The Emergence of Stability in Diverse Supply Chains

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The distribution of products from manufacturer to distributor to wholesaler and finally to retailer (the Supply Chain) exhibits surprisingly erratic behavior, popularly termed the Bullwhip Effect.

Recently a group at the Santa Fe Institute's Business Network formed a team to study the Bullwhip effect via John Sterman's classic Operations Research game called the Beer Game. One of our goals was to discover mechanisms that would "dampen" the chaotic behavior, self-organizing the system into a stable one.

Two mechanisms were investigated: increasing the visibility up and down the supply chain for each member of the chain, and converting the chain from a linear form to a network or mesh form. Both effects provided a simple Self-Organized network where improvements in individual choices dampened the variations in the overall chain.

History

While investigating the dynamics of supply chains in the 1980's, researchers were surprised to find that presumably stable commodities exhibited surprisingly chaotic inventory properties. Demand for these products, rather than being constant, varied considerably, and the associated Supply (inventory at the manufacturer and warehouses) fell into uncontrolled erratic behavior.[4]

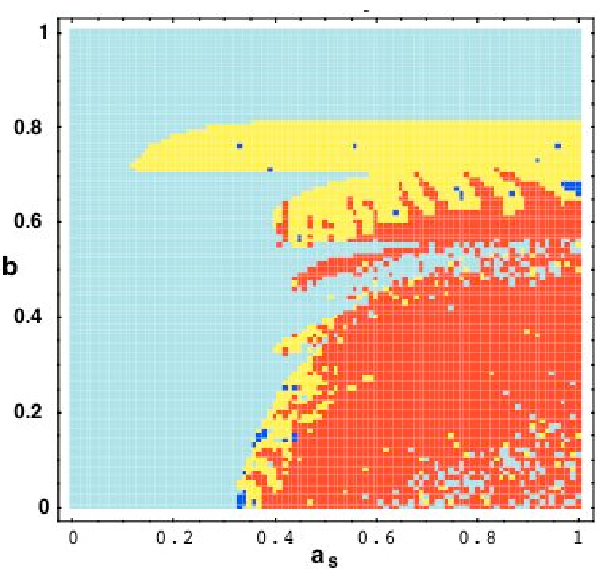

Figure 1: Inventory Volatility Landscape

A classic study[2] of this behavior looked into Pampers, a disposable diaper for babies produced by Proctor and Gamble. Presumably the number of babies and their daily requirements for clean diapers would provide a nearly constant demand, and the associated supply chain would be quite stable and predictable. Studies showed, however, that the pampers supply chain showed highly erratic, chaotic behavior.

MIT's John Sterman[5] invented a simple supply chain board game, called the Beer Game, where four players managed inventory in a four level supply chain: Beer Factory, Distributor, Wholesaler and Retailer. Each turn of the game represented one week's ordering and receiving of inventory into stock. A two-week supply queue, and a one-week ordering queue, existed between each player, introducing delay and uncertainty. The "customer" for this supply chain had simple behavior in every play of the game: buy 4 barrels of beer each week for four weeks, then buy 8 barrels from then on, thus introducing a simple step function for customer demand.

Players attempt to minimize a cost function based on $.50 per barrel for storage, suffering a $2.00 per barrel penalty for having inventory reduced to zero, thus not being able to fulfill orders (under-stock).

Sterman's seminal work was to quantify typical human behavior, rather than attempting to "solve" the problem of optimizing the supply chain. Players try to minimize their costs but typically exhibit panic between having too much inventory and not having enough. Sterman found a set of equations that accurately mimic this behavior.

The ValueNet Project

The Santa Fe Institute (SFI) has a Business Network (BusNet) composed of over 50 corporate partners interested in applying complexity techniques to their businesses. Two recent improvements in supply chain technologies prompted BusNet members to ask if these could reduce the chaotic behavior within supply chains. These were 1) Radio Frequency ID tags (RFID) and 2) improved Internet communications.

An initial group of over 20 interested parties meet twice to decide upon a project[3]. The project selected was to use an existing RePast model of the Beer Game, and modify the model in two areas. First, to model the impact of RFID and its software infrastructure, the model was modified to allow agents to see further down the supply chain than just the current incoming orders. Second, to consider the impact of the Internet, the linear supply chain model was replaces with a "mesh" network with multiple factories, distributors, warehouses and retailers.

The project was carried out by five members of the ValueNet team, joined by a sixth member in the latter stages of the development to help add sophisticated visualization techniques. The results were presented to the SFI BusNet over a period of three SFI biannual meetings.

Visibility (RFID)

The initial Beer Game hid information from the players by placing orders on cards upside down on a playing table. This was simulated by having the RePast agents use a queue between themselves, with only the end of the queue visible. Agents were free to keep as much "local knowledge" as they wished. This included their pending incoming supply orders "in the pipe" and their current inventory for fulfilling incoming demand orders. Using the human behavior model discovered by Sterman, this results in extreme volatility for certain parameter settings.

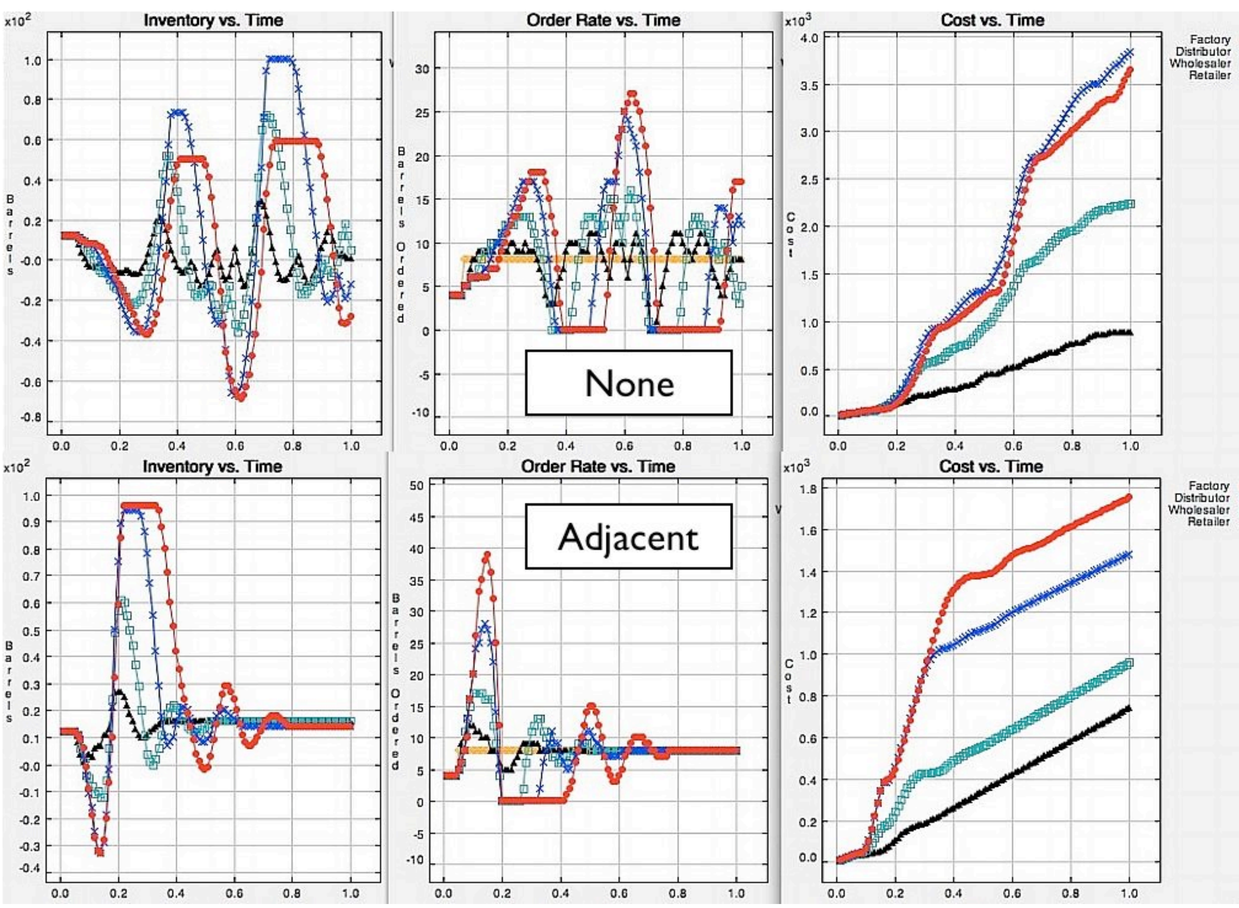

Figure 2: The effect of visibility on volatility.

To model the impact RFID technology introduces into supply chains, it was decided to parameterize how far down the supply chain the agents could see. Thus, for example, the Factory agent could see its incoming orders to any level, even all the way to the Retailer.

The result was dramatic: with vision increased just one level, the volatility within the supply chain dampened quickly, self-organizing into a simple steady state, constant order supply chain In the figure above, the top three graphs, labeled "None" (for no additional visibility) show the standard Beer Game volatility over a run of 100 weeks. The bottom three, labeled "Adjacent", show the result of increasing visibility just to the adjacent agent. Note the dampening, reaching constant order rates near week 80, and the much-reduced cost values for the four agents.

Mesh (Internet)

The classic Beer Game uses a linear supply chain, consisting of just one of each agent type (Factory, Distributor, Wholesaler and Retailer). It was decided by the ValueNet team that a more "modern" supply chain would use the Internet to access many vendors. Thus a Beer Factory would use multiple Distributors, which in turn would use multiple Warehouses and so on.

In our initial Mesh study, the agents simply uniformly fulfilled their inventory requirements among their providers, with no bargaining or auctions and indeed with no price differences among them.

As in the visibility study, the volatility in the linear supply chain decreased, self-organizing into a steady state, constant order supply chain. Below, the top diagram shows a mesh networked supply chain with two of each agent type serving a single customer. The bottom three graphs show the dampening effects of the mesh network, producing a stable supply chain at around week 70.

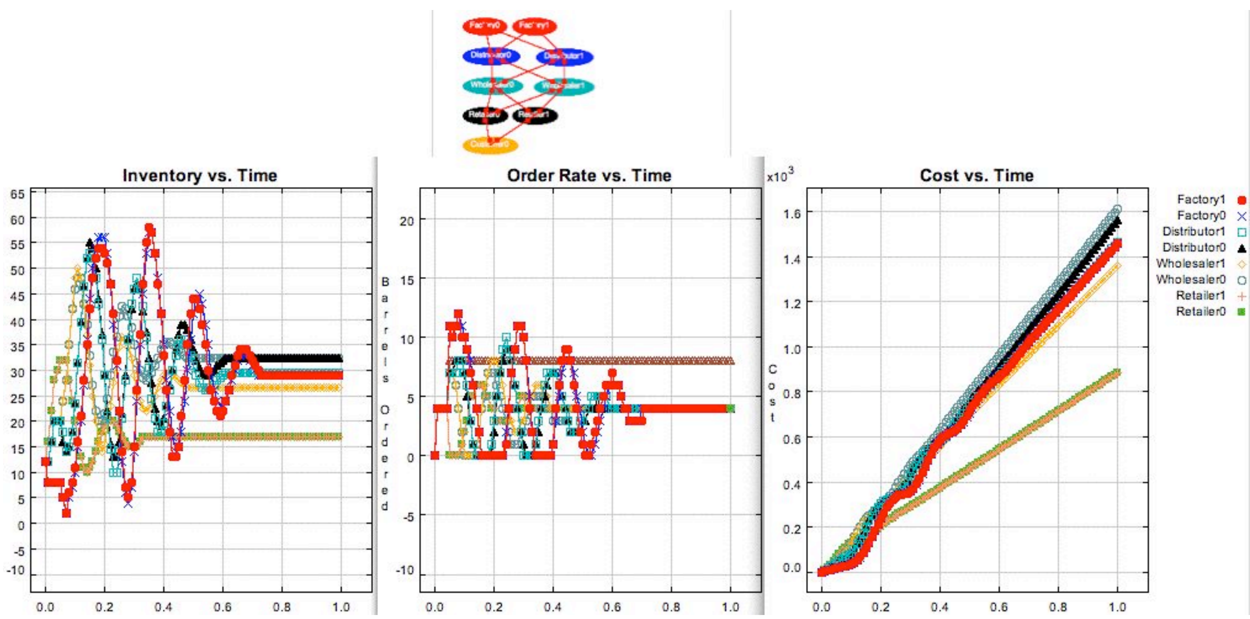

Figure 3: The effect of a mesh supply chain on volatility

Summary

The classic Beer Game, with the Sterman human behavior model, provides an interesting environment for investigating self-organizing within supply chains. Two such investigations: one on increased visibility in the demand for products, the other on a more general network topology, dampened the volatility of the supply chain.

In terms of Self-Organization, the key feature here appears to be that the addition of greater diversity (increased visibility, mesh network topology) within the supply chain promotes a more stabile environment. This view of Self-Organization was nicely articulated by John Holland when he posed the question: How is it possible to buy a sandwich in Manhattan with fresh lettuce, only hours old? It would be impossible to organize this by a city planning office. But instead, individual agents, with sufficient local knowledge and resources, perform this miracle, solving an NP-complete problem "well enough". The key is providing enough local knowledge and resources, but not too much and not too constrained.

Workshop Discussion Material

The initial ValueNet exploration did not attempt to analyze the Beer Game from the standpoint of Self-Organization. Rather it used tools of the Complexity community to simulate the supply chain, and to investigate two modifications to it. This section presents material for discussing the Beer Game via Self-Organization.

Exploring the literature on Self-Organization[1] reveals multiple formal approaches, each of which defines a measure for organization and uses it to study the increase or decrease of a system's organization. Statistical Entropy provides a probabilistic measure. Chaos theory uses basins of attraction arguments to discuss reducing access to restricted parts of the systems phase space, thus adding structure. (Note this does not mean optimal, merely more stable.)

Less popular is an attempt to analyze a system for potential improvements using these measures, i.e. for prediction. This holds true for Complexity in general: it is very difficult to tell what rules should be used to achieve a desired result. For example, it is difficult to derive a constitution that would produce a desired set of social behaviors.

The Sterman human behavior model has two rules: the demand forecasting rule and the inventory maintenance rule. The Visibility experiment modifies the forecasting rule by using the downstream demand as the prediction. Note that this demand is not optimal, but is itself conditioned by knowledge of its downstream demand, and so on. The Mesh experiment modifies the inventory rule by spreading the orders evenly among the multiple suppliers.

The Beer Game stabilizes when it reaches a point of constant cost for each agent. It need not be optimal however (i.e. have the desired inventory level), the rules simply produce a steady solution, escaping volatility.

The state space for the Beer Game can be approximated by collecting 24 state variables such as orders in transit, internal state variables, inventory and control parameters. Presuming orders in [0-40), inventory in [-110 +140), and two internal order state variables for each component, the state space size is roughly 1.074*10^39 (1,073,741,824,000,000,000,000,000,000,000,000,000,000) This is conservative using only observed variation. A state based analysis could either use the state variables to define a landscape to look for minima, or analyze the state space for basins of attraction.

A thermodynamic analysis of the Beer Game would consider the customer demand as the energy input, the delivered goods as the work of the system, and the total cost (inventory and backorders) as the generated heat.

Finally, a statistical entropy analysis shows the quiescent states as minimal entropy, thus "organized". More interesting would be to include the impact of the two experiments on the entropy of the system over time as an indicator that they a-priori lead to Self-Organization.

A simple NetLogo model of the Beer Game with Visibility added is available for our use at: http://backspaces.net/Models/beergame.html

References

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