Origin and Evolution of Supply Chain Networks using Complex Adaptive Systems
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Abstract

How does decision-making of individual firms result in the emergence of different supply chain network structures? In this research we use a complex adaptive systems based framework to grow and evolve supply chain networks to answer the question. We are using an agent-based hybrid simulation (discrete time and discrete event) methodology to implement the framework. Preliminary results and analysis show an underlying structure to the origin, growth and evolution of supply chains.

I. Introduction

Why is the supply chain structure of the florist industry so different from those found in the manufacturing sector? The florist industry has a vast number of retail outlets, with a correspondingly vast number of suppliers. The manufacturing sector, such as in the automobile sectors, is composed of few major manufacturers, more direct suppliers, and a large number of tiers. Are there certain simple decision-making rules used by individual firms that result in these diverse structures? Limited research has been done in the field of supply chain networks to address the challenges of operating in different types of supply chains (Harland et.al, 2002). Most of the work done in this area has mainly focused on simplified, linear flow of materials, money and information, taking a less strategic and more logistical perspective (Choi and Liker, 2002) (Harland et.al, 2002). Our paper introduces a new research framework based on Complex Adaptive Systems approach for answering the above questions.

Considering a supply chain as a complex adaptive system (CAS), we break down a supply chain into two principle components, namely, supply chain environment and the firms (called nodes in our model). The nodes reside in the environment and attempt to satisfy the environmental demand, driven by simple decision-making rules. The interaction between the nodes results in an overall complex behavior of the system and gives rise to the different structures. There are some other hidden factors like environmental conditions, government regulation, or business rules that affects the formation and evolution of supply chains. To test and validate these conditions we have developed a simulation framework called CAESAR (Pathak and Dilts, 2002) that implements the research model. The paper is organized in the following manner. Section II provides a brief review of past modeling techniques and their limitations in addressing our question. Section III then introduces our research model of a supply chain network within a complex adaptive system framework. Section IV presents our research methodology, i.e. a hybrid simulation approach for implementing the framework. Section V presents a typical simulation that we ran for an elementary supply chain and some of the preliminary results are provided. Section VI presents some preliminary analysis and discussion; Section VII summarizes and outlines the future research that we will undertake.
II. Modeling of Supply Chains

Supply networks are complex bi-directed networks, having parallel and lateral links, loops, bi-directional exchanges of material money and information, encompassing a “broad strategic view of resource acquisition, development, management and transformation” (Harland et.al 2002). Researchers in the past have used various types of modeling techniques for analyzing supply chain networks. Pyke and Cohen, (1993) and others (Chandra, 1993), (Altıok and Raghav, 1995), used operational research techniques to model and study the dynamics of a supply chain network. Forrester (1961) used system dynamics approach; integrating systems of ordinary differential equations (ODE) over time to study and analyze the dynamics of a supply chain network. Simon (1952) used classical Laplace transforms to model such systems, Towill (1991), improved upon Forrester's work by considering tiered structures in supply chains (two/three tiers). The system dynamics community then extended the general model of stocks and flow for understanding the qualitative behavior of supply chains (Parunak,1998) (Riddalls et.al, 2000). Porter and Taylor (1972), and several other researchers (Porter and Bradshaw, 1974), (Bradshaw and Daintith, 1976), (Burns and Sivazlian, 1978) used discrete time difference equations based modeling approaches for analyzing a supply chain. Ho and Cao (1991), Cao (1992) represented and analyzed supply chains using discrete event simulation (DES) models.

Principal limitations of these techniques are that they are unable to model formation and behavioral based dynamics of a supply chain and the analysis can become quite complex for dynamic supply chains. Moreover all these approaches assume a relatively static supply chain network structure and try to optimize the flow in the network. The inherent assumption of a static supply chain network structure limits the use of these approaches for studying the dynamics of supply chain networks (Riddalls et.al, 1993). Parunak (1998), Kohn, Brayman and Ricey (2000) have more recently utilized agent-based techniques for optimizing the physical flow in a supply chain. Their approach takes into account the information-based dynamics between the supply chain entities along with the physical flow and does not assume a static structure. These approaches, though addressing some of the limitations mentioned earlier, focus more on optimizing the operational efforts of a firm in the supply chain thus taking a more logistical and less strategic view of supply chains.

None of these approaches can answer how supply chains are formed and how they evolve over a period of time thus failing to address the strategic issues of managing dynamic supply chain networks.

III. Growing Supply Chains within a Complex Adaptive Systems Framework

We suggest a complex adaptive system (CAS) based approach for modeling supply chains. A CAS is a system that emerges over time into a coherent form adapting and organizing itself, without any singular entity controlling or managing it (Holland, 1995). Choi et.al (2001) characterizes a CAS with three important foci; namely, 1) Environment (dynamism, and rugged landscape), 2) Internal mechanisms (deals with agents, self-organization and emergence, connectivity and dimensionality), and 3) Co-evolution (quasi equilibrium and state changes, non-linear changes, and non-random future). We base our research model on similar constructs.
Our research model consists of an environment where supply chain entities (suppliers and manufacturers) reside. The environment has various attributes such as munificence (i.e., abundant resources) or scarcity. Environment can be noisy (with uncertain communication) or be loss-less (i.e., perfect transmission of information). The environment in which supply chain entities reside also contains demand information for a product (price, timing, and capacity) and information on the product architecture itself.

Each entity in a supply network is represented as a node in the network. Each node has a ‘fitness’ value that represents how fit the node is to survive in an environment. If the fitness value of a node drops below the environmental threshold, the node dies. The fitness value of a node is evaluated and updated based on a fitness function defined for each node. The node behavior is driven by the simple rules that every node follows.

Every node has a pool of strategies or internal mechanisms to achieve their goals. Rules operationalize these strategies and they are driven by objectives and constraints that define the goals of a node. An example of a simple objective for a node can be to be a low cost producer while not to interacting with more than one manufacturer. Timing, capacity and budgetary constraints are examples of additional node constraints.

The results of implementing such node strategies in specific environments results in co-evolving supply chain structures.

The research model presented in the previous section can be precisely represented in set theoretic notations. There are two major constructs of the model: the environment where the nodes exist and the nodes themselves (see Figure below).

Environment $E$ is a 5-tuple where

$$E = \{V, A, T, n, P\}, E \neq \emptyset$$

$V$ is environment variable tuple that represents the environment demand variables, namely,

- Demand price of a product $p$ (unit is USD)
- Lead time for delivery $t_l$ (hours)
- Demand volume $v$ (unit)

Mathematically $V$ can be represented a 3-tuple where

$$V = \{p, t_l, v\}, v \neq \emptyset \text{ and } (p, t_l, v \in R)$$

$A$ represents environmental attribute that determines what type of environment the supply chain networks are emerging. There are four environmental attributes, namely,

- “M” = Munificent environment
- “S” = Scarce environment
- “N” = Noisy environment
- “L” = Loss less environment

We are considering the following four types of environments based on the combination of the above four attributes.

{“M”, “N”} Munificent and noisy environment
{“M”, “L”} Munificent and loss less environment
{“S”, “N”} Scarce and noisy environment
{“S”, “L”} Scarce and loss less environment

Mathematically A can be represented by a 2-tuple such that
\[ A = \{A_1, A_2\}, A \neq \Phi \] where
\[ A_1 \in \{“M”, “S”\} \]
\[ A_2 \in \{“N”, “L”\} \]

Environment E has an associated environmental threshold value represented by T (for each type of environment determined heuristically). Any node having fitness less than the environmental fitness level dies. The environment contains an initial set of nodes. The nodes attempt to fulfill required demand and thus form interrelationships amongst them. The nodes together with the set of relationships forms a graph and represent the supply chain network structure.

\( n_i \) represents nodes. Each node has a set of objectives and constraints and a corresponding pool of strategies. Also each node has a fitness value between [0,1]. The fitness value is used to determine which node will receive the order and which may eventually die.

Thus \( n_i \) can be represented by a four-tuple such that
\[ n_i = <O, C, S, F> \] Where \( O = \{O_1, O_2, \ldots O_n\} \) represents a finite set of node objectives
\( C = \{C_1, C_2, \ldots C_n\} \) represents a finite set of node constraints
\( S = \{S_1, S_2, \ldots S_n\} \) represents a finite set of node strategies
\( F = [0,1] \) represents node fitness value.

Mathematically the supply chain network structure can be viewed as a bidirected graph \( N \) with Nodes representing the vertices and the relationships between the nodes as edges of the graph. \( N \) can be defined as a two-tuple \(<n, R>\)
\[ N = <n, R>, \text{ such that} \]
\[ n = \{n_1, n_2, \ldots n_k\} \land n_j = \{\text{nodes}\}, n_j \neq \Phi \]
\[ R \subseteq n \times n = \{r_1, r_2, \ldots r_j\} \land r_s = <n_s, n_y> \text{ such that} \]
\[ (n_s, n_y \in n) \land n_s \neq n_y \]

\( P_a \) is a n-tuple, where n is greater than 1 and represents the product architecture set.
\[ P_a = \{p_1, p_2, p_3, \ldots p_n\} \]
Where \( pn \) represents sub-products. If n=1, then there are no sub-parts. If there are sub-parts then \( p_1 \) always represents the complete assembled product (called the master product in our model).
IV. Implementation of Framework: Hybrid Simulation of supply chain networks

To operationalize our research model we have built a simulation environment called CAESAR (complex adaptive supply chain simulation environment) that allows a modeler to specify a CAS environment and its corresponding attributes, and a set of nodes with operational rules and strategies. CAESAR is a hybrid simulator having both discrete time system (DTS) (Ziegler, 2000) and discrete event simulation (DES) concepts (Ziegler, 2000). The entire simulation is based on a single time reference (discrete time simulation modeling). Basic unit is defined as a tick. The environment controls the entire simulations based on this simulated clock tick (DTS) where as nodes are event (DES) triggered and do not have any idea of the simulation clock tick. Nodes respond to fulfill stochastic environmental demand and in the process form inter-relationships that gives rise to the supply chain network structure. The CAESAR framework conceptualizes the environment as shown in the research model as a parent node that controls the entire simulation process. The environment node generates the stochastic demand information and also initiates the simulation. It also keeps track of the unfit nodes and removes them from the environment at periodic intervals.

The CAESAR simulation toolkit is being developed by integrating a number of tool suites into a single framework. The heart of the framework is the MadKit platform [24].
MADKIT (Multi-agent Development Kit) is a versatile; java based agent development platform that can be used for cross-platform multi-agent system development. MadKit platform allows us to model the nodes and the environment as java agents thus capturing all the nuances described in the research model.

So far we have identified a research gap in the area of supply chain networks and have suggested a framework based on complex adaptive systems to investigate the reasons behind different types of supply chain networks. The next section describes our initial simulations that we have run to test if the framework works and if some interesting structures could be observed from some basic initial conditions and node rules.

V. Typical simulation and preliminary results

The initial startup conditions for the simulations have been heuristically decided. The environment has a threshold value between 0 and 1 that indicates the minimum fitness required for a node to survive. Threshold value close to 1 indicates harsher environment (e.g. scarce and noisy) whereas closer to zero indicates more beneficial environments (e.g., munificent and loss-less). Any node trying to survive in the environment should have a fitness value greater than or equal to the environmental threshold. The environment also contains a product description that specifies the finished product as well the sub-parts that constitute the finished product. The modeler specifies a price range for each of these parts, sub-parts, and assembly cost as well. The environment utilizes these ranges to generate a random demand price between the upper and lower ranges specified by the modeler. The demand variable consists of the price at which a node should supply and the volume that needs to be supplied. Delivery lead-time and other factors are not considered for this simulation.

Nodes in this simulation are non-intelligent ones. They try to fulfill the stochastic demand in every demand cycle without checking if they have the required capacity to meet the demand or whether they should judiciously price their products to win more contracts; and thus constant interaction takes place between the nodes and the environment. An evaluator agent (part of the environment) determines a node’s fitness and it performs some specialized functions like distributing the stochastic demand that is generated by the environment between the nodes, keeping track of node fitness and killing unfit nodes. As described previously a tick can be set in the modeling environment (in seconds) and sets the simulation speed. The System time unit provides this functionality in the simulation environment and also provides mechanism for environment, evaluator and nodes to check the current tick value. The system time unit counts from 0-10 tick and then resets the tick count to 0 and starts all over again.

To begin with we set up a simulation experiment such that the fittest node (fitness values generated randomly between 0-1) was awarded the entire contract. The node manufactures internally up to its production capacity defined by the capacity constraint. The remainder of the demand is subcontracted to other nodes. For sub-contracting the node determines the best price quotation for either the entire finished part or individual sub-parts. We started with four nodes equal in all respects except their fitness values. The fittest node was awarded the demand. Every node has a fitness function that calculates and updates the fitness of each nodes based on profits or losses they make in each demand cycle.
The basic rule that was supplied to the evaluator was that
1. The fittest node gets the contract
2. Any node falling below the environmental threshold (0.3) dies

The basic rules for the nodes
3. Increase your fitness and try not to die (objective).
4. Manufacture up to internal capacity (capacity constraint)
5. Accept entire demand and subcontract to other nodes what you cannot make (objective).
6. Wait for 10 seconds to accept all the bids (timing constraint).

The simulations were run for 10 demand cycles. At the end of 10 demand cycles we observed the structure of the supply chain network that had grown. The table below shows the types of observed growth structures of supply chains.

![Types of Observed Growth Structures](image)

**Figure 2: Types of Observed Growth Structures**

### VI. Analysis and Discussion

The growth structures presented in the previous section were formed during the simulation cycles because the nodes interacted between themselves to fulfill the stochastic environmental demand. The primary reason for interaction was to increase their respective fitness (primary goal for the nodes). If the demand was greater than the internal production capacity of a node subcontracting occurred and tiered supply chain structures were formed. The structure of the chain completely depended on the capacity constraint of individual nodes, their fitness values and the stochastic environmental demand. The nodes that could not increase their fitness above the environmental threshold value, died.

Though the simulation experiments were very preliminary and simplified it provided us with useful insights. First it helped us to test our CAS based framework for growing supply
chains. We were able to take the principal concepts of a CAS (Environments and entity) and map it within a supply chain framework. The experiment strengthened our beliefs that the growth structures were indeed supply chains as material, information and money flowed between individual firms to satisfy a global demand, just like a real life supply chain. The underlying settings of the supply chain was quite simplified and in some sense unrealistic as nodes were non-intelligent and did not use any strategic decision making rules. But as per the basic property of a CAS, the interaction effect between the individual entities in the environment resulted in an overall behavior and the nodes arranged themselves in different observable patterns. Thus such an approach allows us to capture the complex informational and behavioral dynamics in a supply chain network (something that other frameworks could not tackle adequately).

The framework would eventually allow us to test other properties of the structures like stability, depth, mortality rates of firms etc. Based on such results we are able to show an underlying structure to the origin, growth and evolution of supply chains and also establish if there are certain simple basic rules that result in the formation of diverse supply chain structures. This in turn provides a strategic insight to managers operating in dynamic and fast changing supply chain environments.

VII. Summary and Future work

This paper identifies a research gap in the field of supply chain networks and suggests a CAS based approach for addressing the strategic issues of managing a complex supply chain network. The paper presents past modeling approaches and their limitations and suggests a complex adaptive system model of a supply chain. The primary constructs of the research model consist of nodes representing firms in a supply chain residing in a supply chain “environment”, interacting with each other to fulfill a global demand. The paper then describes CAESAR simulation framework that implements the research model and allows a modeler to run simulations of complex adaptive supply chain networks. As an initial example presents a simulation with four non-intelligent nodes following simple encoded rules and no decision-making capability in four different types of environment. Preliminary results of the simulation identify some basic growth structures and suggest that there is an underlying structure to the origin growth and evolution of supply chain networks.

The work till date is just the stepping-stone for more promising research to come. In this paper we presented the framework and illustrated its use with a very simplistic example. Subsequently we plan to make the nodes intelligent such that they are more aware of the environmental conditions and based on that can utilize the correct strategies for managing their position in the supply chain. We plan to use encoded learning models within the nodes so that they could adapt themselves to a changing environment. What we would hope to see is how decisions made on certain key aspects in a supply chain setting such as price, volume, delivery time, and different environment types result in diverse supply chain network structures.

VIII. Reference


http://www.madkit.org


