17:15:51 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 02/23/95

Active

Project #: E-24-619 Cost share #: E-24-337 Rev #: 6
Center # : 10/24-6-R7673-0A0 Center shr #: 10/22-1-F7673-0A0 OCA file #:
Work type : RES
Contract#: DDM-9215564 Mod #: OPAS 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):
BARTHOLDI J J ISYE (404)894-3036

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

Award period: 921101 to 960430 (performance) 960731 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	150,000.00
Funded	0.00	150,000.00
Cost sharing amount		8,000.00

Does subcontracting plan apply ?: N

Title: PRODUCTION LINES THAT BALANCE THEMSELVES

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Bendall 894-4820

Sponsor technical contact

F. HANK GRANT
(202)357-5167

NATIONAL SCIENCE FOUNDATION
1800 G STREET, NW
WASHINGTON, DC 20550

Sponsor issuing office

MARTIN V. GEARY
(202)357-9602

NATIONAL SCIENCE FOUNDATION
1800 G STREET, NW
WASHINGTON, DC 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 -
ISSUED TO EXTEND PROJECT TERMINATION DATE TO APRIL 30, 1996 VIA OPAS FORM.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/29/97

Project No. E-24-619 Center No. 10/24-6-R7673-0A0

Project Director BARTHOLDI J J School/Lab ISYE

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-9215564 Contract Entity GTRC

Prime Contract No.

Title PRODUCTION LINES THAT BALANCE THEMSELVES

Effective Completion Date 960430 (Performance) 960731 (Reports)

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

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REPORT.

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	N
	N

E-24-619 SLT

September 14, 1993

Dr. Hank Grant
Operations Research and Production Systems
National Science Foundation
1800 G Street, NW Washington DC 20550

Dear Dr. Grant,

This is to report the progress made by my co-PI, Don Eisenstein, and me on grant #DDM-9215564, "Self-organizing logistics systems". Funding officially began last September so we have finished our first year.

As you might recall, we began our work by specializing in the apparel industry, where there has recently been introduced an unusual way of coordinating workers that requires them to move among the work stations. We refer to this as *TSS*, since that is the (trademarked) name used by the company that promotes this style of manufacturing in the apparel industry.

Our main accomplishment of this year has been to conclude that, by sequencing the workers along the production line from slowest to fastest, such a line becomes *self-balancing*; that is, without management intervention or intention by the workers, an optimal balance of work will spontaneously emerge.

We have also documented the practical value of our analysis. For example, there is reduced need to do time-motion studies—which are quite expensive—because the assignment of work to stations need not be perfect: any imbalances will be "smoothed over" by the movement of the workers. Also, such a line adapts sponaneously to perturbations; for example, when a worker takes a break the work content of the line will be spontaneously and optimally reallocated among the remaining workers. Also, unlike traditional assembly lines, the production rate can be cheaply and easily fine-tuned by simply adjusting the number of workers on the line. (In contrast, the production rate of a traditional assembly line can be adjusted only in coarse and expensive ways such as adding another shift or rebalancing the line.)

Our conclusion, that the workers should be sequenced from slowest to fastest, has been confirmed in three ways:

Mathematical analysis, in which we established the conclusion for a very general mathematical model

Site visits, during which we talked to many shop floor managers and workers. Visits included those to

- Americas 21st, Inc., Greenville, SC (Sep 23, 1992)
- Riverside Fashions, Norris, SC (Sep 23, 1992 and October 14, 1992)
- The Coach Factory, Carlstadt, NJ (Jan 29, 1993)
- Champion Products, Raleigh, NC (Apr 21, 1993)

Experiment , in which we filmed and analyzed the movements of actual workers on the shop floor at the Apparel Manufacturing Technology Center at the Southern College of Technology.

Invited talks include the following:

- Dynamics Days, Phoenix, January 1993 (conference of mathematicians and physicists)
- the TIMS/ORSA Joint National Meeting, Chicago, May 1993
- the IBM Manufacturing Productivity Symposium, October 1993
- Cornell University (to be scheduled)
- University of Michigan (to be scheduled)

We have completed one paper, "A production line that balances itself", and submitted it to *Operations Research.* (A copy is enclosed). Three additional papers are in draft form.

Meanwhile we have extended our work to warehouses, where we show that a variant of TSS can be applied so that the order-picking system becomes self-balancing. In this case the system spontaneously *tends* to reallocate work among the pickers to account for seasonal changes in demand or changing consumer preference. The analyis here is rather more difficult (at least for us) because it is heavily stochastic. We have enlisted the aid of Professor L. Bunimovich, a famous mathematical physicist who specializes in the dynamics of stochastic systems.

We are working with warehouses of SuperClub Videa in Atlanta and Rank Video Services America in Chicago to refine and validate our analysis. Again, we are keeping our mathematics firmly based in the real world, by testing our models in these warehouses.

During the remaining year of this project we intend to complete analysis of the warehouse system and try to extend some of these ideas to production lines that have more complicated topology than simple flow lines. IBM at Austin and Raleigh have expressed interest in our ideas and have invited us to visit their plants. This might provide us with a chance to test our ideas in still another manufacturing

environment.

Sincerely,

John J. Bartholdi, III
Professor e-mail:
john.bartholdi@isye.gatech.edu

cc: OCA, Georgia Tech

E-24-619
2

This is a copy of what I sent to NSF and OCA on June 5, 1996. NSF confirmed receipt.

Production Lines that Balance Themselves
NSF project 9215564
Final Report

John J. Bartholdi, III

December 6, 1996

1 Summary of completed project

The project devised, developed, and proved the concept of self-balancing production lines. We built mathematical models and rigorously analyzed their behavior; and then we implemented such lines in industrial settings, where they performed with great success. Our ideas seem most immediately applicable to order-picking in warehouses, where we believe they bid fair to replace the current standard technique of organizing pickers.

The basic idea is to sequence workers from slowest to fastest along a flow line; and to move work in process according to a "bucket brigade" protocol, in which each worker carries work forward until the last worker finishes and walks back to take over the worker of his predecessor, who walks back to get more work, until the first worker walks back to start a new item. Such a line will spontaneously re-allocate work to achieve the maximum production rate.

2 Technical information

- Papers submitted
  - J. J. Bartholdi, III and D. D. Eisenstein. "Bucket brigades: A self-organizing order-picking system for a warehouse", submitted (1996).
  - J. J. Bartholdi, III, D. D. Eisenstein, C. Jacobs-Blecha, and H. D. Ratliff. "Design of bucket brigade production lines", submitted to *Operations Research* (1995).
- Papers accepted
  - J. J. Bartholdi, III, L. A. Bunimovich, and D. D. Eisenstein. "Dynamics of 2- and 3-worker 'bucket brigade' production lines", accepted by *Operations Research* (1995).

- A. Ramudhin, J. J. Bartholdi, III, J. M. Calvin, J. H. Vande Vate, G. Weiss (1993). "A probabilistic analysis of 2-machine flowshops", to appear in *Operations Research.*

- Papers published

  - J. J. Bartholdi, III and D. D. Eisenstein. "A production line that balances itself", *Operations Research* **44**(1) (1996).
  - J. J. Bartholdi, III (1993). "An interactive program to balance assembly lines", *International Journal of Production Research* **31**(10):2447–2461.