NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Laboratory for Information and Decision Systems Cambridge, MA 02139	Production Research	DAR-7817826
	4. Award Period From 8/1/78 To 1/31/82	5. Cumulative Award Amount $659,800

6. Project Title

SYSTEMS ASPECTS OF FLEXIBLE AUTOMATED MANUFACTURING NETWORKS

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The benefits expected for the factory from recent technological advances (such as flexible manufacturing systems, robots, VLSI, and local computer networks) will not be fully realized unless there is a corresponding improvement in the organization, management, and control of the production process. For that purpose, we have studied several specific relevant areas, including (a) transfer lines and assembly/disassembly networks, (b) deterministic scheduling, and (c) control of material flow in production systems with unreliable machines. The techniques employed include the formulation of Markov process models and numerical analysis for (a); complexity analysis and combinatorial optimization for (b); and mathematical modeling, hierarchical control, dynamic programming, and numerical analysis for (c). Simulation is also used to help formulate ideas and to test results.

We have found that certain design and control decisions, including the amount of buffer space made available for in-process inventory and the reconfiguration of the scheduling policy after a failure or a repair, can have a profound effect on the performance characteristics of systems. We have developed methods for treating these issues in small systems and we have evolved specific research directions for treating them in larger systems.

The FlexMan computer system has been developed in preliminary form. This system makes project results available to outside users who need not be expert in computers or in the methods employed. Passwords can be obtained by contacting the principal investigators.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (√)	Approx. Date
a. Abstracts of Theses		x			
b. Publication Citations		x			
c. Data on Scientific Collaborators		x			
d. Information on Inventions	x				
e. Technical Description of Project and Results			x	x	May, 1982
f. Other *(specify)* Symposium, other presentations, related activities		x			

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Stanley B. Gershwin Michael Athans	Stanley B Gershwin Michael Athans	April 22,'82

ATTACHMENT A

Brenda Pomerance	BS	EE&CS
Paul Dishop	BS	EE&CS
Mostafa H. Ammar	MS	EE&CS
Ellen L. Hahne	MS	EE&CS
John N. Tsitsiklis	MS	EE&CS
Magid M. Ibrahim	MS	Management
R. Paul Wiley	MS	EE&CS
Joseph G. Kimemia	Ph.D.	EE&CS

INVESTIGATION OF A 3-MACHINE TRANSFER LINE

by

Brenda Pomerance

Submitted to the Department of Electrical Engineering and Computer Science on May 25, 1979, in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science.

Abstract

A Markov model for a three machine two-buffer transfer line is presented. The line specification and operating parameters are discussed. Experience with the computer program used to obtain the steady state probabilities of the line is discussed.

The response of the operating parameters to variation in each of the specification parameters is described. Explanations for line behavior are presented. Through the explanations, an intuitive understanding of a three machine transfer line is obtained.

Thesis Supervisor: Stanley B. Gershwin

Title: Lecturer, Department of Electrical Engineering and Computer Science

BOUNDING METHODS FOR A K-MACHINE TRANSFER LINE

by

PAUL MARTIN DISHOP

Submitted to the Department of Electrical Engineering
on May 22, 1981 in partial fulfillment of the
requirements of the Degree of Bachelor of Science in
Electrical Engineering

ABSTRACT

The basic unit of a production system is the transfer line. A Markov model of the transfer line is presented. In the model, machines have geometric failure and repair probabilistic distributions and are separated by finite interstage buffers.

Several methods of obtaining upper and lower bounds on the throughput of k-machine lines are discussed. PL/I programs are presented which implement these bounds using existing programs that solve two- and three-machine transfer lines exactly.

Thesis Supervisor: Dr. Stanley B. Gershwin
Title: Principle Research Scientist,
Laboratory for Information and Decision Systems

MODELLING AND ANALYSIS OF UNRELIABLE MANUFACTURING ASSEMBLY NETWORKS WITH FINITE STORAGES

by

MOSTAFA HAMED AMMAR

Submitted to the Department of Electrical Engineering and Computer Science on May 23, 1980 in partial fulfillment of the requirements for the Degree of Master of Science.

ABSTRACT

A Markov chain, queueing theory model of an assembly network is presented, of which the transfer line is a special case. Machines are unreliable and buffers have finite capacities. The aim of the research is to calculate performance measures of such systems.

Fundamental equivalence properties, which include transfer line reversibility, are stated and proved. These properties group networks with different structures into equivalence classes. The relationship among the performance measures of members of the same equivalence class are discussed.

A method for obtaining measures of performance of the networks is presented. This is a systematized and slightly modified version of the one that appears in Gershwin and Schick(1980). The solution is complete for two- and three-machine systems, and conjectures are made into how it extends to larger systems.

Thesis Supervisor: Dr. Stanley B. Gershwin
Title: Lecturer, Department of Electrical Engineering and Computer Science; Principal Research Scientist, Laboratory for Information and Decision Systems.

DYNAMIC ROUTING IN AN UNRELIABLE MANUFACTURING NETWORK WITH LIMITED STORAGE

by

ELLEN LOUISE HAHNE

Submitted to the Department of Electrical Engineering and Computer Science on January 13, 1981 in partial fulfillment of the requirements for the Degree of Master of Science

ABSTRACT

Optimal dynamic routing strategies are computed for a simple manufacturing network with unreliable machines and finite storage buffers. A Markov process model of the system incorporates random processing times and random failures and repairs. Routing policies which maximize system throughput are computed using a variation of D. J. White's method of successive approximations. The optimal routing rule and several heuristics are compared with regard to structure and performance over wide ranges of the system parameters.

Thesis Supervisor: Dr. Stanley B. Gershwin

Title: Lecturer, Department of Electrical Engineering and Computer Science

Principal Research Scientist, Laboratory for Information and Decision Systems

Thesis Supervisor: Dr. Michael Athans

Title: Professor of Systems Science and Engineering

Director, Laboratory for Information and Decision Systems

OPTIMAL DYNAMIC ROUTING IN AN UNRELIABLE MANUFACTURING SYSTEM

by

JOHN NIKOLAOS TSITSIKLIS

Submitted to the Department of Electrical Engineering and Computer Science
on January 22, 1981 in partial fulfillment of the
requirements for the Degree of Master of Science in
Electrical Engineering and Computer Science

ABSTRACT

This thesis considers the optimal dynamic routing problem in a queueing system of three machines and two finite storage buffers. Machines are assumed to be failure prone and the material level in the buffers is assumed to be continuous. The objective is to optimize the long–run average performance of the system.

Cost–to–go functions of dynamic programming are defined and a set of partial differential equations for the cost–to–go functions is derived under any fixed dynamic routing strategy. Necessary and sufficient conditions for optimality involving the cost–to–go functions are also derived. Two iterative algorithms for optimizing the performance of the system are proposed.

The case where the average production rate of the system is to be maximized is considered in more detail and the particular case where the lead machine is perfectly reliable is completely solved, theoretically and numerically.

Thesis Supervisor:	Stanley B. Gershwin
Title:	Lecturer, Department of Electrical Engineering and Computer Science
	Principal Research Scientist, Laboratory for Information and Decision Systems
Thesis Supervisor:	Michael Athans
Title:	Professor of Systems Science and Engineering
	Director, Laboratory for Information and Decision Systems

Modeling and Analysis of Automated Manufacturing Systems with Focus on Equivalence and Computational Complexity

by

Magid Mounif Ibrahim

Submitted to the Alfred P. Sloan School of Management on May 20, 1980, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Unreliable automated manufacturing systems can be represented with Markov chain models. The research objective is to provide analytical tools for calculating performance measures of such systems.

A discrete material flow model is presented for general networks of unreliable machines and finite storage buffers. Fundamental equivalence properties are proved under some assumptions which are shown to hold for a large class of realistic systems.

A continuous material flow Markov chain model of a three-machine transfer line is discussed in two cases: 1) machines with equal processing speeds and 2) machines with different processing speeds. The state probability distribution is shown to be a solution of a system of partial differential equations. Some solution methods are analyzed and computational requirements are assessed. Based on this assessment conclusions and future research directions are suggested.

Thesis Supervisor: Stephen C. Graves
Associate Professor of Management

Thesis Cosupervisor: Stanley B. Gershwin
Lecturer, Department of Electrical Engineering and Computer Science
Principal Research Scientist, MIT Laboratory for Information and Decision Systems

ANALYSIS OF A TANDEM QUEUE MODEL OF A TRANSFER LINE

by

Richard Paul Wiley

Submitted to the Department of Electrical Engineering and Computer Science on September 30, 1981 in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

ABSTRACT

Transfer lines are modelled as a set of finite queues in series with exponential service times. Two models of machines are considered: the first assumes the machines are perfectly reliable and the second assumes the machines are subject to failures and repairs. The steady state probability distributions of three-machine transfer line models, with both types of machines, are sought by choosing a sum-of-products form for the probabilities. The performance parameters of the transfer line are then calculated using the steady state distribution.

The solution method is then extended to analyze the reliable three-machine transfer line where the first buffer is infinite. The sum-of-products solution form is shown to be related to the matrix geometric solution form in the context of the mentioned model.

Thesis Supervisor: Dr. Stanley B. Gershwin

Title: Senior Research Scientist, Laboratory for Information and Decision Systems

HIERARCHICAL CONTROL OF PRODUCTION IN FLEXIBLE MANUFACTURING SYSTEMS

by

JOSEPH GITHU KIMEMIA

Submitted in to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the Doctor of Philosophy Degree in Electrical Engineering

ABSTRACT

The problem of controlling production in an automated flexible manufacturing system (FMS) is described. The system consists of machines which can perform a variety of operations on a family of parts. The system also has a transport mechanism which delivers parts to and from machines, and internal and external storage buffers. Computers supervise the operations of all the elements of the FMS. The chief difficulty faced by the control system is to meet production requirements for the parts while the machines fail and become repaired at random times.

A multi-level hiearchical control algorithm is proposed. A flow control level continuously regulates the production rate for the part family. The paths that the parts follow within the system are chosen by the routing level of the algorithm. A sequence controller dispatches parts into the system so that the production and path flow rates are maintained.

The flow control level is formulated as an optimal control problem for a system subject to sudden change of structure. It is shown that optimal policies are feedback laws which are piece-wise constant. Sub-optimal control schemes which approximate the optimal policy are developed. Lower levels of the hierarchy guarantee that the production rates chosen by the flow control level are achieved.

A simulation model based on a planned electronic components assembly system is used to test the effectiveness of the hierarchical controller. Simulation results show that the multi-level algorithm is effective at meeting the demand on the FMS with low inprocess inventory provided that the production requirements are within the effective capacity of the system. A simple computational procedure for determining the effective capacity is developed.

Thesis Superviors: Dr. Dimitri Bertsekas

Title: Professor of Electrical Engineering

Dr. Stanley B. Gershwin

Title: Lecturer & Principal Research Scientist

ATTACHMENT B

Publications

Listed below are those papers or reports that were written or published after February 27, 1979. Earlier documents are listed in Attachment B of the final report of NSF Project APR76-12036.

Papers

Gershwin, S.B., M. Athans, and J. E. Ward, "Progress in Mathematical Methods for Manufacturing Systems, 1979," Record of the Seventh NSF Grantees' Conference on Production Research and Technology, Ithaca, New York, September, 1979. (Also issued as MIT LIDS Report LIDS-P-929.)

Gershwin, S.B. and M. Ammar, "Reliability in Flexible Manufacturing Systems, "Proceedings of the 18th IEEE Conference on Decision and Control," December, 1979. (Also issued as MIT LIDS Report LIDS-P-934, August, 1979.)

Ammar, M. H. and S. B. Gershwin, "Equivalence Relations in Queuing Models of Manufacturing Networks," Proceedings of the 19th IEEE Conference on Decision and Control, December, 1980. (Also issued as MIT LIDS Report LIDS-P-1027, revised, January, 1981.)

Gershwin, S.B., M. Athans, and J. E. Ward, "Progress in Mathematical Methods for Manufacturing Systems, 1980," Record of the Eighth NSF Grantees' Conference on Production Research and Technology. Stanford, California, January, 1981. (Also issued as MIT Report LIDS-P-1062.)

Gershwin, S.B., and O. Berman, "Analysis of Transfer Lines Consisting of Two Unreliable Machines with Random Processing Times and Finite Storage Buffers," AIIE Transactions, Volume 13, No. 1, March, 1981.

Gershwin, S.B., J. G. Kimemia, and E. R. Ducot, "Research in Complex Materials Handling and Assembly Systems, 1981," Record of the Ninth NSF Grantees' Conference on Production Research and Technology, Ann Arbor, Michigan, November, 1981. (Also issued as MIT Report LIDS-P-1133, August, 1981.)

Kimemia, J. G., and S. B. Gershwin, "An Algorithm for the Computer Control of Production In a Flexible Manufacturing System," Proceedings of the Twentieth IEEE Conference on Decision and Control, San Diego, California, December, 1981. (Also issued as MIT Report LIDS-P-1134, revised January 1982.)

Tsitsiklis, J. N., "Characterization of Optimal Policies in a Dynamic Routing Problem," submitted for publication to Journal of Optimization Theory and Applications. (Submitted as a revision of MIT Report LIDS-R-1178), February, 1982.

Gershwin, S. B., and I. C. Schick, "Modelling and Analysis of Three-Stage Transfer Lines with Unreliable Machines and Finite Buffers," to appear in Operations Research.

Kimemia, J. G., and S. B. Gershwin, "Flow Optimization in Flexible Manufacturing Systems," submitted to the International Journal of Production Research.

Kimemia, J. G., and S. B. Gershwin, "An Algorithm for the Computer Control of Production in a Flexible Manufacturing System," submitted AIIE Transactions.

Castanon, D. A., B. Levy, and S. B. Gershwin, "Diffusion Approximations for Three-Stage Transfer Lines with Unreliable Machines and Finite Buffers," submitted to the Twenty-First IEEE Conference on Decision and Control, Orlando, Florida, December, 1982.

Castanon, D. A., B. C. Levy, and S. B. Gershwin, "Diffusion Approximations of Transfer Lines with Unreliable Machines and Finite Storage Elements," submitted to Advances in Applied Probability. (Also issued as MIT LIDS Report LIDS-P-1183, March, 1982.)

Reports

Gershwin, S. B. and I. C. Schick, "Analysis of Transfer Lines Consisting of Three Unreliable Machines and Two Finite Storage Buffers", ESL-FR-834-9, August, 1979.

Hitz, K. L., "Scheduling of Flexible Flowshops," LIDS-R-879, March, 1979.

Berman, O., "Efficiency and Production Rate of a Transfer Line with Two Machines and A Finite Storage Buffer, "LIDS-R-899, April, 1979.

Kanellakis, P. C., and C. H. Papadimitriou, "Local Search for the Asymmetric Traveling Salesman Problem," LIDS-P-927, August, 1979.

Gershwin, S. B. and I. C. Schick, "Modelling and Analysis of Two- and Three- Stage Transler Lines with Unreliable Machines and Finite Buffers," LIDS-R-979, March, 1980.

Ammar, M. H., "Modelling and Analysis of Unreliable Manufacturing Assembly Networks with Finite Storages, "LIDS-TH-1004, June, 1980.

Ward, J. E., "TI-59 Calculator Programs for Three Two-Machine One-Buffer Transfer Line Models," LIDS-R-1009, November, 1981.

Gershwin, S. B., and I. C. Schick, "Continuous Model of an Unreliable Two-Stage Material Flow System with a Finite Interstage Buffer," LIDS-R-1039, September, 1980.

Ammar, M. M., and S. B. Gershwin, "A Partially Formulated Method for Solving Three-Machine Transfer Lines," LIDS-TM-1046.

Hitz, K. L., "Scheduling of Flexible Flow Shops-II," LIDS-R-1049, October, 1980.

Hahne, E. L., "Dynamic Routing in An Unreliable Manufacturing Network with Limited Storage," LIDS-TH-1063, February, 1981.

Tsitsiklis, J. N., "Optimal Dynamic Routing in an Unreliable Manufacturing System," LIDS-TH-1069, February, 1981.

Wiley, R. P., "Analysis of a Tandem Queue Model of a Transfer Line," LIDS-TH-1150, September, 1981.

Gershwin, S., B., "Manufacturing Systems Research in France--Trip Report, June, 1981," LIDS-P-1171, January 1982.

Ibrahim, M. M., "Modelling and Analysis of Automated Manufacturing Systems with Focus on Equivalence and Computational Complexity, "LIDS-TH-1190, December, 1981.

Pan, Y., "Analysis of Transfer Lines Consisting of Two Unreliable Machines and Finite Storage Buffers," in preparation.

Kimemia, J. G., "Hierarchical Control of Production in Flexible Manufacturing Systems," in preparation.

ATTACHMENT C

DATA ON SCIENTIFIC COLLABORATORS

David A. Castanon	Research Scientist
Nathan H. Cook	Professor (Mechanical Engineering)
Elizabeth R. Ducot	Research Staff
Bernard Levy	Assistant Professor (EE and CS)
Yuhuan Pan	Visiting Scientist
John E. Ward	Research Staff
Mostafa H. Ammar	Graduate Research Assistant
Ruth Bardenstein	Graduate Research Assistant
Magid M. Ibrahim	Graduate Research Assistant
Joseph G. Kimemia	Graduate Research Assistant
John N. Tsitsiklis	Graduate Research Assistant
R. Paul Wiley	Graduate Research Assistant
Leon Ekchian	Graduate Student
Ellen L. Hahne	Graduate Student
Paul Dishop	Undergraduate Student
Brenda Pomerance	Undergraduate Student

ATTACHMENT F

ADDITIONAL INFORMATION

1. Symposium

The M.I.T. Industrial Liaison Program held a symposium on "Automation Research" on February 24 and 25, 1981. The LIDS group, including Dr. Stanley B. Gershwin, Professor Michael Athans, Mr. Joseph G. Kimemia, and Ms. Elizabeth R. Ducot contributed a half-day session on "Automated Materials Handling and Manufacturing."

2. Additional Presentations

Dr. Stanley B. Gershwin made presentations on the subject matter of this project at:

University of Michigan, October, 1979
M.I.T. Sloan School of Management, December, 1979
University of Delaware, March, 1980
M.I.T. Laboratory for Manufacturing and Productivity, April, 1980
University of California, Berkeley, January, 1981
IBM Watson Research Center, March, 1981
Renssalaer Polytechnic Institute, April, 1981
Ford Engineering Laboratory, April, 1981
ORSA Conference, Toronto, May, 1981
Caterpillar Tractor, January, 1982
CAM-I, Inc. Conference, January, 1982

Mr. Mostafa H. Ammar also made a presentation to the ORSA Conference, Toronto, May, 1981. This presentation is discussed below.

Mr. Joseph G. Kimemia will present his results with Dr. Gershwin at:

Harvard University, April, 1982
Optimization Days Conference, Montreal, May, 1982

Dr. Gershwin will make a presentation at the

SME Conference, Philadelphia, May, 1982

Dr. Gershwin was Chairman of sessions on manufacturing systems at the IEEE Conference on Decision and Control in December, 1979, and December, 1981. He was co-chairman in December of 1980. He will be a session chairman in the SME conference in Philadelphia and the Optimization Days Conference in Montreal, both in May, 1982.

3. Associated Activities

a) The FlexMan system continues to be maintained with funds from the MIT Industrial Liaison Program. In addition, FlexMan is being made a part of some proposals that are written to continue our work in this area.

b) Dr. Gershwin was a guest of the Centre National de Recherche Scientifique of France in June of 1981. He had the opportunity of visiting many French laboratories that are studying manufacturing systems. A detailed trip report is available (LIDS-R-1171).

c) A proposal was submitted to the U.S. Army Human Engineering Laboratory at the Aberdeen Proving Ground for further research, specifically applied to the Letterkenny Army Depot in Chambersburg, PA. The proposal is currently in the procurement process and work is expected to begin in June, 1982.

d) Mr. Mostafa H. Ammar won Second Prize in the 1981 George Nicholson Student Paper Competition of ORSA/TIMS. He gave a talk at the May, 1981 Joint National Meeting of the Operations Research Society of America, The Institute of Management Sciences, and the Canadian Operations Research Society in Toronto, Ontario. The prize was awarded at that meeting.