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When Do Minor Shortages Inflate To Great Bubbles?

Paulo Gonçalves

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Abstract:
When demand exceeds supply, retailers hedge against shortages by placing multiple orders with multiple suppliers. This artificial growth in orders can severely affect suppliers, creating excess capacity, excess inventory, low capacity utilization, financial and reputation losses. This paper contributes to the understanding of order amplification caused by shortages, by providing a comprehensive causal map of the supplier-retailer relationships and a formal mathematical model of a subset of relationships. It provides closed form solutions to the dynamics of supplier backlogs when supplier capacity is fixed and simulation analysis when it is flexible. Parameter sensitivity provides a deeper understanding of long-term impacts and suggests emphasis for solution policies. For instance, the ability to quickly build capacity can effectively reduce the bubble size. Finally, the time it takes retailers to perceive supplier's delivery delay is an important leverage in controlling retailers' inflationary ordering. In particular, longer retailers' perception delays contribute to system stability.

Keywords:
System dynamics, supply chain, order amplification, supply shortages, simulation.

System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology
30 Wadsworth St., E53-358A
Cambridge, MA 02142
Phone 617-258-5585
Fax: 617-258-7579
paulog@mit.edu

1. Motivation

Supply shortages constitute a common and recurring supply chain problem, impacting industries ranging from personal computers to pharmaceuticals. Shortages often take place in industries characterized by costly capacity and long acquisition delays (Cachon and Lariviere 1999) or during the introduction of new products, when demand is uncertain, and new processes, when production yield is uncertain (Lee et al. 1997a). Shortages often lead to lower corporate growth (Savage 1999) and loss of shareholder value (Singhal and Hendricks 2002). In addition, they can lead to excess production capacity and inventories, as the example from the semiconductor industry shows (Baljko 1999, Greek 2000).

During a 1995 shortage of microprocessors, suppliers like Intel and AMD had to allocate production capacity among several retailers such as Dell, Compaq, HP, and several others. To improve their chances of supply, retailers placed multiple orders with suppliers. Since suppliers could not differentiate between true demand and retailer-created demand, they easily mistook retailers' speculative orders for an increase in demand. Hence, suppliers responded by increasing safety stock of raw materials and components, speeding up production, adopting overtime policies, and building additional production capacity. However, as production capacity increased allowing suppliers to meet demand, the retailers' need to hedge against supply shortages disappeared and so did their speculative orders. The artificial *bubble* in demand quickly burst leaving manufacturers with huge inventories, reduced prices and unwanted excess capacity.

Sadly, order cancellations (and products returns) are common practice in several industries. Hence, examples of inflated demand generated by product shortages are abundant. For instance, orders for DRAM chips in the 1980's went through a similar process (Lode 1992). Hewlett-Packard lost millions of dollars in unnecessary capacity and excess inventory after a demand surge for its LaserJet printers (Lee et al. 1997b). Facing shortages of Pentium III processors in November 1999, Intel planned to introduce a new production plant early 2000 (Foremski 1999). Later that year, blaming order cancellations by large customers and economic slowdowns, Intel warned that its revenues would fall short of projections and that sales would be flat for the quarter (Gaither 2001). More recently, Cisco Systems lost over US$ 2.5 billion in inventory write-offs due to inflated retailer orders for their products (Adelman 2001).

While the immediate consequences of shortages are clearly identified in the literature, some of the long-term impacts and the mechanisms leading to them are not well understood. This research investigates the impact that retailers' locally rational decisions may have in reinforcing the initial shortage dynamics, leading to more dramatic and long lasting impacts to supply chain performance. The research follows a system dynamics methodology to study this problem and to investigate policies capable of mitigating its impacts. The aim is to inform both academics and practitioners dealing with demand bubbles generated by shortages

My analysis suggests that a *transient* shortage in supply can *permanently* drive the supplier to a low performance equilibrium, in which backlogs and delivery delays are high, when she cannot increase capacity to meet retailers' needs. In addition, supplier's ability to bring capacity online can help reduce the impact of shortage. However, she still goes through a transient period of low performance, as it takes time to bring new capacity online. When the additional capacity becomes available and retailers start receiving their orders, the bubble bursts. The burst is characterized by a period of order cancellations followed by a period of reduced demand, while retailers are depleting their excess inventories – an inverse bubble when orders are much lower than they would traditionally be. As the bubble bursts, suppliers are left with excess inventories and capacity greatly exceeding the amount of product in short supply. Furthermore, the *faster* the supplier can add new capacity the *lower* the impacts of the bubble, that is, it will require *less* capacity, it will face a *shorter* period of low performance with *lower* backlogs and *shorter* delivery delays. Hence, the ability to quickly bring capacity online helps suppliers prevent the growth in the bubble. However, capacity flexibility alone may not be a sustainable way to prevent demand bubbles, since it is costly and suppliers are still left with excess capacity. As it turns out, the perception of shortages will depend both on supply and demand, hence acting on both aspects can have more effective results. For instance, the size of the bubble is also greatly influenced by the amount of competition in the industry, hence the *fiercer* the competition among retailers the *greater* the bubble in retailers' orders. To avoid the impact of competition, suppliers may choose to give priority to preferred retailers or to limit the number of retailers that they will work with.

Moreover, my analysis suggests that an important leverage point in the system is the time delay it takes retailers to perceive the supplier' delivery delays. When the supplier provides real-time information about delivery delays to retailers the system is highly unstable. This takes place because retailers react instantaneously to the readily available information. So, if retailers see an increasing delivery delay they will respond rapidly and will inflate their orders to hedge against shortages only making the situation worst. In contrast, when the supplier provides information about delivery delays with a long time delay to retailers the system is more stable, because it will take time before retailers over-react, giving the supplier an opportunity to act – speeding up production, increasing overtime, increasing safety stocks of raw material and components – to reduce delivery delays. Interestingly, the idea of suppliers providing delayed information about delivery delays and inventory availability goes in direct opposition to current industry trend to introduce information systems providing real-time information to all parties in the supply chain. Unfortunately, these real-time information systems may be introducing a great deal of instability leading to the creation of larger than ever demand bubbles. While companies claim to have saved millions of dollars in purchasing and ordering operations, the costs associated with over-ordering may far exceed the savings generated from the accurate processing of orders.

This paper proceeds as follows. The next section provides an overview of the relevant academic literature. Section 3 describes the phenomenon and discusses its dynamics. Section 4 presents a formal model followed by results and analyses in section 5. I conclude the paper with a discussion about insights and areas for further research.

2. Literature Review

There is an extensive system dynamics and operations management literature addressing inventory instability in supply chains. The first formal system dynamics model on inventory oscillations date back more than 40 years ago and coincide with the emergence of the field of system dynamics (Forrester 1958, 1961). Forrester suggested that the oscillatory behavior in demand was caused by the structure (including the feedback nature) of the system. Around 1958, Willard Fey converted this early supply chain work into a game, which subsequently evolved into the famous beer game. Subsequent system dynamics research focused on investigating oscillations in different supply chain settings. For instance, Mass (1975) considered the interrelationship of inventory oscillations and its impacts on a company’s labor force. Morecroft (1980) investigated the implementation of Material Requirements Planning (MRP) systems on a company’s supply chain and showed that the faster response time could increase the frequency and amplitude of inventory oscillations.

Departing from the modeling work in supply chains and motivated by research on bounded rationality and experimental economics, researchers in system dynamics focused their attention on experimental research. In the context of supply chains, system dynamicists have focused on characterizing how managers make decisions and investigating whether such actions can generate pathological dynamics. For instance, Sterman (1989a, 1989b) conducted human-subject experiments in a four stage supply chain setting to demonstrate that the sources of oscillation and increase in variability were managers' misperceptions of feedback and their inability to account for the supply line of orders. Diehl and Sterman (1995) continued this work to consider how feedback complexity, in a two-echelon supply chain, affected decision-making.

In sharp contrast to this behavioral explanation of supply chain instability, the operations management literature offers a number of operational explanations. For instance, Lee et al. (1997a, 1997b) suggest that rational agents are able to generate demand variability through four operational causes: demand signal processing, rationing (supply shortages), order processing, and price variations. Chen et al. (2000) verify that the bullwhip effect takes place because of two operational causes: a specific demand forecasting technique and order lead times. While the dispute among researchers defending operational or behavioral causes of supply chain instability is far from over, a recent article by Croson and Donohue (2000) suggests that the bullwhip effect still exists in the absence of three (e.g. price fluctuations, order batching and demand estimation) out of the four normal operational causes offered by Lee et al. (1997a, 1997b). Their study does not control for product shortages, which is the emphasis of this paper.

Papers addressing supply shortages emphasize two aspects of them: the games that take place among different agents and the impact that the product allocation mechanism has on retailers' demand variability. For instance, Lee et al. (1997a) develop a single period game theory model with rational agents to show that strategic behavior among retailers, leading to demand inflation, can take place when the supplier allocates insufficient capacity in proportion to retailer orders. The supplier in their model has imperfect information since she cannot distinguish true demand (customers' orders) from those inflated by retailers. The authors suggest that capacity allocation in proportion to past sales (turn–and–earn) can mitigate this problem, but they do not model this case. Cachon and Lariviere (1999a) examine how a turn–and–earn allocation mechanism impacts retailer behavior and supply chain performance, showing that it allows suppliers to improve profits at the expense of retailers' and even the supply chain performance. Cachon and Lariviere (1999b) explore the impact of other allocation mechanisms and the supplier's decision to build capacity. They build a sequential game theory model where suppliers choose the allocation scheme, retailers place their orders and then suppliers decide on how much capacity to build. Their findings suggest that no truth-inducing allocation mechanism can maximize retailer profits, and attempts to implement such a mechanism may result in lower profits for all (supplier, retailers, and the supply chain).

While previous research on demand variability provides a rich context for the impact of shortages, the emphasis on game theory requires equilibrium and supply chain assumptions that may not be realistic in real supply chains. This papers expands on this research by investigating out-of-equilibrium dynamics and more realistic production physics, such as: (a) capacity constraints that may take place due to long capacity acquisition delays; (b) endogenous and variable delivery delays, due to changing order backlog and supplier capacity; and (c) perception and adjustment delays, rather than instantaneous access to information and immediate adjustment to desired levels. Finally, previous research explores policies that are limited in nature to address different allocation mechanisms. I propose to investigate a broader set of policies, under a proportional allocation mechanism, and the impact of different parameters in mitigating the amplification in orders.

3. Dynamic Hypotheses

In a decentralized chain with a single supplier and multiple retailers (Figure 1), I hypothesize that retailers' managers inflate orders when insufficient supply is allocated in proportion to retailers' orders. This takes place in the following way: Under supply shortage, suppliers will have long delivery delays and high delivery uncertainty. Consider retailers' reactions to a long delivery delay. First, they will adjust the increase in the delivery delay by *ordering ahead* of their needs. If they keep a supply line of 2 weeks of inventory to meet expected sales for a product with 2 weeks delivery delay, once the delivery delay increases to 4 weeks retailers will adjust the supply line accordingly. Retailers will order twice as much to maintain the same supply line. By ordering ahead retailers increase even further the backlog of orders, resulting in an even higher delivery delay. Another consequence of longer lead times is retailers' desire to build up of safety stocks – *correcting inventory to lead times* –, since a larger inventory buffer would prevent retailers from running out of stock due to longer lead times.

However, retailers must place more orders to build up safety stocks, which increases the supplier's order backlogs and makes future lead times even longer. Figure 2 shows the reinforcing loops (R1) *Order Ahead* and (R2) *Correct Inventory to Lead Time*.

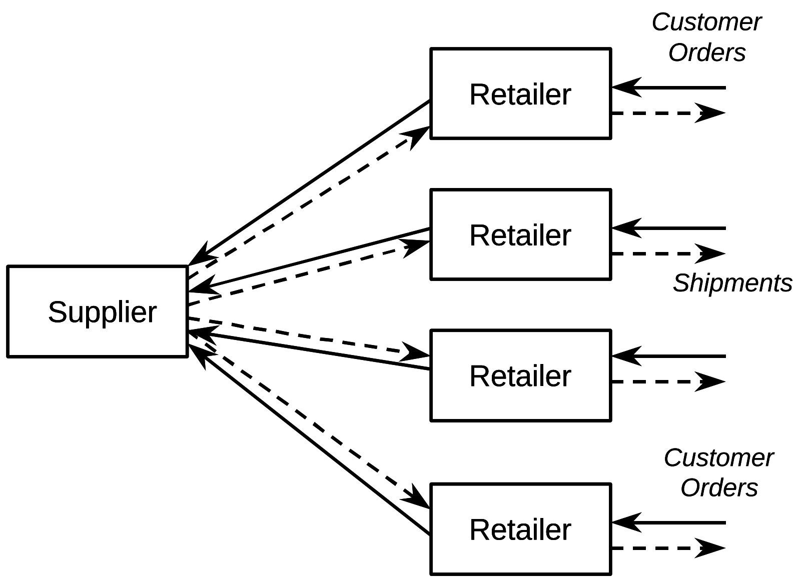

Figure 1. Supply chain structure

Now, consider the retailers' reactions to receiving only a fraction of their orders. As shipments fall short of retailers' orders, retailers' perception of suppliers' delivery reliability drops. Retailers adjust to this reduction in reliability by ordering more than necessary. Since they expect to receive just a fraction of their total orders, retailers inflate orders – *ordering defensively* – in hopes of getting just what they need. So, if retailers have been receiving half of their orders when the supplier allocates capacity in proportion to his orders, they double their orders hoping to get the quantity desired. By ordering defensively retailers increase supplier's backlog of orders even further, resulting in an even more restrictive allocation policy. Furthermore, retailers increase their safety stocks in response to reduced delivery reliability – *correcting inventory to delivery reliability*. But to increase their safety stocks retailers must place even higher orders building up supplier's backlog of orders even further. This results in an even tighter allocation policy and a further decrease in delivery reliability. Figure 2 shows the reinforcing loops (R3) *Order Defensively* and (R4) *Correct Inventory to Delivery Reliability*.

The supplier can expand capacity to balance the effect of the reinforcing loops in the system – *Adjust Capacity* – loop (B2). Interestingly, as supply becomes available the reinforcing loops begin to act in a virtuous way. As backlog decreases and delivery delay falls, retailers have no need to order ahead or to maintain large safety stocks. Hence, they reduce their supply line and their desired inventory levels accordingly. This leads to a decrease in orders and a further drop in supplier's backlog level. Analogously, as backlog drops delivery reliability improves and retailers stop ordering defensively, leading to further decreases in backlogs. Once the supply becomes available, orders disappear quickly by virtue of the same reinforcing loops that caused them to increase in the first place.

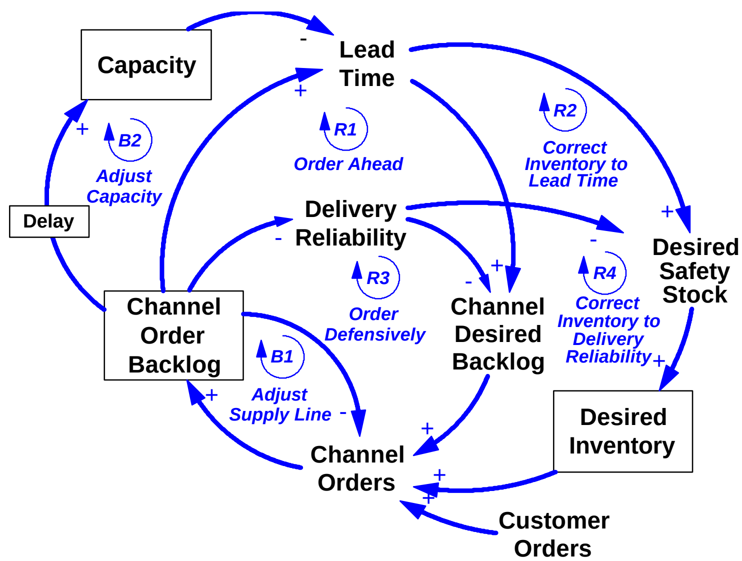

Figure 2. Dynamic hypothesis for demand bubble problem

From the description above, it appears that the characteristic behavior of demand bubbles would be represented by an overshoot-and-collapse in orders due to retailers' response to a supply shortage. During the initial shortage period, retailers' over-reaction inflates the bubble through over-ordering. Then as supply normalizes, the bubble bursts due to retailers' over-reaction in canceling outstanding orders. Moreover, since shortages occur frequently due to costly capacity, long capacity acquisition delays, uncertain demand for new products, and uncertain production yields for new processes we can expect to see repeated cycles of sharp overshoot-and-collapse in orders typical of demand bubbles. In addition, since demand bubbles occur during supply shortages, demand bubbles do not take place in a predictable fashion. In that sense, understanding why and when shortages take place can be very helpful in mitigating their impacts.

Finally, to gain a deeper understanding of the processes generating the bubbles and to investigate policies that can effectively mitigate their impact I build a formal mathematical model of the relationships discussed above.

4. The Model

The model emphasizes the internal causes of system behavior. In particular, the focus of is on retailers' endogenous reactions to supply shortages and the positive loops reinforcing such actions to create bubbles in demand. While exogenous shocks can influence system behavior, they provide little policy leverage to managers, since their causes lie beyond their control. The model presented here includes only one of the possible retailers' reinforcing loops: the Ordering Ahead (R1) loop. While this provides a limited view of the problem complexity, if by itself it is capable of generating the demand bubble phenomenon, it can be useful in guiding the derivation of insights. In addition, if included, other reinforcing loops would only make the problem more pronounced. For the sake of simplicity, I consider the relationship of a single supplier selling a single product to multiple retailers.

The supplier's backlog of orders (*B(t)*) increases by retailer demand (*R(t)*) and decreases by shipments (*S(t)*) and cancellations (*C(t)*), according to the differential equation 1. Retailer demand has two terms: a true customer demand (*d(t)*) and a backlog adjustment term (*AdjB*). The first term is the real demand retailers observe. The second term is the adjustment between the channel desired backlog (*B*(t)*) and suppliers' actual backlog. This term allows the supplier to adjust her backlog over an adjustment time (t_B) if she observes an increasing desire for her products. Equation 2 shows retailer demand. In addition, the desired channel backlog is a function (*f*) of delivery delays, which is given by the ratio of backlog to shipments. The function of delivery delay represents retailers' response to supplier's ability to fill demand.

$$\dot{B}(t) = R(t) - S(t) - C(t) \tag{1}$$

$$R(t) = d(t) + \frac{B^*(t) - B(t)}{t_B} \tag{2}$$

Consider now the flows of shipments and cancellations. The minimum of desired shipment rate (*S*(t)*) and available capacity (*K(t)*) determine the amount of shipments (*S(t)*). That is, shipments will normally be determined by the desired shipment rate unless there is not sufficient capacity. Also, the desired shipment rate depends on the ratio of backlog and the target delivery delay (t_D), as shown in equation 3. Cancellations depend on the difference between total orders received by retailers (S_r) and total customer orders (D_c). If there are more retailers' orders than customer orders then retailers will cancel the excess in the time to cancel orders (t_C). If there are less retailers' orders than customer orders there are no cancellations (eq-4).

$$S = MIN(B/t_D, K) \tag{3}$$

$$C = MAX(0, D_c - S_r / t_C) \tag{4}$$

The supplier's capacity ($K(t)$) is a smooth of retailer demand (eq-5), with a time constant given by the time to build capacity (t_K). Moreover, the amount of total orders received by retailers (S_r) accumulates supplier's shipments to retailers (eq-6) and total customer orders (D_c) simply accumulates true customer demand (eq-7)

$$\dot{K}(t) = \frac{R(t) - K(t)}{t_K} \tag{5}$$

$$\dot{S}_r = K \tag{6}$$

$$\dot{D}_c = d \tag{7}$$

An additional simplifying assumption allows the supplier to maintain a fixed market share over time. While prolonged poor reliability will, in general, lead to loss of market share, there are instances when suppliers can retain their market share despite poor performance. This is often the case when the companies have patented products or their industries have huge barriers to entry.

To represent retailers, I aggregate them into a single retailer. This assumes homogeneity among different retailers, that is, that they will influence model behavior in the same way due to shortages. This assumption does not hold in general since retailers have different size, negotiating power, inventory policies, etc. however, retailer heterogeneity has little impact on retailers' reactions to delivery delays. When delivery delay is larger than desired, retailers inflate their orders. While each retailer will inflate by different amounts the model provides an estimate of the average inflation by all retailers. Hence, the assumption of retailer homogeneity does not impact the model dynamics. Furthermore, I assume that retailers can cancel orders without incurring any penalties. This holds true in many industries such as semiconductors, networking equipment, electronics, agribusiness, and several others.

A function (*f*) captures retailers' locally rational behavior of placing speculative orders when the delivery delays increase above normal. In particular, when faced with long delivery delays retailers order ahead, that is, they increase their expected delay above the delivery delay quoted by the supplier. Increasing their expected delay is intendedly rational to retailers, since they believe that the supplier will try to avoid loosing sales at all costs, even by giving a delivery delay quote that is more optimistic that what it really is. The retailer's bias can be captured in a number of different ways. In the simplest case, I assume a retailer's bias proportional to the actual delivery delay quoted by the supplier, that is, that retailers will adjust their expected delay more for longer delivery delay quotes. [1] Hence the retailers' response to delivery delays can be captured by a linear function of delivery delay with a slope of α ($f = \alpha\ B/K$, where $\alpha > 1$).[2] This function embeds the assumption that supplier shipments will be proportionately distributed among retailers. The business press provides ample anecdotal evidence for retailer's speculative ordering behavior under proportional allocation (Greek 2000). Academic research also supports this assumption. Using a game theory model, Lee et al. (1997a) show that retailers behave strategically, inflating orders, when a supplier allocates capacity in proportion to orders. Hence, in aggregate, retailers' action to inflate orders is intendedly rational.

It is rational for retailers to place more orders than necessary because the more they order, under a proportional allocation mechanism, the more product they are likely to receive. Moreover, by over-ordering retailers avoid the psychologically difficult possibility of being left without supply. Furthermore, often in industries plagued by such retailer behavior the costs associated with over-ordering (penalties for cancellations and returns – if they exist) are much smaller than the costs associated with under-ordering (unsatisfied customers, unrealized sales and potential loss in market share). All such aspects provide an additional incentive for retailers' strategic behavior. Finally, retailers will cancel orders once the total amount of products received from suppliers surpasses the total demand from customers as shown in equation 4.

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[1] I also assume that when delivery delays are lower than the target, retailers simply adjust their ordering without a bias.

[2] The linear function capturing the proportional bias of retailers is useful to obtain a closed form solution to the problem when the supplier does not invest in new capacity. When the supplier has fixed capacity shipments are bounded by available capacity and hence delivery delays are determined by the ratio of backlog and capacity. In the more general case, used throughout the simulations including the case for variable capacity, the function (*f*) is a non-linear function that captures a stronger adjustment as delivery delays increase but saturates for delivery delays of 6 months and higher.

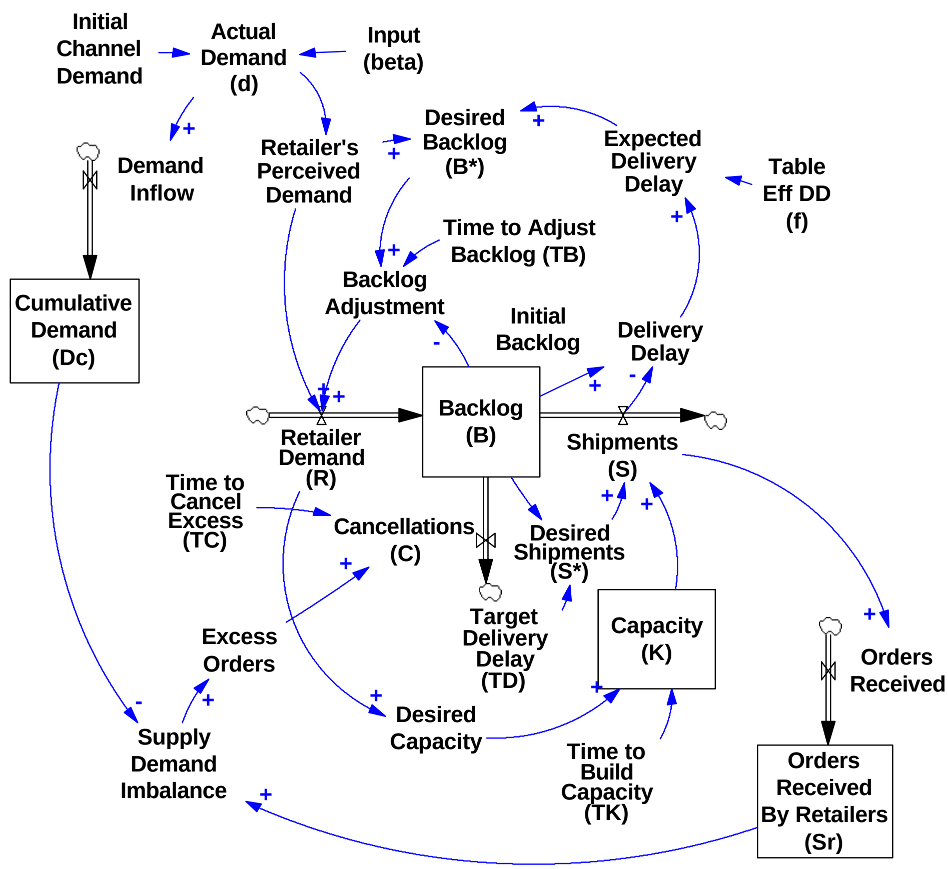

Figure 3. Model diagram for supplier-retailer system

Now consider the supplier's actions. One possibility is to assume that the supplier does not respond strategically to retailers' order inflation, that is, the supplier is oblivious to retailers' actions despite order cancellations and product returns. This does not seem plausible. Alternatively, it is possible to assume that over time the supplier learns to discount retailers' orders when delivery delays are high. Consider the outcome. When the supplier discounts the orders received she intensifies the product rationing perceived by retailers, resulting in even more inflated orders. Again, the supplier knows better than to believe in the retailer so she discounts part of the orders and sends whatever she believes appropriate. The problem is that the supplier does not know true customer demand, making it difficult for her to assess how much to discount. Consequently, retailers will always have an advantage in their ability to order more to compensate for supplier's actions. So, even when suppliers are compensating for (discounting) retailers' orders it is plausible to assume that order inflation will prevail. Instead of explicitly representing the supplier's discounting of retailers orders, it is possible to interpret the shape of the linear function[3] as the *net result* of retailers' and supplier's actions.

In terms of the supplier's operations, she adjusts her backlog level according to the desired channel backlog and she attempts to fill orders to maintain a desired target delivery delay. Capacity constraints, however, can limit the supplier's ability to ship, causing delivery delays to increase. Finally, the supplier can expand capacity as she perceives demand to increase. Figure 3 shows the system dynamics model described above. And the set of differential equations (8-11) below represent a fourth order system of first order differential equations when the supplier is capacity constrained and there are no order cancellations.

$$\dot{D}_c = d \tag{8}$$

$$\dot{S}_r = K \tag{9}$$

$$\dot{K} = \frac{d}{t_K} + \frac{d \cdot f(B/K) - B}{t_B \cdot t_K} - \frac{K}{t_K} \tag{10}$$

$$\dot{B} = d + \frac{d \cdot f(B/K) - B}{t_B} - K \tag{11}$$

5. Model Analysis

This section investigates the behavior of the model in greater detail. First, it provides a closed form solution to the model when the supplier has fixed capacity. Then, it considers model behavior when supplier has flexibility to change capacity. Since the model complexity increases significantly insights in this case is derived from simulation. Finally, the last section provides sensitivity analysis to explore the impact of important parameters on model behavior.

5.1. Fixed Capacity

First I investigate the model behavior when the supplier does not introduce new capacity. I implement this by setting the time to build capacity (*TK*) to an extremely high value. This has the equivalent effect of breaking the feedback link from supplier demand to available capacity. I simulate the model for five years with a transient increase and subsequent transient decrease in true customer demand, using actual (customer) demand as the input to test model behavior. I start the model in steady state equilibrium. (In the absence of any changes in demand the model

[3] And the non-linear table function in the case of flexible capacity.

behavior remains the same.) Then, I introduce an input composed of a 10% temporary increase (a pulse starting at t = 6, lasting for 6 months) followed by a 10% temporary decrease (a pulse starting at t = 12, lasting for 6 months) in demand (Figure 4). This is equivalent to a period of supply shortage followed by a period of excess supply.

$$d = \begin{cases} (1+b)\cdot K, \ if \ t_0 \le t < t_1 \\ (1-b)\cdot K, \ if \ t_1 \le t < t_2 \\ K, \ if \ t_2 \le t < T \end{cases} \tag{12}$$

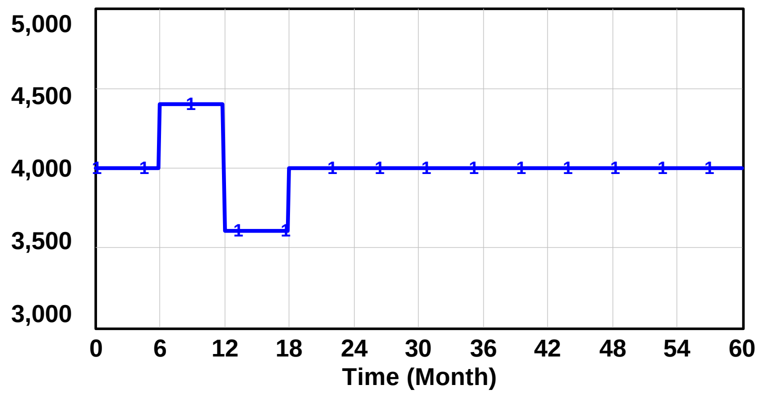

Figure 4. A transient increase and decrease in customer demand

Since the increase and decrease in demand have the same magnitude and duration, any changes in model behavior capture retailers' response to relative shortages in supply. That is, if retailers would not over-react to during the supply shortage period, then the period of excess capacity would be exactly sufficient to bring the system back to equilibrium. During the high demand period retailers never receive all orders placed. However, during the low demand period suppliers have a chance to meet the excess demand from the previous period exactly due to the symmetry of the test. Since suppliers will never ship more products than real customer demand, when capacity is fixed and limited, retailers never have a reason to cancel orders. Hence, the fourth order system characterized by equations (8-11) can be reduced to a first order system. Since cancellations do not take place information about total customer orders (D_c) and orders received by retailers (S_r) in equations (8-9) does not impact the state of the supplier's backlog or retailer's response. Hence we can ignore equations 8-9. And since capacity is fixed equation 10 reduces to a constant. The system is reduced to equation 11, where it is possible to consider a linear function ($f = \alpha B/K$, where the slope $\alpha > 1$) for retailers' response to delivery delays. This captures a retailers' bias proportional to the actual delivery delay – the higher the delivery delay the higher retailers' expected delivery delay.[4] Hence, the resulting system is given by equation 13.

$$\dot{B} = d + \frac{d \cdot a \cdot B / K - B}{t_B} - K \tag{13}$$

Now, let $g = \frac{d \cdot a / K - 1}{t_B}$ and let $j = d - K$ then substituting 12 into 13 it is possible to write:

$$\dot{B} - gB = j \tag{14}$$

where: $g = \begin{cases} (a-1)+ab \big/ t_B, & if\ t_0 \le t < t_1 \\ (a-1)-ab \big/ t_B, & if\ t_1 \le t < t_2 \\ (a-1) \big/ t_B, & if\ t_2 \le t < T \end{cases}$ and $j = d - K = \begin{cases} b \cdot K, & if\ t_0 \le t < t_1 \\ -b \cdot K, & if\ t_1 \le t < t_2 \\ 0, & if\ t_2 \le t < T \end{cases}$

Note that the equilibrium for the model is given by $B = -j \big/ g$ and that γ represents the eigenvalues of the system. Hence, it is possible to describe the system stability for each region. Given that α > 1, we note that in the first region ($t_0 \le t < t_1$) the eigenvalue is real and positive resulting in an unstable system. Since the supplier's capacity is smaller than demand retailers inflate orders and backlog increases exponentially with a growth rate of $(a-1)+ab \big/ t_B$. In region two ($t_1 \le t < t_2$), when demand drops below the supplier capacity, the system is still unstable if $b < \frac{a-1}{a}$, that is, when the relative aggressiveness of retailers' responses ($a - 1 \big/ a$) is larger than the percentage increase in demand (b). Hence, very aggressive retailers will continue to increase their orders even when the system has excess capacity to meet customer demand. Moreover, when retailers are not aggressive, the system is stable and backlogs decrease exponentially to equilibrium with a rate of $(a-1)-ab \big/ t_B$. Note that for α > 1, the rate of growth in period one strictly higher than the rate of decline in period two. Hence the supplier backlog cannot return to the initial level after the period of excess supply. The difference between the initial backlog and the backlog level at the end of period two captures the impact of retailers' aggressiveness to the

[4] Under fixed capacity delivery delay never drops below one; hence, there is no need to worry about order deflation.

supplier. In the last period ($t_2 \le t < T$), the system is always unstable for $\alpha > 1$, since the eigenvalue γ is given by $(a-1)/t_B$. Note that when $\alpha = 1$, that is, when retailers order the exact amount to perfectly compensate for the delivery delay they experience (myopic retailers), the previous results change. First, the rate of growth (b/t_B) in the first period equals the rate of decline ($-b/t_B$) in the first period. Hence, backlogs can return to the initial equilibrium level when the magnitude and duration of excess demand is the same as the excess supply. Finally, when $\alpha = 1$, the eigenvalue in the last period ($t_2 \le t < T$) becomes zero ($\gamma = 0$), revealing that the system will remain in equilibrium. It is possible to write the equations for backlog over time, by finding the solution to the first order differential equation given by eq-14:

$$B = -\frac{j}{g} + C \cdot e^{g \cdot t} \tag{15}$$

And, when $t_0 = 0$, $e^{\gamma t} = 1$. So: $C = B_i + \frac{j}{g}$, where $i = 1, if\ t_0 < t < t_1; i = 2, if\ t_1 < t < t_2; i = 3, if\ t_2 < t < T$

$$B = (B_i + \frac{j_i}{g_i}) \cdot e^{g_i \cdot (t - t_i)} - \frac{j_i}{g_i}$$

$$B = \begin{cases} (B_0 + \dfrac{bKt_B}{(a-1)+ab}) \cdot e^{\left.(a-1)+ab\middle/t_B\right. \cdot (t-t_0)} - \left.bKt_B\middle/(a-1)+ab\right., \ if\ t_0 \le t < t_1 \\ (B_1 - \dfrac{bKt_B}{(a-1)-ab}) \cdot e^{\left.(a-1)-ab\middle/t_B\right. \cdot (t-t_1)} + \left.bKt_B\middle/(a-1)-ab\right., \ if\ t_1 \le t < t_2 \\ B_2 \cdot e^{\left.(a-1)\middle/t_B\right. \cdot (t-t_2)}, \ if\ t_2 \le t < T \end{cases} \tag{16}$$

To further describe the behavior of retailers we include a saturation effect for the maximum delivery delay *(M)* tolerated by retailers. This captures the idea that after a maximum delivery delay retailers will not invest their time to adjust their orders further and instead may look for alternative sources of supply.

$$\dot{B} + \frac{B}{t_B} = \frac{MK}{t_B}$$

$$B = (B_S - MK) \cdot e^{\left.-(t-t_S)\middle/t_B\right.} + MK$$

The equation for supplier backlog, when retailers tolerate a maximum delivery delay, is a goal seeking behavior leading to a final equilibrium value of *MK*. Now consider the range of possible retailers' reactions. As illustrated before reactions can range from the myopic to the very aggressive. A myopic retailer will adjust his orders exactly to compensate for the increase in delivery delay. In this case, the slope of the retailers' response to delivery delay function is one ($\alpha = 1$). An aggressive retailer will adjust orders by much more than the required compensation. The slope of the expected delivery delay function is more than one ($\alpha >> 1$) such that the relative aggressiveness of retailers' responses ($a - 1/a$) is higher than the percentage increase in demand (b). A "normal" retailer will still adjust orders by more than the required amount but the relative aggressiveness of retailers' responses is lower than the percentage increase in demand. As seen in the earlier derivation, even myopic retailers will order more during shortages to compensate for the supplier's inability to meet demand. However, as soon as demand lowers, retailers reduce their ordering accordingly until suppliers' backlogs return to equilibrium. Normal retailers, however, order more than necessary to compensate for the short supply and while backlogs decrease when there is excess supply, they never return to the equilibrium level. In addition, since delivery delays are above normal and retailers have a consistent bias to inflate orders, the system becomes unstable. With the introduction of the saturation, the system reaches a low performance equilibrium, where the delivery delay equals the saturation delivery delay (M) and the product of customer demand and the saturation delay (KM) determines the equilibrium level for the supplier's backlog. This situation is similar for aggressive retailers, with the exception that backlogs do not decline during the period of excess supply. Figure 5 shows the behavior of supplier backlogs, with the introduction of a saturation effect.

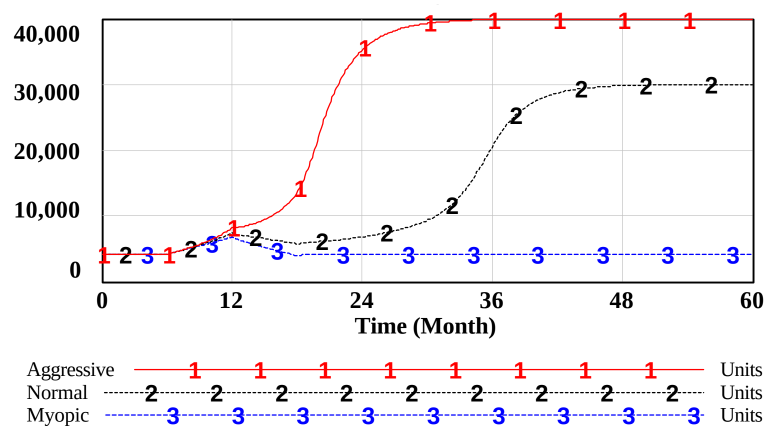

Figure 5. Supplier's backlog with saturation effects[5]

[5] Where the following parameter have been used: $b = 0.1$, $M_a = 10$, $M_n = 7.5$, $K = 4{,}000$, $a_a = 1.2$, $a_n = 1.05$.

Naturally, suppliers have a chance to invest in new capacity when they experience shortages. However, production capacity can only come online after some time delay. The next section investigates the impact of capacity flexibility on system behavior.

5.2. Variable Capacity

Allowing the supplier to introduce new capacity makes the system much harder to solve.[6] Hence, I simulate the model for five years (from equilibrium) with a transient increase in demand to gain intuition about the model behavior. Then, at the end of the first year I allow a transitory 10% increase in demand that lasts one year.

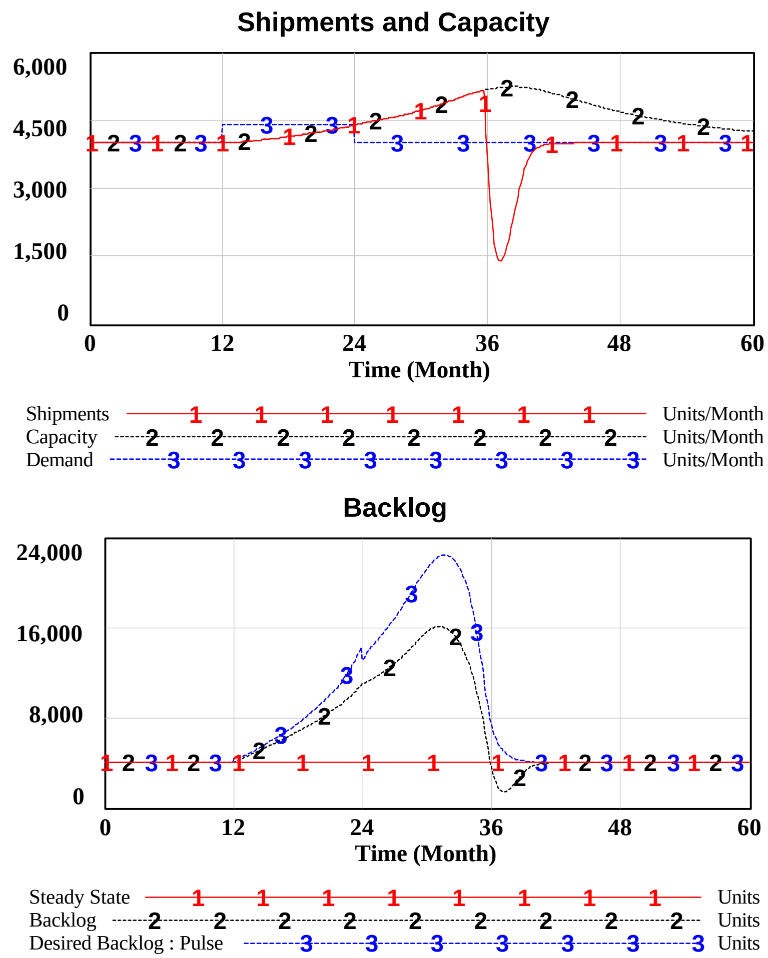

Figure 6. Supplier's (a) shipments and (b) backlog for a 10% transient increase in customer demand

[6] It results in the fourth-order system (8–11) of nonlinear differential equations presented in section 4.

Figure 6a shows demand, shipments and capacity for the supplier; figure 6b shows supplier actual and desired backlog compared to the steady state equilibrium. Due to the increase in customer demand, retailer orders surpass the supplier's capacity causing an increase in backlog. Over time, the supplier builds capacity to meet the increase in demand. At the end of year two, available capacity finally meets customer demand, but retailers still inflate their orders due to large backlogs and delivery delays. Since supplier capacity is still insufficient to meet retailers' inflated demand, backlogs continue to increase. As a result of the sustained increase in retailers' demand, the supplier continues to invest in capacity to satisfy a booming market. The increase in supplier's capacity and backlog represents an important aspect of the system behavior. While customer demand increases by 10% during a model year, capacity increases by more than 30% to balance the order inflation by retailers. Comparatively, backlogs increase by 300% relative to its equilibrium level in response to the transient increase in demand. Hence, the increase in customer demand causes a disproportionately high increase in supplier capacity and backlogs.

When supplier shipments finally meet retailers' demand, the backlog reaches its maximum. At the same time, as more capacity becomes available and shipments increase, delivery delay decreases. Retailers respond to lower deliver delays by not inflating their orders. In fact, retailers start canceling orders as supply availability normalizes and the total retailer orders increase beyond total customer orders. Interestingly, the initial boom of the demand bubble is in sharp contrast with the steep decrease in orders that takes place when the bubble bursts. The burst is characterized by a sharp increase in order cancellations followed by a period of reduced demand, while retailers are depleting their excess inventories. The behavior is not only characterized by the inflated increase in demand but also by the sharp burst (inverse bubble) caused by cancellations and reduced order rate. Figure 7 shows the evolution of supplier's actual and retailer's expected delivery delays as well as retailers' order cancellations.

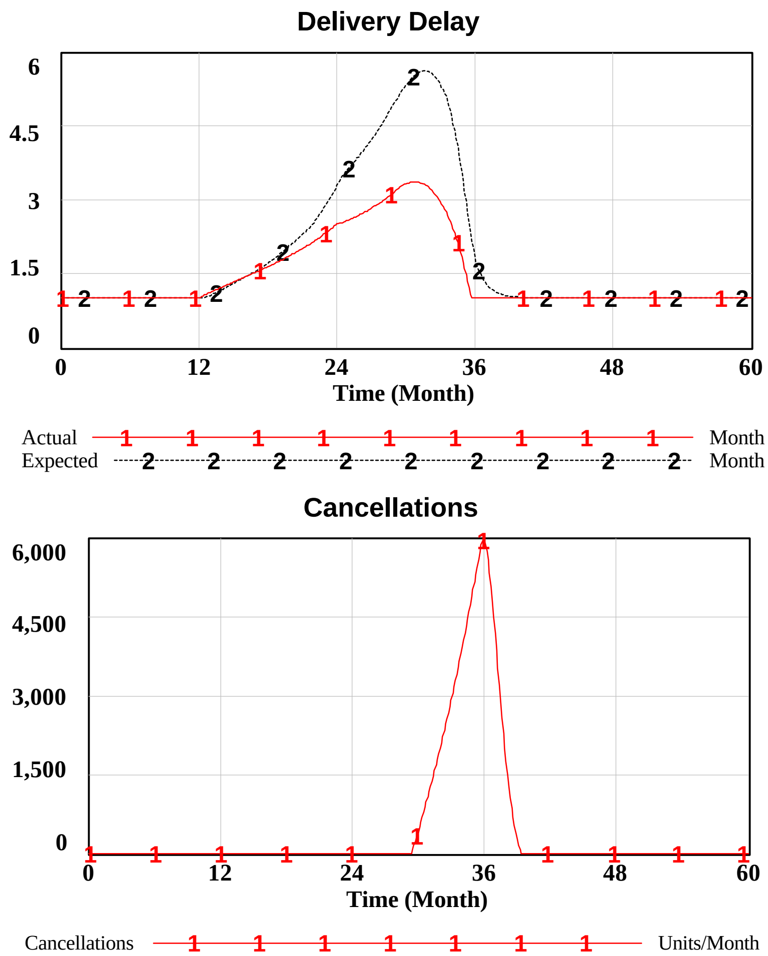

Figure 7. (a) Delivery delays and (b) cancellations for a 10% transient increase in customer demand

The relationship between delivery delays and supply-demand imbalance becomes clear in the following phase plot (Figure 8). The graph shows that as shortages take place and total customer orders (D_c) exceed the total amount of orders received by retailers (S_r), the expected delivery delay increases. Also, since the supply-demand imbalance is given by the difference between total orders received by retailers and customer orders ($S_r – D_c$), the supply-demand imbalance becomes negative. As a result of long delays, retailers inflate their orders and over time the supplier invests in new capacity to meet the perceived growth in demand. Suppliers' ability to increase shipments prevents the supply-demand gap from decreasing even further. However, delivery delay continues to increase for a while because the supplier still accounts for retailers' inflated orders. Moreover, supplier's still high backlogs translate into high delivery delays and further inflated orders. So, even though the retailers are closing the gap on customer demand, supplier's delivery delay is getting worse.

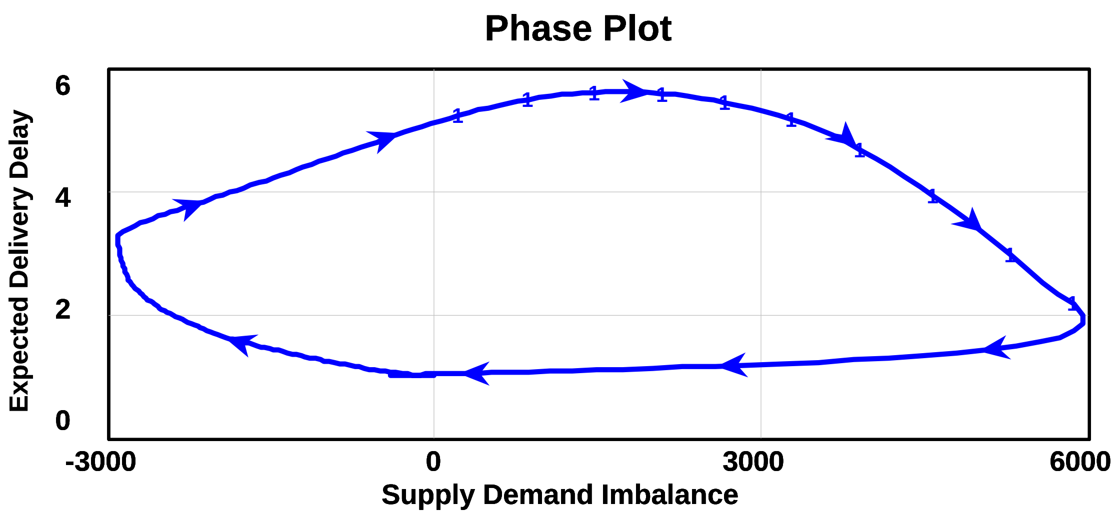

Figure 8. Phase plot supply-demand imbalance for a 10% transient increase in customer demand

When the supply-demand gap is zero, retailers start canceling orders. However, backlogs and delivery delays will continue to increase while retailer demand is larger than shipments and cancellations. As the supply-demand imbalance increases, retailers cancel a greater fraction of their orders. With more supplier capacity available and more cancellations, suppliers can run down their backlogs and decrease delivery delays. Retailers adjust by not inflating their orders. Now as the positive loops act on the virtuous way, retailers do not inflate their orders and suppliers can quickly run down backlogs. Consequently, at the time of the inverse bubble, when retailers are canceling existing orders, suppliers experience low retailer demand, excess capacity and run down backlogs. Over time, the additional capacity and the improved performance of the supplier allow her to run down the backlog to its initial equilibrium condition. But as figure 6 shows it takes more than one year after the shortage in supply for backlog to return to equilibrium. Finally, since capacity acquisition and disposal takes much longer, capacity is still above the equilibrium level three years after the end of the shortage in supply. To get further insight into the model the following sections provide sensitivity analysis on several model parameters.

5.3. Sensitivity Analysis

This section investigates the sensitivity of the model behavior with respect to changes in the time to build capacity, the time it takes retailers' to perceive the actual delivery delay quote provided by suppliers and retailers' reactions to delivery delay and. For the first two tests, I run the simulation model allowing the parameter to be twice as high and half as low as the base case run. For the last test, I introduce different (table) functions to capture retailers' responses.

5.3.1. Time to build capacity (t_K)

Now let me investigate the impact of the time to build new capacity on system behavior. I test how the model behaves under different capacity acquisition delays ranging from 6 months to 2 years. Figure 9 shows the results for backlogs.

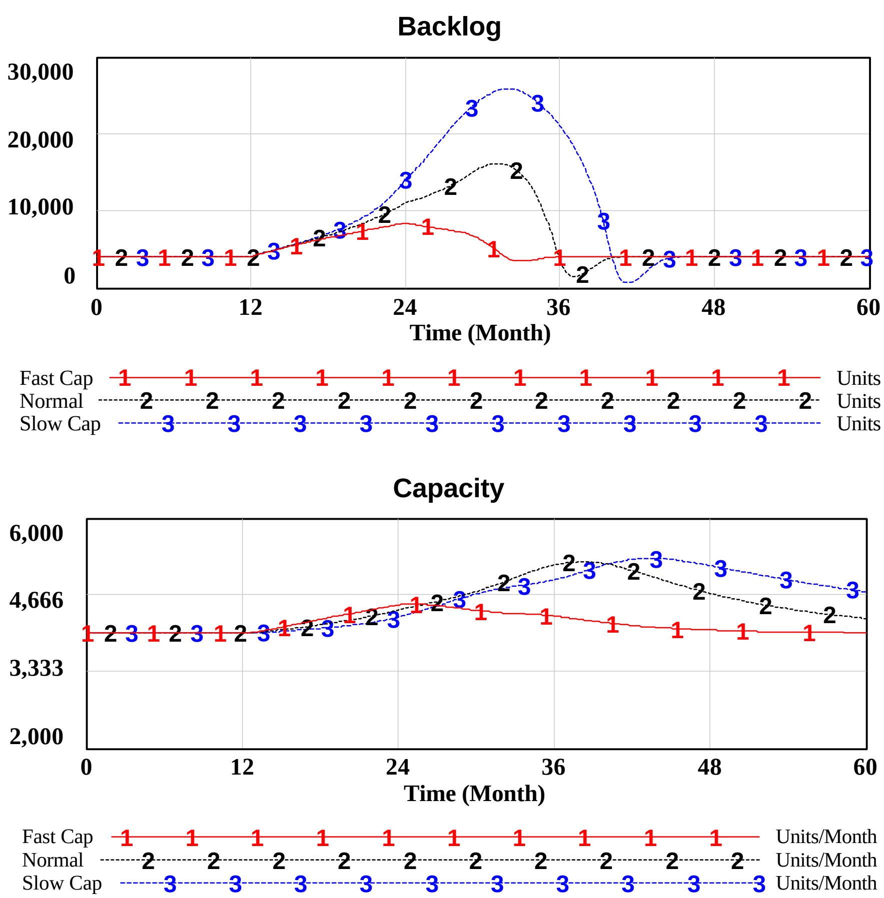

Figure 9. Supplier's (a) backlog and (b) capacity under different delays to build capacity

Shorter capacity acquisition delays (FastCap) leads to lower capacity level and an earlier peak. Longer delays (SlowCap) result in a higher capacity level as well as a later peak and a longer period of excess capacity. The results suggest that the supplier's ability to build capacity quickly can reduce the size of the bubble and the duration of the problem. Since introducing new capacity typically requires a long delay companies have devised strategies that gives them flexibility to ramp up production. In particular, the semiconductor industry builds the building infrastructure (the shell) well in advance such that it does not become an additional constraint in ramping up production of a new fabrication facility. The equipment then is positioned as it becomes necessary. While rapidly building capacity prevents the bubble from growing, it is important to notice that even when capacity can be quickly introduced, backlogs still doubled in size, for a 10% increase in demand.

Suppliers often have the flexibility of adding capacity to deal with a long trend increase in capacity. But capacity expansion is always costly and once the investment has been made suppliers would like to make the most out of it. However, we observe that due to the order inflation, suppliers tend to introduce much more capacity – the longer the delay in introducing capacity the higher the capacity commitments – than the actual increase in customer demand. Unfortunately, the additional capacity brought online is poorly used. As soon as the bubble collapses, the supplier is left with unused excess capacity. Actually, the situation portrayed in the model is very conservative since it assumes that it is possible to run down capacity as quickly as it is to introduce it. This assumption often does not hold. A more realistic assumption, accounting for longer delays to run down production capacity, would lead to higher excess capacity for suppliers. Hence, while capacity flexibility mitigates the problem, by itself it may not be an effective means to deal with the impact of retailer strategic ordering due to shortages.

5.3.2. Time for Retailers' to Perceive Delivery Delay

I now examine the model's sensitivity to the perception delay retailers experience before they learn about the supplier's quoted delivery delay. Information systems providing real time information about quantities available to promise and delivery quotes between a supplier and a retailer have decreased this delay to virtually zero. However, this push towards system integration and information sharing often takes place when there is a dominant player in a supply chain. While many large companies adopt such integrated information systems, with the intent of increasing chain visibility for better planning and forecasting, the majority of small and medium companies do not yet have such integrated systems in place.

Here, I investigate the impact of the length of the retailers' perception delay on system behavior. I test the model under different perception delays ranging from no delay (No Perception Delay which represents integrated information systems providing real time information to retailers) to 2 months (Long Perception Delay which represents Mom & Pop businesses checking their inventory positions sporadically). Figure 10 shows the results.

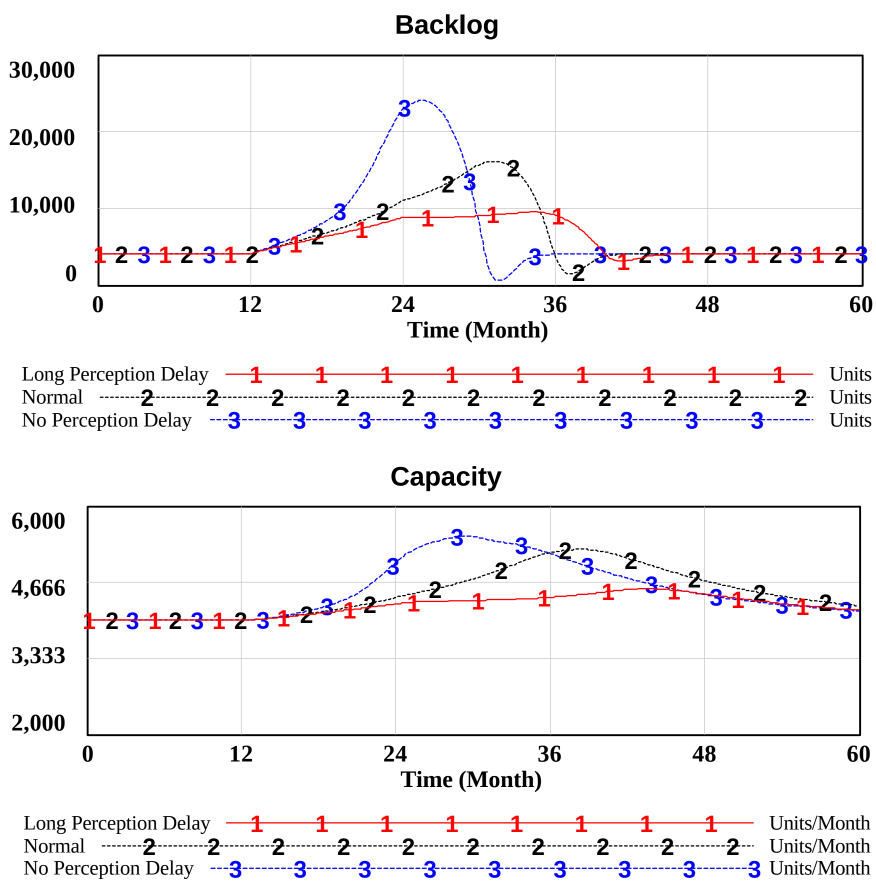

Figure 10. Supplier's backlog under different perception delays

The system is much more stable when retailers learn about delivery delays with a long perception delay. By providing all parties real time information, current supply chain management systems, linked seamlessly through the Internet, may be introducing a great deal of instability in supply chains. The business press provides some commentary of how real time supply chain management impacts the economy (Schwartz 2001).

> "The Internet, with its myriad online connections, speeds the transmission of ideas, good and bad, and amplifies their reach. It has allowed business managers to peek into every link of the supply chain that feeds their manufacturing processes, and to change direction with a nimbleness that would have been unimaginable just a few years ago."

The Chairman of the Fed, Alan Greenspan, supports a similar point of view:

> "The faster adjustment process raises some warning flags. Business managers have access to more information, but everyone gets similar signals. As a consequence, firms appear to be acting in far closer alignment with one another than in decades past. The result is not only a faster adjustment, but one that is potentially more synchronized, compressing changes into an even shorter time frame."

While the new supply chain management systems provide more accurate and real time information capable of reducing purchasing and ordering costs, no one realized how the information might be used. In particular, these systems have not been designed to account for feedback complexity and the impact of the use of the information. The results of the analysis suggest that allowing faster adjustment (No Perception Delay) may cause more aggressive behavior by retailers and a stronger impact of shortages, which explains the larger magnitude of more recent impacts (Figure 10). The experience of business managers tends to agree with this result (Clancy 2001).

> "By sharing knowledge of orders or parts shortages or other factors, companies across the high-tech industry are probably more in sync than they ever have been before. This has been the promise of the e-business revolution, but no one ever realized how this information might be used. I'd say we're getting our first taste of how companies might react to up-to-the-minute operational information. In short, they would move more quickly to protect profits. Even Fed Chairman Alan Greenspan has theorized publicly that the improved efficiency of forecasting systems has exacerbated the severity of the economic slowdown, which gripped the country more quickly than anyone predicted."

Finally, the results suggest that the costs associated with over-ordering may far exceed the savings generated from accurate processing of orders. In that sense, it is important to further investigate the role that supply chain management tools may be playing in the economy.

5.3.3. Retailers' reactions to delivery delay (f)

I now explore the aggressiveness of retailers' reactions to quoted delivery delays. A fully myopic (or naïve) strat egy for retailers simply adjusts their orders in proportion to the increase in the delivery delay. There is no bias under the myopic strategy ($\alpha_M = 1$). This strategy is myopic because it does not take into consideration the strategic actions of other retailers competing for the same scarce supply. And it is naïve in its assumption that the supplier provides the true delivery delay quote. Hence, this strategy represents the mildest possible way in which retailers react to delivery delays. In contrast to the myopic case, retailers in the base case (normal) will adjust their expected delivery delay to account for strategic behavior from other retailers or the supplier. The function that describes retailers' expected delivery delay is a non-linear function that captures a stronger adjustment as delivery delays increase but saturates (when actual delivery delays equals 6 months) at a value of 7.5 months. Under the aggressive strategy, retailers' inflate their orders more aggressively than under the base case, which translates into a function with a higher slope and a higher saturation value, at 10 months. In the following set of tests, I run the model under the three strategies. Figure 11 shows the functions representing retailers' reactions under each strategy.

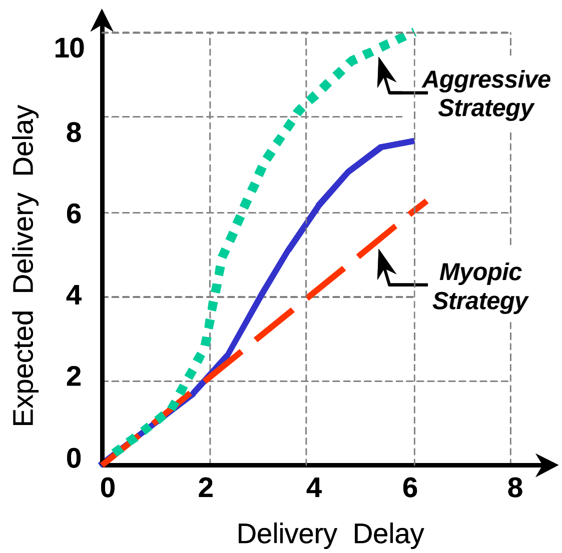

Figure 11. Sensitivity of retailers' reactions to delivery delay

Figure 12(a) shows backlogs under each retailer response. First, it is important to notice that even under retailers' myopic scenario – no strategic ordering among retailers – backlog and the expected delivery delay still increases. This result is analogous to the case when capacity is fixed. However, backlogs returns to the equilibrium level gradually rather than decreasing sharply as systems with strategic ordering. Second, the aggressiveness of retailers' competition matters. In the normal case, a maximum retailer bias increases the expected delivery delay by 25% (from 6 to 7.5 months), causing backlogs to increase by a factor of four (reaching a level that is higher than 16,000 units). In the aggressive case, a maximum retailer bias causes a 66% (from 6 to 10 months) increase in the expected delivery delay, leading to an increase in backlogs by a factor of seven times (reaching a level that is almost 30,000 units).

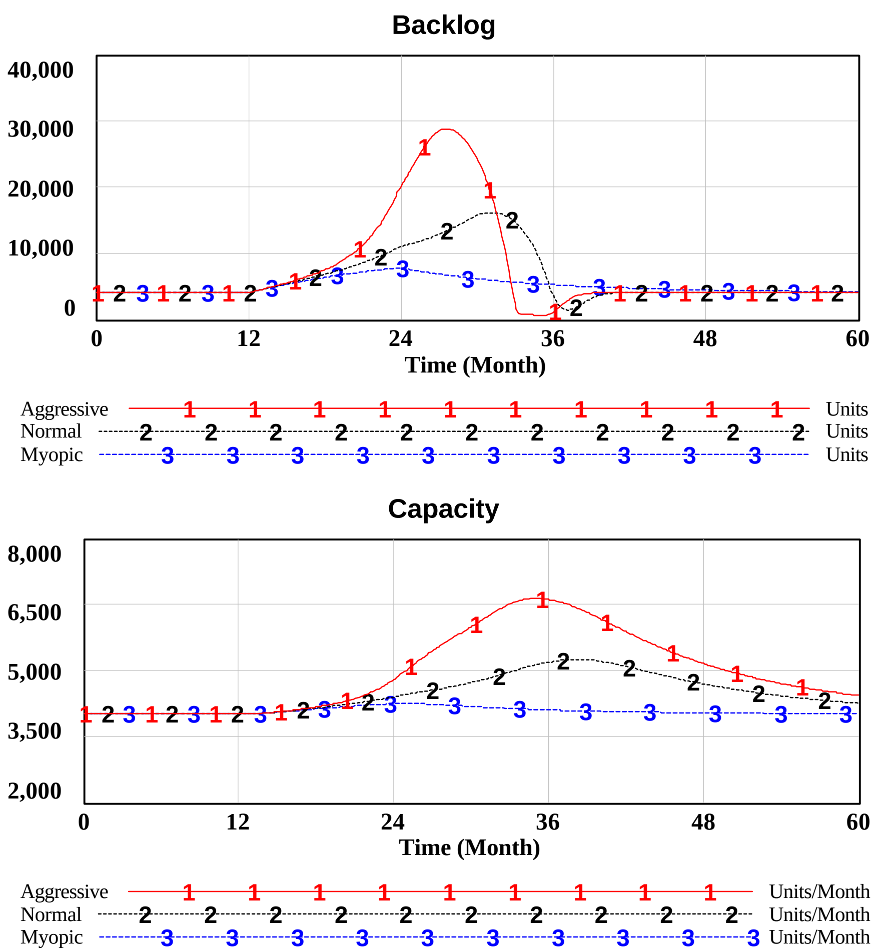

Figure 12. Supplier's (a) backlog and (b) capacity, different retailers' reaction functions

Figure 12(b) shows the supplier's capacity under different retailers' strategic scenarios. In the myopic case the supplier increases her capacity by 5%; in the normal case, by 30%; and in the aggressive scenario by more than 65%. Thus the supplier accumulates much more capacity than desired when retailers have a very aggressive strategy to obtain their orders. There are a couple of different interpretations for retailers' responses. One possibility is that it represents individual retailers' responses to shortages. Hence, individuals with more aggressive natures may respond in a more emphatic way than other individuals, inflating their orders more. In this context, the supplier may choose to focus on managing the orders of aggressive retailers, to prevent the reaction of other competitor retailers.

Another possibility is that the responses capture the competitive environment retailers face. Hence more aggressive responses can be expected in more competitive environments. In that case, we would expect to see *more pronounced* demand bubbles in industries where the amount of competition among players is intense. Furthermore, since the number of players can influence the nature of the competition, limiting the number of retailers that a supplier tends to may help suppliers to mitigate order inflation. Alternatively, suppliers may choose to give priority to preferred retailers, preventing them from being impacted by shortages when they occur.

6. Policy Discussion

In this paper, I considered the phenomenon of bubbles in demand that can take place when retailers compete for the supply of scarce products. The paper contributes to the understanding of the phenomenon by providing a comprehensive causal map of the relationships leading to retailers' inflation of orders. In addition, I provide a formal mathematical model for one of the possible retailers' reinforcing loops: the *Ordering Ahead (R1)* loop. By assuming that supplier capacity is fixed, it is possible to obtain closed form solutions to the behavior of supplier backlogs. Even when myopic retailers order the exact amount to compensate for an increase in delivery delays system performance decreases, leading to higher backlogs and longer delivery delays. If retailers are aggressive, the analysis suggests that a *transient* shortage in supply can *permanently* drive the supplier to a low performance equilibrium, in which backlogs and delivery delays are high, when she cannot increase capacity to meet retailers' needs. The supplier's ability to bring capacity online can help reduce the impact of shortage. However, she still goes through a transient period of low performance, as it takes time to bring new capacity online. When the additional capacity becomes available and retailers start receiving their orders, the bubble bursts. The burst is characterized by a period of order cancellations followed by a period of reduced demand, while retailers are depleting their excess inventories. As the bubble bursts, suppliers are left with excess inventories and capacity greatly exceeding the amount of product in short supply. In fact, the supplier's capacity and backlog represents important aspects of the system behavior. For instance, a 10% *transient* (one year) increase in customer demand can induce capacity increases on the order of 30% to balance retailer's order inflations and backlogs can increase by 300% relative to its equilibrium level.

Furthermore, the *faster* the supplier can add new capacity the *lower* the impacts of the bubble, that is, it will require *less* capacity, it will face a *shorter* period of low performance with *lower* backlogs and *shorter* delivery delays. Hence, the ability to quickly bring capacity online helps suppliers prevent the growth in the bubble. However, capacity flexibility alone may not be a sustainable way to deal with demand bubbles. Even when they limit the impact of the demand bubble, suppliers are left with excess capacity. This effect is particularly important when adequate time constants for the depreciation of capacity are taken into consideration. Since a rapid introduction of new capacity can have a significant reduction in the size of the demand bubble, it is important to consider flexible strategies for quickly bringing new capacity online.

In addition, the analysis suggests that an important leverage point in the system is the time delay it takes retailers to perceive the supplier' delivery delays. When the supplier provides real-time information about delivery delays to retailers the system is highly unstable. This takes place because retailers react instantaneously to the readily available information. So, if retailers see an increasing delivery delay they will respond rapidly and will inflate their orders to hedge against shortages only making the situation worst. In contrast, when the supplier provides information about delivery delays with a long time delay to retailers the system is more stable, because it will take time before retailers over-react, giving the supplier an opportunity to act – speeding up production, increasing overtime, increasing safety stocks of raw material and components, and bringing up new capacity online – to reduce delivery delays. Interestingly, the idea of suppliers providing delayed information about delivery delays and inventory availability goes in direct opposition to current industry trend to introduce information systems providing real-time information to all parties in the supply chain. Unfortunately, these real-time information systems may be introducing a great deal of instability leading to the creation of larger than ever demand bubbles. While companies claim to have saved millions of dollars in purchasing and ordering operations, the costs associated with over-ordering may far exceed the savings generated from the accurate processing of orders.

Interpreting the aggressiveness of retailers' responses as a measure of market competitiveness, the results suggest that more pronounced demand bubbles would take place in industries where competition among retailers is intense. To avoid the impact of competition, suppliers may choose to give priority to preferred retailers or to limit the number of retailers that they will work with.

Finally, a number of researchers (to name a few: Kaminsky and Simchi-Levi 1996, Gupta, Steckel and Banerji 1998) have analyzed policies (e.g., centralizing ordering decisions, reducing order lead-times, and sharing Point-of-Sales (POS) data) for reducing demand variability. Particularly important to demand bubbles is the availability of POS data. If suppliers had access to such data it is arguable that they would not be facing such harsh conditions since they could distinguish true demand from retailer-inflated demand. However, it is unrealistic to expect that retailers plagued by shortages would be willing to share such information with their suppliers in the first place, since it would limit their ability to obtain more products when needed. In addition, those retailers who might be willing to share such information would potentially risk receiving less than others who would be inflating their orders.

In summary, this paper contributes to the discussion of order amplification in supply chains due to supply shortages. It offers a comprehensive causal map of the relationships leading to retailers' inflation of orders and a formal mathematical model of one reinforcing loops of retailers' response. It provides a closed form solution to the behavior of supplier backlogs when supplier has fixed capacity and an analysis of the simulation when capacity is flexible. Finally, parameter sensitivity analysis explores how the model behavior changes due to parameter changes, leading to a deeper understanding of the long-term impacts of demand bubbles and policies solutions that may mitigate their impacts.

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