An Analysis of Complex Adaptive Computer Manufacturing Supply Network Evolution in Competitive Markets

Selen Onel, Abe Zeid and Sagar Kamarthi
Department of Mechanical and Industrial Engineering
Northeastern University
Boston, MA 02115, USA

Abstract

Unlike in the past, global markets, suppliers, and consumers are more connected today than ever, creating a rapidly changing ecosystem. While this is good for all, it makes markets more competitive and forces businesses to adapt to market trends to survive. This paper focuses on highly dynamic complex adaptive computer manufacturing enterprise ecosystem (CMEE). In previous studies, many systems were studied using equation based approaches, conventional simulation approaches or a combination of both. However, these modeling approaches are limiting to capture the dynamics of complex adaptive systems. Therefore, this paper proposes a realistic agent based approach which allows us study a scalable, reconfigurable, agile and adaptive CMEE. It investigates CMEE complexity from a complex adaptive systems perspective by utilizing the concepts of self-organization and adaptation borrowed from biological ecosystems and the agility and alignment concepts from manufacturing systems.

Keywords
Agent-based simulation modeling; complex adaptive systems, supply chain

1. Introduction

Today, business environment is full of environmental disturbances that force enterprises to quickly adapt to changes. An enterprise operating in this turbulent ecosystem requires the necessary adaptation, alignment, and agility skills to survive. It should be agile enough to transform itself into an enterprise that fits into the ecosystem and align its goals with those of suppliers and customers. Also, success and continuation of a product in this ecosystem is as important as its innovation and introduction into market (Cavinato 1992; Ellram 1993; Lee 1993). Therefore, different strategies were developed to sustain products and survive environmental disturbances. Enterprises develop different strategies to anticipate and cope with forthcoming changes. Consequently, many enterprises have spent increasing amounts of time, money, and effort to predict system changes and control system behavior. However, efforts to manage CMEE have often led to frustration and helplessness. Managers have struggled with the prediction and control of dynamic and complex nature of enterprise ecosystem. For instance, rapid changes that occur at different parts of the ecosystem are often outside the purview and control of a single enterprise.

Many research questions were formulated during the process of transformation and adaptation of enterprises to rapidly changing markets. One such question is "how to approach the changes and which techniques to use during the transition period". Swaminathan (1998) stated in his research that the decision-making process in the supply chain for a computer manufacturer was centralized to a great extent; few suppliers were extremely important whereas others were mainly controlled by the manufacturer, and a major part of the supply chain was owned by the manufacturer.

However, today's diverse, heterogeneous, and hierarchical ecosystem force supply networks exist in an environment sensitive to initial conditions or to small perturbations. Therefore, a traditional supply network with a tree-like or hierarchical structure lacks the main survivability, flexibility, scalability, and adaptivity properties.

The search for a model that accurately reflects an ecosystem's underlying complexity and dynamism leads most scientists some kind of computer simulation (Kaihara 2003; Kim 2009). Kaihara (2003) proposed a supply chain management (SCM) that computes multi-agent behavior. Kim (2009) modeled a supply network as a complex adaptive system (CAS). He used an agent-based social simulation (ABSS), a research method of simulating social systems under the CAS paradigm. Just as Kim, many scientists recognized supply networks as CASs (Li 2009; Nair, Narasimhan et al. 2009; Pathak 2009; Nair and Vidal 2011; Amini, Wakolbinger et al. 2012).

In our research, we address issues of computer manufacturing enterprise ecosystem (CMEE): computer manufacturing collaboration, customer satisfaction and supply network. Similar to the above studies we treat CMEE as a complex adaptive supply network (CASN) and investigate the evolution of topological structures and dynamic behaviors of the CMEE via an agent-based simulation model. In our research, we consider adaptivity, agility, and alignment as the key components to successfully survive in the business ecosystem. In biology adaptation is defined as the evolutionary process, which takes place over many generations, whereby a population becomes better suited to its habitat. In an enterprise ecosystem however adaptability is defined as the ability to change when an unexpected change occurs or an unforeseen opportunity appears. An enterprise ecosystem has significant dynamism and necessitates constant adaptation. In this ecosystem, emergence of new and non-traditional competitors and increasing customer demands disturb the current position of companies in the market. The key factors of being sustainable and competitive are being able to respond timely and adapt new technologies and ideas. The enterprises which neglect the change become irresponsive and are not able to use the opportunities that come into play in everyday business. Enterprises should embrace change to move the company forward and keep the company's competitive standing.

Second measure, agility, is the ability of producers of goods and services to thrive in rapidly changing, fragmented markets. Agility is a comprehensive response to the challenges posed by a business environment dominated by changes and uncertainties. It requires rapid decision making and execution and being nimble to new markets and technological trends. Companies, which are not agile enough, are not able to anticipate fundamental marketplace shifts. Nearly 90% of executives surveyed by the Economist Intelligence Unit believe that organizational agility is critical for business success (Economist 2009).

The third measure, alignment of enterprises, refers to the synchronization of shared goals and objectives of a set of companies in an ecosystem. Failure of alignment may cause decrease in sales and profits, missed delivery dates, unmatched priorities and therefore chaos in the system. It is not enough to set clear, realistic goals and share those with the market. Complex market structure requires developing concrete strategies and effective communication tactics to achieve alignment goals and bring value to the enterprise. Alignment of companies has many benefits such as increased sales, higher profits, lower costs, lower turnovers, satisfied employees and better customer service.

The simulation model contains all the above described measures implemented into customer and supplier agents. Each agent has different algorithms and rules for its intelligent behaviors and choice of optimization. The simulation model is analyzed using well-established methods (Pritsker 1979; Kelton 1998; Law 2007).

2. Agent Based Simulation Model

We develop an agent based simulation model to make theoretical investigations of CMEE feasible and to support decision making in real enterprise ecosystems. We use the special purpose simulation modeling environment NetLogo (Wilensky 1999) to simulate enterprise ecosystem and to understand the dynamics of CMEE. The enterprises are constructed using collections of condition-action rules to be able to "perceive" and "react" to changes in their environment, to pursue their goals, and to interact with other enterprises, for example by selling and buying goods via supply-demand links.

2.1 Model Design

As Terano et al. (2005) stated, an agent based model consists of a number of software objects called agents, the core units of simulation, interacting within a virtual environment. In our simulation model computer manufacturing enterprises (CMEs), suppliers, and customers are agents communicating in the virtual CMEE. Each agent has a degree of autonomy and has goals that it aims to achieve. It also reacts to and acts on CMEE and on other horizontally or vertically interacted agents. Each agent is specialized according to its intended role in the CMEE. There are two types of main agents in the simulation model: customer agents and supplier agents. All supplier agents share specific common attributes, including the inventory, demand, product price, production rate, budget, energy and fitness value.

Supplier agents are divided into three groups according to the product produced and service provided that are vertically integrated: Tier 0 (supplier of main interest), Tier 1, and Tier 2.

Customer agents are also divided into 3 groups according to their shopping preferences:

- Customers who buy the products provided by the most reliable supplier in their area of search.
- Customers who shop according to the popularity of the product provider in their area of search.
- Customers who buy the products offered with lowest market price in their area of search.

An agent has several characteristics at a given time instant such as agent attributes, agent knowledge, agent interactions, agent behavior and learning. Agent attributes characterize an agent's state at a given instant of time. Current inventory, current financial position, current market position, different costs associated with production are some of the attributes that characterize an agent's state. Dynamic attributes change over time either as the result of internally triggered events such as material transfers from work-in-process inventory to finished-goods inventory or as a result of interactions with other agents such as receipt of an order, shipment of an order and payment for an order.

Agent knowledge can be summarized as the level of awareness of an agent about its local and global neighbors. Therefore generally, the concept of agent knowledge consists of a global view and a local view. Global view requires the knowledge of states and actions of other agents. In our simulation model, customer agents have the global view in terms of being aware of brand preferences and favorite products of other customer agents.. However, supplier agents have a local view. Therefore, each supplier agent has incomplete information of the state, actions, current decisions, future plans and past performance of other agents.

Agent interactions define an agent's relationship with other agents and with its environment. In CMEE, collaboration is an essential mechanism to integrate and propagate information distributed pervasively among agents. Interactions between the agents can correspond to the interactions between the real-world markets. With such a model, emergent patterns of action (e.g. "enterprises and customers") may become apparent from observing the simulation.

Supplier agents experience both vertical and horizontal interactions under different rules and limitations. The horizontal interactions in the simulation model can be summarized as follows: (1) Customer to customer interactions, (2) Tier 0 to Tier 0 interactions, (3) Tier 1 to Tier 1 interactions, and (4) Tier 2 to Tier 2 interactions. Similarly, the vertical interactions are as follows: (1) Customer and Tier 0 interactions, (2) Tier 0 and Tier 1 interactions, and (3) Tier 1 and Tier 2 interactions.

In our simulation model, in order to secure their positions, suppliers in different tiers keep track of their number of vertically and horizontally integrated neighbors; if the number of their links is below a certain threshold they immediately look for new connections. Also suppliers drop their weakly connected neighbors and try to link with stronger candidate collaborators. Here they use the revenue of each company as the selection measure. They also keep track of the technological changes in the market. A company might choose to adapt to changes in the market or become resistant to changes. Therefore, a company might be in either one of these states:

- Adaptive: Company follows and introduces technological changes.
- Resistant: Company is resistant to any change in the market.
- Neutral: Company track changes in the market and is ready to take action but not taking any actions yet.

Also, according to their predefined strategies, each supplier might either try to align with other companies in the system by changing its product price closer to market average, or if the company is not interested in aligning with other companies in the market and prefers to compete greedily, it decreases its product price below market average to sell more products.

2.2 Model Structure

In our simulation model, the CMEE model structure (agent ecosystem) can be considered as consisting of three main elements.

- Environment
- Agents that reside in the environment
    - Enterprises which correspond to supplier agents
    - Customers who correspond to customer agents

- Collaboration links enable information flow from one enterprise to another. Collaboration links form or dissolve among enterprises (supplier agents) according to environmental rules and agent decisions.

The environment where the agents reside and interact in the simulation model has a static component and a dynamic one. The static component consists of environmental rules and environmental fitness threshold levels. Environmental rules represent the rules of behavior that characterize and define an enterprise. The enterprise survival or extinction in the enterprise ecosystem is determined by environmental fitness threshold values. For example, an environmental fitness threshold value for survival represents the necessary energy level that each enterprise in the environment must maintain in order to "live" in the enterprise ecosystem. In that sense, each enterprise has an energy attribute and must fulfill its tasks, in order to be a viable member in the environment. For example, every enterprise must sustain some level of financial viability; if it falls below this financial level, the enterprise may die in the simulation which corresponds to filing for bankruptcy in the real world.

The dynamic component of the environment includes changing customer needs, time-varying demand and price in that environment and number of enterprises that exist in the environment. In this environment, every agent has a set of strategies that it uses to make decisions to achieve its objectives under constraints imposed by the environmental rules. Generally, enterprises make two types of decisions: with whom to link in the environment, and how to set their attribute levels. In the simulation environment, decisions are made according to agent ecosystem rules. Agent ecosystem rules define the event handling routines. Rules that are used in each run depend on the type of the agent at which a function is processed. For example, each iteration agents decide to become adaptive, resistant or neutral according to an adaptation function. If an enterprise decides to become adaptive, the rules belong to adaptive agents applied for that enterprise. Our simulation model uses rules such as material flow rules, information flow rules, cash flow rules, agent based rules, and global rules.

3. Simulation Study

In this study, our aim is to observe how the number of customers, suppliers and simulation clock vary in each run. We investigate how market averages change and how the order, inventory and supply volume deviate with environmental conditions in the market. We study how different market behaviors of suppliers influence customer purchase behavior. Also we analyze how the market conditions affect suppliers. We observe the relation between the number of suppliers and the competitive behavior of suppliers. Therefore, the performance measures that we study in this simulation are: (1) number of suppliers in the system, (2) number of customers in the system, (3) ecosystem life time which corresponds to CMEE survival as a whole, and (4) deviation of order, inventory and supply volume.

In the simulation, two termination conditions are present: (1) If the number of any supplier type goes to zero then end the simulation; and (2) If all suppliers are resistant to changes in the market, then end the simulation. In order to observe the effects of the first condition the second termination condition is deactivated. Then the simulation is run with the same inputs for 1000 iterations and the following variables are recorded:

- Number of Tier 0 suppliers when termination condition is met.
- Number of Tier 1 suppliers when termination condition is met.
- Number of Tier 2 suppliers when termination condition is met.
- Number of customers when termination condition is met.
- Simulation clock / ticks when termination condition is met.

In addition to those observed variables that are listed above, effects of environmental conditions are also recorded. It is a well-known fact that predicting the exact future behavior of a complex system, such as a CMEE, is not possible; however, this does not imply that the future is random. In fact, complex systems exhibit patterns of behavior that can be considered archetypal or prototypical (Choi, Dooley et al. 2001; Mitsuishi 2008). The existence of such a pattern in CMEE is the environmental conditions. What we mean by environmental conditions is the economic state of the market. There is always a good time followed by a recession and sometimes end up with severe economical conditions, like depression. In order to model this, we added different types of environmental conditions to our ABM, such as environmental conditions representing: (1) the good economic times, (2) normal economic times, and (3) severe economic times. According to the effects of those conditions, we observe customer purchase power, customer demand, amount of raw material, companies' production rate, sales, product price, energy of companies, and budget of companies.

4. Results

In all 1000 simulation runs, supplier volume and customer volume in the system are recorded. As expected, the deviation of the number of different customer types in the system is close to each other and mostly following the environmental condition trends. However, the deviation of number of different supplier types in the system follows a more interesting trend. It is observed that 64 percent of the time termination condition 1 (if the number of any supplier type goes to zero then end simulation) is met because Tier 2 suppliers are extinct. However only 1 percent of the time termination condition 1 is met because of the main suppliers, which shows that companies, which are on the top of the vertical integration, are stronger in the market and survive longer. A graph of deviations of different type of suppliers at the end of each simulation run is given in Figure 1.

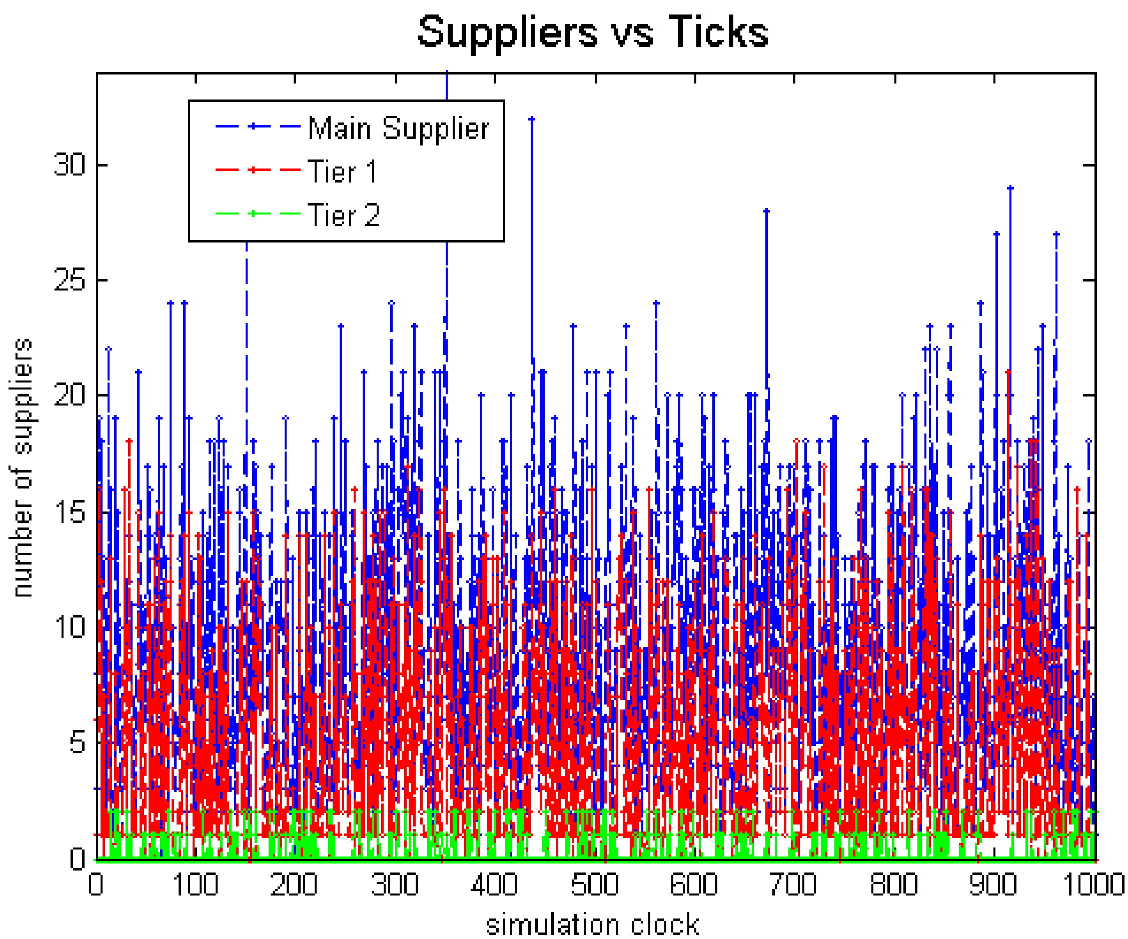

Figure 1: Number of Suppliers versus Simulation Clock

Also, the deviation in simulation termination time in the system is observed. The statistical results show that there is a significant deviation in market life expectancy according to current environmental conditions of the market. In the simulation, the three different types of environmental conditions (good economic times, normal economic times, and bad economic times) produce the following results:

- Customers' purchase power decreases when environmental conditions get harsher. Customers with a limited budget are willing to spend less money so that demand to products decreases.
- As a result of decreasing customer demand sales decrease.
- Because of decreasing sales, companies decrease the product price to vitalize product sales.

- Decreasing sales forces companies to decrease the production rate, so that they order fewer raw materials and keep fewer inventories.
- Since both sales and production rate decrease, energy and budget of companies decrease significantly.

One can see that one negative effect in the market creates a domino effect and affects every layer of the supply chain. All these results can be observed in Figure 2.

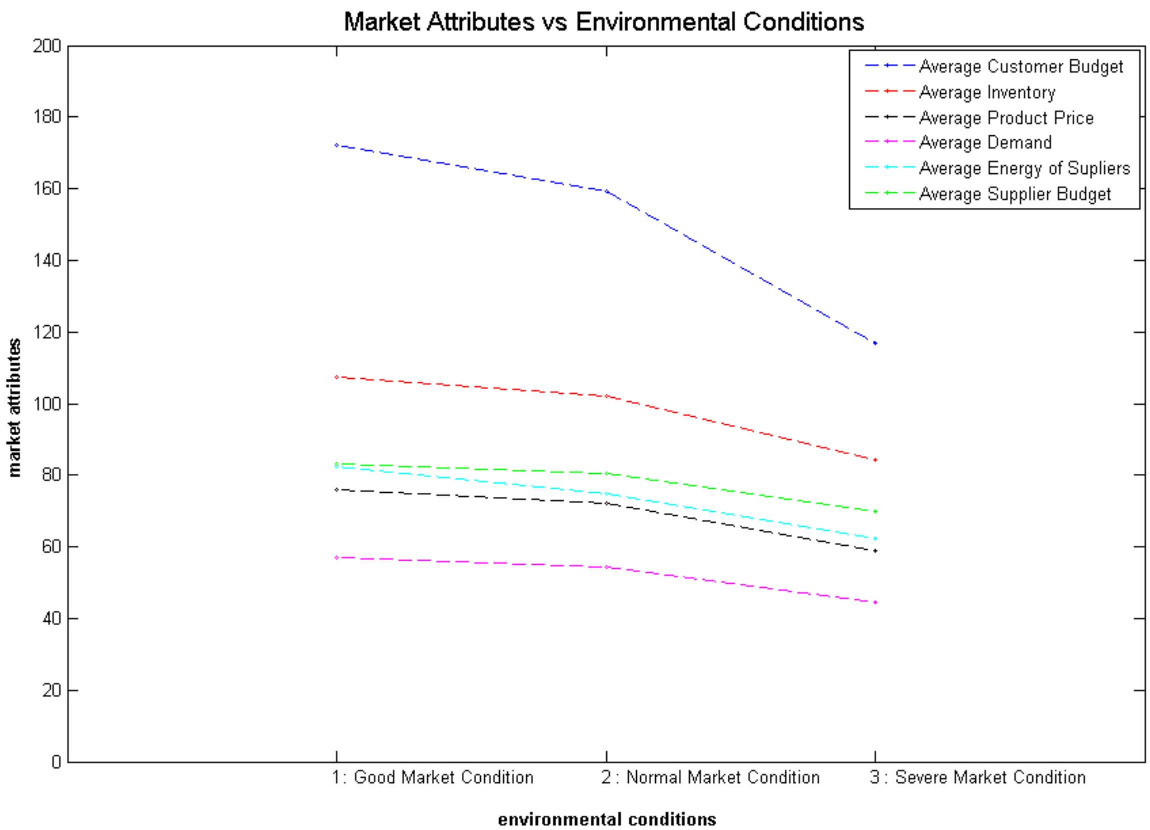

Figure 2: Market Attributes versus Environmental Conditions

5. Conclusion

Based on the aforementioned analysis, we tried to derive and investigate adaptation mechanisms in CMEE to better understand their possible evolutionary paths. Specifically, we tried to deliver the following: (1) using agent based methods to study evolution and self-organization of CMEE, (2) developing an accurate comprehensive model for understanding CMEE, (3) conducting a comprehensive study on the effect of uncertain and rapidly changing business environments in the CMEE by considering adaptation, alignment and agility of the CMEE, and (4) performing statistical analysis of the resultant model. The ultimate goal of this study is to provide methodologies and tools for CMEs to transform and optimally reconfigure themselves to competitively operate in a rapidly changing complex adaptive ecosystem. In order to simulate aspects of CMEE, we constructed an agent based simulation that contributes to the understanding and building of agile CMEs. This simulation model also helps to find enterprise architectures which bestow the right balance between being rigid and being conducive to modularization and self-organization by using the agent based approach.

In this study, we showed that companies, which are on the top of the vertical integration, are stronger in the market and survive longer than the enterprises which are away from the main customer. We investigated the effects of three different environmental conditions; the good economic times, normal economic times, and severe economic times on enterprise ecosystem survival. The statistical results showed that there is a significant deviation in market life expectancy according to current environmental conditions of the market. It was observed that the customers' purchasing power decreases when environmental conditions get harsher; since customers with a limited budget are willing to spend less money.

As a result the customer demand for products decreases, which consequently decreases the sales. These also cause a decrease in the product price to vitalize product sales. Decreasing sales forces companies to decrease the production rate so that they order fewer raw materials and keep fewer inventories. Since both sales and production rate decrease, energy and budget of companies decreases significantly. Those results showed that one negative effect in the market creates a domino effect and affects every layer of the supply chain. In this research, we showed that the use of complex adaptive systems allows timely diagnosis and detections of abnormalities in the operations of a CMEE. As a result computer manufacturing enterprises, which are agile and robust to uncertainties and rapid changes, function well in the dynamic business environment.

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