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**Ant Based Logistics Self-organization: Starting Fundamentals and Research Design**

A thesis submitted to the requirement of Master's of Science in Management of Technology

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Second Supervisor: Dr. Erik den Hartigh

August 2009
Thesis Title

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Born in Addis Ababa, Ethiopia in the 5th of April 1982

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My heartfelt regards are also extended to all my professors for their positive energy during my study years. My special appreciation goes out to my classmates who have made my two years study joyful and an experience of a life time. To all family and friends that had impacted my life one way or the other, I say “THANK YOU ALL AND MAY GOD BLESS YOU”.

Alexander Gebremedhin Shibeshi
August 2009
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Executive Summary

This thesis argues for self-organization of logistics systems based on principles derived from the foraging activities of ant colonies. By self-organization it is meant units in the logistics system perform their duties without directives from a central command and control unit on a regular basis. The units undertake their operation with guidance from a set of principles.

The starting point for this thesis is the increasing complexity of logistics systems of global manufacturing operators. For various cost and marketing objectives manufacturing firms have global supplier base and global customer base. Added to this are increased market competition and a service savvy customer. These all factors coupled with increased IT competency have played significant roles in increasing the complexity of logistics systems. This calls for logistics systems to be more proactive than remain reactive for changes in and outside the system as is the case in most traditional logistics chains.

With this generalized background information on present day logistics complexity, the thesis aims at developing model self-organizing principles for logistics systems based on the foraging traits of ant colonies. The choice of ants as a basis for this thesis is due to:

- Biologically ants are among the most evolutionarily successful species on earth (there are more than 10,000 species of ants and on a mass basis they are equal to the human race)
- Their daily activities resemble logistics activities at a conceptual level (they transport, store and protect their daily and future food consumption)
- Their ability to use simple, but effective, rules of governance at individual levels to self-organize their activities which, at a global level, is a very complex output for their cognitive capacity

On top of these all, a successful mathematical algorithm, called ant colony optimization, has been developed in the early 1990’s based on the pheromone trailing patterns of ants in foraging. This algorithm has proved to be one of the most prominent mathematical tools to solve iterative problems. Nevertheless, mathematical solutions are usually starting points for decision making. And evidently, algorithms based solutions are effective for operational and sometimes for tactical decision making. But as is known well, logistics decisions have strategic components as well, which is quite critical and shapes the other decisions.

Consequently, with background information from such approaches, the thesis addresses its main objective by asking the following central research question:
“what principles can be extracted from ant-colony foraging traits for use in logistics systems self-organization”

To aid as inputs for answering this research question, the following sub-research questions are also addressed in the thesis:

- How do the current global manufacturing logistics systems fit into the characteristics of complex systems?
- What is self organization? What are its principles? How can ant colony and logistics systems self-organization be related?
- What fundamental similarities can be drawn between different logistics functions and decision, and daily activities of ants?

A step by step answering of the aforementioned research questions builds the case for:

- Need for self-organizing logistics systems
- Need for developing principles of self-organization in manufacturing logistics
- Need for expanding research in self-organizing logistics systems

In order to achieve the outlined objectives and answer the research questions on the way, the main methodology employed in conducting the thesis is literature synthesis. Various publications from ant biology research, complex and self-organization sciences and logistics management are used. In addition the book “The Ants” with its detailed study of ant colony behavior is used as a primary input for technical terms and concepts concerning ant colony biology. Another similar method used in pursuing the thesis is replicating the logic in ant colony behavior to logistics systems. In this approach, a behavioral manifestation a typical ant colony has developed from evolution is translated to an equivalent application in a logistics system as conditions dictate.

Resting on the outlined research questions and the accompanying methodology to address the same, the major findings of this thesis are:

1. The inherent make up the logistics of a typical global manufacturing firm fits quite well with the characteristics of complex systems. The main characteristics of complex systems are: dispersed interaction, no global controller, cross-cutting hierarchical structure, continual adaptation, perpetual novelty, and out-of-equilibrium dynamics. Present day logistics systems, due to factors like globalization, customer demand, market competition and increased IT capacity, conform to these characteristics of complex systems more often than not.

2. Units in complex logistics systems need to self-organize their operations as it is difficult to control and coordinate each activity from a central unit. In literature it is quite customary to
recommend the use of self-organization to deal with problems that could arise with ‘the complexity’ of the complex systems. In biology there are social species that exhibit complex behavioral patterns. Examples are school of fish, bee colonies and ant colonies. Instances of complex behavioral manifestation in these species are division of labor, caring for their young, and collecting food. These behaviors may not be complex per se, for humans perform more complex duties than these. However, when their limited cognitive capacity is taken into consideration their self-organization patterns are quite remarkable. It is well documented in literature that these self-organizing species have developed, through evolutionary processes, a certain set of ‘rules’ to follow to accomplish their daily operations. Consequently, in logistics systems, the main target in attempting to self-organize units should be developing similar ‘rules’ that can serve as building blocks.

3. An abstract comparison of ant colony behavior and logistics operation indicate stark similarities between the two. The starting point for investigating these abstract similarities is the mere fact that daily activities of worker ants resemble logistics operations – ants transport food consumption for the colony from source to nest (which can be seen as an inbound sourcing and transportation), they store food items in their nest for future use (which can be equated to warehousing in logistics), and their arrange their nest in a typical fashion with their young and food items stored in separate places (which can be compared to warehouse layout). Using these mere observations and similarities, comparison is made by choosing three correspondences: supplier selection vs. food source selection in ants, logistics transportation vs. worker ant transportation, and warehousing in logistics vs. food and brood storage and sorting in an ant colony. The important point these correspondences convey is that, due to such similarities, ant colonies, as they do self-organize their daily activities, can be used as sources of insights in the quest for self-organizing logistics operations.

4. What ants do in self-organizing their daily tasks is following a set of rules which are developed from evolutionary adaptations. This idea is translated into a typical logistics system of a manufacturing firm for it to be self-organizing – a set of principles are developed. But, prior to these principles, the agents in a given logistics system are categorized into four: warehousing, transportation, scheduling and dispatching. This segregation is done to streamline the objectives of each agent. The following series of tables shows the metrics that can be used in measuring the impact of activity of the agent, the principles developed for the given agent, and the respective objective of the agent. For comparison similar connotations are presented for ant colonies.
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<td>Establishing threshold levels</td>
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<td>Metrics: Order-to-dispatch time</td>
<td>- If an item is highly critical for production and sales, its threshold level should be higher.</td>
</tr>
<tr>
<td>Objective: Maximizing the yield in ‘order-to-dispatch time’</td>
<td>- If an item is highly critical, it should get higher value in measuring customer satisfaction levels.</td>
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<td>- The higher the uncertainty of the external factors impacting the availability of a given item, the higher should be the threshold level of the item in the warehouse.</td>
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<td>Warehouse resource allocation</td>
<td>- The larger is an item’s payoff in maximizing the ‘order-to-dispatch time’, the higher it shall be ranked in the priority function for resource allocation.</td>
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<th>Logistics agent, metrics and objectives</th>
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<td><strong>Logistics Agent: Transportation</strong></td>
<td>Choice of mode of transportation</td>
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<tr>
<td>Metrics: Dispatch-to-customer-receipt time</td>
<td>- The larger the distance an item has to be transported, the more exhaustive the list of alternatives should be and the more selective the agent should be in choosing a typical mode of transportation.</td>
</tr>
<tr>
<td>Objective: Maximizing the yield in ‘dispatch-to-customer-receipt time’</td>
<td>- The higher the risks of external factors involved in transportation, the more selective the transportation agent shall be in choosing a given mode.</td>
</tr>
<tr>
<td></td>
<td>- Under intense service delivery competition, use small size and frequent transportation schemes until the point of maximum acceptable loss.</td>
</tr>
<tr>
<td></td>
<td>- The higher the number of small size and frequent shipments demanded, the more selective the transport agent should be in appropriating resources to product type.</td>
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### Logistics agent, metrics and objectives

**Logistics Agent: Scheduling**
- **Metrics:** Order-to-delivery cycle time
- **Objective:** Maximizing the yield in ‘order-to-delivery cycle time’

**Governing principles for self organization**
- The higher is the position of a product in the high end – low end spectrum, the larger should be the degree of freedom provided while making logistics schedules for this product.
- When assigning tasks to resources, use an incremental technique of capacity fitting.

### Logistics agent, metrics and objectives

**Logistics Agent: Dispatching**
- **Metrics:** Dispatch-to-customer receipt time
- **Objective:** Maximizing the yield in ‘Dispatch-to-customer receipt time’

**Governing principles for self organization**
- Use incremental dispatching of resources; more resources shall be deployed in a particular pattern only when it is proved that this is the practical solution at that specific instant.
- The longer the dispatching distance and time, the more considerate the agent should be in load matching.

### Ant agent, metrics and objectives

**Ant Agent: Foraging**
- **Metrics:** Energy
- **Objective:** Maximizing the yield in ‘Energy’

**Governing principles for self organization**
- The greater the distance the ant travels from the nest to a food patch, the longer she should take to select the food item.
- The greater the distance the ant travels to a food patch, the more selective the ant should be in choosing a food item.
- The higher the temperature, the more selective the forager should be in food patches.

In conclusion, the research in ant colony-logistics area is quite vast and a lot remains to be investigated. In particular, influencing ant colony behaviors in a laboratory setup from purely logistics perspectives could result fascinating discoveries. For such undertakings multidisciplinary research teams composed of biologists, logistics practitioners, mathematicians etc. need to be formed with streamlined objectives. The result could be a vast research area with abundant knowledge pool.

*Key words: complex sciences, logistics complexity, self-organization, logistics self-organization, ant colony, ant colony foraging, principles of self-organization.*
1. Introduction

Logistics systems are becoming complex day by day (Windt & Hulshmann, 2007). To address this complexity, various complex methods of designing and controlling logistics systems are continually being developed. Global suppliers base, global customers base, the need of firms to diversify to different markets, a highly service savvy customer, advances in information technology, and other similar factors are principal reasons for logistics complexity. And logistics, rather than being the usual cost unit, has shifted to be an integral – value adding unit in most companies. When ‘exceeding customer expectations’ took center stage in the motto of most firms, the importance of various logistics functions became quite significant as they proved indispensible competitive tools in the market.

Complexity is divulging deep into logistics systems, and tackling logistics problems using theories from complexity science has become a common trend. The customary design and control approaches to logistics systems are still very useful. They, however, are less robust in dealing with dynamic and complex logistics developments. The principles of self-organization observed in social insects provide insight into how a given manufacturing logistics system be devised so as to structure itself in a self-organized manner without a need for central command and control.

1.1 Motivation

Science and engineering continually resort to biology for ideas to make innovations and improvements. The biology of ants provides an abundance of knowledge that we can use as inspiration in search of new ideas for practical applications. The pheromone trailing behavior of ants, for example, was the basis for documenting one of the most famous mathematical algorithms – the Ant Colony Optimization (ACO) (Dorigo & Stutzle, 2004) (a short overview of the ACO algorithm is provided in Appendix A). The main premise of this thesis is that principles of self-organization can be developed for logistics agents from governing rules of ants in foraging. The mathematical approaches to vehicle routing, scheduling and other logistics functions that use ACO provide tools for solving detailed logistics problems that are usually encountered at operational levels. But, ants are seen wondering around, an observation can be made of them performing logistics functions – they transport, they store, they protect etc. their catch. These stark similarities of ant colony and logistics functions are the starting point in the assertion that ant colony biology has more than algorithms to offer for logistics systems study. As a result, in this thesis, conceptual principles of structuring logistics system are developed for it to be self-organizing. The individual ant is a simple organism with almost no cognitive capability. It follows
a set of simple rules to accomplish its tasks (Holldobler & Wilson, 1990). But when the colony overall is observed, it is quite a complex group. What is taken from this is that agents in logistics systems can follow simple principles to efficiently perform their tasks in the complex logistics system.

1.2 Research Aims

The central objective of this thesis is:

To develop model self-organizing principles for logistics systems based on the foraging traits of ant colonies

The logistics of most manufacturing industries has become complex driven by global supplier base, global customer base, global manufacturing base, increased product variety, increased IT competency and similar other factors. Consequently, central command and control of the total logistics chain has become difficult, if not impossible. As a result the field of self-organization seems a promising field to apply to logistics systems. In essence, directing research in logistics to self-organization could prove to be an effective tool for managing complex logistics systems. In addressing the main research objective, the thesis touches upon other sub-objectives that will build the case for self-organizing logistics systems:

a) To briefly introduce the concept of complex science and self-organization in logistics contexts (chapters 4 and 5).

b) To outline abstract similarities between logistics functions and daily operations of ants (chapter 6).

c) To provide an orientation to future research in ant based logistics self-organization through research design (chapter 8).

d) To provide a list of conclusions and reflections on the study undertaken (chapter 9)

1.3 Research Questions

The customary method of organizing a given logistics system is through top – down (or central command and control) approach. In such a system decisions regarding different logistic functions like warehousing and transportation are taken by a central unit. The decisions are then executed by the different logistics units with very little room for flexibility. The advantages and limitations of such central command logistics systems is described below.

Advantages

- A complete oversight of the logistics chain providing little room for mistakes by ‘lower level’ units
- The chain is in general visible and responsibility can easily be attached

**Limitations**

- It lacks flexibility – the logistics system lacks pro-activeness
- Quite difficult to manage when the logistics network is complex – when there are multiple production sites, global customer and supplier base
- The information system employed becomes very difficult to comprehend, if the chain is complex
- The decision maker will be faced with multiple objectives to fulfill at the same time, increasing the decision space. Thus, it requires complex algorithmic approaches and thus ‘soft’ aspects of decision would be ignored/or are given less focus

In order to reduce the impact of these limitations with the majority of the advantages kept intact, it is vital to vie for logistics units to self-organize their activities. For this, however, they require a set of guidelines, or principles, to follow while making decisions.

Consequently, based on these, the central question of this thesis is:

“What principles can be extracted from ant colony foraging traits for use in logistics system self-organization?”

In answering this question, the thesis achieves its principal objective of developing model (or exemplary) self-organizing principles for logistics agents.

In answering this question, however, there is a need for building the case for why it is need to self-organize a logistics system. Consequently, in order to present the present state of global manufacturing logistics systems, the following sub-questions are raised:

1. How do current global manufacturing logistics systems fit into the characteristics of complex systems?
2. What is the concept of self-organization? What are its principles? How can ant colony and logistics systems self-organization be related?

In answering these two questions, the thesis achieves the objective of introducing complex science and self-organization in the context of logistics.

3. What fundamental similarities can be drawn between different logistics decisions and functions, and daily activities of ants?

This question is raised to give a basis for why ants are used as sources for developing the formulations in this thesis.
Figure 1.1: Research concepts and the associated research objectives.

1.4 Research Methodology

Table 1.1 shows the research questions, the objectives they will achieve and the corresponding methodology used in this thesis to answer these research questions. As outlined in the table the dominant methodology used in this thesis is literature synthesis. This thesis research is a preliminary study on how ant behavior can be used in organizing and managing logistics systems. What is done here is basically 'borrowing' theories from ant colony biology studies to formulate propositions that can further be refined in future research. Apparently, as outlined by Stock (1997), such an approach is not new to logistics management research. The author claims that theory establishment in logistics is not rich in heritage as compared to more established sciences like anthropology or philosophy and thus much of logistics research has roots borrowed from the more established disciplines.


<table>
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<th>Objectives</th>
<th>Methodology</th>
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<tr>
<td><strong>Fitting logistics to complexity concepts?</strong></td>
<td>Framing logistics in terms of complexity sciences so that we can use the approaches in complex science to deal with logistics</td>
<td>Literature synthesis from complexity sciences and logistics management</td>
</tr>
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<td><strong>Chapter 4</strong></td>
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<tr>
<td><strong>How to deal with complexity?</strong></td>
<td>To underline that self-organization principles are the recipes for dealing with complex systems and create relation with biological self-organizing systems</td>
<td>Literature synthesis from self-organization articles, both in biological and physical systems</td>
</tr>
<tr>
<td><strong>Chapter 5</strong></td>
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<tr>
<td><strong>Correspondence between ant colony and logistics operations?</strong></td>
<td>To clearly outline why we chose ant colony as a basis for our approach in this thesis and indicate the kinds of similarities that can be exploited for improving logistics systems.</td>
<td>Replicating the logic in ant colony literature to logistics systems</td>
</tr>
<tr>
<td><strong>Chapter 6</strong></td>
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<tr>
<td><strong>Principles for self-organizing logistics agents?</strong></td>
<td>For agents to have a clearly formulated objectives, metrics for decision making and better organization</td>
<td>Abstract analysis of logistics concepts with logic derived from ant colony foraging theory</td>
</tr>
<tr>
<td><strong>Chapter 7</strong></td>
<td></td>
<td>Linear algebra for a sample case (formulas from exponential regression to relate dependent and independent variables)</td>
</tr>
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Table 1.1 Research questions, objectives and methodology

1.3 **Outline**

Next to this introductory chapter, chapter 2 provides account of biology of ants. The physiology of a typical worker ant, colony structures and procedures in ant colony foraging are described briefly.

Chapter 3 presents the methodology utilized in this thesis. A conceptual framework derived from different book and article sources is provided and steps of using this methodology is described.

Chapter 4 & 5 introduce the concepts of complexity and self-organization. Characteristics of complex systems are outlined and logistics complexity is described by referencing to these characteristics. The self-organization chapter builds on the concept of complexity and describes how self-organization is portrayed form logistics perspective.

Chapter 6 draws general parallels between logistics operations and ant colony activities. Supplier selection & food source selection, transport logistics & food transport by worker ant, warehousing
& food and brood storage and sorting in ant colonies, are the topics that are discussed in this chapter.

Chapter 7 is the main part of this thesis. It presents principles of organization and performing tasks for four principal logistics agents: the scheduling agent, the warehousing agent, the transportation agent, and the dispatching agent. It is argued that these agents shall develop metrics against which they will evaluate their performance and the aim of each of these agents should be maximizing the yield in these metrics. In this way, an agent can self-organize its operations and increase its performance.

In chapter 8 a research design is outlined for verifying the principles developed in chapter 7 and furthering ant colony – logistics management research. The necessary steps to undertake in performing such research, sample research questions and other areas of research interest are discussed. In addition research setup and organization and expected outputs from such researches are put forth.

Conclusion on the thesis and reflection on the study is provided in chapter 9.
2. The Biology of Ants

2.1 Introduction...

All ants are classified under a single family, *the formicidae*. They are among the well studied social insects. And, like their fellow social insects, they belong to the order *Hymenoptera*, which does also include the bees, wasps, sawflies, ichneumons, and other similar organisms (Holldobler & Wilson, 1990). The commonly found worker ant has three body parts, the head, thorax and abdomen. Attached to the head is a pair of elbowed antennae used for detecting chemicals, air currents, vibrations and in some species it is used as contact point for transmitting mechanical interaction (Holldobler & Wilson, 1990).

Ants are among the most evolutionarily successful species on earth. This is evident in no other than their existence on the face of earth; they have been around for more than 100 million years (Holldobler & Wilson, 1994). Their success is also exhibited through their presence everywhere on earth except in places like the Antarctic. Holldobler and Wilson (1990) attribute this evolutionary success of ants to three basic traits:

The first reason is “they were the first group of social insects that both lived and foraged primarily in the soil and in rotting vegetation on the ground. In a way, this provides shield from other competitive, but arboreal species”.

The second reason is the fact that ants are armored with “stings and toxic chemicals weapons, making the ant workers formidable predators”.

A third reason is their “foraging efficiency” which is achieved through “the use of odor trails laid over the surface” enabling them to recruit partners for cooperative foraging.

A combination of these and other evolutionary traits developed throughout their existence gives them great environmental and social adaptability. For instance Holldobler and Wilson (1990) assert that “under most circumstances groups of workers are better able to forage for food and defend the nest, because they can switch from individual to group response and back again swiftly and according to need”. Not many species can show such an extraordinary ability to adapt to scenarios as they arise.

2.2 Colonial Life...

Almost all ant species are highly social, living in colonies ranging from a few individuals to over millions, depending on the type of species and the relative age of the colony (Holldobler & Wilson, 1990). The colony has one or a few queens responsible for reproduction and setting up the colony
at the first place, and a number of sterile worker ants. The worker ants are responsible for (i) expansion of the initially small nest built by the queen (ii) feeding the colony (iii) taking care of the brood (egg, larvae and pupae) and (iv) defending the colony (Holldobler & Wilson, 1990). In accomplishing these obligations ants follow a very structured division of labor in their colonies. That is, in most colonies young worker ants are usually responsible for taking care of brood inside the nest. The bigger ants with a relatively higher strength and powerful sting are deployed to defend the nest and resources. The median ants are usually assigned to the task of foraging. However, this is not a strict rule and in most species an ant may be doing different tasks at different times as per the demands at that instant. The social life in ants in biological literature is usually termed *Eusociality*. The term is used to describe the highest level of social organization in ants and other insects like bees and wasps. Wilson (1971) states that the term particularly refers to three aspects of social cooperation in these species: “reproductive division of labor (queens usually are the ones laying the eggs), overlapping generations and cooperative care for young”

**2.3 Foraging in Ants...**

Foraging in most ant species is a collective process and is one of the most important activities to the colony. It is not uncommon to see ants in our gardens travelling in a particular path and carrying items for consumption (like flies, or other food stuffs) with them. Generally the following paragraph outlines how a typical ant forages:

‘A forager (a scout ant) leaves the nest entrance in either a random or a consistent direction. A travel phase ensues, during which the worker maintains a constant compass bearing and moves directly away from the nest. At some point during the travel phase the forager shows a high frequency of turning, marking the beginning of search. During search, food resources are encountered and selected based upon a forager's physical caste, age and prior experience, the trip distance, thermal stress, resource quality, and the colony's current nutritional status. Depending on the ant species and size, the density, or quality of the food, the forager may communicate information to nestmates about its location and recruit additional foragers’ (Traniello, 1989)

The steps in foraging can be summarized as:

i. Scout ants go away from nest in search for food

ii. Upon finding a food source they mark (through their pheromone trails) the position of the food source and their path back to the nest

iii. In the nest they ‘inform’ fellow foragers of the food source and make recruitment for cooperative foraging

iv. Recruits follow paths which have higher concentration of pheromone trails
v. The foraging process continues until the source is depleted or another attractive source has been found.

The foraging process is one of the epic ant colony functions, as ants, with no evident cognitive capabilities, show tremendous efficiency in performing it and thus can be used as a basis for developing various principles in science and engineering.

2.4 Conclusion...

Ant colony life patterns provide abundance of knowledge and could be sources for new insights for use in devising new systems and improving existing systems. Their evolutionary success and existence in almost all habitable land on earth is evidence for their ability to perform tasks exceptionally well. Ants’ primary tasks in their respective colonies involve transportation of food from source to nest, storage of food and water, caring for brood, protecting the colony etc. These tasks correspond to logistics operations like transportation and storage. Thus in devising new logistics systems and improving existing ones, ant colony ‘logistics’ mechanisms could provide useful insights.
3. Development of Research Framework

3.1 Introduction

In this chapter a step by step development of the research framework used in this thesis is described. First, an abstract representation of ant colony foraging and logistics systems is provided. They describe what is meant when using these concepts throughout the thesis. The case for self-organizing principles and research design is made by following through the logics of complex logistics systems, agent based approaches and ant foraging principles. A figurative representation of the framework is provided at the end.

3.2 Ant colony foraging

Abstract representation of ant colony foraging gives a pictorial overview of the steps undertaking while worker ants of a typical colony forage. Pheromone trails (and its concentration) play significant roles in shaping the decision of ants to forage or not at a particular instance.

![Figure 3.1: Steps in ant colony foraging](Adapted from the website of sciencebuddies)

3.3 Logistics system

Logistics is represented as a series of transportation and warehousing activities starting from suppliers to customers and the corresponding information flows throughout the chain. The logistics system is the totality of this structure and is comprised of four agents – the scheduling, transport, warehousing and dispatching agents (Adapted with adjustments from Fox et al., 2009).
Figure 3.2 shows abstract representation of the logistics system and the corresponding logistics chain.

3.4 Complexity

With these abstract representations let’s now build our conceptual framework. The general methodological framework is shown in figure 3.3. Let’s start from the right side of the figure, complexity of logistics systems. Perona and Miragliotta (2004), supported by their empirical research, report that reducing complexity in logistics systems is among the core competitive advantages of firms. That is, companies reporting less complexity in their logistics chains have higher levels of efficiency and effectiveness. But this, the authors claim, is in no way associated with reducing their product varieties. In fact, most companies report increased product varieties, which in turn increases parts variability and which seemingly should have increased logistics complexity. The finding of their research ascertains the fact that complexity can be reduced by other methods than reducing part numbers or product varieties. In fact, complexity is reduced by
simplifying logistics operations. How can logistics operations be simplified? We will return to this question later.

### 3.5 Agent based systems

Different authors (Fox et al., 2000; Wang et al., 2006) recommend the use of agent based approaches in dealing with issues of Supply Chain and Logistics that are characterized by complexity. Based on Fox et al. (2000), with minor adjustments, here the logistics agents are categorized into four: the warehousing, transportation, Scheduling and dispatching agents. The agents are intelligent units of the logistics system that make the respective decisions based on past and forecasted information – they constitute both reactive and proactive traits required for robust decision making. The enhanced capabilities of the agents’ decision making are partly due to advancements in IT – technologies like RFID playing significant roles (Windt & Hulsmaan, 2007).

### 3.6 The Case for Self-organization in Logistics

Once we have identified these agents, the issue is how to organize them in a way that copes with the underlying complexity of the entire system with astounding efficiency and effectiveness. Different authors (for example, Windt & Hulsmann, 2007; Peters et al., 2008) assert that agents in logistics systems shall be structured in self-organized manner for the complexity to effectively be dealt with. Windt and Hulsmann (2007) confer that “the resulting complexity can no more be managed feasibly by means of centralized planning and control”. By self-organization it is meant to refer to “the system functions without central control, and through contextual local interactions. Components achieve a simple task individually, but a complex collective behavior emerges from their mutual interactions” (Serugendo et al., 2004).

In summary, it is outlined, until now, that logistics systems are increasingly becoming complex and dealing with such complexity requires application of agent based approaches. And the different agents, it has been conceptualized, can be structured in a self-organized manner. The question now is a big ‘How?’ This is when we turn our attention to nature – the ant colonies.

### 3.7 Principles of Self-organization in Logistics Based on Foraging in Ants

Serugendo et al. (2004) claim that the study of self-organization has been around since 1953 and its linkage with natural systems began with the study of the behavior of insect societies. Insect societies, for instance ants, exhibit the properties of self-organization in activities like foraging, nest-building, clustering and collective sorting. Insects use the mechanism of stigmergy to coordinate these activities (Serugendo et al., 2004). Stigmergy refers to “a class of mechanisms that mediate indirect interactions between animals” (Theraulaz et al., 2003). The self-organizing
patterns in ant colonies “emerge from a population of ant workers having each their own individuality as well as limited access to information” (Detrain & Deneubourg, 2006).

Foraging is one of the self-organized behavioral traits of the workers of ant colonies. In most ant species, foraging is coordinated through pheromone trails. Pheromone trails are chemicals produced by worker ants used to make paths on the ground, such as from food source to nest (Dorigo & Stutzle, 2004). Through the usage of these pheromone trails ants perform their foraging duties by following some rules that maximize the yield in energy of the overall colony (Holldobler & Wilson, 1990).

Now we return back to the previous question of ‘How can logistics operations be simplified and structured in a self-organized pattern?’ To answer this question, we recognize that ants follow simple rules to self-organize their foraging activities (these rules are detailed in chapter 7). From these rules principles are derived for the four logistics agents to effectively self-organize their respective activities. Chapter 7 explains these principles in detail. Figure 3.3 shows the architecture of the methodology that we use in this thesis.

![Research Framework](image)

**Figure 3.3: Research Framework**

### 3.8 The Logic of the Research Framework

The research framework (figure 3.3) shows the approach followed in this thesis. It starts with abstract representation of ant colony foraging and logistics systems. Figure 3.1 shows this abstract representation of ant colony foraging – it starts with a scout ant’s first maneuvers to locate a food
source and ends with the evaporation of pheromone trails signaling the end of foraging. Figure 3.2 shows an abstract representation of logistics systems – it is indicated as a series of warehousing and transportation operations. These abstract representations provide boundaries on what is meant by foraging and logistics systems in subsequent sections.

Before detailing what specifics we can extract from ant biology for logistics operations, an assessment is made if logical comparisons can be made between ant colony daily activities and logistics operations. These comparisons will be used for subsequent synthesis and conclusions that are derived for using ants in this research. For most of these analyses the thesis relies on academic literature both from biological and logistics sciences.

As shall be seen in detail in the next chapter, logistics operations are becoming increasingly complex due to various factors like globalization, IT capacity and market diversification. It is stressed that present day logistics systems fit quite well into the characteristics of complex systems. And in chapter 5 it has been stipulated that self-organization schemes are generally put forth as solutions to complex systems. Chapter 5 also emphasizes that agents in self-organizing systems, biological or physical, follow simple rules to form patterns in their activity. Consequently, we identify relevant agents for logistics systems.

The argument built until now is that logistics systems are becoming complex, this complexity can be addressed through self-organization and that self-organizing agents follow simple rules to accomplish their tasks. The next step, then, is deriving self-organizing principles for logistics agents. To develop these principles, foraging in ants as a reference is chosen. The reason is that, primarily the fact that foraging is similar to the transport operation in logistics and secondly because it is one of the widely investigated ant colony behaviors in ant biology. The principal premise is that biological systems, through natural selection in evolution, have developed effective and efficient mechanisms of performing their duties. Based on the self-organizing principles developed, a formulation how future research in this area can be done is provided.
4. Complex Systems and Logistics Complexity

4.1 Introduction

This chapter introduces the concept of complex systems from logistics perspectives. In doing so, it gives response to the research question “How does current global manufacturing logistics systems fit into the characteristics of complex systems?” To understand what a complex system means, first a brief introduction to the concept of complex systems is provided. Then, the characteristics of a typical complex system are outlined. Subsequently, an analysis will be made to see whether a typical manufacturing logistics would ascribe to these characteristics of complex systems.

4.2 Complex systems

The complex system ideology is driven by the concept ‘the whole is more than the sum of its parts’ (Guckenheimer & Ottino, 2008). It refers to several real world setups where parts of a system are coupled in a non-linear fashion. Whereas a system made of linear couplings of parts will be available for the principle of superposition (the system is the sum of its individual components), in a non-linear system the sum exhibits properties that are of a higher degree intricacy than its individual components. Such intricacies are the reasons behind coining the term ‘complex systems’. Examples of such systems are, from biology: nervous system, ant colonies, termite colonies, bee colonies etc and, from physical sciences: power grids, transportation networks, internet, telecommunication networks etc. (Dorigo & Stutzle, 2004; Camazine et al., 2003) The word ‘system’ originated from the root word ‘systema’ meaning ‘organized whole’ and literal (dictionary) meaning of ‘complex’ is ‘twisted together’. Thus in complex systems the condition is that the ‘organized whole’ is made through simple individuals interacting in manners that are ‘non-linear’. Consequently, for the purpose of this paper, by complex system it is meant ‘a system of many parts which are coupled in a non-linear fashion and give rise to properties of the system that are by far more intricate than the individual components making up the system’. Such a system can be a continuous, discreet or hybrid. Additionally, this definition signifies that a complex system consists of a large number of mutually interacting dynamic parts. An investigation shall be made to see if these parts can be organized to interact/communicate in simple patterns and follow simple principles in performing their duties to give rise to complex systems.
4.3 Characteristics of complex systems

The concept of complex systems has various explanations in literature, and thus its characteristics are framed in different ways by different actors. For the purpose of this paper we will adopt the approach by Arthur et al. (1997). The authors, from an economics perspective, present the following characteristics of complex systems:

i. **Dispersed interaction:** by this the authors mean the overall property of the system ‘is determined by the interaction of many dispersed, possibly heterogeneous, agents acting in parallel’. Specifically, the interactions can be virtual as well as physical, or they can be direct or indirect. The central point is that ‘the action of any given agent depends upon the anticipated actions of a limited number of other agents and on the aggregate state these agents co-create’.

ii. **No global controller:** this means the actions and/or interactions of agents are not directed by a central (or global) controlling unit. Bonabeau (1998) extends this characteristics by adding that activities are mediated in a ‘decentralized manner through interactions among individuals and between individuals and their environment’

iii. **Cross-cutting hierarchical organization:** this implies that the complex system ‘has many levels of organization and interaction’. In a way this means there are various groups, each with distinct task assignment and responsibility. The overall system is not a mere hierarchical structure but one ‘with many sorts of tangling interactions’

iv. **Continual adaptation:** in a complex system, agents constantly modify their actions to adapt to external forces. This, according to Bonabeau (1998), requires resilience and robustness of the system as a whole and also of the individual components of the system.

v. **Perpetual novelty:** by this it is meant that small subsystems are constantly being created, and grow to make existing systems more complex or spin-off to make a new (novel) complex system. And this process continues in perpetuity sometimes forced by external factors and sometimes by inner drive (induced demand comes to perspective here, for example).

vi. **Out-of-equilibrium dynamics:** the above properties by their very nature are recipes for instability and dynamism. Creation of new subsystems, continual adaptations etc signify change happening all the time in the system and the system ‘operates far from any optimum or global equilibrium’. Such systems Arthur et al. (1997) have called them ‘adaptive nonlinear networks’.
Other characteristics often mentioned in literature about complex system are: *non-linearity, relationships containing feedback loops, openness, have history, nested, boundaries are difficult to determine, and dynamic network multiplicity* (Bonabeau, 1998)

### 4.4 Logistics as a complex system

The council of logistics management (*www.cscmp.org*) defines logistics as:

> “the process of planning, implementing and controlling the efficient, effective flow and storage of goods, services and related information from point of origin to point of consumption for the purpose of conforming to customer requirements”.

Logistics responsibilities include: outbound transportation, intra-company transportation, warehousing, inbound transport, materials handling, and inventory control. Such diverse tasks indicate that logistics covers a wide array of areas, making the logistics management task very complex involving multitude of tasks. Let’s see how logistics conforms to the previously outlined characteristics (coined by Arthur et al., 1997) of complex systems by taking each, one by one and describing logistics tasks.

1. **Dispersed interaction:** with increased IT systems and globalization, the logistics network has become much dispersed. Imagine a typical logistics network for a multi-national production company. Its raw materials may come from very distant – geographically dispersed sources and its end products may be distributed throughout the globe. It may have various production sites, which can be located at afar shores, and may involve in production of similar products in each market or different products tailored to fit specific markets. Multiple product lines in a given facility, raw materials and accessories coming from different locations across the globe, finished products distributed worldwide – are a few of the testimonies for a logistics system meshed with dispersed interactions at various levels.

2. **No global controller:** applied to a logistics system this characteristic is closely related to the property of dispersed interactions. With reference to automobile industry, Windt and Hulsmann (2007) emphasize on the increasing number of part variances leads to various possible combinations and they assert that ‘*the resulting complexity can no longer be managed feasibly by means of central planning and control systems*’. The involvement of 3PL providers at different positions in the logistics chain (which are geographically distributed, as outlined) makes the central control proposition of logistics systems highly impractical. Thus, coordination shall be achieved at micro-levels to meet the global need of the system.
iii. **Cross-cutting hierarchical structure:** in logistics chains, trust (and thus loss of central command and control by the core firm) is very important. The competition arena has shifted from product-to-product to supply-chain against supply-chain of the entire network. This leads to loose organizational boundaries as firms in logistics chains require intensive cooperation to stay competitive in the market. Companies in a logistics chain interact not only for the sake of exchange of products and services but also while devising strategies. Such boundary-less organization formats intensify the complexity as communications will usually follow informal chains as agents get to know each other personally or frequent contacts lead to cutting formal chains of command for sharing vital information.

iv. **Continual adaptation:** Wilsson and Waidringer (2005) report that in reality logistics systems are ‘uncertain, non-linear and increasingly complex’. They recommend the use of Complex Adaptive Systems (CAS) approach to solving logistics management problems, i.e. mechanisms based on ‘assumptions of a more adaptive character, i.e. fewer mechanistic assumptions’. Such assertions of logistics networks coupled with the fact that customer demands are increasingly becoming volatile (i.e. rapidly changing) in most industries, demand a continually adapting logistics network to successfully avert challenges in a proactive manner.

v. **Perpetual novelty:** Wilsson and Waidringer (2005) similarly report that ‘the individual level is of major importance for logistics management since it is on this level that actions are performed and affected by autonomous individuals. As a result of their actions and their perpetual interpretations of the outcome of other individuals’ action, global phenomena emerge’. In logistics, the individual can be interpreted as both a unit within a firm (it can be a person or a machine) and an organization interacting with another. Such individualistic orchestration of processes in the logistics chain will result in novel ways, unknown before to the entire chain, of conducting logistics functions. Such undertaking might eventually lead to other novel ideas, and these to others, and this process goes on for perpetuity. Thus, it is no more advisable to structure logistics chains in a static way. Rather, increasing firms’ capacity to adapt to changes in demands within and outside the logistics chain is quite vital to remain competitive in business.

vi. **Out-of-equilibrium dynamics:** the conventional approach to organizing logistics functions has increasingly become based on an argument that logistics relationships have increasingly become unpredictable and highly dynamic (Wilsson & Waidringer, 2005). Stressing again, a logistics chain seldom remains static as market and other factors demand constant change. The changes can take different forms as they are
very much subjected to individual agents in the logistics chain. However, minor shifts can be recipes for huge structural adjustments in the total logistics chain. Therefore, the logistics system is boiling little by little (it is constantly out of equilibrium) to impact a major change.

4.5 Conclusion

In conclusion, present day logistics systems for most companies are quite complex driven by an ever increasing customer expectation, globalized market, constant innovation, fierce competition and similar other factors. As a result, describing logistics systems using static methodologies is naïve. So, we should resort to methodologies expressing business logistics as complex systems shall be used for both academic and practical purposes. As outlined above, present day logistics systems fit quite well into the six principal characteristics of complex systems. The framing of logistics as a complex system calls for principles of self-organization which are the point of concern of the next section. The figure below shows a complex logistics system circled by the six properties of complex systems.

![Figure 4.1: properties of complex systems and logistics complexity](image)
5. Self-organization in Ants and Basic Principles

5.1 Introduction

In the previous chapter we have seen the concept of complexity and how it relates to logistics systems. So, the next logical question is ‘how can such a complex system be organized so that it won’t be chaotic and lead to a complete disintegration of the entire system?’. As has been outlined, these complex systems are dynamic, and thus posing different sets of problems continually which can sometimes be beyond the control of a central commanding unit. Consequently, we can assert that such systems are difficult, if not impossible, to control centrally. As a result different practitioners have resorted to self-organization principles in structuring complex systems. Thus, in modern literature the concepts of complexity and self-organization are almost inseparable. A wide variety of self-organization principles are utilized in dealing with complex systems in different fields. In doing so, units in the complex systems have reasonable levels of autonomy and dictate the evolution of the system. Self-organizing systems acquire their order and pattern through local interactions without the influence of an internal or external ‘higher body’.

5.2 Self-organizing Biological Systems

Camazine et al. (2001) have written a whole book on self-organizing biological systems. In their deliverance, biological systems, starting from the simplest bacteria, exhibit self organizing patterns at different levels. They assert that for self-organization to work as intended positive and negative feedbacks, controlling feedbacks, information astuteness etc play significant roles. Among the case studies they provide, for example, of self-organizing biological systems are: fish schools, trail formation in ants, comb patterns in honey bee colonies, termite mould building. Similar to physical self-organizing systems, the principal theme in these biological systems is the fact that individual units rely on local interactions for their daily operations and the central unit has little, if any, impact on operations (the central unit in biological systems can be the queen of ants, bees, wasps or the ‘leader’ of that typical group).

Well, now that we have outlined these biological systems self-organize their daily activities, the next question is ‘how do they do it?’ Bonabeau (1997) states that social insects, for example, accomplish self-organizing patterns through the use of various communication methods and by following simple governing rules. For instance, bees use dancing rhythms whereas ants use chemical substance (pheromones) to convey messages to their fellow neighbors. The built-in trait that stimulates a typical social insect to act in a given fashion (with different levels of excitement for different stimulants) is evolutionarily developed mechanism.
5.3 Self-organization in Ants

Dorigo et al. (2000) in their study of usage of ant colony behavior for mathematical algorithms assert that "what particularly strikes the occasional observer as well as the scientist is the high degree of societal organization that these insects can achieve in spite of very limited individual capabilities". This ‘societal organization’ is what is termed self-organization in literature.

Most ants commonly use stigmergy (a chemical indirect communication method) to self-organize their daily routines. Examples of self-organizing patterns in ants are: foraging, division of labor, nest building, cemetery organization, caring for brood, food sorting etc (Dorigo et al., 2000). All these activities are performed without the direct involvement of the central governing body (in this case the queen ant). The ant agents organize their activity by themselves using local information they obtain through pheromone trails. The self-organizing patterns ensure some sort of structural stability in the system (foragers follow a line, workers divide works among them) which otherwise could have been quite erratic and chaotic. Evidently, what we observe in ant colonies is that, even though they are quite many and have different strata, and thus quite complex, the inherent capability of an individual ant to follow certain set of simple rules enables them to effectively deal with problems and is the way of life in such organism. This is what we are going to emulate in later chapters – the ability of agents to follow simple principles or procedures and make the total system work efficiently and deal with problems as they arise.

5.4 Principles of Self-organization

Self-organization is not a new concept. As per Serugendo et al. (2004) it has been around to be explored at least since 1953 with works on insect societies. There are a number of self-organizing patterns observed in artificial and natural systems, where the natural self-organizing systems are being used as inspirations for the artificial ones. Also termed autonomous cooperation, self-organization has increasingly become a solution for problems arising in complex systems. The concept of self-organization was originally introduced in the context of physics and chemistry to describe how microscopic processes contribute to macroscopic structures in out-of-equilibrium systems (Bonabeau et al., 1997). Windt and Hulshmann (2007) assert that, among other things, the increased complexity in logistics systems is due to production in global networks, an exponential increase in the amount of data with the use of new ICT, and product structures with a high number of variations. Thus, the traditional-central planning and control methods become less feasible as they can barely accommodate such complexity. Thus, self-organizing logistics systems are not simply choices but vital strategic tools for firms to become successful in their respective market. Technologies like ICT and RFID play significant roles in structuring logistics in a self-organized way.
There are three important principles that self-organizing structures exhibit: indirect local interactions, no central control and existence of emergent properties (Bonabeau et al., 1997). The following paragraphs describe these concepts in detail.

i. *Indirect local interactions*: imagine a logistics system where the ‘core firm’ mobilizes every logistics issue. Everything is centrally planned and controlled, the ‘core firm’ will have Enterprise Logistics Management Software capable of handling large data, the firm’s dominant power in the logistics chain gives it so much leverage that it is able to drive the entire logistics chain strategy. In such a logistics organization, directions on how to perform logistics activities follow a top-down approach and interactions between different logistics units are centrally coordinated. Such a system is a direct opposite to the self organization concept depicted. On the other side of the continuum, imagine a logistics system with no central controller. Information flows in the system without a need for approval from a command center. The different logistics agents exercise their judgment, as conditions dictate, on how to approach a certain situation. Individual units in the system make decisions, coordinate activities and ‘learn’ to make future logistics activities more effective and efficient. In such a system interactions are indirect and more informal. They are exercised at local levels (i.e. global controller does not exist) and the output of the interaction, however, has an impact on the total system. This is one of the principles of self organized systems, there is no global controller and interactions are indirect, exercised at local levels

ii. *No-central control*: associated with the indirect interactions, agents in self organizing systems are not controlled centrally. Rather simple rules are used as guidelines in coordinating tasks. In natural systems, these rules are behavioral manifestations developed through evolution. And in artificial systems, these rules can be guidelines developed for decentralized coordination, algorithmic decision support tools, and signals (either electrical or wave), among the few. For the individuals making the decisions, local information is deemed enough. Added to this, the agents would be open to change, and consequently, as their actions impact the total system, a self-organized system would be in constant dynamism. This in turn enables the system to benefit from individual cleverness. That is, whereas in centralized systems directions come from the ‘boss’ on how to perform tasks, in decentralized self-organizing systems individuals make their own decisions on how to pursue their course of action. This ‘sovereignty’ is the source of new ideas in such systems, and this is related to the concept of ‘perpetual novelty’ described in complex systems

iii. *Existence of emergent properties*: emergent properties are at the center in describing any kind of self-organized system. This property is the result of local interactions at the
level of individuals comprising the system. The agents that compose the structure interact in simple manners at their levels but in the totality of the structure, this interactions manifest a complex pattern, which is the emergent property. Examples of patterns formed in this way in natural systems are, school of fish, a raiding column of army ants, the synchronous flashing of fire flies, and the complex architecture of the termite mound (Camazine et al., 2001). By emergent it is meant to describe a process by which a system of interacting subunits acquires qualitatively new properties that cannot be understood as the simple addition of their individual contributions (Camazine et al., 2001). For an artificial system, emergent property ascribes to the principle of giving enough autonomy for subunits. Such decentralization of decision making and interaction gives rise to multiple forms of patterns in a single system that makes it quite complex at the global level. But for the individual components, the methods of interaction are simple and can easily be exercised. Thus, emergent properties at local levels, even though quite simple, makes the entire system manageable, innovative and at the same time dynamic.

5.5 Conclusion

In this chapter we have outlined the concept of self-organization in biological as well as physical systems. We stressed that it is quite customary to resort to self-organization principles to effectively deal with complex systems which otherwise create system instability and chaos. Agents in self-organizing systems, whether physical or biological, achieve their patterns by following ‘simple rules’. Developing rules (which are termed principles in this paper) for self-organizing logistics agents is the central aim of chapter seven.
6. Ant Colony – Logistics Correspondence

6.1 Introduction

Ants are among the most ubiquitous animal species on earth – we see them almost everywhere from our gardens to the most sophisticated places. When studied closely, ants exhibit some fascinating traits. Careful observation of their travel patterns for example reveals that each ant follows a very strict path from one point (usually their nest) to another (a food source) except some rogue ants wondering around the area. When further focused, it can be seen that in their return paths ants do carry food (which can be in a liquid ingested form or solid form) back to their colony nest. Study of their nest structure reveals that ants do store food items for future use and behavioral and physiological studies show that they use different communication methods to coordinate their activities.

Consider basic logistics operations. In a given manufacturing firm, what logistics operators do is transport and store items – transport raw materials, spare parts, transport work in process through different parts of the firm, store finished goods and distribute finished goods to customers. To coordinate these processes with each other and other processes in the firm, various communication tools are utilized. As can be observed there are stark similarities between basic logistics operations and activities of ants. Thus, this section, and in fact this paper, is built under the premise that we can draw parallels between tasks of ants and logistics operations and in effect be able to develop different alternatives to organizing and operating logistics processes.

6.2 Supplier selection in Logistics Vs Food Source Selection in Ants

Consider a classical manufacturing company. At the supply side, the very first act would be selection of a set of suppliers from a pool of global supplier base that could provide the necessary inputs for its production. Now, to select among the various suppliers at its disposal, the purchasing unit uses different selection criteria set by the policies of the firm. Different firms use different selection criteria with varying weights to a given criteria. Among the criteria commonly used are:

i. Cost: the price the suppliers set on their products

ii. Quality: the firm has a set of quality criteria that the inputs to its manufacturing shall meet. A supplier delivering products of higher quality with lesser costs would be favored.
iii. Accessibility: the geographic location of the supplier is an important determinant factor as it impacts the cost and time of transportation

iv. Others: factors like flexibility (stated for example through the ability of the supplier to respond positively to increase in demand) and competence (for example stated in terms of skills for future product feature changes)

These and other similar factors play significant roles in choosing a given supplier. Let’s now see how an ant colony assesses and chooses a given food source among various others. This, consequently, will be used to see comparative procedures of supplier selection.

Decisions on selection of a food item for subsequent foraging as forwarded by Holldobler and Wilson (1990) can be summarized as follows. An individual worker (the scout ant or the recruiter as is called in myrmecology) chooses a particular food source according to the nutritional needs of the colony and the richness and appropriateness of the food. To indicate the levels of these criteria the individual ants lay varying levels of pheromone which dictate the pattern of total foraging ants. The first important factor in the decision process is the size of the resource under the scout’s assessment. A larger sized food source would be a constant resource and logically would increase the colony’s productivity for prolonged period, and thus would be highly favored. However, not only the size but also the type of the food source would also impact the decision: a colony would have a demand for a particular type of food source (for example, starch) at a particular instance and another type (for example, protein) at another. That is, the favorableness weights given to a particular food type is different at different instances. Additionally the quality of the food source impacts the decision of recruiting other foraging ants to the food source highly. A food source, for example, of highly concentrated sucrose would be favored than one with low concentration, all other factors remaining the same. The second important factor impacting food source selection decision is the source’s temporal and spatial distribution pattern. A temporal pattern is indicative of the time it takes to retrieve the food source to the nest. Evidently, a food source taking shorter duration for transport would be favored. The spatial pattern is not only an indicative of the distance from the source to the nest (which is directly correlated to the temporal pattern) but also the closeness of the food source to ‘rival’ colonies. A source close to other colonies is disfavored for it could potentially result in a colossal fight which in turn leads the colony to lose a huge amount of energy.

Confirming the above assessments of food source selection criteria is the paper from Traniello (1989). The author reports that “laboratory studies of path use by Solenopsis Geminata have shown that colonies recruit more foragers to sucrose patches that are closer to the nest, larger, or of higher concentration than to more distant, lower-quality, or smaller patches”. Similarly, Portha et al. (2004), after a series of experiments, conclude that “Lasius Niger has now proved to be able to integrate in its foraging decisions food related parameters such as food type, volume, quality
and productivity, as well as non-food related factors such as brood presence, physical environment, and home range marking”.

Now let’s compare and contrast the supplier and food source selection by the resource agent of a manufacturing company and the scout of an ant colony. Among the selection criteria that can be equated are sustainability of a supplier and the size of a food source. It has been stated in the previous paragraphs that ants have strict preference for larger size sources. The scout ants indicate this to their fellow foragers by laying strong pheromone trails on the food source. In essence, it can be asserted that the amount of pheromone laid is proportional to the size of the food source. And for larger size food sources they show willingness to travel further away from their nests. Similarly, the resource agent (or the purchasing unit of a firm in most companies) prefers a sustainable source for the company’s critical inputs. Usually, firms are willing to pay a bit higher premiums for suppliers which provide the items that are critical to production. In addition, they try to build long term and commit significant resources in shaping relationships with these sources. Thus, it can be asserted that the criteria size of resource in ants and sustainability of supplier in a manufacturing firm are comparable, both serving as critical evaluation criteria in making decisions of choosing a given food source in ants and a given supplier in a manufacturing firm.

Another selection criteria that can be paralleled are nutritional needs of the food source for the colony and item’s importance in the production function. Holldobler and Wilson (1990) state that scout ants shift their emphasis from carbohydrates to oils or proteins, or in the reverse direction according to the needs of the colony. This is dictated by the response they get from the inside of the nest, where worker ants will be less responsive to a type of food they have in abundance inside their nest. Now let’s put input materials in a continuum where at one end we have critical items that are required immediately and at the other extreme we have support items (or items in abundance in stores). What would happen in the course of production is that when a given input is less available in the company’s raw material stores, its label in the continuum increases moving up from being just a mundane item to being quite critical when its level in stores decreases to that is deemed so low to essentially disrupt production. Thus, as do ants prefer bringing in a given food type to another at a particular instance, the resource agent’s planning is set in such a way to have critical items available at all periods with optimal inventory levels of each of required production inputs.

Insight from scout ants has revealed that they respond positively to quality food sources. This was confirmed by their relatively swift response to a richer carbohydrate source. Holldobler and Wilson (1990) also stress that various ant species scouts show willingness to travel further from their nests for a higher valued food source. However, they won’t search indefinitely and neither will they travel kilometers in search for quality sources, they have limits. In essence, they strike
balances between energy expended in search and foraging, and the quality of the food source obtained. Similarly, manufacturers demand quality inputs for their manufacturing and are usually willing to pay larger fees for quality raw materials or spend money on long transportation distances. However as do scout ants, the resource agent has to strike a balance between how much cost to incur in search and retrieval of a quality source and the value this resource adds in the final output or production process.

The spatiotemporal criteria deemed important for scout ant decision of the viability of a certain food source can, similarly, be compared to the accessibility criteria of a resource agent’s choice of a supplier. Let’s take two suppliers, supplier A and supplier B. And assume that the resource agent has to choose between these two. Of the factors that this agent will take into consideration is the closeness of these two suppliers to the production unit and obviously, with other selection factors remaining the same, the supplier which is relatively close to the production facility would be favored in the decision. But if for example supplier A is geographically close to the firm (thus minimizing transportation cost and time) while supplier B provides superior quality or less cost for its supplies, the firm will be faced with a tradeoff. Therefore, supplier selection, as seen in this trivial case, is not a simple ‘yes’ or ‘no’ decision, but requires a complex analysis from the spatio-temporal perspective. Similarly, choice of a particular food source at a specific time by an ant colony for foraging from a multitude of food sources is not a simple decision but involves a complex set of communication patterns and tradeoffs (until now I have not found a detailed research (statistical or otherwise) on the decision patterns of ants when provided with multiple food sources, but the general consensus among biologists is that ants make decisions based on energy optimization schemes). The cost the ant colony incurs while foraging, usually expressed in energy expended in search and retrieval of food (Holldober & Wilson, 1990), and the benefit that would be obtained from the food source, expressed in energy gained, are critical factors in selecting a particular food source at a given instance. This can be equated to the cost benefit analysis which is directly related to the accessibility criteria that logistics agents do when selecting a particular supplier.

6.3 The Transport Logistics Vs Worker ant Transport

Consider a single plant manufacturing company which uses a number of inputs to produce its final product. In most circumstances the sources of these inputs (the suppliers) are geographically dispersed. For each supplier, as a result, an optimal route for transportation shall be designated. The consequence is complex route plans from sources to the core firm. However, the quantity of items supplied from some sources may sometimes be too little to be worthy of a dedicated full truck load shipment directly to the manufacturing facility. Under such circumstances the logistics agents use cross-docking centers to consolidate supplies of similar characteristics making the transportation cost effective. Similar cases can be made for the distribution logistics of this single
plant manufacturing firm. It is common that the customers for its products are also geographically dispersed. As a result, the distribution transportation planning is quite complex designed to optimally address the needs of its customers without compromising the cost of distribution. The quantities of final products the company transports vary depending on the capacity of, for example, the retailer or wholesaler, their market share, season of the year etc. Consequently, one of the critical decisions the logistics unit has to make is the number, size and geographic locations of its final goods warehouses which in turn signify the customer order decoupling points. Part B of figure 6.1 shows a representation of distribution networking and materials management (sourcing) can be visualized as a mirror replica of this.

Figure 6.1: Comparison between ‘highway trunks’ and Distribution networks

Trunk trails and ‘highway’ formation by some species of ants was revealed by Holldobler and Wilson (1990) as shown in part A of the figure above. The authors state that *the trunk trails used for foraging are typically dendritic in form; each one starts from the nest vicinity as a single thick pathway that splits first into branches and then into twigs.* The trunks and highways are *traces of orientation pheromones enduring for periods of days or longer.* These paths are made to ensure that there is easy access to persistent food sources. In most circumstances the network of trunk, branches and twigs are optimal allowing the ant colony to maximize its energy gain.

Even though the research on trunk and highway formation in ant colony foraging transportation is not deeply investigated, for example the rationale behind branching at a particular point, they can be compared to the sourcing routes and distribution routes that logistics agents design in
transporting raw materials and finished goods respectively. As do ants want to minimize their energy expenditures effectively maximizing their energy gains, the aim of the logistics agents in route planning is minimizing transportation expenditures, effectively maximizing the firm’s profits. Starting from the premise that ants have developed such optimal designs of their transportation routes through natural selection by using indirect communication mechanisms, in-depth study of the trunk and highway formation may result in new insights into how logistics agents can decide where to for example locate cross-docking centers (which can be compared to the branching points) or customer decoupling points and locating different warehouses in distribution planning which can also be equated to the branching points.

Consider another main concern in designing/planning transportation network routing: Flexibility plus reliability. Transportation routes are planned in such a way that failure or blockage of a part of the network won’t create hindrance for the overall operation of the total network.

![Figure 6.2: Alternative transport routes](image)

To illustrate this, take the illustrative exemplar simplistic network shown above. Let’s say that the route planner has three options to choose from in transporting items from A to B: ACDFB – route 1, AGHJIB – route 2 and AKLMNOB – route 3. For convenience let’s say that route -2 is shorter than route-1 and route-1 is shorter than route -3. With other factors remaining the same the planners route choice will be route- 2 > route-1 > route-3. Let’s say for instance that link HI of route-2 is in blockage or has failed. Under this circumstance, the planner will be forced to scrap all of route-2 and look for the next best alternative, route-1. But, the only problem with route-2 is link HI and if the planner can find an alternative to this link only, there might be no need to scrap the total route-2. This enables the planner to keep the preferred route with minor adjustments. As a result, such a parallel-series route arrangement, as it is called in literature, even though relatively flexible than a simple series network arrangement, lacks reliability of providing optimal alternatives.
Insight into worker ants’ food transportation schemes reveals the series-parallel cooperative operations scheme (Holldobler & Wilson, 1990). The authors also affirm that such an arrangement is also a common practice in the design of control devices. The series-parallel scheme as observed in ant colony is given in the figure below (Holldobler & Wilson, 1990). Such a system provides the colony with high security because when a colony member fails to complete a task another is likely to succeed. When such arrangement is applied to the network routing used for describing parallel series network routing scheme (shown in Figure 6.2) (the figure above) it is depicted in Figure 6.3 (figure below).

Figure 6.3: series-parallel (A) and parallel-series(B) connections

The series-parallel arrangement gives the planner more options for route planning. For instance a simple series-parallel arrangement shown in figure 6.3A gives the planner four options of route selection to reach from origin to destination. Whereas, the same components arranged in parallel-series (figure 6.3B) gives the planner of only two options. On top of this, it is evident from the series-parallel arrangement that a failure of one link won’t cause the failure of the whole network. In essence, this implies that such an arrangement increases the reliability of the total network.

6.4 Warehousing in Logistics Vs Food and Brood Storage and Sorting in an Ant Colony

The ant colony nest stores larva, eggs and cocoons (collectively called brood), and also different kinds and sized of food. Essential to our approach here is the fact that the colony keeps all of them separated in the nest (Parunak, 1997). As an example, when an egg hatches, the larva does not stay with other eggs, but is moved to the area dedicated for larvae. Through such observation Parunak (1997) has developed a simple algorithmic approach on how ants sort their food and brood in their nest. This approach is described below.

1. Wander randomly around the nest
2. Sense nearby objects, and maintain short term memory (about ten steps) of what has been seen
3. If an ant is not carrying anything when it encounters an object, decide stochastically whether or not to pick up the object. The probability of picking up an object decreases if the ant has recently encountered similar objects.

4. If an ant is carrying something, at each time step decide stochastically whether or not to drop it, where the probability of dropping a carried object increases if the ant has recently encountered similar items in the environment.

What differentiates this ‘algorithmic’ approach is its mere simplicity of explaining a complex behavioral pattern. In addition, it is evident that such a system of sorting and storage has given ants the natural stamina to go through difficult times (like winter seasons) without experiencing major setbacks. In essence, their storage and sorting system is highly efficient – it enables them to store optimal levels of food (by type and size), it enables them to utilize their nest structure optimally, and enables them to differentiate brood at different levels of their maturity so that they will be given care tailored to their need. Such insights give basic building blocks for designing artificially intelligent storage, sorting and retrieval mechanisms which are increasingly becoming household names in logistics warehousing.

In industrial logistics warehousing plays a significant role in smoothening operations in logistics chains. It provides convenience by providing raw materials and finished goods as demanded. Industrial warehousing usually involves storage, sorting and retrieval of items on large scale and systematic way. Among others, warehousing in manufacturing is essential for:

- To smoothen seasonality of final products and raw materials
- For continuous production
- To avoid unhealthy price fluctuations both in raw materials and finished goods which endanger the existence of the firm, i.e., it helps in avoiding risks
- Increasing availability of resources (like production facility)

Logistics warehousing decisions involve multitude of questions of which ‘how much to store at a specific warehouse by type and by size’ and after this ‘how to structurally sort these items in the given warehouse’ are the most significant. The ‘how much to store...’ decision is dictated by factors like demand, supply and predicted future price of items. The ‘how to store...’ decision is usually very complex involving tedious algorithms.

Now let’s go back to the ants and see what drives storage and sorting in the nest. Holldenber and Wilson (1990) stipulate that nest ants refrain to let in (or refuse to pick up) to the nest a food of a particular type if it is already in abundance in the nest. These ascertain that ants do not store a particular food type indefinitely, i.e., their nutritional demands and space limitations dictate the type of food to be stored in the nest. And the amount stored in the nest depends on the maturity
of the colony which is directly correlated with the number of individual ants residing in the nest and the reproductive activity of the colony. Other factors that dictate the amount stored in the nest include the seasonal weather variations where ants store bulk of items in sunny seasons for use in the relatively inactive winter seasons.

The factors that affect the amount of stockpiles of food kept in an ant colony nest can be summarized by the function:

\[
\text{Amount stored} = f \{\text{colony needs for brood production, nest size, environmental factors, availability of the food items in the surrounding, the type of the food}\}
\]

It has been shown that ants need to store optimal levels of food for maximizing brood production as this is the mechanism that ensures the continuation of the species. Similarly in logistics warehousing is balancing act that craves for optimal levels of raw materials and finished goods in stores to maximize sales. Store layout and sorting in industrial warehousing has become increasingly complex due to the variety and number of items at store that guarantee differing customer demands that it is so often done using artificially intelligent systems. These intelligent units use algorithms in sorting and storage, and these algorithms are built up from simple rules of engagement. The ant colony storage and sorting algorithm forwarded by Parunak (1997) gives insight onto how we can use ant colony methods to algorithmic approaches of industrial warehousing. The following table summarizes the correspondence between ant colonies and logistics.

<table>
<thead>
<tr>
<th>Logistics</th>
<th>Ant colony</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factors considered in Supplier selection</strong></td>
<td><strong>Factors for food source selection</strong></td>
</tr>
<tr>
<td>- Sustainability</td>
<td>- Size of food patches</td>
</tr>
<tr>
<td>- Production needs</td>
<td>- Nutritional needs of the colony</td>
</tr>
<tr>
<td>- Quality of the raw material source</td>
<td>- Quality of food source</td>
</tr>
<tr>
<td>- Accessibility of supplier</td>
<td>- Spacio-temporal factors</td>
</tr>
<tr>
<td><strong>Logistics Transportation</strong></td>
<td><strong>Worker Ant Transportation</strong></td>
</tr>
<tr>
<td>- Distribution networking</td>
<td>- Highway trunks</td>
</tr>
<tr>
<td>- Transportation networking</td>
<td>- Series-parallel channeling</td>
</tr>
<tr>
<td><strong>Warehousing</strong></td>
<td><strong>Food and brood storage and sorting</strong></td>
</tr>
<tr>
<td>- Algorithmic allocation</td>
<td>- Algorithmic sorting of food and brood</td>
</tr>
<tr>
<td>- Decisions are driven by demand, supply and future price of items</td>
<td>- Decisions are impacted by need for brood production, nest size, environmental factors, availability and type of food</td>
</tr>
</tbody>
</table>

Table 6.1: Summary of ant colony-logistics correspondences
6.5 Conclusion

The outlined correspondence between ant colony activities and logistics operations indicate striking similarities and are indicative of the vast pool of knowledge that can be obtained from studying ant systems. These similarities could prove vital when logistics systems are becoming complex and the prescription is self-organization. This is because, ant agents, with little cognitive capacity, can self-organize their daily activities and thus indicating that logistics systems can be structured in a similar fashion. Building on these correspondences we delve into ant colony foraging in the following chapter and show how insightful ant colony behaviors are for logistics operations.
7. Ant Foraging Based Logistics Self-organization Principles

7.1 Introduction

In the previous chapters the case for self-organizing logistics agents was built. It has been stressed that factors like globalization and increased IT capacity are adding up to the complexity of logistics systems in most global manufacturing companies and that complexity in systems can be dealt with by self-organizing the systems’ units. It has been outlined as well that self-organization is evident in different biological systems like ants, bees, school of fish etc. These biological systems provide starting points for devising self-organizing physical systems. Specifically, in chapter 6 selected correspondences between ant colonies and logistics operations are discussed.

An important point that taken from these chapters is that self-organizing units, either physical or biological, require rules of governance to abide by, so that the system won’t end up being a complete mess. In this chapter, the scope of the analysis is narrowed to foraging in ants (for reasons discussed in chapters 1 and 8) and rules in foraging are provided. Based on these rules, principles of governance for self-organizing logistics agents are developed.

7.2 Schemata for Analysis

The individual foraging ant is used as a frame of reference for each of the logistics agents: warehousing, transportation, scheduling and dispatching. The rules the individual ant follows to self-organize its daily activities are used as starting points for formulating principles for self-organization of each logistics agent. These rules and principles lead to ease of communications and guidelines for decision making. Consequently, such structuring leads to simplicity of operations at local levels. However, when the total structure, in both ants and logistics, is observed, it is quite complex at global level. The metrics assigned for each logistics agent and individual ant serve as basis for decision making. The figure below shows the schemata and the relationship between the concepts.
7.3 The Theory of Foraging

Biological literatures explaining the foraging behavior of ants derive theories of foraging that are essentially composed of optimality models. The basis in these studies is that there are activities of foraging that cost energy like search or travel and transport and models idealize the organism as seeking to maximize its net energetic yield. Thus, the marginal value utilized, or “currency” in foraging theories is Energy. The foundation of development of these theories is the assumption that evolution by natural selection has modified behavior in one of four basic ways so as to increase this currency: (1) choice of food items (optimum diet), (2) choice of food patch (optimum patch choice) (3) allocation of time invested in different patches (optimum time budget), and (4) regulation of the pattern and speed of movement.

Holldobler and Wilson (1990) state that “the analytic advantage of employing energy as the basic currency is that it can be folded one way or the other into all colony processes”. In particular the authors state the following advantages of using energy as a currency for modeling ant foraging:

i. the biomass and biomass growth of the colony or any portion of it can be translated into energy units

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1 Adapted from Holldobler & Wilson, 1990
ii. *foraging success, brood care, and other nurturant activities can be translated into energy gained*

iii. *protective activities, including nest defense and construction, can be converted into calorie equivalents saved because of the reduction in mortality and impaired colony functions that such activity avoids*

iv. *metabolism and mortality can be converted directly into caloric loss*

The principal premise in developing such theoretical approaches to foraging is that the primary objective of the colony is continuation of existence of the colony kin well into the future. Such an objective is met through the production of new queens. Thus, ‘so long as the production of new queens remains a linear function of the amount of energy harvested, ant colonies can be expected to maximize their energy yield.’

In order to achieve this objective of maximizing energy yield the ant populace at the colony level follows strict procedures of foraging. The general foraging pattern is **search – recruit – retrieve**. The search is a process of looking for and selecting food sources based upon a forager’s physical caste, age, and prior experience, the trip distance, thermal stress, resource quality, and the colony’s current nutritional status (Traniello, 1989). Once a food source is selected as relevant for the colony’s needs, mass communication methods (both physical and chemical) are employed to recruit other worker ants to help carrying the food from source to nest (this is the case in central place foraging, some ants also store foods at outposts); such processes where ant scouts move a group of nestmates toward a newly discovered food site is called recruitment (Cassill, 2003). The recruited workers help in further recruiting others to retrieve the food back to nest until it is depleted or colony needs are satisfied. The communication syntaxes displayed in the search, recruitment and retrieval play vital roles for the overall efficiency in foraging.

In the search – recruit – retrieve foraging pattern the scout ants (they are the once who go out and look for and select a food source for foraging) and the recruits follow ‘rules of thumb’ that are geared towards maximizing the energy yield of the colony. The following is synthesized process of foraging and each step is associated with rule(s) utilized to structure foraging and ultimately maximize the energy yield of the colony.

1. A scout ant leaves the nest in a random direction in search for a new food source. In making a decision on which direction to follow it applies a phenomenon called ortsresse (Holldobler & Wilson, 1990). This is a situation where the scout ant utilizing its previous learning experience; sites where food sources proved to be more rich and persistent serve as starting points in the search. The first foraging rule that is applied to scout ants is thus: *start the search pattern randomly using previous proven rich and abundant sources as starting positions.*
2. Upon finding a food source evaluate the relevance of the food source to the colony needs. The volatility is determined if it passes some threshold level that excites the scout ant. The threshold level depends on the nutritional level of the colony, a hungry colony having lower levels. If the source is deemed relevant, mark the position using pheromone releases and take a sample back to the nest.

3. On the way back to the nest the scout ant is required to lay incoming pheromone trails on the path followed that would serve to direct the scout and fellow foragers back to the food source.

4. Upon reaching the nest, the scout ant should ‘advertise’ the sample taken, and use communication methods like increased walking tempo, stroke nestmates with antennae or waggle heads (Cassill, 2003) to excite other foragers and in the process recruit them for foraging.

5. When proposition to forage a given source is accepted, the scout ant leads its fellow foragers to the food source by following incoming pheromone trail laid and further laying subsequent pheromone trial to reinforce the path.

The five rules of engagement listed are followed by scout ants. When a scout approaches nestmates to pursue foraging they also have rules of thumb to follow. These rules are presented as follows.

6. Nestmates when presented with a food source choice assess the food sample with antennae, then respond to or resist recruitment based on the quality of food advertised, their employment status, and their level of hunger.

7. Upon reaching the food source, the ‘regular’ foragers and the scout take maximum capacity loads and lay pheromone on their travels trails to further strengthen the path. A pheromone strong path will also serve as an attraction for increased recruitment of foragers. This process continues until the source is depleted or it is not required anymore.

The following are theoretical predictions that natural selection has shaped the ants to follow (Holldobler & Wilson, 1990):

- The greater the distant the ant travels from the nest to a food patch, the longer she should take to select the food item.

- The greater the distance the ant travels to a food patch the more selective the ant should be in choosing a food item.

- The higher the temperature, the more selective the forager should be in food patches.
7.4 Logistics Systems: Agents and organization

Ghiani et al. (2004) state that logistics systems are made up of three main activities: order processing, inventory management and freight transport. Order processing is an information flow from the customer (or it can be a sales forecast) to a number of logistics operations. Different units in the logistics system will plan their activities based on this information. Inventory management is the planning and control of stockpiles of goods waiting to be manufactured, transported or sold (Ghiani et al., 2004). It helps to smoothen the flow of the total logistics operations. Freight transport is managing the in and out movement of raw materials and finished products. It enables manufacturers be able to produce and sell their produces at the place of their choice. It plays a great impact on the level of service provided to customers.

In order to perform these key logistics systems activities four logistics agents are identified: the warehousing agent, the transportation agent, the scheduling agent and the dispatching agent. The common themes in logistics management have been issues like integration of activities or to have a central information command and control unit. However, such types of systems have their own apparent challenges. Slater (2007) states that the inherent problems are: the logistics organizational structure within the firm may be fragmented and the logistics channel may be disjointed. Hence, the approach presented here builds on this fragmentation and disjoint; that is, rather than advising firms to organize their logistics in a different way (for example, through integration) it acknowledges that firms can and should be able to organize their logistics operations the way it fits their strategic makeup. What this means is that however differently the logistics agents are framed, a rule based approach to accomplishing tasks suffices for making a logistics system work efficiently. The approach provided here of segmenting logistics agents into the aforementioned four categories is not the absolute sole way of devising logistics system. Rather, it serves as a demonstration on how to organize logistics units by using rule based mechanisms. The subsequent sections describe this approach in detail for the four logistics agents stated above.

7.5 The warehousing agent

Warehousing is an important logistics operation that ensures a certain level of service throughout the logistics channel. This is achieved through increasing availability of raw materials, components parts and final products. In doing so, warehousing functions increase time and place utility. The parallels drawn here between ant colony and warehousing is described as follows. In an ant colony, the larger the distance covered or the larger the area swept in search for a food source, the higher is the probability of finding an abundant food, and thus the more energy can be added to the colony’s energy reservoir. However, this proposition comes with a staggering cost to the colony, expressed through the high energy expenditure required for searching and foraging
such a ‘large’ area or distance. In essence, the colony has a distance limit after which the colony will have diminishing returns from foraging. As a result, the foragers have to balance the area covered and the energy expended in foraging. Similarly, the more items stored in a company’s logistics chain, the shorter is the ‘order-to-dispatch time’ (this concept will be described shortly). But this comes with additional fixed (like owning new warehouse facilities) and variable (for example, opportunity cost of tied up capital) costs.

As described above, the currency deployed in ant colony foraging is energy; similarly here in warehousing functions the currency used is ‘order-to-dispatch’ time. The aim in warehousing is, thus, maximizing the yield in ‘order-to-dispatch time’. The yield in ‘order-to-dispatch time’ is defined as the level of service envisaged to be achieved (through conformity with customer orders) minus the cost incurred to achieve this level through warehousing at different points in the logistics chain. Similar to using calorie as a measurement unit in foraging energy, dollar or euro units can be used to measure the ‘order-to-dispatch time’. Of course it is difficult to quantify the ‘level of service’ in monetary terms. However, estimations on time reductions or increase of sales due to the warehousing functions can be used as frame of references in quantifying. In order to maximize the yield in ‘order-to-dispatch time’ in warehousing, decisions from strategic to operational play significant roles. Typical decisions in warehousing categorized accordingly are:

- **Strategic**: examples; location of warehouses, technology deployed to facilitate warehouse operations (e.g. RFID systems, bar codes etc), size of warehouses, type of warehouses (public vs. private) etc

- **Tactical**: examples; type of material handling system deployed in the warehouse, warehouse layout, threshold of items in the warehouse etc.

- **Operational**: example; allocation of resources (labor and handling equipment) on the different warehousing operations

From these decisions in warehousing two are chosen for further exploration using principles of ant foraging. The first one is the development of rules for how to determine threshold level of items in store and the other is for resource allocation in warehouse operations.

1. Establishing threshold levels

It has been outlined in the ant colony governance rules that scout ants and ‘regular’ foragers have threshold levels that would instigate them to act on a specific way (an example is decision of scouts to start laying pheromone trails and start the recruitment process for foraging). Similarly, the threshold storage levels shall act as ‘red flags’ for some kind of action. These threshold levels, however, should not necessarily remain constant throughout the production period. Rather, they shall be revised continually to account for changes throughout the logistics chain. Changes in
logistics chain, for example, may arise from changes in demand levels for products. This is comparable to foraging ants’ change in threshold level in accordance with the nutritional needs of the colony. These relationships can be expressed in functional format as:

Ant colony foraging: \( T_a = f(\text{nutritional need of the colony, } N_a) \)

Warehousing: \( T_w = f(\text{production and sales needs of the firm, } N_f) \)

The aim in warehousing, as put forth previously, is to maximize the yield in ‘order-to-dispatch time’. Apparently, it would be advantageous to map out how different items in a given warehouse contribute to this yield. All items are not equally significant in maximizing this currency – some items have a highly positive contribution whereas others have less. Consequently, using this level of contribution criticality to the yield function, the following principles (or rules) are developed on the basis of ant colony foraging:

**Principle 1.1:** If an item is highly critical for production and sales, its threshold level should be higher

**Principle 1.2:** If an item is highly critical, it should get a higher value in measuring customer satisfaction levels

**Principle 1.3:** The higher the uncertainty of the external factors impacting the availability of a given item (example, factors like the price of the item in the market place), the higher should be the threshold level of the item in the warehouse.

### 2. Warehouse Resource Allocation

Managing big industrial warehouses is a daunting task. Warehouses are becoming increasingly complex and the quest to use all the three dimensions of the warehouse further increases this complexity. With this comes the versatile and flexible material handling equipments like overhead cranes, AGVs and other intelligent robotic systems. Added to this is the need to have an efficient labor force tasked to operate such complex equipments. However, these resources are not in abundance and should be managed efficiently to ascertain a seamless workflow in the warehouses.

Again evaluation is made of such allocation decision with respect to maximizing the ‘order-to-dispatch time’, the preferred currency for evaluating warehouse operations. The reasoning in these decisions making is that a resource assigned to a particular task at a given time could have been used to perform another task, i.e. any assignment decision involves an opportunistic cost. Consequently, when a resource is assigned to perform, say, task A, it should give a better payoff in maximizing the ‘order-to-dispatch time’ than the next best alternative, task B. Using this approach, prioritizing algorithm based principles are developed.
Principle 2.1: prioritize items in warehouses for movement into and out of warehouses: the larger is an item’s payoff in maximizing the ‘order-to-dispatch time’, the higher it shall be ranked in the priority function for resource allocation.

One of the things that should be emphasized here is an item’s payoff in maximizing the ‘order-to-dispatch time’ is a variable function; it varies accordingly with, for example, production and sales schedules, demand fluctuations etc. Thus, to prioritize resource deployment, at each instant, an algorithm of the type described below can be utilized. Such a principle can very much be a guidance to warehouse layout for spare parts stores.

Start resource deployment

Randomly choose an item A for prioritization from a pool of items requiring movement

Search for an item with higher payoff function than the item picked from the pool

If an item B has a value higher than the item A, replace item A with item B

Repeat

Principle 2.2: picking the item for movement and further deployment. In assigning a resource to moving an item to, from or within the warehouse, pick the item with the higher payoff value and deliver it to its next destination (for example, to the production facility). At the final destination assess the best alternative task to perform prior to returning back to original position. The best alternative deployment of the resource is once again to a task that has a higher payoff in maximizing the yield in ‘order-to-dispatch time’

The above two principles are derived from the food selection traits of an ant colony. In the previous sections, it has been outlined that an ant colony uses a form of ‘algorithmic’ assessment in selection of a particular food source for foraging. It has been theoretically argued that the basis for the selection decision ultimately lies on the naturally inept trait of opting for a food source that meets the colony’s nutritional demand at that specific time. This, in turn, has been formulated to be in sync with the energy demand of the colony during that moment. Similarly, in logistics warehousing, the development of a single currency, the ‘order-to-dispatch time’, gives a decision foundation that enables the warehousing agent to be able to see the totality of the warehouse from a single evaluation perspective. Consequently, global optimization solution to resource allocation can be obtained, contrary to applying different metrics for different resources and resulting in sub-optimal solutions.

7.6 The Transportation Agent

Transportation is one of the key tasks in logistics operations. The transportation agent is concerned with the efficient movement of items from source to destination. In today’s global
business environment the transport function has become even more significant as firms are not limited by geographic barricades to harness their sources of production and sale of their outputs.

Transportation in industrial logistics is a two sided operation. The first is the inbound transportation where raw materials, production accessories, and machinery spare parts are moved from suppliers to production and warehousing facilities. The second is the outbound transportation where produces of the firm are moved from production and warehousing facilities to respective customers. The movement of production byproducts can also be considered as outbound transportation, but it is not of major concern here.

In academia and practice, there are a number of transportation optimization tools; each having a different approach to the objective functions and the variables involved in the optimization scheme. In this paper the objective put forth is maximizing the yield in ‘dispatch-to-customer-receipt time’. In inbound transport the dispatch can be thought of as the instant where the items are unleashed from the suppliers. And the customer receipt can be equated to the instant the resource reaches the respective warehouses or production facility. Consequently, such equivalencies enable us to use the same currency throughout the total transportation network.

The aim of the transportation function is framed here as maximizing the yield in ‘dispatch-to-customer receipt time’ similar to ant foraging where the aim is maximizing the yield in energy. The yield in ‘dispatch-to-customer receipt time’ is defined as the difference between the benefit obtained by transporting a given item from source to destination and the cost incurred in transporting the item. The benefit, even though usually intangible, can, for example, be operationalized by comparing it to another transportation scheme and accounting for the difference in service level. A common denominator for the benefit and cost can be dollar or euro units. In order to maximize this yield, transportation decisions of the three pillars, strategic, tactical and operational, play significant roles. Typical decisions in these spectrums are:

i. Strategic: transportation network design, choice of transportation resources ownership (private or third party)

ii. Tactical: Choice of mode of transportation

iii. Operational: fleet size

Now that a uniform currency has been established in the transport network that can be equaled to the foraging currency of energy, it is time to develop principles in transportation emulated from ant colony foraging. For this, two decisions, choice of mode of transportation and fleet size assignment, are chosen and principles for decision making are formulated.

1. Choice of modes of transportation
The choice of the mode of transportation(s) is one of the critical decisions the transportation agent has to make. The four general modes of transport are: water, land, rail and air. In deciding the mode of transport, the agent has the option of one type or a combination to choose from.

The choice of mode(s) of transport is a very difficult balance. Whereas shipments using water are less expensive and accommodate large bulks, they are generally slower and increase inventory costs. On the other side of the continuum, a choice of air transportation provides the luxury of quick shipments and less expensive inventory. However such luxuries come with strings attached to them as air cargo shipments are way expensive and in one go only a limited amount of bulk can be transported.

In addition to being a balancing act, the choice of mode of transportation is heavily dependent on accessibility in the transportation route and type of product to be transported. Accessibility is meant to signify, for example, if an item is transported from source to destination where there are no ports or sea lines, the water transportation option is out of consideration. The same holds true if railways are absent. By the same token, when transporting perishable or short expiry date products, the transportation agent is forced to choose faster transportation modes. These all issues should be factored in while making the mode selection decision and formulating the decision problem as one that should maximize the yield in ‘dispatch-to-customer receipt time’ gives a global perspective.

Now we turn our attention to a situation where the transportation agent has multiple alternatives at its disposal and develop guiding principles to base his/her decision on. Derived from the principles of foraging in ants, the following are guiding principles to base decisions on to maximize the yield in ‘dispatch-to-customer receipt time’.

**Principle 3.1: the larger the distance the item has to be transported, the more exhaustive the list of alternatives should be and the more selective the agent should be in choosing a typical mode or combination of modes of transportation**

Long distance transportation usually has elaborate list of alternatives. For example, take an item to be transported from the US to the Netherlands. Inside the US the item can be transported by land, rail, water (depending on the position of the source) or a combination of these to a suitable sea-port or airport. Other transportation combinations are shown in the table below.

<table>
<thead>
<tr>
<th>Area</th>
<th>Land</th>
<th>Air</th>
<th>Water</th>
<th>Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insider the US</td>
<td>Okay</td>
<td>Okay</td>
<td>Okay/Not-okay</td>
<td>Okay/not-okay</td>
</tr>
<tr>
<td>From US to NL</td>
<td>No</td>
<td>Okay</td>
<td>Okay</td>
<td>No</td>
</tr>
<tr>
<td>Inside NL</td>
<td>Okay</td>
<td>Okay/Not-okay</td>
<td>Okay</td>
<td>Okay</td>
</tr>
</tbody>
</table>

Table 7.1: choice of mode of transportation
In addition to these straight alternatives, other strategies may come apparent to the transportation agent. One such strategy is an option of consolidation. The item may have a size that is not optimal for water transportation, but when it is kept for a while and other items are added to the transportation mass, water transportation may once again be a feasible alternative. And, in doing so, the transportation agent may maximize the yield in ‘dispatch-to-customer receipt time’

Consequently, decision on mode of transportation, especially in long distance transportation, is a daunting task to the transportation agent. And this principle emphasizes that options should be exhausted and in choosing the best alternative, the target should be that it should be able to give a better yield on ‘dispatch-to-customer receipt time’ than the next best alternative.

This principle is derived from ant colony foraging principle of “the greater the distant the ant travels from the nest to a food patch, the longer she should take to select the food item”. Similarly here, the longer the distance the more exhaustive alternatives should be.

Principle 3.2: the higher the risks of external factors involved in transportation, the more selective the transportation agent shall be in choosing a given mode.

It has been outlined that in ant colonies external factors like temperature and humidity have impacts on foraging decisions. For example, a high external or ambient temperature increases the metabolic activity of a given ant and in effect increased its energy expenditure while foraging. This in turn will have an effect on the total energy yield of the foraging activity. Similarly, in transportation there are external factors like excessive traffic, piracy, high sea currents. CO₂ emission laws etc that impact the choice of the mode of transportation. Such factors increase the expenditure in ‘dispatch-to-customer receipt time’ and thus lowering the total yield. They are impediments that should be factored in while making the mode choice decision. They, in essence, expand the mode choice decision arena. Thus, it is required of the transportation agent to be more selective when such external impediments have significant roles in the transportation operation.

2. Decision on fleet size

Another critical decision the transportation agent faces in daily operations is choosing fleet sizes – Truck Load (TL), Less than Truck Load (LTL), or parcel shipments. Obviously, the transportation agent chooses TL shipments over the others, if available from source to destination. However, delivery date commitments and service level envisioned for their customers coupled with not enough items to transport for the full TL distance and vastness of transportation networks force companies to resort to the other fleet size options – the LTL and parcel.

In choosing a particular type of fleet size, the transport agent faces a difficult dilemma of keeping high customer service levels but with high costs of small size and high frequency shipments.
Subsequently, some fundamental principles are developed for taking decisions on fleet sizes based on foraging principles of ants. The currency (or metrics) used, once again, is the ‘dispatch-to-customer receipt time’ and the aim is maximizing the yield in this currency.

**Principle 4.1: Under intense service delivery competition, use small size and frequent transportation schemes until the point of maximum acceptable loss.**

It is not uncommon to find firms using logistics transportation as a means of competition in the market to differentiate themselves through service. But such exceeding logistics service performance comes at a cost and thus at a loss to the firm, compared to its nearest competitors. In this principle it is demanded to develop the maximum acceptable loss. The bottom line here is that firms keep high level of service delivery to sustain and expand their customer base. That is, an increased service level helps to build up good relationship with customers, which in turn locks-in customers to the company’s products. In order to do this, the company is required to have better service delivery levels than others in the same industry. But this comes with higher cost (compared to competitors, putting the company in a disadvantageous position in terms of costs incurred) of small size and frequent shipments – and initially (before locking-in and expanding the customer base) this comes at a big loss to the company. This is because initial sales may not signify the amount of service delivery level provided. Thus, in using transportation (and thus, delivery service) as a competition tool, it should be mandatory to develop the ‘maximum acceptable loss’ limit.

This rule is developed from a similar pattern in ant colonies. Ant colonies usually defend a certain foraging area from another nearby competitive colony. Through fighting the colony loses a bunch of its worker ants which can be considered as energy loss, as energy has been used in the development process of the worker ant from egg to adult. The colony has an acceptable loss limit which it is willing to sacrifice for a food source at a particular time. If the colony decides the food source is not sustainable in providing the energy level it demands, and thus it is not worth fighting for, it may decide to migrate to another terrain or surrender this specific food source. The reason behind, as put forth by Holldobler and Wilson (1990), is the fact that the colony, by natural selection, strives to maximize the energy yield it obtains from a typical food source.

Similarly, the aim here is to maximize the yield in ‘dispatch-to-customer receipt time’. An increase in service levels through short delivery periods, by using small size and frequent fleets, is an attempt to excel in the market and fend off competition. The end result is a satisfied customer willing to pay premium prices for the service. Eventually, through sustained customer relationship and expanding customer base, the initial cost of transportation will be recovered just as the ants get energy profit from defending a sustainable foraging field. But the loss sustained initially could not be infinite, and thus, the small fleet size and frequent shipments should be carried only if the initial loss is equal to or smaller than the maximum acceptable loss.
**Principle 4.2:** The higher the number of small size and frequent shipments demanded, the more selective the transport agent should be in appropriating resources to product type.

This rule is based on a quest to construct product oriented fleet size strategy. Products, for the purpose of giving fleet priority, are categorized across the high end – low end spectrum. Products at the high end are those that fetch premium prices and subsequently customers demand higher level of service. For these products small size and frequent fleets could be more viable so as not to compromise delivery time in search for bulk transportation. Products at the low end of the spectrum are those which are sold at regular prices and subsequently, building a high level of customer service is not the primary prerequisite. For these products, a more prudent, fleet size strategy that balances acceptable delivery times with larger and less expensive shipments shall be devised.

The antidote for this principle is an ant colony strategy of being more selective in distance foraging. It has been outlined in the previous sections that ants are more selective (gunning for highly energy rewarding sources) when foraging far away from nest. In doing so, it is argues, they will maximize their energy yield. Similarly, following this principle, the transportation agent will maximize the yield in ‘dispatch-to-customer receipt time’. This is because high end products have higher returns on relatively high investments in small size and frequent fleets.

### 7.7 The Scheduling Agent

The scheduling agent is responsible for scheduling and rescheduling activities in the logistics chain, exploring hypothetical ‘what if’ scenarios for potential new orders, and generating schedules that are set to the dispatching agent for execution (adapted from Fox et al., 2000). Scheduling decisions usually fall under the tactical decision making process.

A number of algorithms and software are available that enable the agent to make optimal schedules. The different algorithmic scheduling decisions are based on optimizing certain parameters like minimizing mean tardiness or WIP. Quite frequently when agents make schedules, they assign degrees of freedom to activities. The degree of freedom is devised give the dispatching agent sufficient room for maneuver when actually deploying resources, thus providing a certain extent of flexibility of operations.

The measuring tool envisaged to be applied in scheduling logistics activities is the ‘order-to-delivery cycle time’. So, the objective of the scheduling agent can be formulated as the one which maximizes the yield in ‘order-to-delivery cycle time’. This metrics is taken from the description of the task of the scheduling agent outlined in the previous paragraph. The task of the scheduling agent, it can be inferred, starts when establishing cases for potential new orders and ends when plans are established to ascertain the exact allocation of resources to deliver as per the
requirements of the order. So, the order-to-delivery cycle (it starts from the customer and ends at the customer, thus it is a cycle) is the frame of reference for scheduling logistics activities.

The figure below shows positioning of logistics in the interaction between a given firm and its customers.

Figure 7.2: positioning scheduling in the logistics chain

The input for a schedule is customer orders (or forecasts) which constitute amount of products and delivery dates. The output of a schedule is a plan for resource engagement with a reasonable degree of freedom and when this plan is executed the delivery requirements are met. So, the primary target here is to extrapolate some principles for schedule developments from ant colony foraging behavior that will maximize the yield in ‘order-to-delivery cycle time’. This objective can be equated to the objective of maximizing the yield in energy for the ant colony.

The following are two of these principles.

*Principle 5.1: The higher is the position of a product in the high end – low end spectrum, the larger should be the degree of freedom provided while making logistics schedules for this product.*

Here the principal assertion is that high end products usually have strict delivery schedules. The provision of sufficiently enough degree of freedom enables to avert any unprecedented delay in the logistics process which would greatly damage the reputation of the company in the eyes of the customer. However, large degree of freedom has its own disadvantages; there is a point of diminishing returns of providing excessive degree of freedom. This is because an unusually high degree of freedom results in idleness of resources which otherwise could have been used to perform other activities. That is, the expense of high degree of freedom (DOF) is an opportunity cost. An acceptable level of DOF for high-end products, as stated earlier, has the benefit of accounting for unforeseen delays in the logistics processes. This in turn has the benefit of a satisfied customer as delivery dates will be met unconditionally. This implies a further increase in the yield of ‘order-to-deliver cycle time’. But higher DOFs come at expenses of unused resources.
counted as opportunity cost. Thus the duty of the scheduling agent is balancing such contradicting demands in the logistics process. The calculus behind giving more DOF to high-end products is that, the high customer service to high end products has higher yield in ‘order-to-delivery cycle time’ than providing same to low end products.

This principle is a direct interpretation of ant colony behavior in foraging. Scout ants spend more time and travel large distances in search for better quality food items which is in sync with the colony’s specific need at that particular period. The high DOF can be equated to the long period spend by the scout and the high end products to high quality food items.

*Principle 5.2: When assigning tasks to resources, use an incremental technique of capacity fitting.*

Scheduling is looking into the future, it is experimenting if targets can be met, it is constantly changing – it is never constant. It needs constant updates due to, for example, increases in capacity, increases in demand or similar other factors. And as a prediction into the future which is uncertain, it is not 100% perfect. Unpredictable events like rush orders can change the total scheduling scheme developed. That is why at the beginning of this section (the scheduling agent) rescheduling agent is put forward as part of the scheduling process. Thus, in this principle a focus is given to incremental adjustments. This makes schedules more adept to changing scenarios, either external or internal. From a pure business perspective, it makes sense to target for full capacity utilization of available resources while making schedules. But this has its drawbacks, especially when making the very first scheduling round. This is reinforced by the fact that it is very difficult, if not impossible, to exactly predict the human capacity. What happens when schedules are made in parity with full capacity is that resources will usually be overloaded. The final result is large queue of tasks needing attention. Eventually, the effect is unmet delivery times and a loss in the yield of ‘order-to-deliver cycle time’. The incremental adjustments help the scheduler to determine the optimal level of capacity utilization that maximizes the yield in ‘order-to-delivery cycle time’.

This principle is derived directly from recruitment procedures of ants while foraging. When scouts find a food source, they recruit (using their pheromone trails) other regular foragers to assist in food retrieval. The newly recruited foragers themselves recruit other fellow foragers by laying pheromone trails whose concentrations indicate the level and quality of food source to be foraged. The recruitment won’t continue indefinitely; the pheromone trailing pattern stops (then pheromone decaying starts) and other foragers, due to less strong pheromone signals, won’t join the foraging process. Had they simply joined, the trail will become over crowded - disproportional to the food to be carried. The colony, in turn, will expend a lot of energy due to the large congestion thus decreasing its energy yield. This incremental recruitment process is the inspiration for incremental assignment of resources to tasks while making schedules. If not done
incrementally, similar to the ant congestion, capacity over flow or under flow will result which are unfavorable to the scheduling agent as they decrease the yield in ‘order-to-delivery cycle time’.

7.8 The Dispatching Agent

The dispatching agent performs the order release and real time floor control functions as directed by the scheduling agent (Fox et al., 2000). The dispatching agent assigns resources to tasks in real time in accordance with the DOFs provided by the scheduling agent. Consequently, dispatching decisions, by their very nature, fall under operational decisions. In this paper dispatching includes both backward and forward task assignments. The backward dispatching implies the assignment of resources to tasks that are required to retrieve raw materials and accessories required for seamless production. And forward dispatching is meant for allocation of resources for outbound logistics – distributing products to customers. Therefore, the principles developed are applicable for both types of dispatching.

As is the case for transportation, the metrics applied for measuring dispatching is ‘dispatch-to-customer receipt time’. And consequently, the objective of the dispatching agent is maximizing the yield in ‘dispatch-to-customer receipt time’. The primary concern in dispatching is whether due dates can be met, and thus keeping up to the customer service level set by the firm’s policy, without significant impacts on the cost structure. For example, if we take vehicle dispatching, small size and frequent assignments may have the advantage of high customer service levels and low storage costs. But, such deployment of transport resources will increase the transportation cost in terms of both long term (example, owning a number of vehicles) and short term (example, costs like fuel consumption). As a result, the duty of the dispatching agent is striking a balance between these two conflicting objectives.

The following are exemplary principles developed from ant colony foraging behavior that can be applied to logistics dispatching.

**Principle 6.1: Use incremental dispatching of resources; more resources shall be deployed in a particular pattern only when it is proved that this is the practical solution at that specific instant.**

This principle is a practical alternative to algorithmic approaches to dispatching. This is significant in no more than vehicle routing problems. When dispatching vehicles for transportation, the dispatching agent strives for attaining the optimal route. This optimal route is usually obtained by using complex mathematical algorithms. The common trend is deploying vehicles in a particular route which is deemed optimal. This principle influxes certain flexibility into the rigid optimal approach. The optimal route which is identified through the mathematical algorithm can be used as a starting point. A few vehicles shall be deployed in this route first and the result of usage of this route shall be registered. That is, the time it has taken the vehicle to
cover the distance of this route and report from the vehicle operator of the detail route information shall be factored in. Such information processing shall be done in real time when the vehicle is in the specified path, for example, through electronic data signaling equipment attached to the vehicle that reports data associated with transport (like the state of traffic, the weather condition etc). Vehicles in subsequent deployments shall be given real time feeds of earlier developments and shall have alternative routes at their disposal. The operators of the vehicles shall give due consideration to the information feed and make instant route changes, if necessary, which will maximize the yield in ‘dispatch-to-customer receipt cycle time’. In such a way the vehicle operators self organize the vehicle dispatching operations. Such approaches to self-organization can be emulated in other dispatching operations as well.

This principle is derived from recruitment in ant colony foraging. Recruitment is an incremental process in ants. A scout ant, in identifying a food source, informs few fellow foraging workers of its finding. The foragers follow the scout and they in turn disseminate the information through indirect means (through pheromone trailing). Other foragers join the crew and the decision to join or not for foraging are left to the individual ant. The pheromone trails can, in this case, be seen as equivalent to the information sent by earlier dispatched vehicles. The original vehicles deployed correspond to the scout ants, the foragers correspond to the subsequent vehicles joining the earlier vehicles.

Such deployment strategy, through its flexibility and decentralized decision making, guarantees efficient utilization of resources. In vehicle routing, for example, through real time data feeds, vehicles can avoid excessive traffic jams by choosing alternative routes. The result is increased availability of resources which in turn ascertains increasing the yield in ‘dispatch-to-customer receipt time’.

*Principle 6.2: The longer the dispatching distance and time, the more considerate the agent should be in load matching.*

Long distance and long hour dispatches are expensive and need to be conducted with vigor. For example, a half empty truck travelling for miles is using an expensive means of transport. So is a truck going full load to destination but returning back empty. Thus, long distance and long hour dispatches need careful consideration of details, a simple optimal route selection, for instance, is not usually the overall solution. Rather, routes that cover multiple destinations with better load matching even though not optimal might give better results. In addition, reverse routes with loading shipments might be preferred than empty truck loads with optimal forward routes. Therefore, load matching in dispatching is usually a difficult balance. The dispatching agent shall determine until what load level, to how further a distance and to how long a typical assignment is preferred to another kind of plan. With distance and time longevity, the issue confronting the dispatching agent will further increase its complexity.
As outlined the ultimate target in dispatching is maximizing the yield in 'dispatch-to-customer receipt time'. The empty or half empty trucks, for example, can be considered to result in negative yields while analyzing to choose a particular route and the corresponding load matching. These decisions are day to day operations and demand a high level of flexibility form technical application tools (like software) and greater attention to detail from the floor operators.

This principle is derived from ant colony foraging behavior of being highly selective on food sources that are distant from nest. That is, the longer the distance of foraging site from the nest, the more selective ants become in choosing their food source, ultimately maximizing their energy yield.

### 7.9 Illustrative Ideal Case

In the previous sections we have developed a series of principles for self-organizing logistics agents based on ant colony foraging. In this section a demo of how these principles can be used in practice is given by using warehouse threshold level and how this level can be calculated for a given product as an example.

Consider an ideal firm F. For simplicity assume that this firm is in business for production and sales of a single product X. Just to show how we build the threshold formula, assume that this product is made of components C₁ and C₂.

The first principle of warehouse threshold level states that:

> “The highly critical an item is for production and sales, the higher should its threshold level be”

Here, it must be acknowledged that criticality is a very subjective criteria; it depends on the type of company, the type of market it operates on, the kind of competition, and similar other factors.

Let's represent the criticality of a given item by \( R_i \)

But the threshold level of a given product is not only dependent on the criticality of itself but also the criticality of its component parts. For example an abundantly available component in the market could not be at the same level of criticality as to that which is in constant shortage in the supply market.

Consequently, from this principle we can assert that

\[
\text{Threshold level is directly proportional to criticality of an item at a given instant}
\]

\[
\text{Let's represent Threshold level of product X at instant } i \text{ to be } T_i
\]

Then,

\[ T_i \propto R_i \]
Changing the proportionality into equation

\[ T_i = \alpha_i R_i^{\alpha_i} \]  ...........................................(1)

Where \( \alpha_i \) is the proportionality constant and \( \alpha_i \) is the constant which determines the extent of proportionality (whether linear or exponential). For linear relations \( \alpha_i = 1 \) and for exponential relations \( \alpha_i \neq 1, 0 \) and in cases of critically insignificant items \( \alpha_i = 0 \)

So, for our case of two components and a single final product, the threshold value at a given instant can be formulated as

\[ T_i = \alpha_1 R_1^{\alpha_1} + \alpha_2 R_2^{\alpha_2} + \beta x R_x^{\beta_1} \]  .............................................(2)

The second principle that we have developed for threshold level determination is:

“The higher the uncertainty of the external factors impacting the availability of a given item (example, factors like the price of the item in the market place), the higher should the threshold level of the item in the warehouse be”

For demonstration, let’s take the price fluctuation from these ‘external factors’ and show how it impacts the threshold level \( T_i \). The higher the price fluctuation, the higher should be the threshold level to smoothen these variations.

That is,

\[ T_i \alpha_i V_i \]  where \( V_i \) is the risk of high price fluctuations at instant \( i \)

\[ i.e. \text{ Threshold level is directly proportional to the risk of product fluctuation} \]

\[ T_i = \alpha_i V_i^{b_i} \]  ..............................................................(3)

Where \( \alpha_i \) is the proportionality constant

\( b_i \) is the constant that determines the extent of proportionality (linear or exponential)

For our case of product \( X \) with components \( C_1 \) and \( C_2 \), the threshold value \( T_i \) of product \( X \) considering the price fluctuation as the only factor can be given as:

\[ T_i = \alpha_1 V_1^{b_1} + \alpha_2 V_2^{b_2} + \beta x V_x^{b_1} \]  ...............................................(4)

Now, the next logical question is whether the threshold level is dependent only on external factors and criticality of items. The answer is, of course not. There are multitudes of other factors, many of which can be case specific, that impact the threshold value of an item to be stored in a
warehouse. Among these, as an example, let's consider the size of an item and how it could impact the threshold level.

Here, by the size of an item it is meant its physical dimensions. The impact of the size of a given item is factoring by relating it with warehouse operations. Larger sized items require relatively bigger spaces in warehouses and are difficult to maneuver, decreasing the warehouse space flexibility and thus efficiency of the warehouse in general. This increases the cost of storing these ‘large’ size items. Consequently, the warehousing agent tends to reduce the threshold level of these items in the warehouse.

Thus,

*Threshold level is inversely proportional to the size of the item under consideration*

i.e. \( T_i \propto \frac{1}{S_i} \) where \( S_i \) is the size of the item

changing the proportionality to an equation, we will get

\[
T_i = \alpha_i \left( \frac{1}{S_i} \right)^{c_i} \tag{5}
\]

Where \( \alpha_i \) is the proportionality constant and \( c_i \) is a constant that determines whether the relationship is linear or exponential

For our example of product \( X \) with components \( C_1 \) and \( C_2 \), the threshold level when considering size as the only factor can be given as:

\[
T_i = \alpha_i \left( \frac{1}{S_i} \right)^{c_i} + \alpha_2 \left( \frac{1}{S_2} \right)^{c_2} + \beta_x \left( \frac{1}{S_x} \right)^{c_x} \tag{6}
\]

Now, we can combine equations (2), (4) and (6) to develop the threshold value \( T_i \) of product \( X \) when the three factors (criticality, price fluctuation and size) are all taken into consideration at the same time. The combined formula is:

\[
T_i = \varphi \left[ \alpha \left( \frac{R_v^h V_v^h}{S_v^h} \right) + \alpha_2 \left( \frac{R_2^h V_2^h}{S_2^h} \right) + \beta \left( \frac{R_x^h V_x^h}{S_x^h} \right) \right] \tag{7}
\]

\( \varphi \) is a proportionality constant that takes care of the relationship when all the three are factored in and similarly \( \Phi \) is a constant that indicates, once again, the linear or exponential effect of all these factors when taken at the same time.
Equation (7) can be used as a foundation for developing a general formula for a threshold level of a given product X at an instant i with n components considering criticality, risk of price fluctuation, and size as the only factors that impact this threshold level.

The general formula, logically induced from equation (7) can be given as:

$$T_i = \varphi \left[ \sum_{j=1}^{n} \alpha_j \left( \frac{R_j^a V_j^b}{S_j^{c_j}} \right) + \beta \left( \frac{R_x^a V_x^b}{S_x^{c_x}} \right) \right]$$

The constants \( \varphi, \alpha_j, a_j, b_j, c_j, \beta, \) and \( \Phi \) as discussed in the previous paragraphs indicate the proportionality and whether the proportionality is linear or exponential. They can be determined statistically from historical data. The exact values are case specific and cannot be generalized. The common underlying point, however, is that the constants shall reflect the warehousing agent’s objective of maximizing the yield in ‘order-to-dispatch’ time.

### 7.10 Conclusion

Based on the previous chapters of complexity, self-organization and general parallels between ant colony activities and logistics operations, in this chapter we have developed principles of self-organization and decision making for logistics agents – which were categorized into warehousing, transportation, scheduling, and dispatching agents. The principles developed are not final points but initial footings on how we can formulate logistics operations using natural/biological systems. By using simple linear algebra mathematics a sample ideal case was presented to show how we can extend these principles into mathematical formulations and thus produce concrete results. It was outlined that the variables coined require statistical and/or experimental data for exact formulations of the equations. Consequently, in the coming chapter a research design is provided on how to further this research area.
8. Designing Research Agenda

8.1 Introduction

Current trends on ant colony based research are mainly concentrating on Ant Colony Optimization (ACO), its different variants and its application in different disciplines (For brief descriptions about ACO refer to appendix A). In chapter 6 and in detail in chapter 7 this paper has discussed that a more abstract (or higher level) correspondence between ant colony traits and logistics operations could result in other applications of ant biology, especially in logistics management. What has been done in these chapters is replicating the logic in ant colony theories to logistics applications as conditions fit. Through these, we have asserted, self-organization of logistics agents can be achieved so that companies can effectively deal with the increasing complexity of logistics systems. The dominant methodology we employed in formulating the theoretical perspectives is the usage of combining observations and experiments in various literatures both in logistics management and ant colony biology. From these literatures we not only have used experimental evidence on behavioral manifestations of ants and examine the current status of logistics management research, but also approaches on how to research such topics.

This thesis is aimed at providing the fundamentals (or starting platform) for ant colony based logistics management research. The ultimate target of most researches is to finally generate theories for the discipline they are intended to. Thus the aim of this chapter is to provide a roadmap for developing logistics theories for self-organization based on ant colony behavior and relevant case study research.

8.2 Validating Principles

In chapter 7 we have developed self-organizing principles for the four logistics agents – warehousing, transportation, scheduling and dispatching – based on ant colony foraging rules. And in section 7.7, by using an ideal case, mathematical formulations of interpretations of these principles was discussed. Consequently, the first step in follow up research shall be testing and validating these principles in real case study. In order to do so, it is recommended to use the principles as hypotheses or propositions and following relevant research steps in confirming or rejecting the hypotheses. We will explain this by using one principle as an example.

Let’s take principle 3.1 “The longer the distance the item has to be transported, the more exhaustive the list of alternatives should be and the more selective the agent should be in choosing a typical mode or combination of modes of transportation”
To test and validate this principle, or any of the principles for that matter, the step by step procedure that can be employed is:

1. Select a case company and investigate the application of this principle
2. Expand the pool of case studies to observe any similarities and differences between companies in the same industry or different industries
3. Generalize a theory for the principle under investigation

In each of these steps the research approach can be determining the intermediate variables involved in the research method to utilize and the associated research questions. As it is obvious from the steps we are undertaking a research endeavor of developing theory from case studies. This is an inductive logic; and even though questionable for validity philosophically, it is still a widely used method in scientific research.

For our sample principle (principle 3.1), for example, the intermediate variables can be speed required in the logistics chain, type of product, accessibility etc. Subsequently, the primary research question can be framed as “what are the important intermediate variables that affect choice of mode of transportation?” Next to this the research can follow with the question “what is the significance of these variables on a typical transportation mode choice?”

The first question is more qualitative and relevant data to account for the research question can be collected by using direct observation and/or interviews. The second question, however, is quantitative and we need to measure the effect of each variable on transportation mode choice and the dependence between these variables internally. Data to substantiate hypotheses and research questions can be collected through questionnaires and/or archival studies. The table below shows the summary of this approach.

<table>
<thead>
<tr>
<th>Sample study</th>
<th>Intermediate variables (examples)</th>
<th>Research question (examples)</th>
<th>Study type</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision on choice of mode of transportation</td>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type of product</td>
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<td>Accessibility</td>
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<td></td>
<td>What are the important intermediate variables?</td>
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<td>What is the significance?</td>
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<table>
<thead>
<tr>
<th>Qualitative</th>
<th>Direct observation</th>
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<tr>
<td>Interview</td>
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<table>
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<tr>
<th>Quantitative</th>
<th>Questionnaires</th>
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<tbody>
<tr>
<td>Archival studies</td>
<td></td>
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</tbody>
</table>

Table 8.1 Summary of research approach
8.3 Extending the Research Arena

The principles developed in chapter 7, as discussed, are derived from foraging rules in ants. The foraging rules are, in turn, derived from biological observations and experiments. The aim of the researchers of ants is advancing the knowledge base in myrmecology. Consequently, the logistics researcher could be wondering what could have resulted if we could intervene (or stimulate) in the ant colony experiments from logistics perspectives. Similarly, the reader of this thesis could be asking why the principles were developed from foraging only, why not from food storage, food and brood sorting, or from division of labor. Partly the answer for these questions is the fact that foraging in ants is a well documented study in ant colony literature. On top of this, the time limitation in doing this thesis meant that it is imperative to narrow the scope as ant colony biology is a vast research area in itself. Consequently, it is of vital importance to clearly indicate how the logistics management – ant colony research can further be explored.

Materials

As indicated above the target in the envisaged research is to intervene in an ant colony’s life from logistics perspectives, observe how the colony reacts to these interventions, and emulate relevant responses to logistics management. Consequently, for it is a prominent source of insight, it is mandatory to have ant colonies at different stages of their development. Holldobler and Wilson (1990) have discussed how to culture and transport ants and the researcher can used these methods in setting up the colonies. These authors also assert that an ant colony does not require an exceedingly large area for its development, indicating establishing an ant laboratory is not space intensive.

In most researches concerning ants we need to record the movement of ants to understand their activities. Nevertheless, the number of ants in a particular scene is numerous and they usually move quite fast. Therefore, high speed – high resolution camera is usually required. Other than these, depending on the type of experiment we intend to perform special types of materials might be required.

Methods

Obviously experimentally observations are the methods directly used in the ant colony biological research. The data collected from the experimental analyses can be analyzed using different statistical methods. The commonest methods in formulating relationships between variables in ant colony behavior are usage of exponential regression and Monte Carlo simulation (an example can be found at one of the epic experiments in ant colony studies of the double bridge experiment, Deneubourg et al., 1990). To translate between relevant ant colony behavior and a logistics operation we can use replicating logic with necessary adjustments as key method. After formulating logically viable propositions, case study research (in a company) can be used to
evaluate and test these propositions. From the case studies generalizations can be obtained which can be used in constructing computer models or other applications.

Research Organization

The research requires expertise both from logistics management and myrmecology. Knowledge in logistics management – like warehousing, transportation, logistics IT – is imperative. Additionally, knowledge on statistical methods, for example regression analysis is also vital. Thus a multidisciplinary team from logistics, myrmecology and mathematics could provide quality research outputs.

Possible outcomes

Researches like this (ant colony optimization is an example) have resulted in paradigm shifts in various disciplines. Thus, if conducted with the right support (financial and physical) and with committed personnel, they can be inspirations for multitude of ideas both in academia and practice. Following are list of possible outcomes from ant colony behavior based logistics research:

- New alternative approaches to logistics management – solving complex logistics issues with simple imperatives
- Fundamentals for algorithms building and computer simulation programs
- One of the difficult issues in logistics management is decentralizing decisions to different units as organizational boundaries in logistics are thin. Using methods from ant colony behavior, for example, we have shown performance measurement tools. These can further be extended in the total supply chain for different actors involved
- We can formulate different mathematical tools to be used by logistics managers
- A comprehensive procedure on how to design and measure performance for a completely self-organizing logistics system
- For existing logistics systems we can formulate performance measures, efficient communication methods and progressively changing into self-organizing systems
- Scientific publications on both ant colony biology and logistics self-organization

8.4 Other Areas of Research Interest

Bonabeau and Meyer (2001) outline various applications of swarm intelligence in the airlines, telecom, electronic, internet etc industries. Their principal argument is that ants and other swarms follow simple rules to perform their tasks and manage the complexity of their organization. And, such simplistic rule formulation can be extended to business. They argue
variations of their simple yet powerful approach can help solve a number of business problems. The characteristics of these insect colonies that make them evolutionarily so successful are:

- **Flexibility**: the colony can adapt to changing environment
- **Robustness**: even when one or more individuals fail, the group can still perform its tasks
- **Self-organization**: activities are neither centrally controlled nor locally supervised

These are concepts that most business strategists and managers related to and they have become the most frequently discussed concepts in business. In literature it is usually formulated that flexibility, robustness and self-organization are prescriptions for inefficient, underperforming, or improvement needing logistics chains. But here we argue that these concepts are not always the best way of solving logistics chain problems and that a company’s phase of evolution plays a significant role in formulating the level of flexibility, robustness, and self-organization that the logistics chain requires for efficient operation.

According to Van Asseldonk (1998) a company’s phase of evolution is categorized into four: capacity, industrial homogeneity, industrial heterogeneity, and mass customization\(^2\). Here we formulate ant colony based strategic logistics management issues. There is little in ant colony literature that concerns with how foraging and other activities differ at different stages of the colony’s development. Stages of an ant colony development (here termed evolution phases) can be categorized according to, for example, the colony’s age or the rate of change of production of new queens.

![Table 8.2 Correspondence between a company’s phase of evolution and ant colony developmental stages (here termed phases of evolution for convenience)](image)

\(^2\) For more on a company’s phase of evolution and the associated logistics system properties refer to Appendix C
Issues that could be studied using such phase based analysis, for instance, are:

- How does division of labor in the colony differ at each stage (for example, percentage of workers deployed at full throat foraging and those remaining to accomplish in-house activities.

- The organization of the nest at different phases of the colony's developmental stages.

These and other similar studies when conducted through experimental interventions to obtain desired results can give insights into how logistics can be structured at different stages in a company's phase of evolution.

Another important aspect is *multiple queen ant colonies*. These are colonies of ants having more than two queens in single nest. They are the least documented and how they organize foraging, brood care, and interactions among workers and queens remains to be investigated. If artificially cultured and experimental observations are made, these types of colonies can give newer approaches to strategic supply chain management for *multi-plant* firms. They also can provide new insights on how to cooperate and compete (competition), which is a difficult balance to make in a global economy.

Yet another area that can get inputs from ant colony research is traffic management. Interested readers are directed to Appendix B for further elaboration in this respect.
9. Conclusion and Reflection

9.1 Conclusion

The central research question on which this thesis is based on was formulated as “what principles can be extracted from ant colony foraging traits for use in logistics system self-organization?” But, prior to answering this central question, the thesis addressed other questions that were the basis for the case for self-organizing logistics systems. Subsequently, the thesis had subordinate research questions, which strengthen the central objective of the thesis.

The first issue outlined in the thesis is the prevalent complexity of logistics systems. This is done to assess the current state of a typical globally oriented manufacturing logistics chain. Thus, the research question raised was “How does current global manufacturing logistics systems fit into the characteristics of complex systems?” The basic characteristics of complex systems as expressed in Arthur et al. (1997) are: dispersed interaction, no global controller, cost cutting hierarchical organization, continual adaptation, perpetual novelty, and out-of-equilibrium dynamics. Outright assessment of current trends in global manufacturing companies, through simple observation of facts indicates that logistics systems of these companies fit such characterizations more often than not. Consequently, it can be concluded that logistics systems of globally networked companies can be counted as a complex system and all the logic prevailing to complex systems can be applied to these logistics systems.

After affirming logistics as one of the complex systems, the logical next question is how complex systems can be organized and dealt with. In literature (for example Bonabeau, 1997) it is quite customary to find complex systems and selforganization intertwined – in fact the two concepts are two faces of the same coin, wherever there is complexity, the self-organization schemata will also be there. Consequently, a series of research questions are raised to understand the self-organization concept and create a link between logistics and ant colony. These research questions are formulated as: what is self organization? What are its principles? And how ant colony and logistics system self-organization can be related?

Self-organization is a term coined to represent a pattern that is created by units in a given system without the direct influence of a higher central command and control unit. The individual units of the system follow certain rules (or principles) and adapt accordingly with changes in and outside the system. Quite a variety of biological systems exhibit such a property. It is especially evident in social insects among which ants are one species.

From literature it has been synthesized that the three main properties of a self-organizing system (whether physical or biological) are – the availability of indirect local interactions, the absence of a central control unit and the existence of emergent properties. Consequently, it is concluded that
governing rules (or principles) for any self-organizing system should foster these three properties. In ant colonies the following of certain evolutionarily developed rules has led to the species to be one of the most complex, even though the individual ant has a limited cognitive capacity, organisms on earth especially its colonial life. What is taken from this rule based interaction and autonomous governance is that, if certain principles are developed, logistics systems can be structured in a self-organized way. This has led to the investigation of the existence of any similarities between ant colony activities and logistics operations.

Subsequent analyses of the ant colony-logistics correspondence ascertain a set of similarities between these two at an abstract level. The similarities investigated are: supplier selection in logistics vs. food source selection in ants, logistics transportation vs. worker ant transportation, and warehousing in logistics vs. storage and sorting in ant colonies.

- The correspondence between supplier selection in logistics and food source selection in logistics and food source selection in ants reveals that ants use the criteria of a sustainable food source in making food source choices. Similarly, resource units in logistics vie for a sustainable source of raw materials for it assures uninterrupted production. In addition, food source selection based on nutritional needs of the colony by scout ants can be paralleled with variable criticality levels of inputs in the resource continuum of the company. Similarly, as do logistics units prefer, and are willing to pay higher premiums, for quality food sources foragers in ants show willingness to travel greater lengths for quality food sources.

- The correspondence between transport logistics and ant colony transport reveals similarities between distribution networking in logistics and highway or trunk formation in ants. By transportation networking it means the location and allocation of logistics facilities across the total logistics chain. Another similarity revealed is the usage of series – parallel network connection in both ants and in logistics route planning.

- The correspondence between brood and food storage in ants and warehousing in logistics reveals the balancing act that both face in storage. Ants are selective in the amount and type of food they store and warehousing in logistics does the same. Subsequently, both worlds crave for optimal levels of items in their stores for efficiency and effectiveness.

In answering the above mentioned sub-questions, the case for self-organizing logistics systems based on ant colonies is made. Thus, the focus now is the central question of “what principles can be extracted from ant colony foraging traits for use in logistics system self-organization?” Agents in a logistics system are categorized as: warehousing, transportation, scheduling and dispatching agents. For each agent self-organizing principles are formulated based on foraging rules of ants. The foraging rules in ants are:
• The greater the distance the ant travels from the nest to a food patch, the longer she should take to select the food item.

• The greater the ant travels to a food patch, the more selective the ant should be in choosing a food item.

• The higher the temperature, the more selective the forager should be in food patches.

Based on these seemingly simple self-organizing rules used in ants’ daily activities and other background information on ant colony foraging, the following principles are developed for the enlisted four logistics agents.

1. **Warehousing Agent**

   Establishing threshold levels
   
   • If an item is highly critical for production and sales, its threshold level should be higher.
   
   • If an item is highly critical, it should get higher value in measuring customer satisfaction levels.
   
   • The higher the uncertainty of the external factors impacting the availability of a given item, the higher should be the threshold level of the item in the warehouse.

   Warehouse resource allocation
   
   • The larger is an item’s payoff in maximizing the ‘order-to-dispatch time’, the higher it shall be ranked in the priority function for resource allocation.
   
   • In assigning a resource to moving an item to, from or within the warehouse, pick the item with the higher payoff value and deliver it to its next destination.

2. **Transportation Agent**

   Choice of mode of transportation
   
   • The larger the distance an item has to be transported, the more exhaustive the list of alternatives should be and the more selective the agent should be in choosing a typical mode of transportation.
   
   • The higher the risks of external factors involved in transportation, the more selective the transportation agent shall be in choosing a given mode.

   Decision on fleet size
   
   • Under intense service delivery competition, use small size and frequent transportation schemes until the point of maximum acceptable loss.
The higher the number of small size and frequent shipments demanded, the more selective the transport agent should be in appropriating resources to product type.

3. Scheduling Agent

- Use incremental dispatching of resources; more resources shall be deployed in a particular pattern only when it is proved that this is the practical solution at that specific instant.
- The longer the dispatching distance and time, the more considerate the agent should be in load matching.

4. Dispatching Agent

- The greater the distance the ant travels from the nest to a food patch, the longer she should take to select the food item.
- The greater the distance the ant travels to a food patch, the more selective the ant should be in choosing a food item.
- The higher the temperature, the more selective the forager should be in food patches.

9.2 Reflection

An approach to organize the total logistics chain of a given manufacturing company based on self-organizing ant colonies is a ‘revolutionary’ undertaking. As has been described in the different chapters of this thesis, the scientific world with respect to ants is engaged totally in finding clues for developing mathematical algorithms. From the beginning of this thesis the premise was that ant colonies have more than algorithms to offer for logistics systems. Consequently, this thesis is only the beginning of what could turn out to be a vast research area in logistics management. Among the major factors future research in this discipline shall focus on are:

- Dedicated ant colony research where experimental directives are taken from logistics perspectives
- A case by case assessment of which ant colony behavioral manifestation give vital inputs to the type of logistics system
- Assessment of communication systems in logistics and how self-organization using ant colony as a basis can contribute to these communication systems

Such studies can have positive impact in furthering the ant colony-logistics research
9.3 Limitations

This thesis is based on ant colony behavior documented in different biological literature. The perspectives of these documents, consequently, are purely biological; i.e. the experiments are designed to further biological sciences. Thus, one of the limitations is that the different claims could further be refined if experiments were influenced from logistics perspectives. In fact, chapter 8, it is recommended to use such approaches to get better results.

Another limitation in the thesis is that ant colony behavior is described categorically. However, various literature show different species of ants exhibit different behavior. Thus, studying species tailored behavior may result in further new insights for logistics applications.
References


Dorigo M. Stutzle T. Ant Colony Optimization. MIT Press. 2004


Serugendo G. Foukia N. Hassas S. Karageorgos A. Mostefaoui SK. Rana O. Ulieru M Valckenaers P. Van Aart C. *Self organization, paradigms and applications*. Lecture notes in computer science (2977) 1-19, 2004


Van Asseldonk A.G.M. *Financial value creation, from ‘mass individualization, business strategies applying networked order to create economic value in heterogeneous and unpredictable markets’* TVA Management BV 1998

Appendix

A. Ant Colony Optimization

Belonging to the family of swarm intelligence methods, Ant Colony Optimization (ACO) is a metaheuristic in which a colony of artificial ants cooperate in finding good solutions to difficult discrete optimization problems (Dorigo & Stutzle, 2004). Ant Colony optimization algorithms are developed on the basis of the double bridge experiment (shown in the figure below) by Deneubour et al. (1990).

![Figure A.1 The double bridge experimental setup](image)

In this experiment, real ants are released from their nest for search of food sources in such a way that they would choose from either of the two paths of the bridge. The model is based on the principle that after $i$ ants have crossed the bridge there are $i$ pheromone units on the bridge, of which $A_i$ are on branch $A$ and $B_i$ are on branch $B$. The ant going out for search of food chooses its path with probabilities $\text{Prob}_A$ and $\text{Prob}_B$ depending on $A_i$ and $B_i$ (the number of ants that have previously chosen each branch). With this choice, the ant subsequently adds pheromone on the path chosen, i.e.

$$\text{Prob}_A = \frac{(k + A_i)^n}{(k + A_i)^n + (k + B_i)^n}$$

where $\text{Prob}_A + \text{Prob}_B = 1$

$A_{i+1} = A_i + \text{Prob}_A$, $B_{i+1} = B_i + (1 - \text{Prob}_A)$ and $A_i + B_i = i$

And where $n$ is a stochastic variable that takes value 1 or 0 with $\text{Prob}_A$ and $\text{Prob}_B$ respectively

$n$ determines non-linearity of the choice, a high value of $n$ meaning that if one branch has only very slightly more pheromone than the other, the next ant that passes has a very high probability of choosing it.

$k$ corresponds to the degree of attraction attributed to an unmarked branch, i.e., the greater the $k$, the greater the marking necessary for the choice to become significantly non-random.
Monte-carlo simulations generate that the values for k and n approximate to 20 and 2 respectively.

*The above equation is a general choice function that quantifies the way in which a higher concentration on branch A gives a higher probability of choosing A, depending on the absolute and relative values of A_i and B_i.*

*The above real-ant path selection model was the inspiration for the development of ACO and still is an integral part of it. In ACO, artificial ants (substituting for the real ants) explore the solution space for problems that require optimization and these artificial ants exchange information on the quality of these solutions through a scheme that is similar to real ants. The key foundations of the ACO as presented in Dorigo et al. (2006) is described below.*

In ACO, an artificial ant builds a solution by traversing the fully connected construction graph GC (V, E), where V is a set of vertices and E is a set of edges. This graph can be obtained from the set of solution components C in two ways: components may be represented either by vertices or by edges. Artificial ants move from vertex to vertex along the edges of the graph, incrementally building a partial solution. Additionally, ants deposit a certain amount of pheromone on the components; that is, either on the vertices or on the edges that they traverse. The amount $\Lambda$ of pheromone deposited may depend on the quality of the solution found. Subsequent ants use the pheromone information as a guide toward promising regions of the search space.

*The ACO metaheuristic is given the algorithm:*

Set parameters, initialize pheromone trails

```
while termination condition not met do
    ConstructAntSolutions
    ApplyLocalSearch (optional)
    UpdatePheromones

endwhile
```

After initialization, the metaheuristic iterates over three phases: at each iteration, a number of solutions are constructed by the ants; these solutions are then improved through a local search (this step is optional), and finally the pheromone is updated.

*Dogrigo et. al (2006) claim that Ant Colony Optimization is one of the most promising approaches to approximate solution of difficult to optimize problems (commonly referenced*
as NP-hard problems). They substantiate their claim by stating that ACO has been tested for more than 100 NP-hard problems and has proven to be a good method for solving such problems. They categorize the type of problems tackled by ACO into:

- Routing problems: these are conditions like distribution of goods
- Assignment problems: where a set of items (objects, activities, etc) has to be assigned to a given number of resources (locations, agents, etc) subject to some constraints
- Scheduling problems: which are concerned with the allocation of scarce resources to tasks over time
- Subset problems: where a solution to a problem is considered to be a selection of a subset of available items

B. Traffic Management

B.1 Introduction

Traffic management in metropolitan areas is the efficient usage of available transportation resources in response to dynamic traffic conditions (Roozemond, 1996). Consequently, the author confers that the tasks of traffic management are: use roads to their optimal capacity, maximize safety, inform the traffic participants about traffic conditions, road conditions, weather etc. However much robust the traffic systems have become, it is still a common seen to watch heavy traffic jams in major metropolitans of the world. In addition to the average time spent on traffic jams, environmental concerns have taken center stage in traffic management discussions. On top of this, in urban areas the traffic condition is quite complex resulting from extended options in mode of transport (public versus private, motor versus non-motor driven, like bicycles etc), differences in speed of transport, and higher uncertainties of occurrences of unprecedented events (Roozemond, 1996). Behavioral factors, of traffic participants, also play important roles in traffic management. They extend the unpredictability of conditions in traffic thus usually requiring non-linear approaches to modeling.

B.2 Traffic Management in Ant Colony Foraging

Different media outlet reports acknowledge the highly efficient traffic management of ant colonies while foraging. This report[^3] for example takes interviews from renowned scientists in the

[^3]: http://abcnews.go.com/Video/playerIndex?id=7775658
field to assert that traffic management in ant colonies can be used as a benchmark for future traffic systems design and improving existing systems. For more on media reports on ants’ traffic management, let’s see the following two articles.

“The Thursday 14th August 2008

Cosmo Magazine

DIJON, FRANCE: Biologists are learning that ants have an increasingly large number of inbuilt rules which govern their behaviour on foraging trails, and which could offer clues to better control human crowds.

In the human world, road signs and traffic lights coordinate the movement of vehicle and pedestrian traffic to prevent collisions. Ants, however, are able to manage the two-way movement of large numbers of individuals by following a few simple rules.

Stop and go

To find out what happens when ant highways become too narrow for two-way traffic, Vincet Fourcassié, a biologist from Paul Sabatier University in Narbonne, France, set up experiments in the laboratory. The results were detailed at the European Conference on Behavioral Biology held in Dijon, France.

Fourcassié’s team studied the behavior of a European kind of common garden ant, Lasius niger which feeds on sweet secretions produced by the aphids that they farm and protect from predators. They also observed the behavior of the South American leaf-cutting species Atta colombica, which uses cut leaves to cultivate fungi for food.

In the experiments, the ants had to cross a bridge to get from nest to foraging site and back. The researchers found that when the bridge width was reduced – so that there was only room for the ants to move in single file – a clear set of priority-based rules emerged.

In the black garden ants, the rule is not to enter the bridge if another ant is coming from the opposite direction, but if an ant in front of you is crossing the bridge you can follow it. In leaf-cutting ants, the rule is to give priority to ants carrying leaves back to the colony: if a leaf bearing ant is on the bridge, give way; and if he is in front of you, don’t overtake.

Maximising efficiency

In both species these rules allow for orderly behavior which results in groups of ants crossing the bridge together, in one direction, avoiding collisions and hence maximizing foraging efficiency.

Fourcassié said that similar rules seem to regulate movement of humans in crowded situations in absence of signs or other imposed means of traffic control.

Nigel Franks, a biologist from the University of Bristol in England, said these findings were interesting and may contribute to understanding both ant and human behavior in crowds. Franks presented research at the same conference, showing that ant societies have individuals who, like political leaders, make decisions for the entire colony.
Among humans, when a space becomes dangerously crowded — such as at a packed stadium or when people are trying to escape from a burning building — chaotic movement and 'stampedes' can result in injury and even death. Experts believe that studying how ants avert such disasters could give us useful clues to more effectively managing human crowds.”

Another report from National Geographic Magazine is put forth as follows.

“Army Ants Obey Traffic Plan to Avoid Jams, Study Says

John Pickrell
for National Geographic News
February 24, 2003

Just as a city relies on an efficient transportation network, research shows that vast army ant colonies also employ simple mechanisms to organize traffic flow and minimize congestion.

According to a new study, some carnivorous ants use just a few simple rules of thumb to determine the direction taken by prey-seeking raiding parties and to organize potentially chaotic forest-floor freeways, packed with up to 200,000 fast-moving workers.

The scientists found that simple movement rules, obeyed by each ant, collectively add up to the large-scale movement of the entire raiding party. "Local interactions can have a very large influence on large-scale patterns and behavior," said Couzin.

"Many complex and seemingly organized group behaviors...have been shown to emerge from the collective action of individuals that do not have an understanding of the big picture,” commented Martin Burd who studies evolution and behavior at Monash University in Melbourne Australia.

Another simple rule is that ants follow a trail of smelly chemicals, laid down by other ants. Like painted stripes on a road, these chemicals tell the poorly-sighted foragers which way to go.

When raiders set out, they move along the chemical trails at high speed in one direction. However, as they encounter prey, they must return along the freeway to the nest. This task is initially very difficult with an onslaught of speeding traffic coming in the opposite direction.

Couzin and Franks found that a simple difference in the rate at which returning ants are prepared to turn away to avoid head on collisions is enough to order ant-freeways into three efficiently organized traffic lanes.

All the ants instinctively prefer to be at the center of the trail, where the strongest marker fragrance can be found. However, as returning ants—burdened with invertebrate cargo—are less likely to turn to avoid a collision, a stream of these foragers end up forming the central lane of the freeway.

Outbound ants, which more rapidly dodge to avoid collisions, end up forming two lanes on either side of the homeward-bound trail.
This research "shows how simple responses to local information, allows organized traffic lanes to form, instead of a helter-skelter mob of aimless ants...no traffic cops, no road maps, no ministry of transportation," said Burd."

Different experimental studies have shown that ants have internalized methods of managing efficient transportation traffics. If we start from simple ones, the study of Dussutour et al. (2006) shows that Lasius niger ants, while foraging, instinctively choose wider bridge than narrow bridge, when the two bridges are the only options for outbound and nest-bound movements. They assert that overcrowding on the narrow branch plays an essential role in the mechanism underlying the choice of route in ants. This holds true even though the wider bridge is made longer. The reason, the authors claim, is twofold; one is the difference in travel duration between the two paths and the second is the repulsive interactions between foragers when they meet head on.

Another study by Dussutour et al. (2009) on leaf cutter ants (Atta colombica) shows another self governing principles of ants in foraging. The authors take into consideration that most ants are central place foragers; they have to move away from nest empty and return back with food (the former are termed unladen ants while those with carriage are termed laden ants). They claim that there are priority rules that govern the ants' foraging transport which regulate traffic flows in and out of the nest. One of the priority rules outlined is that unladen nest-bound ants do not overtake their laden fellow ants. This has a moderation effect on the speed of the unladen inbound nests (which could have travelled faster because they are not carrying any load) which in turn helps to avoid head-on collisions with outbound ants. The unladen nest-bound ants, however, stick to the cluster and follow the line and their numbers is informative of the level of food availability. The authors make a remark that the complexity of such patterns makes insects excellent models for the study of traffic dynamics and traffic related problems in traffic management.

Yet another and elaborate traffic organization in ants is documented by Couzin & Franks (2002). Their experiments show that the ants form a three lane pattern which results from individual behavior of outbound ants which exhibit a higher rate of turning during maneuvers than do returning (or nest-bound ants). The result is a three lane system where the two outer layers are used by outbound ants and the central lane dedicated to nest-bound ants. The authors claim that such foraging transportation organization reduces the number of high-speed collisions between ants moving in different direction and, consequently, increases the flow of ants to and from the nest. The pattern is the result of local and global (micro and macro, on the authors terminology) desires of the ant colony structure. At local level behavior is driven by the wish to avoid collision with nest members. These local interaction and individual movement rules strongly influence the organization of traffic in foraging.
What we see from the magazine reports and the experimental ant traffic organization assessments is a consensus on part of the academia that natural selection has played significant roles in shaping ant colony behavior that traffic flow is quite efficient. The underlying conclusion is that rule based movements enable the colony to a higher rate of return from food to nest while foraging. Among these rules, priority rules (to give priority for laden ants for example) are the most visible ones. Similarly, in city transport management rules are developed to favor selected means of transportation, like giving priority to public rather than private transport, and ensuring general safety, for example through banning overtakes in some parts of the road, providing speed limitations in different roads etc. The thesis here is that more insights can be obtained from ant colony traffic management (to develop rules), which can make our traffic systems more robust and less jammed. And that, researching deeper into the ant colony from city traffic management perspective rather than pure biology, can further lead to interesting findings. Here by traffic management perspective means finding the commonest problems in traffic management and introducing these problems to the ant colony foraging in the form of different stimulus or blockage. In the following section we will uncover some aspects of traffic management that can use ant colony foraging principles.

**B.3 Ant foraging behavior applied in city traffic management**

Observe driver behaviors in a heavily compounded traffic jam. One of the few behaviors that can be seen is some drivers following others and trying to escape from the jam. Yet another seen can be watching drivers switching from one lane to another. Different approaches have been put forth to modeling driver behavior and subsequently introducing some traffic laws to reduce unnecessarily impacts of such sporadic behavior. Or there is a need to predict driver behavior in order to adjust dynamic traffic signs, or propose alternative routes in navigation devices (tom-tom comes to mind here) or radio. In essence, the need is to reduce commuting time in highly complicated traffic networks in cities and highways. And through understanding these behaviors it might be possible to alternate between actions so that a typical kind of wanted behavior can be stimulated through these actions. You might be wondering what has this to do with ant colony foraging behavior. Well, in the previous section it is outlined that ant foraging traffic management is quite efficient which has been achieved through natural selection. It has also been outlined that there are embedded behavioral rules that guide the individual ant to act in a particular fashion within the ant traffic and this behavior is stimulated by different factors. Here, in traffic systems, we also want to develop traffic rules (like priority rules) that could stimulate a type of driver behavior that will lead to an improved traffic condition. Thus, we see strikingly similar patterns in ant colony foraging traffic behavior and in traffic system. In turn, studying ant colony foraging traffic even further (because different species may exhibit different behavioral patterns, and thus,
yield different rules) would be helpful to our quest in solving the increasingly dynamic traffic management problems. The rules derived from foraging behavior of different ant colony species can be used to make traffic systems more robust by embedding these rules into the different algorithms.

Consider another aspect in road traffic management, traffic lights at a cross-section. These ensure smooth flows at the cross-section by setting different priorities, for example by giving extended green period to the path with high percentage of cars. The control systems dynamically adjust the priorities to avoid congestion on a particular path. But how are these priorities set? Customarily, streets with high traffic lines are given extended green periods over those that have few cars. But how much is ‘high traffic’ and how large should be the green extension? And how are public and bicycle transportation fit into this prioritization? Such kind of questions makes the traffic management at a given square a complex issue. Now, correspond these groups of lights to an ant in foraging. As outlined in the previous chapters, scout and regular foragers have dynamic respond threshold levels depending on the internal colony conditions (like nutritional level) and external conditions (like ambient temperature). Similarly, for the lights at the cross-section, we can develop threshold levels for each factor under consideration (like traffic queues, public transport, bicycles etc) and vary this threshold level under different conditions (for example the time of the day, the location of the square, i.e. whether it is in neighborhoods, around a hospital, police or fire station, in city center, in a highway etc). Ant colony response thresholds, if studied under different conditions, shall provide inspirations on how to formulate the response thresholds for the traffic lights in different conditions.

C. Company’s phase of evolution and logistics system properties

The phases of evolution of companies with their accompanying logistics chain organization is shown in the table below. In each stage the objective of the logistics department and the logistics function differ significantly. And as a result one best medicine is not a prescription for all kinds of logistics problems. Rather solutions shall be tailored according to a company’s phase of evolution. The principal driver in all these is that companies adopt different strategies at each phase of their evolution.

<table>
<thead>
<tr>
<th>Phase of Evolution</th>
<th>Logistics Chain Characteristics</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>- Not well structured</td>
<td>Quite Low</td>
</tr>
<tr>
<td></td>
<td>- Essentially a pull based systems</td>
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<tr>
<td></td>
<td>- The main task of the logistics department is managing a functional, traffic flow activity within the firm</td>
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<tr>
<td></td>
<td>- Movement is unidirectional, moving from materials management to outbound transportation</td>
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</tr>
<tr>
<td></td>
<td>- Objective is to minimize costs against budgetary norms. Cost is simply the lowest rate without any reference to other departmental or organizational factors</td>
<td></td>
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</tbody>
</table>
Logistics is seen as a cost center - Actions taken are usually reactionary

Industrial Homogeneity
- The logistics framework is based on a low frequency batch
- Logistics is essentially a push based system
- It is forecast driven
- The logistics department is conceptualized as the distributor, the entity that makes possible the transfer of goods/services from the firm to the customer
- In addition to minimizing the cost of operations, functions are required to attain bulk efficiency
- In addition to simple traffic flows in the firm, logistics manages inventory as well

Industrial Heterogeneity
- The logistics fundamentals are based on high frequency batches
- It is essentially a pull based system but based on the principles of JIT
- The logistics department is stationed to provide all inbound and outbound flow functions
- The driving force in logistics operations is not merely cost but also the essence of being a competitive department
- Duties in the department include, but are not restricted to, organizing and supervising traffic, warehousing, inventory management, forecasting, scheduling, procurement, order entry, credit collection etc
- Stock reduction across the logistics chain is emphasized
- Logistics here is a value adding process: it minimizes cost, maintaining a high quality service and continuously improving its process as measured by customer-related outcomes
- Logistics operations are benchmarked against the best in the industry

Mass Customization
- Innovative ways of delivering logistics services take center stage
- Logistics plays a role from innovation to final use and disposition of the product
- Logistics functions are aligned to long-term orientation and coordination with the transaction and investment cycles of suppliers and carriers
- Duties include all listed in industrial heterogeneity plus the issues of coordination with suppliers, customers and 3PL providers
- Information system is central to almost every logistics function
- Logistics is pro-active, constantly updating its operations to deliver an improved service
- Value is measured both in terms of cost and time
- Logistics is a very complex function, involving a lot of stakeholders and strives to package its services customized to provide unique experiences to customers

Table c.1: company phase of evolution, logistics and complexity

What we have shown in the previous table is a company’s phase of evolution as seen from a logistics perspective. It is outlined that logistics evolves with a company’s evolution. What determines a company’s phase of evolution? We outline the answer for this in the upcoming few paragraphs.

**Determinants of a company’s phase of evolution**

i. A company’s Age: common wisdom is that, at earlier stage of their life cycle companies usually are in capacity or industrial homogeneity phases. A startup company, if it indeed has an
An innovative product that captures customers' need, will utilize it full capacity to produce and sell as much as it can, unless and otherwise the company's business strategy is built on delivering quality service using logistics as a competitive tool. So in a company at its earliest stage the emphasis is usually on the product, less emphasis is given to logistics. In fact logistics would usually be ad-hoc function. Such characterization fit directly to the lower stages of evolution (the lower stages being capacity or industrial homogeneity)

ii. Portfolio of Product: a large portfolio of products is usually indicative of a company at a higher level of organizational evolution (industrial heterogeneity and mass customization). It indicates variability of products to address specific needs of customers – addressing the service savvy customer need. Added to this would be the requirement of a logistics strategy tailored to address the specific aspect of the product and the customer

iii. Agility of Production Lines: a company at the capacity or industrial homogeneity phase of evolution requires less agility, because in these cases almost all its products manufactured are sold. Uniformity of products are indicative of dedicated and mass manufacturing lines which in turn imply that the cost of switching to producing a different product is high. Such are indicative of less agility of product lines which of course is driven by abundance of demand and a company's lower evolutionary stage. At these stages the production lines are not expected to be agile – as the company can afford producing uniform products as less competition in the market ensure less diverse products and less agility in the production process

iv. R&D Expenditure: R&D expenditures usually are indicative of the level of innovation activity in the firm. Innovations indicate dynamism in the overall operations. This in turn demands high competency from all functions in the company and pro-activeness is the typical characteristics of its departments. Such merits of a company are indicative of its high level of evolutionary stage. Thus, the claim here is that the higher the R&D expenditures of a company, the highly probable is its phase of evolution to lie in either industrial heterogeneity or mass customization

These and other similar factors, when operationalized can be used to measure the level of a company's phase of evolution.