INDEPENDENT AGENTS AND
SELF-ORGANIZING LOGISTICS SYSTEMS

John J. Bartholdi, III

August 1, 2006

Chapter 1

Project Summary

In a self-organizing logistics system effective coördination and allocation of resources arises spontaneously without management or explicit command. Furthermore, self-organization asserts itself at all times, even in the presence of disruption, and so produces behavior that is robust. This can be of enormous value in a military context, especially at times of crisis or rapid mobilization.

Examples of self-organizing logistics may be found among the social insects, such as ants or bees, where no individual is in charge and there is no blueprint or plan. Instead, global organization, such as allocation of foragers to food-gathering sites, arises spontaneously through the interactions of many simple agents.

In previous research we identified an instance of self-organizing logistics in the concept of "bucket brigades", which are a way of sharing work on an assembly line that results in the spontaneous emergence of balance and consequent high throughput. All this happens without a work-content model or traditional assembly-line balancing technology or attention by management.

In the next phase of research we propose to explore several variants of this idea. The most ambitious confer similar capacity for self-organization to the distribution of supplies through a multi-tier inventory system. This would apply, for example, to amphibious transport from sea base to maneuver units, in support of expeditionary operations. Self-organization in this context could confer exceptional robustness on a process that is notoriously subject to disruptions such as adverse weather, high seas, or hostile actions of the enemy.

Chapter 2

Project Description

We will continue to explore how to make logistics systems and supply chains *self-organizing*, by mimicry of the logistics systems of the social insects.

Our first success in this regard was the invention of "bucket brigades", a way of coördinating agents who are conveying product along a line to a common destination. The distinctive and valuable feature of bucket brigades is that they are self-balancing; that is, a perfectly-balanced allocation of work will spontaneously emerge, which reduces any need for the traditional industrial engineering technologies of time-motion studies, models of work-content, or assembly-line balancing. Furthermore, because they are self-organizing, bucket brigade assembly lines spontaneously adapt to the inevitable disruptions during operation.

We will continue this line of research along three fronts:

2.0.1 Implementation.

We will continue to implement bucket brigades in a variety of contexts, document experience in doing so, and, based on this experience, expand our models. We are currently working on two implementations: the Defense Distribution Center in Anniston, AL (see project report for more details) and Carolina Biological Supply (which would be our first implementation in an RF-guided environment and an important proof of concept). In each implementation there has been some new challenge that invites extended modeling so that we build a deeper understanding of self-organization. Among other things, we have learned that it is not always straightforward to adapt bucket brigades. In particular, one must be careful not to destroy the self-balancing mechanism.

2.0.2 Economic analysis of bucket brigades.

We will construct an economic analysis of the effectiveness of bucket brigades at the supply chain level. Previous analysis has been on a smaller scale, such as order-picking within the warehouse, where the emphasis is on throughput. At a supply chain level, there are other issues. Consider, for example, the trucking of supplies from Kuwait to Baghdad. Supplies are at risk en route. The closer supplies get to Baghdad, the more valuable they become, because more work has been invested in them and they are closer to use. From this economic perspective it then makes sense to consider passing loads to ever faster vehicles, so that the carried load accelerates as its value increases, thereby reducing expected value of any loss.

Other uses of bucket brigades

Some other possible uses of bucket brigades remain incompletely explored.

- Tactical use of chaotic behavior:

  Now that we have figured out the causes and conditions for chaos on a bucket brigade assembly line, we want to figure out how to utilize this surprising behavior. Here are two ways that seem worth exploring.

  Disruptive chaos: We would like to be able to induce chaotic behavior in the supply chain of an enemy, to make it uncontrollable (or at least to make it appear uncontrollable) by its owners.

  Constructive chaos: We would like to make our own supply chain appear tactically unpredictable by an enemy. We might do this by making the transfer of materièl appear chaotic.

- Bucket brigades on acyclic, directed networks

  We have adapted the bucket brigade protocol to function on "assembly trees" (directed trees, with all paths leading to a root node) [2]. This models the gathering of work-in-process, along different but converging paths, to a finished product or final destination. Recently, we have been able to do the same for distribution trees, in which all paths lead away from a root node, mimicking the flow of product out from a source. We suspect that this can be generalized to acyclic, directed networks. This might be applicable to problems of mobilization of military resources, wherein materièl may travel by many alternate routes to a final

3

destination. The goal is the self-organization of the transit modes to maximize flow of materièl to the destination: A self-organizing logistics system that would therefore be robust in the presence of disruption.

2.0.3 Independent agents in multi-path supply chains

Self-organization relies on some low-level, generally simple communication between the agents. For example, in bucket brigades the communication is the hand-off of work from one agent to another, with the requirement that agents take work only from agents of smaller index. In effect, this local interaction elicits individual behaviors, each of which contributes to the building of the optimal allocation of work.

This is similar to how social insects such as ants coordinate their supply chains: Individual ants deposit pheromones, which elicit behaviors from other ants that contribute to effective supply chains.

We propose to explore other expressions of this idea in (human) logistics.

When ants deposit pheromones, they send a parsimonious signal, embedding only two types of information. First, the particular chemical deposited elicits reactions specific to it (recruitment, repulsion, etc.). Second, the intensity of reaction is modulated by the intensity of the pheromone deposit, so that stronger scent typically results in stronger response. The pheromone may be reinforced by other ants to amplify the signal, or left to fade. Ant use such signaling in a variety of different ways, the most well-known of which is to recruit nest mates to a foraging path.

In a similar way, we believe we can assign a single number—a parsimonious signal—to each sku in a supply chain that can function like a pheromone, guiding the sku along the correct path to the consumer. Where sufficient information can be embedded in a parsimonious signal, this would allow simple and flexible decision-making all along the supply chain, as for the ants. When information can be compressed to a single number to be interpreted as intensity, then decision-making at every stage is reduced to "select the choice with strongest signal". Furthermore, a collection of strategies can be reduced to a sorted list, with insertions and deletions made simply and quickly. The trick, of course, is to identify when and how to embed the right information into a single number.

One idea for this is to further generalize a result of Hackman and Rosenblatt [3], recently extended by Bartholdi and Hackman [1]. The result, in its simplest form, describes how product should flow through a 2-echelon space-constrained supply chain, as in Figure 2.1.
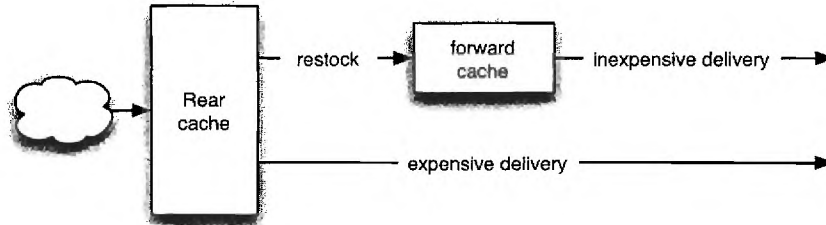
4

Figure 2.1: A 2-echelon supply chain

In this model, many skus (typically tens or hundreds of thousands) flow through the supply chain. There is limited space close to the customer, either because of the cost of retail space or the cost of specialized equipment, such as flow rack, or because the forwardmost area is a cache of supplies close to a war-fighting unit. Because of the nearness to the customer, product can be supplied quickly and cheaply from the forwardmost area, but at a cost of subsequent restocking, whereby larger batches are moved from upstream to the forward area.

This sort of economic choice is most familiar within a distribution center, where the forwardmost area is typically the "fast-pick" area, from which the most important product is picked. (Figure 2.2 shows such an area in the Defense Distribution Center in Susquahanna, PA.) The fast-pick area is the most important real estate in the distribution center, because of (expensive) specialized equipment, the concentration of labor, and the role it has in determining service levels to customers.

This economic structure also exists in larger scale. For example, the Defense Distribution Center in San Joaqin, CA has designated its entire Warehouse 16, with almost one million square feet, to be its fast-pick area, to be replenished as necessary from 22 outlying warehouses.

On a still larger scale—where we intend to focus this research—the forwardmost area might be local distribution points from which supplies are dispensed to troops, while the upstream storage might be an intermediate supply point such as Kuwait.

Hackman and Rosenblatt, as amended by Bartholdi and Hackman [1], showed that the skus with strongest claim to storage in the forwardmost area are those with largest value of:

$$\frac{\text{annual requests}}{\text{Average cubic volume per request}}. \tag{2.1}$$

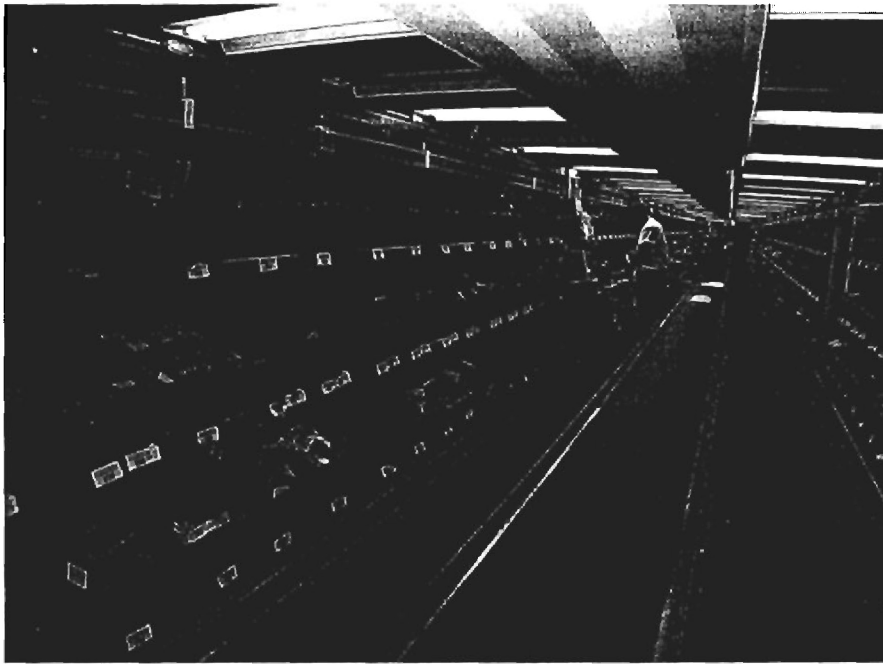We offer two ways of interpreting this result. One way is analogous to the parsi-

Figure 2.2: Forward pick area at Defense Distribution Center, Susquehanna, PA
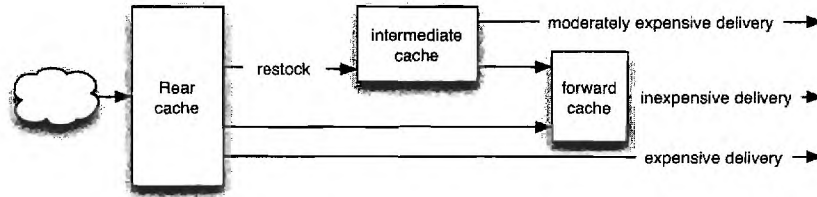
Figure 2.3: A multi-echelon supply chain with multiple paths to the customer

monious signaling by the ants: For each sku there are two possible paths through this 2-echelon supply chain and Expression 2.1 signals the attractiveness of a path (in this case the path through the fast-pick area) to the sku.

It is also possible to interpret this economically, in which Expression 2.1 is the marginal rate of savings to move a sku through the fast-pick area. But—and here is a key insight—this marginal cost summarizes in telescoped form *all the costs along the supply chain*: those of moving product into the forwardmost storage area and subsequently of moving it out. This is quite different from how such decisions are currently made in a distribution center, where the conventional wisdom is to flow the most popular skus through the fast-pick area. This, the conventional wisdom, is wrong because it looks only at the cost of picking the sku from the fast-pick area and ignores the cost of getting it there to begin with.

In preliminary work we have been able to generalize this idea of telescoping the economics of a sku into a single number. Our first tentative result is that, when there are more than one forward area, they can be ranked by cost of shipping product out of each, and then the skus with greatest value of Expression 2.1 have greatest claim to the forward areas that ship least expensively.

Our second tentative result is to show how the economics of any supply chain, of whatever depth and complexity, such as shown in Figure 2.3, can be telescoped down to those of a simple 2-level supply chain. The result is to convert any acyclic supply chain to a collection of independent 2-level supply chains to which our first tentative result applies.

These two results enable decision-making to be decentralized out to the skus, which can then act almost like independent commuters to find their ways from manufacturer to consumer. The decision-maker simply ranks each path through the supply chain by the cost of final delivery. Then each sku, in effect, builds a business plan particular to it,

7

which it offers for consideration. Then the decision-maker can allocate space through the supply chain by choosing the skus with the most attractive business plans. It is worth remarking that this approach seems well-suited to use with RFID tags, particularly the less-expensive and therefore most common, passive tags.

Just as for the ants, one need only distinguish between intensities of the signal. We believe this is a more effective approach than the traditional one of building monolithic optimization models and trying to solve them. Even when such a solution is possible for a monolithic model, it is likely to be both expensive and brittle (hard to update in the presence of changes or uncertainty). In contrast, a decentralized model lends itself naturally rapid construction of and dynamic adjustment to a solution because a good solution has, in effect, been precomputed and distributed amongst the skus competing for space in the supply chain.

We conjecture that routing n skus through m possible paths through a supply chain cannot be further from the optimum than the costs of m skus. Because the number n of skus may be in the tens or hundreds of thousands and the number m of paths may be in the tens, this error would be insignificant in practice.

Bibliography

[1] J. J. Bartholdi and S. T. Hackman. *Warehouse & Distribution Science*. 0.76 edition, 2006.

[2] J. J. III Bartholdi, D. D. Eisenstein, and Y. F. Lim. Bucket brigades on generalized assembly lines. *Eur. J. Oper. Res.*, 168(3):870–879, 2006.

[3] S. T. Hackman and M. J. Rosenblatt. Allocating items to an automated storage and retrieval system. *IIE Transactions: Industrial Engineering Research and Development*, 22(1):7–14, 1990.

Chapter 3

Short biography of the principle investigator

John Bartholdi holds the Manhattan Associates Chair of Supply Chain Management at the School of Industrial and Systems Engineering, Georgia Institute of Technology. He also serves as a Director of The Logistics Institute, one of the largest academic/industrial partnerships in the world.

His research has concentrated on issues of logistics and coördination, including scheduling, routing, distribution, material handling, production, and warehousing. This work has been supported by the National Science Foundation, the Office of Naval Research, the Air Force Office of Scientific Research, the Defense Logistics Agency, the Economic Development Board of Singapore, Pratt & Whitney, Ford Motor Company, Genuine Parts Co., The Home Depot, Manhattan Associates, and FedEx Ground.

Current work has focused on military logistics, in which he developed an interest while serving in US Navy Special Warfare during the US-Vietnam war. Bartholdi is currently advising in the re-layout of US Defense Distribution Centers for the Defense Logistics Agency; and on logistics and supply chain issues for the Ministry of Defence, Republic of Singapore.

Bartholdi was named a "Presidential Young Investigator" by U. S. President Ronald Reagan for 1984–1989. This was based largely on his work with Loren Platzman on vehicle-routing by spacefilling curves, some ideas of which were adopted by the US Strategic Defense Initiative. More recently, his work on order-picking in warehouses, which was supported by the National Science Foundation, was awarded the Prize for Technical Innovation by the Institute of Industrial Engineers in 1999. This work has been described in the Harvard Business Review and in National Geographic and many trade publications covering logistics and supply chain issues.

Bartholdi is co-author, with S. Hackman, of the book "Warehousing & Distribution Science", which employs mathematica and computer models to design and operate distribution facilities efficiently. In addition to the usual scholarly publications, he has published in journals as diverse as mechanical engineering, computer science, mathematics, political science, geography, and biology.

Bartholdi has international experience in logistics throughout Asia and North America. In addition, he has been a faculty member at the University of Michigan, Shanghai Institute of Mechanical Engineering, and the National University of Singapore.

Consulting clients include Yamaha Motor Manufacturing, Snapper Products, Genuine Parts Co., CAPS Logistics, C&S/Sovran Bank, United Technologies, and many others.

Bartholdi teaches courses in logistics at both the professional and the graduate level.

His former students have gone on to become vice-presidents, CEO's, and presidents of major supply chain companies, including Baan, Daewoo, Transplace.com, J. B. Hunt Logistics, Schneider Logistics. Others teach logistics at major research universities, including the University of Chicago, Carnegie Mellon University and the US Naval Postgraduate School.

Recent refereed publications

- Bartholdi, J. J. III, D. D. Eisenstein, and Y. F. Lim (2006). "Bucket brigades on generalized assembly lines", *European Journal of Operations Research*, **168**(3):870–879, special issue on balancing assembly and transfer lines

- Bartholdi, J. J. III and D. D. Eisenstein (2005). "Using bucket-brigades to migrate from craft manufacturing to assembly lines", *Manufacturing and Service Operations Management* **7**(2):121–129

- Bartholdi, J. J. III and P. Goldsman (2004). "The vertex-adjacency dual of a triangulated irregular network has a Hamiltonian cycle", *Operations Research Letters* **32**:304–308.

- Bartholdi, J. J. III and P. Goldsman (2004). "Multiresolution indexing of triangulated irregular networks", *IEEE Transactions on Visualization and Computer Graphics*, **10**(3):1–12.

- Bartholdi, J. J. III and K. R. Gue (2004). "The best shape for a crossdock", *Transportation Science*, **38**(2):235–244.

Chapter 4

Budget

Chapter 5

Report on activities June 2003–June 2006 under Grant #N00014-95-1-0380

5.1 Summary

5.1.1 Chaos and convergence in bucket brigades

Our most recent results have been to establish conditions under which a bucket brigade can and cannot behave chaotically—and there are some surprises.

We focused on a version of bucket brigades that is slightly more general than the Normative Model. These generalizations seem natural when using bucket brigades outside the warehouse or distribution center and in larger scenarios such as supply chains. The key differences of the new model are

- Agents are allowed to pass one another. The only restriction is that, when moving back toward the start of the flow line, an agent with a lower index must always relinquish his work-in-process to an agent of higher index.

- Each agent moves forward at one velocity v_i and back and another velocity w_i.

This version of bucket brigades better captures the flow of product outside a distribution center, such as when it is being conveyed by a fleet of trucks.

Our main results are that:

- A sufficient condition for spontaneous balance is that the workers be sequenced according to *who is slowed least by work*. This generalizes the slowest-to-fastest condition of our earlier work.

- If workers are sequenced other than as described above then the bucket brigade can, and likely will, exhibit chaotic behavior, with work completed at intervals that are indistinguishable from randomness. Perversely, it is possible that the system be driven into chaotic behavior as a result of one agent improving their skills and working faster.

This is only the second instance of provable chaos within a manufacturing model. (The other one is so highly idealized that its predictions would be very hard to observe in real life.) The arguments establishing chaos are quite delicate and technical—and have taken a long time to get right! But the result stands as a cautionary instance: That even a perfectly deterministic and simple system can behave with apparent randomness. This suggests that there might be some variability that is inherent in and ineradicable from the very process of manufacturing. What is even more surprising is that this variability can be so significant that it overwhelms the (deterministic) process.

18

To make this point more vivid, we constructed a bucket brigade with only two agents, with following astonishing properties:

- There are starting positions for which the points at which work is passed from the first agent to the second is both dense and unstable in the unit interval. That means that eventually a handoff will occur arbitrarily close to any given point in the work-content and so there can be no specialization of labor.

- The points of handoff are sensitively dependent on initial conditions.

- The set of starting positions that lead to periodic behavior are dense; but...

- For uncountably many starting positions, the agents will never hand off work at the same place.

- For almost all starting positions, the bucket brigade cannot be meaningfully simulated by any computer of only finite precision.

Chaotic behavior of an assembly line would have costs not only within the assembly line, but also upstream and downstream of the line. Most immediately, the apparently random locations of hand-offs would dilute any learning effect because workers would not experience a stable assignment of work. And because hand-offs could occur almost anywhere on the assembly line, the upstream worker must be prepared to be interrupted within any interval of work content, no matter how small and no matter where located in the sequence of assembly. This renders uneconomical the reëngineering of work to make hand-offs more efficient. In contrast, such improvements are possible when hand-off positions are known in advance, even if only approximately, as for traditional assembly lines; or for bucket brigades in which the workers have been indexed to match the convergence condition (most-slowed to least-slowed). But it is hard to improve the process when work is passed without pattern.

Another difficulty is that apparently random locations of hand-offs is manifest in similarly random completion times of products at the end of the assembly line. Therefore, downstream processes such as checking, packing, and shipping would see arrivals that appeared at random, even though the bucket brigade line was perfectly deterministic. Similarly, consumption of parts to support assembly would be apparently random. This will work against any attempt to achieve just-in-time production and will inflate requirements for safety stock.

19

5.1.2 Networks of bucket brigades

We took a first step towards implementing bucket brigades on networks by showing how the protocol could be adapted to produce self-organization on an "in-tree" assembly network, in which sub-assembly lines merge, with a final assembly line producing the finished product.

This work grew out of work with a factory producing Mitsubishi large screen color TV's. The paper appeared in *European J. Operational Res.*.

5.1.3 Bucket brigades with walk-back times

The original model of bucket brigades assumed that walk-backs happened instantaneously. This was not a reasonable model for a manufacturer of tractors that wanted to use bucket brigades, so we figured out how to adapt the protocol to allow for non-instantaneous walk-backs without destroying the self-balancing mechanism. Implementation was a success (throughput increased immediately) and the technical details of the model appeared in *Manufacturing and Operations Management*.

5.1.4 Other work

Collaborative logistics I have continued new work on integrating the supply chain. This arose from the question of how to share savings generated when parties coöperate but one is upstream of another? For example, the contract manufacturer Flextronics holds two separate caches of the same part for two different customers (downstream retailers). Obviously the supply chain would be more efficient if these inventories could be pooled; but how should the savings be shared among Flextronics and its customers? To be practical, any method of sharing savings must be transparent, fair (in some sense), and resistant to strategic manipulation. With E. Kemahlioglu I have undertaken to study various protocols for pooling inventory and sharing the savings. We have begun by examining Shapley value as a basis for allocating savings. Among the interesting results are the following:

- When there are two downstream retailers, allocating savings by Shapley value is in the core of the game; when there are more than two, it might not be in the core; but if demands at the retailers are independently and normally distributed, then it is in the core.

20

- Under Shapley value allocations, the upstream supplier would prefer to pool the inventory of many downstream retailers; but the retailers would prefer to share with only a few peers.

- Under Shapley value allocations, a downstream retailer would prefer to pool its inventory with either a peer with very high service level or else a peer with a significantly lower service level.

One paper from this effort has appeared in a book and the other has been submitted to *Management Science*.

Fair division   With Paul Goldsman I have tackled some problems in fair division. Among our results:

- An efficient procedure to solve a variety of division problems, including fair division and "ham sandwich cuts" in the plane

- An efficient procedure to construct a *super* fair division, wherein each participant feels he has received strictly more than his share

These results are currently described in working papers.

5.2   Details

5.2.1   Papers published in refereed journals

- Bartholdi, J. J. III, D. D. Eisenstein, and Y. F. Lim (2006). "Bucket brigades on generalized assembly lines", *European Journal of Operations Research*, **168**(3):870–879, special issue on balancing assembly and transfer lines

- Bartholdi, J. J. III and D. D. Eisenstein (2005). "Using bucket-brigades to migrate from craft manufacturing to assembly lines", *Manufacturing and Service Operations Management* **7**(2):121–129

- Bartholdi, J. J. III and P. Goldsman (2004). "The vertex-adjacency dual of a triangulated irregular network has a Hamiltonian cycle", *Operations Research Letters* **32**:304–308.

- Bartholdi, J. J. III and P. Goldsman (2004). "Multiresolution indexing of triangulated irregular networks", *IEEE Transactions on Visualization and Computer Graphics*, **10**(3):1–12.

21

- Bartholdi, J. J. III and K. R. Gue (2004). "The best shape for a crossdock", *Transportation Science*, **38**(2):235–244.

5.2.2 Papers submitted

- Bartholdi, J. J. III and D. D. Eisenstein (2006). "Chaos and convergence in bucket-brigades", submitted to *Operations Research*

- Bartholdi, J. J. III and E. Kemahlioglu (2006). "Centralizing inventory in supply chains by using Shapley value to allocate profits", submitted to *Management Science*

5.2.3 Conference presentations

- Command Leadership Conference of the Defense Distribution Center (April 2006); "Best practices in supply chain management"

- "Setting storage quantities in a forward-pick area", INFORMS San Francisco, November 2005

- "Self-organization in logistics: Lessons from the social insects", Department of Mathematics, Whitman College, October 2005,

- Centre for Scientific and Industrial Research, Johannesburg, South Africa (June 2005); "Designing a network of crossdocks"

- "Chaos and convergence in bucket brigade assembly lines", Northwestern University, May 2005

- "Mathematics of vehicle routing", Antioch College, March 2005

- "Chaos in bucket brigades", Department of Industrial and Systems Engineering, Auburn University, February 2005

- "Optimizing large-scale LTL freight networks", Depto. de Ingeniería Industrial y de Sistemas de la Universidad Católica de Chile, March 2004, Santiago, Chile

- "Computing optimal load plans in a less-than-truckload freight network", International Workshop on IT-Enabled Manufacturing, Logistics, and Supply Chain Management, December 2003, Bangalore, India

- At INFORMS Atlanta, October 2003:

  - With E. Kemahlioglu: Inventory Management for a Supply Chain with Coalition-Forming Players

  - With S. Jernigan: Minimizing Picking and Restocking Costs in Multi-Tier Inventory Systems

  - With D. Eisenstein: Bucket Brigade Assembly with Walk-Back and Hand-off Times

  - With D. Dave: Freight Routing in Less-than-Truckload Networks

- "Self-organization in logistics", Naval Postgraduate School, Monterey, CA, April 2003

5.2.4 Books or book chapters published

- *Warehouse & Distribution Science*, J. J. Bartholdi and S. T. Hackman. This is under constant revision and is freely available on the web (www.warehouse-science. com). It is in use by more than twenty universities around the world, including MIT, Purdue, Auburn, and Arkansas. There is also extensive supporting material on the web site.

- Bartholdi, J. J. III and E. Kemahlioglu (2005). "Using Shapley value to allocate savings in a supply chain", in *Supply Chain Optimization*, J. Geunes and P. Pardalos (Eds.), Springer-Verlag, ISBN 0-387-26280-6.

5.2.5 Patents

(None)

5.2.6 Honors received by any ONR-supported personnel

- John Bartholdi was named an INFORMS Fellow in 2005.

- 2004: Yun-Fong Lim was selected to attend the IIE Doctoral Colloquium.

- 2003: Eda Kemahlioglu was selected to attend the INFORMS Doctoral Colloquium.

Other recognition

Most of page 1 of the Business Section of the *Atlanta Journal-Constitution* (Sunday 11 June 2006) was devoted to my work with bucket brigades ("Ants' efficiency inspires supply chain experts"). Two additional articles described related supply chain research in which I am engaged. Some of this was also covered in a leading German newspaper, *Die Welt* (26 June 2006).

My work on bucket brigades will also be described in a forthcoming article in *National Geographic*, tentatively entitled "swarm intelligence".

Other descriptions of my work on self-organizing logistics systems have appeared in *Harvard Business Review* (May 2001; "Swarm intelligence: a whole new way to think about business" by E. Bonabeau and C. Meyer); and in the trade publication *SMC³ Quarterly Review* (July 2002; "Tech researchers study optimal location of LTL hubs").

All of the research described acknowledges support of the Office of Naval Research.

5.2.7 Number of graduate students supported by ONR funds

Three: Eda Kemahlioglu, Lim Yun-Fong, and Oran Kitterthreeapronchai

Eda has accepted a tenure-track appointment at the Kenan School of Business, University of North Carolina; and Yun-Fong a tenure-track position at the Singapore Management University. Oran has not yet graduated.

5.2.8 Number of post-doctoral researchers supported by ONR funds

Four: Dr. P. Goldsman (USA); Professor C. Mbohwa (Zimbabwe); Professor S. Maturana (Chile); Professor E. P. Chew (Singapore)

5.2.9 Number of undergraduate students supported by ONR funds

One: Yang Yang

5.2.10 Number of underrepresented individuals supported by ONR funds

One: Eda Kemahlioglu (female). She has now graduated and holds a tenure-track faculty position at the Kenan School of Business, University of North Carolina, Chapel

Hill.

5.2.11 Interaction

- Interaction with DoD:

    - COL Ed Visker, Chief of Staff, DDC. He visited me at Georgia Tech in November 2005 and subsequently I visited him at the Defense Distribution Center at Susquahanna, PA, in April 2006.

    - Charles E. Elston, Chief Distribution Division #1, Defense Distribution Center, Anniston, Alabama: advising on implementing bucket brigades to coordinate order-picking from the fast-pick area for small parts

    - I have had initial discussions with COL J. D. Serrano, Commander Defense Distribution Center San Joaquin, and with CDR B. Bailey, Commander Defense Distribution Center Puget Sound, about optimizing layouts, slotting, and bucket brigades.

- Interaction with companies:

    - The Home Depot: Developing tools to locate crossdocks and route freight

    - International Truck & Engine, S. P. Richards Co., Manh Assoc, Staples, Nordstrom: Data-mining customer orders to infer how to stage product for easy retrieval

    - United Distributors, Sanofi Aventis (healthcare), Carolina Biological Supply, Radio Shack: advising on use of bucket brigades in distribution centers.

    - Associated Hygienic Products: facility layout

    - Northrup Grumman (a DoD contractor): initial discussions