SAND2012-8506C

Help from Hoarders: How Storage Can Dampen Perturbations in Critical Markets

Marshall A. Kuypers[1,2], Walter E. Beyeler[2], Matthew Antognoli[2,3], Michael Mitchell[2], Robert J. Glass[2]

[1] Management Science and Engineering Department, Stanford University, Stanford, CA, USA
mkuypers@stanford.edu

[2] Complex Adaptive System of Systems (CASoS) Engineering
Sandia National Laboratories, Albuquerque, New Mexico, USA
{mkuyper, webeyel, mantogn, micmitc, rjglass}@sandia.gov

[3] School of Engineering, University of New Mexico
Albuquerque, New Mexico, USA
mantogno@unm.edu

Abstract. Critical resource supply chains are vulnerable to manipulation because of the un-substitutability of their goods. When a monopoly controls all or part of a market, it has the ability to profit from a reduction in supply of a critical resource. We model this complex adaptive system (CAS) using an agent-based model (ABM) and investigate a strategy to mitigate the potential for exploitation of a market by a monopoly. We find that when entities increase their input resource buffer, they decrease the reactivity of resource prices to supply disruptions, which limits the amount by which monopolies benefit from price fixing. This storage strategy also reduces total system losses due to a perturbation.

Keywords: Complex adaptive systems, Agent-based model, Supply networks, Buffer capacity, Monopoly, Perturbations, Storage, Price fixing

1 Introduction

Critical resources and supply networks are important to model and understand because they have the potential to be crippling and disruptive to an economy. Often consisting of un-substitutable goods, these resource supply chains become even more vulnerable when operated by unfriendly stakeholders or controlled by a monopoly capable of exploitation by supply reduction and price fixing. In this paper, we examine methods by which a monopoly is able to exploit supply shocks and potential mitigation strategies to prevent this behavior.

Economic interactions have been recognized as complex adaptive systems (CAS) for over twenty years (Holland and Miller 1991). Recent research has confirmed that supply networks exhibit CAS behaviors and structures as well (Choi et al. 2001). We use an agent-based model (ABM) developed at Sandia National Laboratories to initialize an environment of interacting agents that consume, produce, and store resources. We use this model to study the ways a monopolized supply chain is vulnerable to price fixing through a scenario where a monopoly controls a critical resource in a fully connected network of interacting agents. We show how the monopoly can profit by reducing its production, thereby increasing the price of its good. Then, we examine how the other agents can reduce the monopoly's ability to profit by enlarging their input resource buffer tanks. Finally, we consider the system effects and policy implications of this work. We find that increasing the buffer capacity reduces the total system loss from a perturbation. The severe price reactivity caused by low storage generates more system damage, while larger buffers benefit the whole system.

1.1 Relevant Literature

This paper draws on multiple disciplines. Relevant work on supply networks as CASs, buffer capacities in supply networks, monopolies, and price fixing is summarized here. Engineers have been studying optimal buffer capacities for several decades (Buzacott 1967). Since then others have developed algorithms and methodologies for investigating supply chain operations in various environments (Shi et al. 2009; Cochran et al. 2009; Zequeira et al. 2007). However, most of these papers consider supply networks as deterministic processes, with a stochastic component occasionally represented to introduce uncertainty. Additionally, the analyzed supply networks have static structures and no adaptability.

Other researchers have argued that supply networks should be characterized as CAS (Choi et al. 2001), and other studies have rigorously tested the validity of treating supply networks as CAS, verifying this designation (Wycisk et al. 2008). We believe that supply chains and economic networks can be studied more effectively by considering their complex adaptive characteristics. In our model, we treat supply networks as CAS and analyze the buffer capacity problem, which to our knowledge has not been done before.

Additionally, we consider a network with monopolistic players and investigate policies that restrict the monopoly's ability to profit from the system through price fixing. A monopoly's ability to price fix has also been well studied, under a variety of constraints (Cabral et al. 1999, Harrington 2005). The practice of price fixing has been repeatedly demonstrated in the real world. The Organization of Petroleum Exporting Countries (OPEC) has been shown to manipulate prices through production levels (Kaufmann et al. 2004; MacFadyen 1993). Other companies, such as De Beers, Enron, and Archer Daniels Midland have also been investigated for price fixing (Labaton 2004; Bergenstock and Maskulka 2001; Weaver 2004; White 2001). While much of the literature hints at ways to prevent monopolies from reaping undue profits, little literature exists that explicitly investigates policies that could protect consumers. Our hope is that this paper will encourage more discussion on mitigating disruptions to critical supply networks.

2 Model Formulation

We use an ABM developed at Sandia National Laboratories to analyze this system (Beyeler et al. 2011). Each agent or entity must consume resources to maintain viability in its environment. To obtain resources for consumption each agent produces and sells a unique resource: each also stores resources as a buffer against disruptions. Agents interact with each other through resource markets in which buyers and sellers are matched using a double auction. These exchanges are executed with the aid of a "money" resource. Agents respond to their environment by adjusting production and consumption rates. We use a state variable 'health' to control the production capacity of an agent, which is a function of recent consumption rates. Consumption, production, and health dynamics are described by a set of coupled nonlinear first-order differential equations.

Each agent processes resources the same way. An agent obtains a resource from the market and stores it in an input tank. The size of this tank is designated by an inventory coverage time parameter. A translation process converts input resources to an output resource. The output resource is stored in another tank before being sent to the market for sale. Figure 1 illustrates this process.

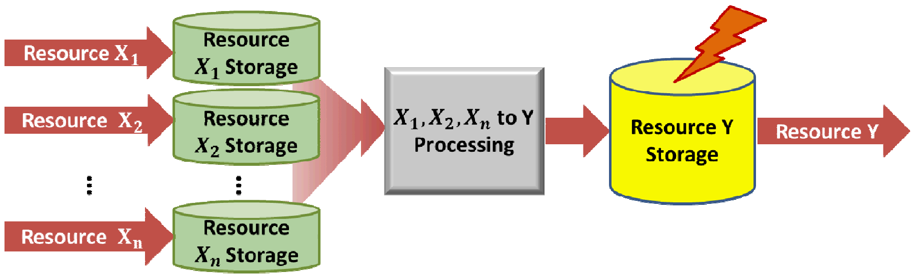

Fig. 1. An agent's resource process (Kuypers et al. 2012). The lightning bolt shows where the perturbation removes resources from the agent's output resource storage tank.

For this model, we use a fully connected network of resource interdependencies, as shown in Figure 2. An exploration of the effect of other types of network structure on the dynamics of the system has been previously explored (Kuypers et al. 2012). For simplicity, we use the fully connected configuration.

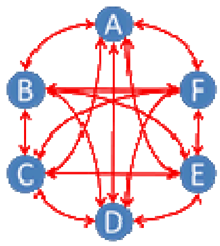

Fig. 2. A fully-connected network. Each node is an agent. Arrows denote resource flows; each agent consumes the resources produced by every other agent.

2.1 Perturbations and Reductions in Supply

Perturbations are introduced in the model by removing a defined amount of a resource from an agent's production storage tank. This creates a shock as the perturbed agent balances the competing interests of refilling its tank with selling its goods, which have become scarce in the market. The resource loss caused by this perturbation travels through the rest of the system by affecting other agents' input resources, which in turn affects their production.

We should also note that a perturbation that takes away some of an entity's produced resource is very similar to a reduction in production. The major difference is that perturbations remove the resource from the perturbed agent, while a reduction in production does not cause the unproduced resource to be lost. However, this distinction does not have an effect on health or money level as we are measuring them. Therefore, we can use perturbations to simulate how a reduction in supply will affect the system.

2.2 Buffer Capacity

The internal processes of an agent are controlled in part by the buffer size, which defines the target amount of stored input resource expressed as the time to consume that resource. Essentially, this defines the size of the buffer tank, or the amount of storage resource to hoard. Large buffer values mean the input storage tank is large. Also, the buffer size affects the agent's bidding prices by controlling the speed at which the bid price is changed. The casual processes that regulate this are shown in Figure 3.

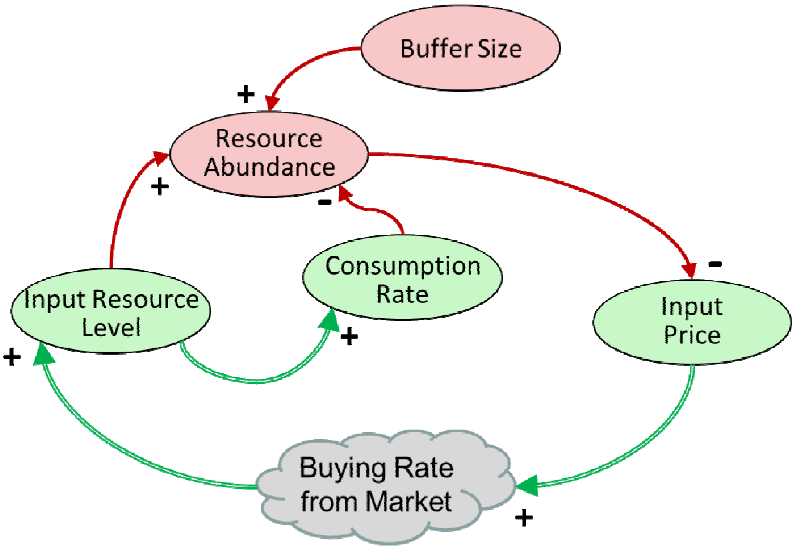

Fig. 3. A casual diagram of an entity's internal processes. Buffer size affects resource abundance, which is negatively correlated with the input price. Larger buffers reduce the premium an agent is willing to pay for a resource.

A small buffer size means the agent runs out of its input resource quickly and it will be willing to pay a premium to replenish its supply. Therefore, the size of the buffer determines how quickly the entity will react to a higher price: if the buffer is small, the agent will end up paying a premium quickly after the initial price spike. A larger buffer allows the entity to maintain production without chasing the price up, which alleviates the effects of the perturbation.

2.3 Substitution

The translation process that converts input resources to an output resource is not constrained to operate on one resource. The translation process can take in several inputs to produce one output. There is limited substitution between resources so that a shortage of one resource can be made up by increasing consumption of other resources. This tradeoff is reflected in Equation 1, which describes the influence of consumption rates on the evolution of health.

$$\frac{d}{dt}h(t) = \frac{1}{T_h}\left[\frac{h_0}{\left(\frac{1}{N_{Ch}}\sum_i \frac{1}{c_{h_i}^{\ *}(t)}\right)^{p_{Ch}}} - h(t)\right] \qquad (1)$$

where $h(t)$ is the health level, T_h defines the decay time of health, h_0 is the nominal health level, N_{Ch} is the number of resources consumed to sustain health, and P_{Ch} is the power of the dependence of health on consumption.

This equation leads to diminishing returns as resources are substituted. For example, as the consumption of resource C_a^* decreases, more and more additional consumption of resource C_b^* is needed to maintain nominal health. A graph of this relationship is shown below, in Figure 4.

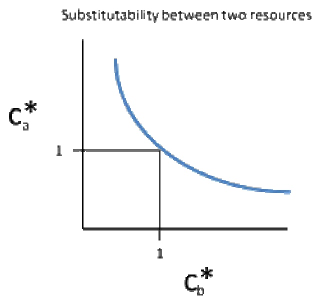

Fig. 4. Substitutability between two resources. As the consumption of resource C_a^* decreases, the amount of resource C_b^* that is needed to make up the difference increases.

This substitutability is generalizable to *n* different resources: each agent can consume multiple resources which are all substitutable as defined in equation 1. Note that this relationship requires that some nonzero amount of each input resource is consumed, regardless of the abundance of other resources.

2.4 Monopoly Strategy

The fact that each resource in this model is produced by a single agent means that each is controlled by a monopoly. Agents in this model do not have a cognitive strategy; they do not decide to price fix. Instead, price fixing emerges from the pricing mechanisms initialized in the model.

2.5 Clarification of Model

We would like to be precise about how we define and classify this model. The system we are modeling is undoubtedly a CAS. Our agent-based model has system dynamic components that govern the evolution of agents' states. The model may or may not represent CAS behavior for several reasons. We are observing a small number of agents, which may not be sufficient to demonstrate complexity under a formal definition. Also, the system may not have enough throughput to trigger complexity, just as a road with one car does not have enough throughput to trigger complex traffic patterns. Some behavior in this model could be classified as emergent, such as the price levels: our hope is to push this system to more interesting displays of emergence. Although the behavior analyzed in this study may not be complex, the ingredients for complexity exist. In this paper, we characterize some important dynamics of the system which is an important part of validating and testing the model. In future studies, we plan to observe complexity that conforms to a more rigorous definition.

3 Market Manipulation

Fixed supply and demand markets are susceptible to manipulation by the suppliers. In our model, we introduce a simple shock on the production tank of Agent F that removes 100% of its stored output resource. The health of the shocked agent decreases initially because it has no resource to sell. Its input flow of money is reduced and the agent scales back its consumption to preserve its money levels. While the resource is unavailable, the other agents bid up the price, since each agent still needs to consume some nonzero amount of resource F. Therefore, as soon as the perturbed agent F starts producing again, it can obtain a high price for its good since the demand for its resource is high. The perturbed agent sells its resources for a premium, which leads to its money level rising, which results in increasing consumption. As a result, the perturbed agent F sees a large health gain as it benefits from providing a scare resource that others need. This process reaches a maximum point, at which the health of unperturbed agents has decreased from paying such a high price that they can no longer afford the perturbed resource. At this point, F must bid down its selling price because agents stop buying its resource and its health begins to fall. This process effectively dampens the perturbation, but the health values experience some overshoot as all the values return to the nominal health level of one. These dynamics are shown in Figure 5.

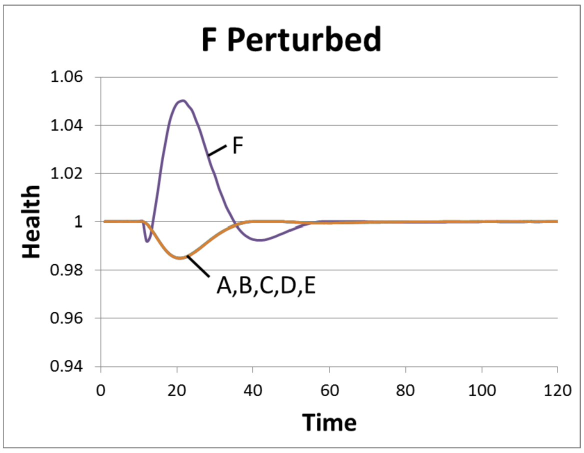

Fig. 5. A perturbation response. Node F is perturbed and experiences a health gain while all other nodes experience a health loss.

The final result of this simulation shows that the perturbed node experiences a net health gain. This result is robust to perturbation intensity, perturbation duration, and changes across a wide degree of parameter values. Some structures, such as the hub and spoke network, remove the incentive for price fixing because feedback patterns couple agents' health values. There are certainly more structures that exhibit this property as well.

However, for the fully-connected network structure the response pattern suggests that certain agents can benefit from inflicting a perturbation on themselves. Such a scenario has, in fact, happened. In 2000, middle-men like Enron convinced California power plants to shut down production, introducing an artificial scarcity into the markets (Weaver 2004). California residential electricity is not tied to demand, so there is no incentive to reduce power consumption during peak hours. They continued to consume power at high rates, which resulted in numerous blackouts now known as the California Energy Crisis. Enron profited enormously by reducing the supply of its product.

OPEC has frequently generated similar market responses through reduction in production levels during times of high prices (Kaufmann et al. 2004). This situation can occur in any market where a supplier or suppliers can cooperate to control a significant portion of the market. By controlling the amount of resource available through a market, suppliers can fix the price.

We are interested in exploring ways to mitigate the consequences of disruptions. Are there policies that people could enact to dampen the perturbation caused by scarcity?

3.2 Dampening Perturbations

Buffer capacity is an excellent method for dampening perturbations. By increasing the level of stored input resource agents create a larger buffer against supply shocks. When a perturbation occurs, agents can wait out price spikes for a longer time by living off their input stores.

The graphs below illustrate the response to a disruption for agents holding different levels of input resources. By tripling the buffer size, the magnitude of the perturbation is reduced, along with the following oscillations. The perturbation duration is lengthened, but the perturbed agent's net health gain is significantly less when the buffer is larger.

For these simulations, the size of the perturbation has been kept consistent in absolute terms and not as a percentage: the total amount removed from the system is the same for both scenarios in Figure 6.

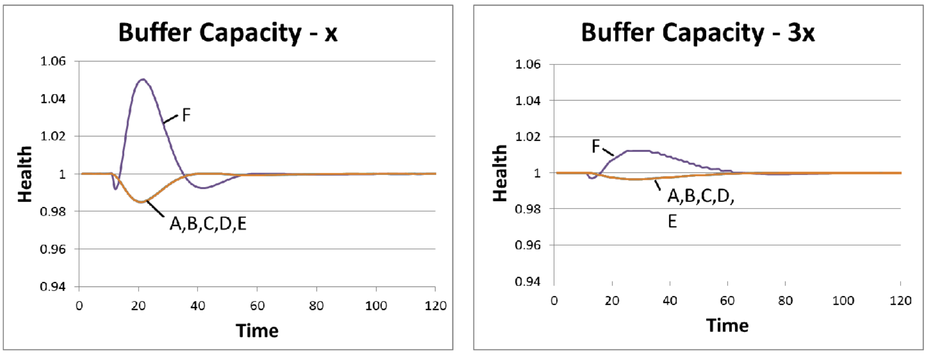

Fig. 6. Illustrating the effect of tripling the buffer size in every agent. The perturbation magnitude is greatly reduced.

What are the implications of this result? Our model suggests that perturbations can be dampened with larger input stores, allowing consumers to be less reactive to price spikes. It is unclear if this would work on a psychological level, since consumers might still behave irrationally and panic during price spikes. For example, before predicted natural disasters, long lines of cars often form at gas stations in anticipation of scarcity in the future.

If cars were made with gas tanks that are double the current size, gas prices might be less volatile. Creating more buffers on the scale of the national Strategic Petroleum Reserve could mitigate perturbations in the US domestic oil market. Of course, expanded resource storage works most effectively when storage costs are negligible and there is no product decay, as for oil and grains. Otherwise, consumers would be paying a premium to maintain above nominal stores, offsetting the savings from a reduced price spike. .

The manufacturing sector has largely decided that the cost of storage isn't worth the protection it offers. The popularity of just-in-time (JIT) manufacturing, lean six sigma, and the Toyota manufacturing system illustrate a sector-wide movement towards less inventory. The challenge is to accurately predict disruptions and risk in order to use these inventory-reducing strategies. Despite the carefully crafted predictions, many companies structured for JIT-like operations experienced huge losses following the September 11 2001 terrorist attacks, coming within hours of shutting down their production lines due to supply disruptions because they considered the probability of certain events to be unlikely ("Terror" 2001). Although JIT focuses on many aspects of production, September 11th prompted many manufactures to double their in-house inventory, despite the increased cost (Martha 2002; Lee and Hancock 2005).

3.3 Quantifying Returns

We are interested in understanding how effective a given increase in buffer capacity is at dampening the perturbation response. At some point, the benefit of additional inventory will be offset by the cost of adding additional storage.

We measure overall benefit by integrating the change in health from the nominal level of one over the simulation. The graphs in Figure 7 illustrate that the largest benefit comes from the first increase, with diminishing returns after that. It would be important to analyze where on this curve a product falls before implementing a policy.

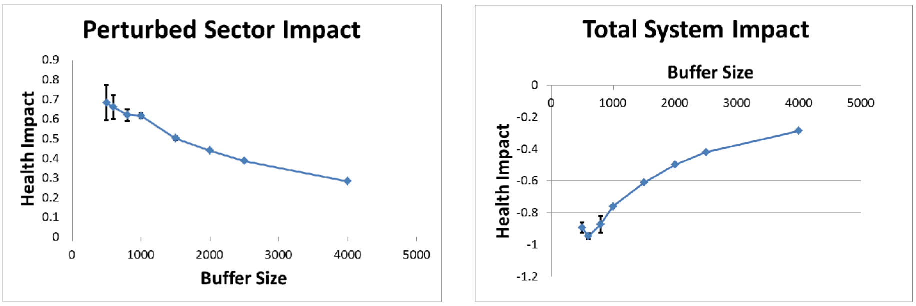

Fig. 7. Perturbed sector impacts. As the buffer size is increased, the perturbed sector's total health gain goes down, while the system total impact goes up. Error bars are the estimated standard deviation derived from 3 model runs.

The net system impact graph is particularly interesting to consider for policy applications. We find that the reduction in the net system impact is larger than the perturbed sector's reduction in profit. This is not a zero sum game. The system as a whole does better when the price spike is reduced.

The system improvement results from consumption processes becoming less efficient when the model is not at equilibrium. If a large price spike occurs, a large shortage of resources causes agents to substitute goods. Diminishing returns due to the substitution causes agents to operate less efficiently the more the price spikes.

In the real world, the inefficiency can be understood as agents paying premiums for inefficient service. For example, when you pay for a package's overnight delivery, the additional cost is spent on the airplane that rushes the box to your city. If the more efficient ground delivery system delivered your package, it would cost less but take more time. The consumer is paying a premium for time, which could add value if the package is holding up the production line, but if the overnight delivery is unnecessarily due to panic then the premium for express delivery is lost. In the model, we see something similar. The price spike causes consumption and production values to get pushed into inefficient regimens, resulting in value leaving the system.

The system level impact is greatly reduced when storage is implemented. Since the benefit is global, or to the entire system, it makes sense that the cost could be global as well. The policy maker would have an incentive to subsidize storage, since it decreases the net loss of the system. Regulating the model can create a more robust network.

3.4 Limitations

In the real world, additional storage comes at some cost. For some resources most of this cost comes in at the beginning as fixed capital costs. If a 100 barrel tank is built, there is an enormous cost to store the first barrel, but the next 99 are essentially free. Therefore, the cost of storage could be implemented as a step function with rising costs for the capacity of storage. Some resources incur additional marginal storage costs such as refrigeration or security. This could be implemented as a constant cost.

Also, most goods have some decay rate. Milk, grain, and gasoline all go bad over time. This is an additional feature we would like to implement into the model.

The hierarchical structure of this model allows us to generalize the buffer capacity solution to many scales. For example, the Strategic Petroleum Reserve is a buffer tank on a national level, and storage can be just as effective for a mid-level distributor or a consumer. The storage will reduce the price reactivity on whatever scale it is applied to.

4 Conclusion

In this paper, we modeled a group of interacting economic agents using an agent-based model. We showed how a perturbation or a reduction in supply can cause a monopoly to have a net profit due to price increases resulting from resource scarcity. Then, we showed how increasing the input buffer of the agents reduces the monopoly's ability to profit from a perturbation or reduction in supply.

We find that, in the case of a fully-connected network, the total system benefits from increasing the buffer capacity of the agents. Increasing the buffer size decreases the reactivity of prices and prevents the agents from entering inefficient regimes of consumption.

Our model does not consider storage costs or decay, but we would like to study these aspects in the future. There is a strong incentive for agents to price fix in the real world, because large profits can be made. This work suggests actions that can be taken by agents, sectors, or governments to mitigate the manipulation of markets by monopolies.

References

1. Bergenstock, D. J., Maskulka, J.M.: The De Beers story. Are diamonds forever? Business Horizons 44(3), 37–44. (2001).
2. Beyeler, W.E., Glass, R.J., Finley, P.D., Brown, T.J., Norton, M.D., Bauer, M., Mitchell, M., Hobbs, J.A.: Modeling systems of interacting specialists. 8TH International Conference on Complex Systems. (2011)
3. Buzacott, J.A: Automatic Transfer Lines with Buffer Stocks. International Journal of Production Research 5 (3), 183-200.
4. Cabral, L.M.B., Salant, D.J., Woroch, G.A.: Monopoly Pricing with Network Externalities. International Journal of Industrial Organization. 17, 199-214. (1999)
5. Choi, T.Y., Dooley, K.J., Rungtesanantham, M.: Supply Networks and Complex Adaptive Systems: Control Versus Emergence. Journal of Operations Management. 351-366. (2001)

6. Cochran, J.K., Kokangul, A., Khaniyev, T.A.: Stochastic approximations for optimal Buffer Capacity of Many-Station Production Lines. International Journal of Mathematics in Operational Research. Vol. 1, No. ½, 211-227.
7. Griffin, J. M., Vielhaber, L.M.: OPEC Production: The Missing Link. Energy Journal 115-132. (1994)
8. Harrington, J.E.: Optimal Cartel Pricing in the Presence of an Antitrust Authority. International Economic Review. Vol. 46, No. 1, (2005)
9. Holland, J.H., Miller, J.H.: Artificial Adaptive Agents in Economic Theory. American Economic Review, Papers and Proceedings 81:365-370. (1991)
10. Kaufmann, R.K., Dees, S., Karadeloglou, P., Sanchez, M.: Does OPEC Matter? An Econometric Analysis of Oil Prices. *The Energy Journal*, vol. 25, no. 4, pp. 67-90. (2004)
11. Kuypers, M.A., Beyeler, W.E., Glass, R.J., Antognoli, M., Mitchell, M.: The impact of network structure on the perturbation dynamics of a multi-agent economic model. International Conference on Social Computing, Behavioral-Cultural Modeling, & Prediction. (2012)
12. Labaton, S.: De Beers Agrees to Guilty Plea to Re-enter the U.S. Market. The New York Times. July 10, (2004)
13. Lee, S.M., Hancock, M.E.: 'Disruption in Supply Chain Due to September 11, 2001', Decision Line March, pp. 8–11.(2005)
14. MacFadyen, A.J.: OPEC and cheating: Revisiting the kinked demand curve. Energy Policy, August, 858-867.(1993)
15. Martha, J.: Just-in-case operations, Warehousing Forum 17 (2) (2002)
16. Sequeira, R.I., Valdes, J.E., Berenguer, C.: Optimal Buffer Inventory and Opportunistic Preventive Maintenance Under Random Production Capacity Availability. Int. J. Production Economics. 686-696. (2008)
17. Shi, C., Gershqin, S.B.: An Efficient Buffer Design Algorithm for Production Line Profit Maximization. Int. J. Production Economics. 725-740. (2009)
18. Terror Attacks Stall Industry,' Ward's AutoWorld, 1 October 2001: ⟨http://wardsautoworld.com/ar/auto_terror_attacks_stall/⟩.
19. Weaver, J.L.: Can Energy Markets be Trusted? The Effect of the Rise and Fall of Enron on Energy Markets. Houston Business and Tax Law Journal. Pages 69-72. (2004)
20. Weaver, J.L.: Can Energy Markets be Trusted? The Effect of the Rise and Fall of Enron on Energy Markets. Houston Business and Tax Law Journal. (2004)
21. White, L. J.: Lysine and Price Fixing: How Long? How Severe? Review of Industrial Organization, 18(1), pp. 23-31. (2001)
22. Wycisk, C., McKelvey, B., Hulsmann, M.: "Smart Parts" Supply Networks as Complex Adaptive Systems: Analysis and Implications. International Journal of Physical Distribution and Logistics Managements. Vol. 38, No. 2, (2008)