**Carl Anderson and John J. Bartholdi, III** (2000). Centralized versus decentralized control in manufacturing: lessons from social insects. Pages 92–105 in "*Complexity and Complex Systems in Industry*," Proceedings, University of Warwick, 19th–20th September 2000, (McCarthy, I. P. and Rakotobe-Joel, T., Eds.). The University of Warwick, U.K. 652 pp. [ISBN 0 902683 50 0]

# Centralized versus decentralized control in manufacturing: lessons from social insects

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## ABSTRACT

In our increasingly competitive world, companies must become more flexible, adaptive and responsive. However, this can be difficult in the face of complexities and uncertainties such as worker absenteeism, machine breakdown, and variation in customer behavior. One group of economies that exhibits such flexibility, even in highly unpredictable environments, is social insects: colonies of ants, bees, wasps, and termites. Because insect societies 1) exhibit the flexible and adaptive behavior desired by industry, 2) achieve this flexibility without any central planning or management, and 3) must coordinate many workers, we posit that they may be an important model system for industrial logistics. We explore some of the strong parallels that exist between industrial and social insect operation supporting our claims with case studies from both areas. We highlight issues and insights from our knowledge of insect society operation that may have real practical implications in industrial logistical operation.

## 1. INTRODUCTION

Many authors have noted that in our increasingly competitive world, companies need to become more flexible, adaptive, and responsive to customers' needs (e.g. Drucker 1988; Hayes & Pisano 1994; Castells 1996; Kelly 1998). A general shift is reported from the more traditional hierarchy-based organizational structure to flatter and more market-based economies. Numerous companies are adopting "supply chain" models in which they attempt simultaneously to increase the integration and coordination between their operations and those of their suppliers and customers (e.g. Bowersox 1991; Castells 1996; Nelson 1998; Sweeney 2000). Unfortunately, faced with the complexities and uncertainties of industry and customer behavior, such integration and coordination in an efficient and adaptive manner can be extremely difficult. However, one group of "economies" that has achieved this goal and has proven extremely successful—and has been doing this not just for many years, but many *millions* of years—are the social insects: ants, bees, wasps, and termites.

Insect societies, a term that refers explicitly to the colony level in social insects, are just as much an economy as any factory and importantly face the same logistical challenges. For instance, insect societies must cope with competition for resources and often must deal with a widely changing and unpredictable environment (e.g. Wilson 1971; Seeley 1995). In addition, colonies may be enormous, requiring the coordination of hundreds of thousands, and in some cases, millions, of workers. Contrary to popular belief, the colonies' activities are generally not coordinated in a centralized manner by the queen(s) but exhibit a very flat organizational structure. Individual workers do not have a global picture of colony operation but act upon local information in real time using simple rules and simple responses (Bonabeau et al. 1997, 1999; Karsai 1999). The result however, of many individuals concurrently acting in such a manner means that a colony is not just a collection of small-brained individuals, but a complex adaptive system (e.g. Seeley 1997; Bonabeau 1998). Because insect societies 1) exhibit the flexible and adaptive behavior desired by industry, 2) achieve this flexibility without any central planning or management, and 3) they must coordinate many workers, we posit that they may be an important model system for industrial logistics.

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This study considers some of the strong parallels between the logistics of industry and insect societies. We highlight issues and insights from our knowledge of insect society operation that may have real practical implications in industrial logistical operation. Traditionally, industrial logistics operate in a centralized paradigm; For instance, a single computer model is often used to update and configure a logistically complex manufacturing process. In contrast, insect societies operate in a decentralized paradigm, i.e. they contain many simple local computational units—the workers themselves—and harness the power of the complex system itself through self-organization (Seeley 1995; Bonabeau et al. 1997). Because of this disparity we have found it useful to frame the rest of the discussion in the context of these two diametrically opposed paradigms (which we first briefly review in a general context). Our claim is that industry, in many situations, should consider making the transition from the centralized to the decentralized paradigm to increase efficiency, and study of insect societies may illustrate why this is so.

To support our claims we include case studies from both industry and biology. A number of these examples highlight the huge practical benefits obtained by industry after adopting decentralized operations inspired by insect societies, while, importantly, some examples highlight the potential perils of implementation of these procedures in the wrong context or situation. Several examples demonstrate particularly strong parallels between industry and insect societies, including some comparisons that have not previously been discussed. While some of these examples are a result of industry taking inspiration directly from social insects, others are the result of "convergent evolution," that is, industry and evolution arriving at the same solution because the problem and relevant issues are the same in both cases. In either case, our overall message is the same: industry may have much to learn from these individually simple but collectively complex creatures.

Table 1: Various characteristics of the centralized and decentralized paradigms.

| | **Centralized** | **Decentralized** |
|---|---|---|
| Processing units (PUs) are usually | expensive | cheap |
| PUs' information is | global | local |
| Data collection process is often | expensive | cheap |
| PUs' data processing algorithm is usually | complex | simple |
| Generally PU's can process data | slowly | quickly |
| "System" robust to a PU failure | no | yes |
| System can get caught in pathological situations | no | yes |
| System can check for global maximum | yes | no |
| PUs usually operate | on scheduled basis | in real time |

## 2. THE CENTRALIZED VERSUS DECENTRALIZED PARADIGM

In Table 1 we summarize a number of features of a centralized and decentralized paradigm. The centralized paradigm is characterized by a complex and omniscient processing unit that is tailor made to solve the problem at hand. As the unit must gather the data from the whole system, its solution algorithms are necessarily complex and problem specific, and cannot easily cope with missing data (Deneubourg et al. 1991). Being problem specific these processing units are potentially able to check that a solution is the globally optimal solution and not some local maximum, and this is not easily achieved in a decentralized paradigm (see below). However, having to utilize more complex algorithms and analyzing more information to obtain a solution means that centralized controllers are often slower at finding a solution than in a decentralized system. Decentralized systems are based upon distributed control in which individual components, e.g. order pickers, robots, paint booths etc., react to local conditions in real time. These components are linked to neighboring components forming a network that can exhibit the desired adaptive behavior (but at some communication cost). Importantly, this approach does not necessarily require complexity at the level of the individual components: the complex adaptive behavior is an emergent property of the system of connections (e.g. Lewin 1995; Bonabeau et al. 1997).

**BOX 1: Bucket brigades in assembly lines and foraging ants**

One way to avoid the expense of time and motion studies is to configure an assembly line so that it balances itself. A self balancing line shares work optimally but without management or engineering ever having to measure that work. Bucket brigades in assembly and distribution are such an example (Bartholdi & Eisenstein 1996; Bartholdi et al. 1999, in press; http://www.isye.gatech.edu/people/faculty/John_Bartholdi/bucket-brigades.html). The operation of bucket brigades is simple: each worker on an assembly line carries a product towards completion. However, when the last worker on the line finishes the product, he sends it off and then walks upstream to take over the work of his predecessor, who in turn walks back to take over the work of his predecessor and so on. (No overtaking is allowed.) Finally, after relinquishing his product, the first worker walks back to the start to begin a new product. When workers are sequenced from slowest to fastest (along direction of product flow) then it can be shown empirically, and proven mathematically, that workers spontaneously gravitate to the optimal division of work so that throughput is maximized.

Bucket brigades are self-organized and thus reduce the need for planning and management because they require no work-content model to share work effectively. Instead, the work is measured by doing it; and workers gravitate to the best division of labor. Furthermore, production is more flexible, agile, and robust than other forms of work organization, such as "zone picking" (e.g. Frazelle 1992), because the assembly line spontaneously rebalances itself to account for disruptions or changes in the work. Agility is also enhanced because bucket brigades reduce work-in-process. Finally, the simple decentralized rule that characterizes bucket brigades makes it is easier to train workers: Everyone follows the same simple rule and so everyone knows what to do next. This can be especially important in supply chains satisfying retail demand, for which work is highly seasonal and which may require employing temporary workers.

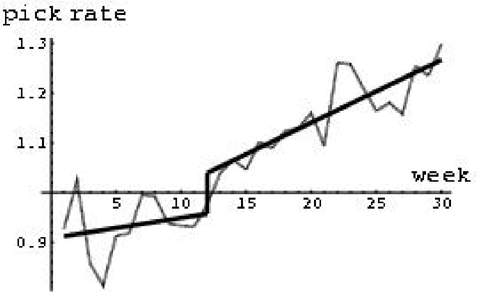

**Figure 1: Average pick rates as fraction of work standard both before, and after, switching from zone picking to bucket brigades (in week 12). The solid line represents best fit to weekly average pick rates**

Bucket brigades have proven spectacularly successful at many industrial sites. For example, the national distribution center of *Revco Drugstores* (now *CVS*) achieved a 34% increase in throughput among its order-pickers after converting from a centralized scheme—in which an industrial engineer daily computed a plan for work-sharing—to bucket brigades—in which optimal work-sharing spontaneously emerges (Fig. 1).

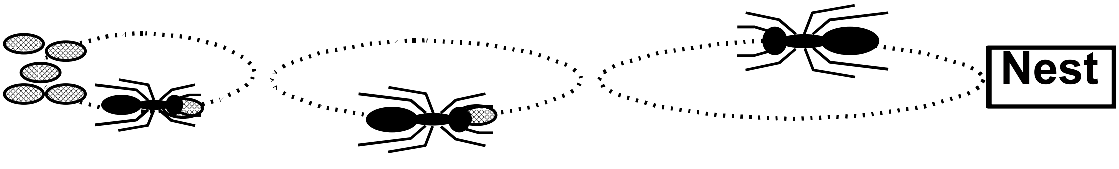

**Figure 2: a bucket brigade in ants**

Interestingly, a strikingly similar pattern of sharing work has been observed in forage retrieval in ants (Reyes & Fernández 1999). *Messor barbarus* ants in southern Spain sometimes retrieve seeds from a source in what appears to be a bucket brigade of up to six workers. The first and smallest ant collects a seed from a source and starts to carry it along a trail towards the nest until it meets a larger worker (Fig. 2). This larger worker takes the seed from the ant and continues to transport the seed towards the nest while the smaller ant turns and walks back towards the seed source. In turn, the larger ant continues along the trail until its seed is taken away by an empty-handed and even larger ant, and so on. The obvious sequence of transfers, they way that ants turnabout and head back towards the source when unladen, and the sequencing of ants from smallest to largest are all very suggestive of bucket brigades.

Under a centralized paradigm, to accomplish both efficient staffing and work-sharing, industrial organizations devote significant engineering time to building and maintaining work-content models. Managers must know how much work is to be done in order to staff for it, and the costs of over- or under-staffing can be severe. Furthermore, to ensure smooth, efficient flow of product along an assembly line, managers must be able to partition and share tasks among the workers. Obtaining the input data for these models is often an expensive and lengthy process: Although data on machine production rates can be collected automatically, worker input data often has to be collected manually through time and motion studies. Indeed this is frequently the major responsibility of the industrial engineering department of any industrial enterprise. Two examples highlight the magnitude of these costs: For the past 17 years, an american food distributor has employed two engineers and one programmer, full time, to establish and maintain work standards in their warehouses, costing an estimated $ 250K annually (Bill Little, *Manhattan Associates*, pers. comm.). Also, *E-Z-Go*, a division of *Textron* (*United Technologies*) hired an engineer to define and produce standard times for the 148 tasks of their golf cart assembly line. This work initially took six months but was effectively a constant process after this period because the assembly line was continuously tweaked and redesigned (Bartholdi 1993 and unpublished data). Under a decentralized paradigm, these costs are greatly reduced because workers react directly to readily available data from their own output and immediate environment and make small local adjustments accordingly (e.g. bucket brigades, Box 1).

One of the most important differences between the two paradigms is system robustness. In a decentralized system, failure of the centralized coordinator can potentially cause catastrophic failure of the whole system (see Box 2). Decentralized systems, on the other hand, tend to be more robust to failure: In general, failure of one of the lower level coordinators does *not* cause system-wide failure and the system can absorb these perturbations and readjust quickly. Thus, if an ant on a foraging trail gets lost then that may represent the loss to the colony of both a forager and its load (if laden), but the foraging system, even if highly cooperative, will continue to function. In fact, insect societies appear to be “designed” around high system redundancy (e.g. Oster and Wilson 1978; Anderson & McShea in press).

## 3. RECONFIGURATION COSTS

There are occasions when the centralized paradigm may be favored over the decentralized paradigm. The centralized paradigm is usually favored when industry faces some complex but *static* problem (e.g. Bonabeau et al. 1999), for instance, determining the best locations for a set of warehouses and crossdocks. This is because a centralized system is more likely to find the global solution, and not some local maximum (Table 1 and below). Importantly, with a static problem any costs associated with a suboptimal solution will be faced in perpetuity, e.g. each and every delivery to a poorly located crossdock.

When the problem is dynamic then decentralized control systems may be favored, especially when reconfiguration costs are low. Dynamic problems are typical for industry in the face of varying customer orders, worker absenteeism, machine breakdown etc. Thus, hereafter we solely consider such problems. Decentralized systems necessarily make continuous adjustments to track the optimal solution. So, when reconfiguration costs are low then the real time changes and improvements afforded by a decentralized paradigm are likely to be favorable. A clear demonstration of low cost, continuous, and self-organized adjustment in manufacturing is the implementation of “bucket brigades” during assembly and distribution (Bartholdi & Eisenstein 1996; Bartholdi et al. 1999; Bartholdi et al., in press), a scheme that was subsequently observed in foraging ants (Reyes & Fernández 1999). See Box 1. Another example of low cost continuous adjustment in an industrial application, but this time a scheme that was *directly inspired* from ant foraging studies, concerns self-organized routing of telephone calls. This is one of the best demonstrations of an efficient, adaptive, and decentralized system based upon specific knowledge of emergent behavior in insect societies and is detailed in Box 2.

## BOX 2: Ant-foraging inspired routing of telephone calls

Various researchers (e.g. Appleby & Steward 1994; Schoonderwoerd et al. 1996; Guérin 1997; Bonabeau et al. 1998) have developed the notion that telephone calls and data packets can be efficiently routed across a telecommunications network using the feedback principles of pheromone trails in ant foraging behavior.

The approach was originally developed to improve routing efficiency on *British Telecom*'s (*BT*) national digital exchange (SDH) network. The problem is thus: When a telephone call is made it may be routed through many telephone exchanges before it arrives at its destination. However, these exchanges can only handle a finite number of calls concurrently and when demand exceeds this capacity the calls "fails," i.e. the caller gets cut off. In addition, demand may fluctuate widely and unpredictably so that a single event, such as a television phone-in competition, may cause many calls to be directed to a single destination. The goal is to route the calls evenly across the network thus maximizing the amount of spare capacity at the exchanges: Consequently, call failure will be reduced (Geake 1994).

*BT* has adopted a centralized approach to route calls using a program composed of tens of *millions* of lines of code (the program is so big that no-one knows the actual value) and incredibly employed half of the computer programmers in the U.K. (C. Winter, formerly of *BT*, pers. comm.). Such a centralized approach is not robust: in 1991, six of the seven million telephone lines in Washington DC were immobilized due to an incorrect digit in the centralized routing program. This caused a cascade reaction as calls were routed from one overloaded exchange to another. However, more recently agent-based research demonstrated that a population of "ant" software agents, each only several *hundred* lines of code, could efficiently spread the call load across the network and reduce call failure. In a similar way that foragers of some ant species lay a chemical trail that informs other ants from the colony of activity on different parts of the foraging trail network, especially at junctions where the trail splits, the software "ants" lay an electronic trail as they move across the network. The ants explore the network laying trails and greater ant traffic flows though less congested areas (i.e. greater spare capacity of the exchanges) so that a stronger "pheromone" trail persists. As a telephone call moves across the network to its destination it uses the ant's information, the relative strength of trails on the different possible routes leading from an exchange, to decide to which exchange it should move next. In turn, a call passing through an exchange reduces that exchange's spare capacity and thus the rate of flow of ant traffic and pheromone deposition. This interplay between ants and calls generates a very robust system that diverts calls away from congested areas. For "popular" accounts of this system see Geake (1994), Ward (1998), and Bonabeau and Théraulaz (2000). More detailed and technical reports are to be found in the original papers (above) and in Bonabeau et al. (1999: 80–93).

When the environment is extremely variable and unpredictable and the costs of reconfiguring a process are particularly high then the centralized paradigm may once again be favored (e.g. Pol & Akkermans 2000). With such conditions, the process should ideally be conservative and minimize those changes otherwise it likely faces the undesirable situation of constantly lagging behind the optimal solution in a suboptimal configuration. This can be taken to be analogous to the "Red Queen" principle in biology (van Valen 1973). In Lewis Carroll's book "*Through the looking glass*" while chasing the Red Queen Alice remarks "In this place it takes all the running you can do, to keep in the same place." This concept was developed by van Valen to describe the necessary changes during co-evolution and arms races. This manufacturing context can be considered as a race between the optimal solution of a continuously changing environment and the configuration of the manufacturing attempting to match it. With high reconfiguration costs, a controlling process should ideally be conservative and minimize those changes. This is something that may be more easily, but not exclusively (Bonabeau et al. 2000 and below), achieved under the centralized paradigm because data may be collated for a period before being acted upon. For instance, Miller (1981) cites a company in which its centralized manufacturing control system was purposely slowed to protect manufacturing from costly changes. Similarly, *Johnson and Johnson* once linked its diaper production facilities directly to *Wal*Mart*'s diaper sales figures. They hoped that such intimacy between supply and demand would essentially help production pre-empt changes in orders from *Wal*Mart* (J. R. Kellso, *Intel*, pers. comm.). Unfortunately however, it transpired that factory reconfiguration costs were expensive enough that it was more profitable to collate sales data over longer periods and only make changes when really necessary. This is particularly applicable when dealing with products, such as diapers, that can easily be stored as spare and emergency inventory.

Even if reconfiguration costs are not low, then a decentralized paradigm can still be useful. Even self-organized systems can be programmed to be conservative when individual units follow a rule such as "I will continue to carry on doing my current job unless there is some important reason for me to change." Box 3 details a clear example of convergent evolution in manufacturing and insect societies utilizing such as rule.

## 4. CUES VERSUS SIGNALS

In relatively complex insect societies it is found that coordination and regulation is often mediated through cues rather than signals (Seeley 1995, 1998; Anderson & McShea, in press), and we suggest that cues may form an important, but currently underutilized, component of manufacturing control. The difference between a signal and a cue is subtle but important: A signal is a deliberate act of communication which has somehow been "*designed*" (in biology by natural selection, and in manufacturing by an engineer) to provide clear and unambiguous information. For instance, an order form or a warning light on a piece of machinery, are both signals. In contrast, a cue also provides information but only incidentally; in short, it has *not* been designed (Lloyd 1983). For instance, the size of a pile of raw material tells you something—we have little/much raw material available—but that pile wasn't designed to provide that information. Similarly, black fumes bellowing from a piece of machinery probably indicates that something is wrong but the engineer did not design the machinery to produce the fumes when there is a problem.

Why may cues be particularly useful? Seeley (1995) argues that in honey bees, group level cues are effectively a summation of many individuals' inputs and thus are expected to be more reliable as an information source. Second, these variables are likely more easily sensed than the underlying variables of supply and demand. Both of these are expected to be of potential importance in manufacturing. Consider a computer manufacturer that takes components from inventory to build a finished product. To calculate the optimal amount of inventory (or forecast when to reorder goods) is a challenge when customer orders are highly unpredictable and variable, and suppliers are unreliable. However, what is of primary importance is that the company does not run out of product with which to construct its computers. The amount of inventory is a powerful cue about when to reorder stock because it a summary of the overall effects of supply and demand in the same way that "population size" is a summary of the combined effects of the underlying, and more complex, variables of birth, death, immigration, and emigration (e.g. Krebs 1994). Moreover, because it is a reliable indicator then the amount of inventory can be linked directly to the supplier so that more product is shipped automatically whenever inventory falls below some threshold level. This is expected to be a growing trend in manufacturing (J.R. Kellso, *Intel*, pers. comm.) and is certainly aligned with the continuous and real time reactions of insect societies.

### BOX 3: Ants, bees, and truck painting

Morley and Eckberg (1998; also Morley 1996) report that at a *GM* automobile plant, trucks roll off the assembly line at the rate of one per minute and are allocated to a booth for painting. Each truck has a pre-assigned color based upon the customer's order and painting takes three minutes. Unfortunately, it takes around two minutes for a booth to switch paint color, which can cause a bottleneck, and is expensive due to wasted paint. Therefore, the aim is to minimize the amount of reconfigurations online.

They implemented a simple market-based approach in which the different paint booths consulted a list of the trucks to be painted and "bid" for trucks to paint. The quality of the bid was directly related to the cost of switching to another color. A booth currently set up for the required color would not have to switch. This saves both paint and time and thus constitutes a high bid for the job. Sometimes an important rush job appears on the list and a booth can put in a medium level bid: "I would have to switch colors, but I can accept this job." Lastly, failing the above conditions, a booth could put in a low bid: "I am available and will accept any job." This market was implemented online with decisions made within a tenth of a second. The scheme produces an efficient self-organized process in which the scheduling of trucks through the booths is produced not centrally but decentrally from the set of booths themselves. The scheme paid great dividends in that there was a 10% reduction in paint usage, half as many paint changeovers, higher global throughput, and overall savings of $3 million per year (ibid.).

Social insects face similar issues as the paint booths and appear to divide their labor using similar mechanisms (Bonabeau et al. 1999; Bonabeau & Théraulaz 2000). Thus, switching from one task to another introduces a cost. For instance, a honey bee forager who switches to an internal task, such as tending brood, may introduce disease into the nest. Conversely, a worker who switches from an internal task to foraging will likely have poorer information concerning where the best forage is to be found than an experienced forager. Switching among internal tasks may also introduce costs because of differences in abilities to perform the tasks. For instance, large "major" ants are not particularly adept at tending the brood, and so they generally avoid this task and concentrate on other tasks, such as defense or food storage, for which they are better suited, unless there is a great need for them to change (Wilson 1985). Gordon (1995, 1999) demonstrated that in harvester ants, workers may switch between four different tasks—foraging, patrolling, nest maintenance, and refuse disposal—when demand for particular tasks is experimentally increased. However, the pattern of switching was not symmetric, thereby implying different thresholds (c.f. quality of bid) to different task stimuli (c.f. truck color), which likely reflects different costs of switching.

In summary, in both paint booths and social insects, by being conservative and attempting to continue in the current task the system is both *efficient*—workers usually tackle tasks that they perform well—and *adaptive*—they are able to switch tasks and work is not neglected.

## 5. LOCALLY-OPTIMAL VERSUS GLOBALLY-OPTIMAL SOLUTIONS

We noted earlier that within a centralized paradigm, a controller may be able to check that a solution is globally optimal and not just some local maximum (excepting [NP-]"hard" problems), and that this is difficult to check within a decentralized paradigm. Self-organized processes are usually "plodding" hill climbing algorithms in which low level individuals attempt to make local improvements which moves the process as a whole towards the summit of the local peak on the adaptive landscape. However, they are usually unable to jump far away from this peak in the way that some centralized algorithms are able, such as simulated annealing with a slow cooling rate (e.g. Aarts et al. 1997), and thus may not reach the peak containing the global optimum.

In the same manner, some social insect research suggests that error, i.e. an evolutionary strategy of making some deliberate level of "mistakes," can enhance the system's adaptiveness by helping the colony to avoid being stuck on a local maximum. For instance, honey bee foragers that have found a productive patch of forage can return to the nest and direct other bees to that site through a dance known as the "waggle dance" (von Frisch 1967). This dance conveys not only the distance of the patch from the nest but also the direction. Weidenmüller and Seeley (1999) suggest that bees are not as adept at following these directions as previously thought and that recruited foragers often stray from the intended path. They suggest that these stray foragers are adaptive at the level of the group because they will often find new unexploited sites: where there is some good forage, there is likely to be more in the vicinity. The same conclusion was previously arrived at arrived by Deneubourg et al. (1983, 1987) when studying the efficiency of trail following in some ants. Individual foragers appeared to exhibit a constant probability of losing the foraging trail per unit distance or time. Once these workers had lost the trail they switched into "random search mode" and these were the ants that found new food patches for the colony. This adaptive error was found to be an important component in the ant-foraging inspired routing of telephone calls: faultless routing agents could get locked into good routes which prevented exploration but error solved this problem (Schoonderwoerd et al. 1996; Box 2).

The above results may have important implications for industry if it seeks to become more flexible and adaptive. Insect societies appear to keep their options open: they usually do not operate at maximal efficiency from moment-to-moment but utilize some of their resources to seek out new potential options which they can rapidly exploit when the need arises. In short, they do not greatly discount the future. Thus, in ant foraging, as food sources are often ephemeral, once a food source is no longer viable they do not have to search for other sources; they already have a set of workers, the lost ants, who are already looking, or indeed have already found, alternative sources. Too often industry operates myopically and spends excessive resources optimizing current operations when it may be more productive *on a longer timescale* to invest in new avenues with high potential; This latter approach appears to be one of the hallmarks of successful companies in the "new economy" (e.g. Stone 2000; see also Useem 1999).

It should be stressed that highly decentralized systems can potentially have huge failings in some circumstances. For instance, large perturbations can cause a system to become stuck on a far-from-optimal local peak from which they are unable to move. This reasonably abstract concept is very readily observed and demonstrable in insect societies. For instance, in some species of army ants, such as *Dorylus nigricans* in which a single colony may contain twenty million individuals, foraging is achieved by overwhelming prey by pure weight of numbers (e.g. Schneirla 1971; Franks, 1989; Gotwald 1995). Consequently there does not appear to be a great need for individual complexity; Moreover, there are theoretical reasons why individuals *should* be simple (see Anderson & McShea, in press). *Dorylus* ants are essentially blind and react to stimuli in a simple and probabilistic fashion (e.g. Franks et al. 1991); Adaptiveness and complexity only emerges at the level of the group. If a group of workers is somehow separated from the rest of the colony a striking and clearly maladaptive situation arises. A blind individual in the group cannot tell how to relocate the rest of the colony and so its best strategy is to follow another member of the group. However, in turn that worker being followed is adopting the same strategy: "follow the ant in front." With every individual acting in the same way a "circular mill" may result: a circle of ants continuously following each other round and round in circles until death (Schneirla 1944, 1971; Fig. 3). Beebe (1921) provides a fascinating account of a mill he saw in Guyana that measured 1200 feet (365m) in circumference with a "circuit time" for each ant of about 2½ hours. The mill persisted for two days, with ever increasing numbers of dead bodies littering the route as exhaustion took its toll, but eventually a few workers straggled from the trail thus breaking the cycle, and the raid marched off into the forest.

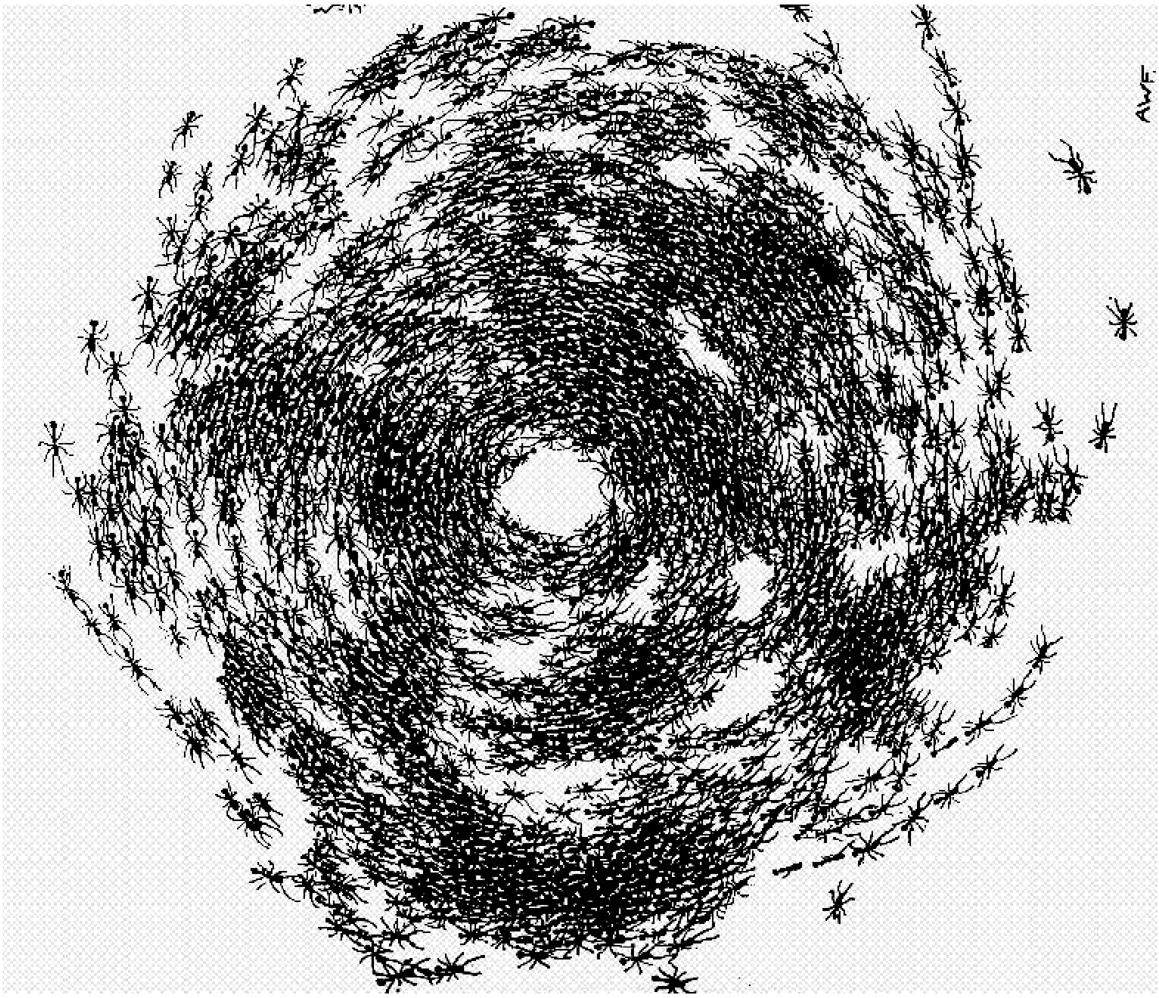

**Figure 3: A circular mill in army ants. If a group of *Eciton* army ants, who are blind, are separated from the rest of the colony they may follow each other around in a circle until they die of starvation. Although each individual is acting optimally—follow the individual in front; as a blind individual this is likely their best strategy—the group as a whole is clearly maladaptive and far-from-optimal, a rare but potential pitfall of the decentralized paradigm. [From: ARMY ANTS by T. C. Schneirla, edited by H. R. Topoff © 1971 by W. H. Freeman and Company. Used with permission.]**

In a circular mill local behavior becomes trapped in a global pattern that perpetuates the problematical behavior. This far-from-optimal behavior is not confined to social insects and below we present two such examples from industry. (We suggest that industry could tell many similar stories.) The first example concerns a manufacturer of wall-covering. Wall-covering is printed by hugely expensive machinery that must be shut down for several hours to change colors or designs and so any manufacturer prefers to make long runs of a single product rather than waste productive capacity in changeovers. Big customers tend to be home construction companies, who find it hard to sell a house before the walls have been finished. At one particular plant, management responded to a sudden surge in rush orders by trying to manufacture a little product for each customer to avoid inflicting massive damage on any one. This meant shorter product runs and more changeovers, which reduced productive time, which meant that the schedule slipped still further behind (pers. obs.). The second example concerns the *United States Postal Service* (*USPS*) and was related to us by H. R. Donaldson (*The Logistics Institute*, Georgia Institute of Technology). When *USPS* first implemented bar codes on envelopes to represent delivery address zip [post] codes for sorting purposes, they began to notice a flood of mis-addressed letters that seemed to circulate in an endless processing/transportation/mis-delivery loop. This was despite the fact that when mis-addressed letter first reached the wrong destination, the delivery carrier would mark up the letter with the correct address (or return-to-sender endorsement) and re-enter the letter in the distribution process. It turned out that the automatic letter sorting system kept re-reading the "bad" bar code and automatically sending the letter back to the wrong address. The problem persisted until the carriers learned to mark out the bad bar code aggressively enough to render it unreadable.

The above examples, particularly those of insect societies, hint that although decentralized processes are self governing, there will always be a need for some centralized authority, such as a manager, to be able to see the bigger picture and override the process if necessary. For instance, Hubanks (1998) points out that when considering a decentralized logistical scheme for military supplies, there is the potential that the system may produce a solution which, *although efficient*, may be undesirable for other reasons not factored into the decision making process. For example all supplies could be sent to a single transfer location (a case of "too many eggs in one basket"), or, may pass through dangerous enemy airspace, both unattractive strategies. In these cases, an overseer has an important role—to overrule the decentralized systems' solutions if necessary—, even if they are only rarely needed.

## 6. WHITE VERSUS BLUE: MANAGEMENT ISSUES

The previous paragraph hints at an important issue when considering a centralized versus decentralized paradigm: the changing role of management. First, there is a real threat to middle management's jobs from increasing decentralization. For instance, when *Kodak* restructured to produce a flatter organization, the distance between manufacturing manager and factory floor fell from thirteen levels to four (Davidow & Malone 1992:168 who also give other such examples; see also Drucker 1988). Second, the role of the remaining managers is likely to change from supervisor to advisor. The generally decreased role of management in a decentralized system is likely to be challenged. Interestingly, despite the proven effectiveness in the self-organized truck painting (Box 3) there was resistance to the scheme from middle management (Morley & Eckberg 1998). Similarly, in the case of *BT* (Box 2) despite the fact that the decentralized routing scheme was proven to be effective, cheap, and robust, this line of research was eventually discontinued because of opposition from upper level management (P. Cochrane, *BT*, pers. comm.)

In insect societies, the workers "on the shop floor" make the decisions using relevant up-to-date information. In most insect societies, the queen is simply reduced to a specialized, but important, role: an egg-laying machine. In effect, each worker, although seemingly insignificant compared to the colony as a whole, has an element of control of colony operations. Similarly, management in an industrial context must come to the realization that their workers, if given some individual control, can be their "eyes and ears" possibly preventing problems before they escalate. For instance, in *Ford*'s Edison (NJ) automobile assembly plant, each worker was given a button that they could push which stopped the assembly line. Although factory-floor workers used these buttons and shut down the facility twenty to thirty times a day, each stoppage was only for about ten seconds and was usually to make some small adjustment or fine-tuning. The daily total of downtime, 200–300 seconds, did not affect production and importantly the number of defects per car fell from 17.1 per car to a mere 0.8 (Peters & Austin 1985:217). In this decentralized system, the workers acting upon local information, the car being built in front of them, were able to correct a problem before it spiraled into a more serious and expensive situation, something that a manager would be unable to achieve. In summary, "*no one is as smart as everyone*" (L. Keely, *Doblin Group*, cited in Kelly 1998:14).

## 7. DISCUSSION

The industrial workplace has changed radically over the years with the introduction of innovations such as just-in-time manufacturing, automated business to business commerce, and the phenomenal growth of e-business. If companies and their associated supply chains are to

## BOX 4: Self-organized patterns in storage systems

There is a tantalizing similarity in self-organized patterns of 1) stored pallets in automated storage/retrieval (AS/RS) systems in warehouses, and 2) stored brood, honey, and pollen in honey bee combs. In a warehouse AS/RS, items are stored in, and retrieved from (using First-In-First-Out), a large rack using a robotic crane. It is a tempting and "obviously good" policy to store an incoming item in the location closest to the input-output point, to reduce crane travel times. (These racks may be 400 feet long [122m] or more, and retrieval from a far location may take in excess of a minute [Wilhelm & Shaw 1996; Tompkins et al. 1995].) However, the result has proven to be counter-intuitive to engineers and perversely inefficient for warehouses. A self-organizing pattern has been observed in which high turnover items tend to be stored and retrieved from locations *farther* from the input-output point and low turnover items stored in nearer locations (Wilhelm & Shaw 1996; Shaw et al. 1998). The result is excess travel time and reduced throughputs.

The self-organizing process and the resultant patterns are suggestive of those in seen in honey bee combs: a central brood area, a surrounding band of pollen, and a large peripheral region of honey (Fig. 4). Camazine (1991) demonstrated that the bees do not store material according to a "blueprint" but suggested that the pattern is generated as an emergent property of five features governing material deposition and removal (see also Jenkins et al. 1992). Two rules "*The queen moves more or less randomly over the comb and lays most eggs in the neighborhood of cells already containing brood*" and "*removal of honey and pollen is proportional to the number of surrounding cells containing brood*" generate a compact central region of brood. Initially, *honey and pollen are randomly mixed*. However, two additional features "*four times as much honey is brought back to the hive than pollen*" and "*typical removal:input ratios for honey and pollen are 0.6 and 0.95 respectively*" imply that pollen (high turnover item) is more likely to be removed and filled with honey (low turnover) which will tend to remove pollen from the periphery.

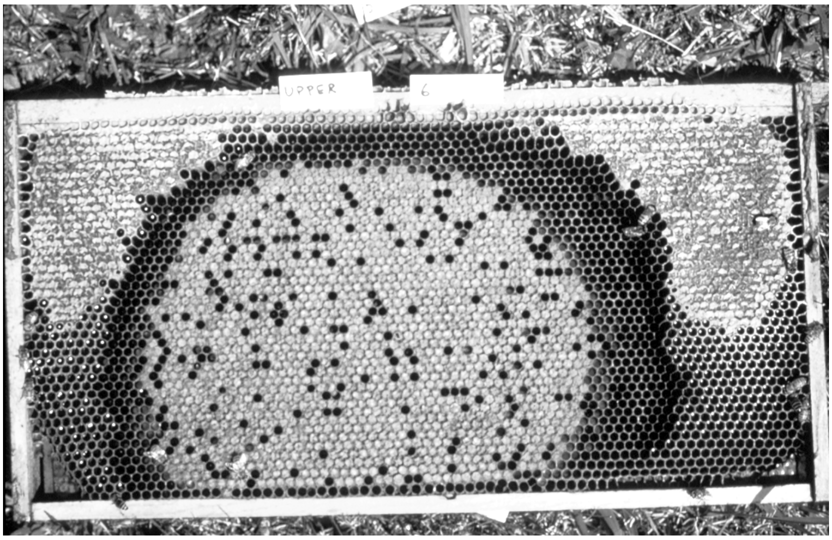

**Figure 4: The self-organized pattern of brood (center), pollen (surrounding ring), and honey (periphery) on honey bee combs. Photo courtesy of Scott Camazine.**

The emergent pattern of storage makes economic sense in the honeybee colony—the queen's activities are concentrated near the center of the nest where she is likely better protected, and pollen is close to where it is needed, i.e. feeding the brood—but is inappropriate in a warehouse, in which emphasis is on rapid throughput of product. This should serve as a cautionary tale for those inclined to simply mimic organization of the social insects: Sometimes the emergent behavior of a self-organizing system can surprise the designers or even confound them.

remain competitive then they must respond more quickly, be more adaptive, and more flexible. In short, they must produce "what I want, where I want it, and when I want it." We have attempted to show that insect societies exhibit this desired behavior and the way that they accomplish this can be a model for industry: decentralized rather than centralized control.

Clearly, the centralized and decentralized paradigms have very different properties and problems associated with them. Recognition of this fact by industry is crucial because it is expected that implementing the wrong control system in the wrong situation will have disastrous effects. Miller (1981) case studies a company that borrowed computer software from a sister company to control its manufacturing in a new plant. After a prolonged period of disastrous "start-up problems" management identified that the problems lay not just in these expected start-up problems, but primarily the result that they were implementing the wrong type of control. The borrowed software, which had been designed for a stable flow type (centralized favored) operation, gave off false signals, and was not effective, when used in their unstable job shop type (decentralized favored) environment.

We have detailed various examples of strong parallels between industrial and insect society operations and fully expect that other examples exist. For instance, Box 4 is suggestive of a parallel between a self-organized pattern of stored items in honey bee combs and in automated storage/retrieval systems in warehouses. To find these though will require cooperation between biologists and industrial engineers, as in the authorship of this study, in true interdisciplinary research. In summary, our "take home message" is that industry, in attempting to become more flexible and adaptive, is shifting (unknowingly) towards a social insect "business model", and may have much to learn from these simple small-brained creatures. As the Bible's sixth chapter of *Proverbs* advises us: "*Go to the ant, thou sluggard. Consider her ways and be wise*."

## 8. ACKNOWLEDGEMENTS

We thank Jennifer L. V. Jadin for comments on an earlier version of this manuscript. CA was supported by funds from *The Logistics Institute* at the Georgia Institute of Technology.

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