotonicity conditions. Under these policies the queue lengths will be stochastically smaller than the queue lenghts under any other policy. Furthermore, these policies minimize standard discounted and average cost functions over finite and infinite horizons.

2 Reversibility and Compound Birth-Death and Migration Processes by the PI. In *Queueing and Related Models*, Oxford University Press, 1992.
The classical birth-death stochastic process is one of the most useful processes for modeling a variety of service or input-output systems with queueing. This process represents a single population and units arrive and depart one-at-a-time. What would be the analogous process for modeling several dependent populations of units, where the units may arrive and depart in batches ? We have developed such a process called a multi-variate, compound birth-death process. In doing so, we have solved some basic problems on the characterization of reversible stochastic processes whose trajectories are generated by certain basic vectors. We have also developed an analogous network process called a compound migration process. Here the populations interact and units leaving a population may move to other populations or exit the network singly or in batches. We identify several families of these processes that are especially suited for manufacturing and communications networks and describe their equilibrium behavior and other performance parameters.

3 Queueing Network Processes with Dependent Nodes and Concurrent Movements by the PI. To appear in *Queueing Systems*, 1992.
This work describes a new class of network processes for modeling networks with dependent nodes and concurrent movement of units. It also shows the structual relations between the classical Jackson network and its ostensively different variations (e.g. quasi-reversible and weakly coupled networks); these are all special cases of a certain "basic" partially balanced network process. This insight provides a general framework for representing some partially balanced dependencies relating to the following situations:

- Alternate routing of units to avoid congestion.
- The arrival rate of units into a network depends on the number of units already there.
- Units are processed in parallel at several nodes.
- The service rate at a node depends on the states of the other nodes (e.g. the rate decreases as downstream congestion decreases.)
- A "starved" node with few units pulls units from its upstream neighbors.
- Service rates are dynamically regulated to increase throughput or balance the workload at nodes.
- Several units merge into one (e.g. manufacturing asemblies) or one unit splits into many (e.g. one email message propagates a family of messages).
- A unit moving in a network requires shared resources (e.g. tools, tokens, data files) that move concurrently with it.

In addition to describing the equilibrium behavior, we describe Monte Carlo methods for computing some of the network performance parameters for large networks.

4 **Travel and Sojourn Times in Stochastic Networks** by K. Kook and the PI. To appear in *Annals of Applied Probability*, 1993.
Ever since the Jackson network process was developed about 30 years ago, a major concern has been how long does it take a unit to travel through a network? Essentially the only basic result in this regard, aside from approximations, is that in an open Jackson network without overtaking (a very restrictive condition), the travel time on a route is the sum of independent exponential sojourn times at the nodes on the route. An analogous result holds for a closed Jackson network (but the node sojourn times are no longer exponential). A thirty year old problem for the Jackson network had been "What is the expected time to travel from one node (or sector of nodes) to another? We solved this and related problems for Jackson networks and for other networks with congestion dependent routing and processing. In doing

this, we addressed a large class of travel times in networks (e.g. the time to visit a node 3 times, or the time to visit each node at least once) and derived an expression for their expected values. We also, extended the classical results for characterizing the distribution of the travel time on overtake free routes for the more general networks with dependent nodes.

5 Travel Times in Queueing Networks and Network Sojourns by the PI. Submitted for publication.
This paper reviews what is known about travel times of units in a network. It also contains new material on Little laws for networks with dependencies. This yields expressions for sojourn times such as the time it takes a unit to move through a network, or the time a unit spends in a sector of a network as a certain type of unit before changing its type and entering another sector. Other problems we address are finding the expected length of a busy period of a node, and finding the expected time interval that the number of units at a node exceed a certain high level. Such information on "high-level" exceedances or extreme values of queueing networks is important for predicting extraordinary work loads (overtime) or emergency situations.

6 Relating the Waiting Times and Queue lengths in Heavy Traffic Systems by W. Szczotka, W. Topolski and the PI. Submitted for publication.
For a single-server queueing system, intuition suggests that an arriving unit's waiting time before its service begins is approximately equal to the number of units in the system times the average service time. Why are there no results to this effect? Because it is not true when the traffic intensity is moderate. However, we show that this approximation is indeed valid for certain systems in heavy traffic. We also give more insight into diffusion approximations for queueing systems. Namely, there are three types of natural diffusion approximations, not just the conventional reflected Brownian motion model. This analysis is a precursor to results for networks.

7 Extreme Values of Random Times in Stochastic Networks by Sungyeol Kang. A PhD dissertation in Industrial and Systems Engineering.

In manufacturing systems, a typical concern is the time it takes for a group of units that will eventually constitute one system to be processed by a network of work stations. This time is the maximum (or extreme value) of the travel times of the units through the network. An example is that 20 units must pass

through a PERT network before they are brought together as one system. The individual network completion times often have distributions that are of phase type or are mixtures of such distributions. This dissertation is a study of extreme values of such distributions. We show that the extreme value distribution of a large sample is asymptotically a Gumbel distribution. We apply these results to model completion times in a Markov PERT network and for group travel times in open Jackson networks when the traffic is light or when the traffic is heavy and the special units are intersperced evenly among many other units.

E24-622

APPENDIX IX

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days after the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

	5/31/93
Principal Investigator/Project Director Signature	Date

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

IMPORTANT
MAILING INSTRUCTIONS

Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

PART IV – FINAL PROJECT REPORT – SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1									
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian..........................										
Black, Not of Hispanic Origin.........										
Hispanic.......................										
Pacific Islander..................										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country 1. China					2	1				
2.										
3.										
D. Total, All participants (A + B + C)	1				2	1				
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the orignal peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

Final Report on NSF Project DDM-9007532
Stochastic Network Processes

Richard F. Serfozo, Georgia Institute of Technology

Project Summary

The general theme of our research has been to develop stochastic network processes for modeling the movement of discrete units in networks. Primary examples are the movement of parts and supplies in manufacturing plants and in distribution systems and the movement of data packets and telephone calls in computer and telecommunications networks. The distinguishing feature of our research is the emphasis on the next generation of *intelligent* networks that will be the backbone of our manufacturing and computer systems. In these networks, the processing of units at the nodes and the routing of units typically depend dynamically on the actual network congestion, and units move concurrently (e.g. batch processing). Most of the present theory of stochastic network processes is for unintelligent networks in which the nodes operate independently, the routes of units are independent, and the units move one-at-a-time. Our goal is to provide an understanding of these more complex intelligent networks by describing their stochastic behavior. In this regard, we have developed the theory of several classes of stochastic processes for analyzing networks.

We have also started research on the performance evaluation of protocols for time-warp parallel simulations. A new interest in simulation software is to develop systems that take advantage of parallel processing by several processes. In such a system, multiple processors generate information independently and then coordinate their activities by periodically sending messages to each other. A major performance question is: What types of protocols for coordinating processors will give the best speedup for various classes of applications? Insights on this and related questions can be obtained by the use of stochastic network processes as we have been developing. The reason is that many classes of simulation applications can be cast as stochastic networks. Furthermore, the simulation program itself is also a stochastic network with the processors as nodes. Our main contribution has been an assessment of the affect of limited memory for certain types of time-warp parallel simulations.

Summary of Research Papers

The following is a summary of the papers we have written for this project during the last two years.

1 Optimal Routing and Servicing in Dependent, Parallel Processing Systems by R. Menich and the PI. *Queueing Systems* , 9, 403-418, 1991.
In a system of independent, identical parallel processing service stations, customers are typically routed to the shortest queue. And any auxiliary mobile server is typically assigned to serve the longest queue. When are these dynamic control policies optimal for *dependent* parallel processing stations? We show they are optimal for a wide class of Markovian systems in which the arrival and service rates at the stations (which may depend on the numbers of customers at *all* the stations) satisfy certain symmetry and monotonicity conditions. Under these policies the queue lengths will be stochastically smaller than the queue lenghts under any other policy. Furthermore, these policies minimize standard discounted and average cost functions over finite and infinite horizons.

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5 Travel Times in Queueing Networks and Network Sojourns by the PI. T appear in *Ann. Operations Research issue on Queueing Networks*, 1993.
This paper contains new Little laws for networks with dependencies. It also reviews what is known about travel times of units in a network. We present expressions for sojourn times such as the time it takes a unit to move through a network, or the time a unit spends in a sector of a network as a certain type of unit before changing its type and entering another sector. Other problems we address are finding the expected length of a busy period of a node, and finding the expected time interval that the number of units at a node exceed a certain high level. Such information on "high-level" exceedances or extreme values of queueing networks is important for predicting extraordinary work loads (overtime) or emergency situations.

6 Relating the Waiting Times and Queue lengths in Heavy Traffic Systems by W. Szczotka, W. Topolski and the PI. To appear in *Stochastic Processes and Their Applications*, 1993.
For a single-server queueing system, intuition suggests that an arriving unit's waiting time before its service begins is approximately equal to the number of units in the system times the average service time. Why are there no results

to this effect? Because it is not true when the traffic intensity is moderate. However, we show that this approximation is indeed valid for certain systems in heavy traffic. We also give more insight into diffusion approximations for queueing systems. Namely, there are three types of natural diffusion approximations, not just the conventional reflected Brownian motion model. This analysis is a precursor to results for networks.

7 Extreme Values of Random Times in Stochastic Networks by Sungyeol Kang. A PhD dissertation in Industrial and Systems Engineering, Georgia Tech.

In manufacturing systems, a typical concern is the time it takes for a group of units that will eventually constitute one system to be processed by a network of work stations. This time is the maximum (or extreme value) of the travel times of the units through the network. An example is that 20 units must pass through a PERT network before they are brought together as one system. The individual network completion times often have distributions that are of phase type or are mixtures of such distributions. This dissertation is a study of extreme values of such distributions. We show that the extreme value distribution of a large sample is asymptotically a Gumbel distribution. We apply these results to model completion times in a Markov PERT network and for group travel times in open Jackson networks when the traffic is light or when the traffic is heavy and the special units are intersperced evenly among many other units.

8 Extreme Queues and Stationarity of Service Systems in Heavy Traffic by Kuo-Hwa Chang. A PhD dissertation in Industrial and Systems Engineering, Georgia Tech.

Knowledge of extreme queue lengths in service systems is needed for designing adequate space in manufacturing or communication systems or predicting when capacity constraints are violated. We show that the distribution of the maximum queue length in a time interval for a queueing system in heavy traffic converges to a new type of extreme value distribution. We also study the processes that record the number of times that the queue length exceeds a high level and the cumulative time the queue is above the level. We show that these processes converge in distribution to compound Poisson processes. The limiting extreme value distribution and compound Poisson processes we obtained can be used in practical computations similarly to the use of limiting normal distributions in central limit phenomena.

The second part of this study concerns a tree-like service system. Markovian network processes are frequently used for modeling service-system networks. However, most networks have dependencies that are not amenable to a Markovian analysis. An example of this is a network in which a unit requires the same service time at each node it visits. Furthermore, in a typical network, the service times and routing of the units may depend on each other. We study a tree-like network with very general non-Markovian dependency assumptions on the interarrival times, service times and routes. We give conditions under which the system is stable (the queue length does not tend to infinity). We show that the waiting times and queue lengths are stationary or asymptotically stationary under some natural conditions, and we characterize the limiting distribution of the system. Finally, we derive the limiting distribution of the waiting times when the traffic in the network is heavy.

9 Markov Interactive Processes by Akram A. Eltannir. A PhD dissertation in Industrial and Systems Engineering, Georgia Tech.

This study develops a new family of multivariate Markov processes called "Markov Interactive Processes". For one subclass of these processes in which several components of the process may change concurrently, the equilibrium distribution has a tractable product form. Although this type of distribution is typical for processes with one-at-a-time movements, it is novel for processes with concurrent movements. Using this distribution, we describe the performance of several network systems and service systems subject to outside random environmental factors. For more general Markov interactive processes, the equilibrium distribution is not tractable. We show, however, that such distributions can be approximated efficiently in the following situations: (a) When one of the components of the process has either very sluggish or very frequent transitions in comparison with the other components. (b) When a component stays in one state for a long while in comparision to its other states. (c) When a component is close to being equally likely to be in any one of its states.

This study also describes the equilibrium behavior of a Markov process whose space is partitioned into regions where one region is a "central region" in that transitions from a non-central region must go through the central one. We apply this model to describe networks systems in which individual routings of the units in this network have this central characteristic.

10 Performance Analysis of Time Warp With Limited Memory by I., L. Chen, S.R. Das, R.F.Fujimoto and the PI To appear in *IEEE Journal on Computer Software*, 1993.

A Time Warp parallel simulation consumes more memory than a serial simulation because it must store extra communication messages and information that may be rolled back (cancelled) due to synchronization constraints. We address the question of the effect of limited memory on the speed of certain simulations with homogeneous processors. Modeling the simulation by a Markov process, we found that the simulation speed increases very fast and then flattens out at a rather moderate level of memory. This shows that there is a reasonable memory threshold beyond which more memory is not really needed.