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Demand and Supply Driven Bullwhip Effect

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Leadership in forest and environmental management, innovation and research

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INTRODUCTION

Abstract

A model of a four-tier supply chain was created using system dynamics software, and made to exhibit amplified oscillations in stock levels due to a sudden change in demand, known as the bullwhip effect. The model was then tested to examine the effects of a sudden change in supply. No bullwhip effect was observed, and the feedback loops inherent in a supply chain prevent it from occurring. A forestry example was used, but the principle is applicable to any supply chain.

Introduction

Many supply chains exist where the dominant factor is a variable demand, according to which desired goods are 'pulled' through the chain from producer to customer. It is well documented that a sudden change in demand can lead to an amplification of orders up the chain, and oscillating stock levels.[2,5,25] This is called the 'bullwhip effect'.[8,15,24,33,36]

In forestry, supply can often be more variable than demand, so goods are typically 'pushed' down the chain instead.[18] It is the purpose of this study to asses the impact of supply variation on the whole chain, and whether the same oscillations occur. To answer this question and any implications of our findings, we will create a model of the forestry supply chain which can replicate scenarios and trial meaningful solutions.

The supply chain we will consider is depicted in Figure 1. This is a four tier chain, in that it comprises four bodies, and a downwards flow of goods from forest to retail.

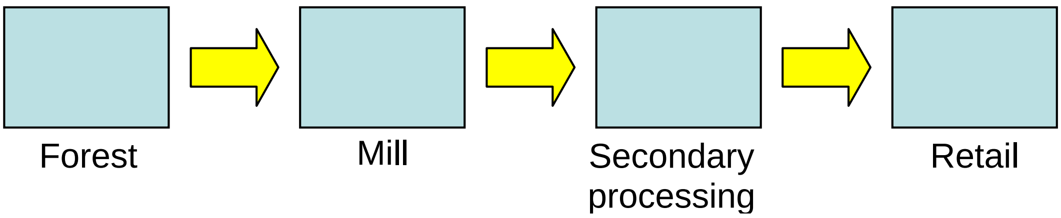


Fig 1 – A simple forestry supply chain

As well as mapping the hierarchy of entities along the chain, a supply chain diagram must also chart the interactions between them[16]. These can be product flows or information flows – which entail orders, contracts, predicted needs, quality control and shared knowledge. The structure of the chain can hold more information on the potential of an enterprise than could ever be assessed from an internal perspective.

It would quickly become impractical to show a real world supply chain using the flowchart style in Figure 1, once factors such as stock levels and ordering policies are included. By using a standard description, the information can be universally mapped and studied. If the interactions could then be described mathematically, this would enable us to turn the diagram into a model, and simulate the supply chain and perform theoretical tests[10].

Creating a model of a supply chain first lets us delve into the intricate interactions held within and, through formularisation, gain a better understanding. When we think we have encapsulated the problem we can test it to the theoretical limits, compare this with reality, and re-evaluate. This in itself can yield many useful insights, but eventually the model should resemble reality at least in the dimensions that we intend to examine it.

METHODS

There are many ways to create a functioning supply chain model, including programming[27], agent-based modelling[11], and system dynamics[1,25,32]. In this study we are using system dynamics on the basis of its established history and wealth of examples.

The concept of supply chain modelling initiated [began?]from Forrester's work on the 'beer game'[10] – a simple supply chain concerning beer distribution which can be used to succinctly demonstrate demand variation oscillations, or the bullwhip effect.[22]

Using the ideas of Van Horne and Marier,[36] the model started with an existing system dynamics version of the beer game with the variable names adapted to forestry. Using only small adaptations, this was ready for experimentation. Figure 2 gives the adapted beer model.

This model was implemented in Powersim softwa2[9], but the adaptation from the original version in another package Stella was marginal. In this standard notation the rectangles depict stocks – volumes of wood in a shared state, where any unit of volume is indiscernible from another, or orders held in a backlog. Arrows depict a flow or transition from one stock to another. This can be a movement from one location to another (e.g., forest to mill), or a process from one form to another (logs to sawn timber, unfilled order to filled order). Circles depict variables – these can be used to calculate other variables, or when attached to an arrow, dictate the rate for that flow (e.g., wood to mill in m^3 per day).

This model shows four independent enterprises in the supply chain; the forest, the mill, the secondary processor and the retailer. They are not aware of each other's sales and stock levels, but do feature 'intelligent ordering'. Intelligent ordering is placing sufficient orders to fill a stock shortage as soon as it becomes apparent, and then not reordering unless the shortage deepens. This is common sense and the minimum level of 'supply chain management' we can expect from any real enterprise.

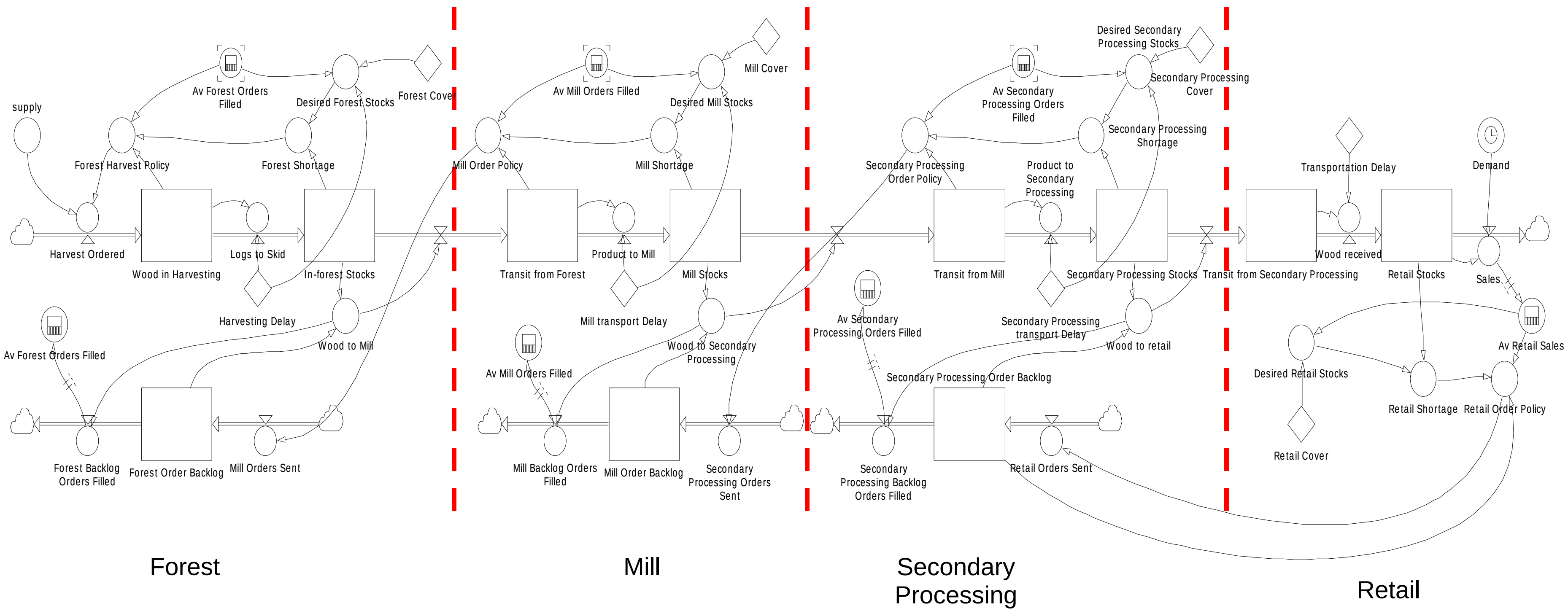


Fig 2 – Forestry Supply Chain Model
Equations given in Appendix I

In a highly reactive 'unintelligent' supply chain, an enterprise may continue ordering whilst there is a shortage, until the shortage disappears. When there is a delay in delivery this will lead to over-ordering, as there will be a large number of orders still to arrive once the shortage is filled. We can assume that any real world supply chain is more advanced than this.

As well as keeping track of historical orders, it is a reasonable assumption that a company will base their desired stock level on historical sales. A simple version of this, as implemented here, is to expect forthcoming orders to be equal to an average of the previous sales over some period of time, here called the 'reference span'. An improved version would be to reorder according to the average, but also extrapolating forwards by studying the gradient of recent sales. A further improvement would be to incorporate the second derivative, and so on. This has not been implemented in any models here, as forestry demand is generally based around flat quarterly contracts.

It is worth noting that the structure for each tier in Figure 2 is essentially the same. Each tier has to wait for a delay before receiving ordered goods (either harvesting or transit), and has its own stocks governed by a *shortage*. This is itself controlled by a *desired stock*, which is the product of the average recent sales (which is equivalent to orders filled), and the coverage. If the stock falls below the desired level, *order policy* dictates that orders will be placed with the tier above for enough stock to fill the deficit.

Orders received go into a *backlog*, and what cannot be immediately filled waits until stock levels are high enough. This is shown in the causal loop diagram in Figure 3.

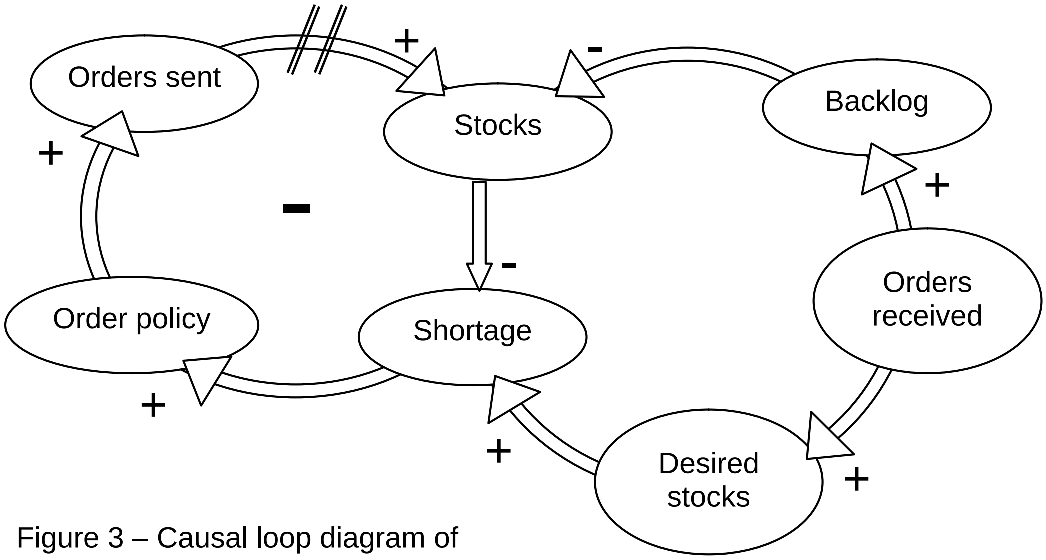


Figure 3 – Causal loop diagram of single tier in supply chain

In a causal loop, any variable that directly affects another is linked by an arrow with a polarity sign, + or -. Plus indicates 'reinforcing feedback' – i.e., if A increases then so does B. Minus shows 'negative feedback', so if A is increasing then B is decreasing, and vice versa. A double line indicates a delay in that feedback. We see in Figure 3, the system is controlled by a negative loop (negative because the sum of all feedbacks in the loop is negative). A negative loop works to keep the system in equilibrium, i.e., the stocks are low so more stock is ordered to bring the level back to the desired volume. There is a delay in this loop, so it may oscillate before reaching a stable level, but for any reasonable delay it should tend towards equilibrium. The exogenous (as far as this single body is concerned) variable here is *orders received*. Note arrows only originate from it, no arrows act into it. This is because the tier in question has no power over the orders it receives, much as the tier above has no say over the orders that it gets. The effect of increasing *orders received* is two-fold: *backlog* increases, which decreases *stock* as orders are filled, but also increases *desired stocks*, which increases the *shortage* and *orders sent*.

With causal loop diagrams you can reverse the direction of an arrow if you change its polarity. You can see that if you reversed the arrows between *shortage*, *desired stocks* and *orders received*, this second loop would also be negative. Thus you have a stockpile controlled by two negative feedback loops that keep it in check despite varying orders received.

This means each tier in the supply chain is inherently stable, but contains a delay and is provoked by incoming orders. If the delay is sufficiently long and the incoming orders suddenly change, then the tier may be forced into a drastic correcting cycle of extreme over-and-under ordering. This, and its consequence to the later tiers, is the bullwhip effect we intend to study.

Simplifications

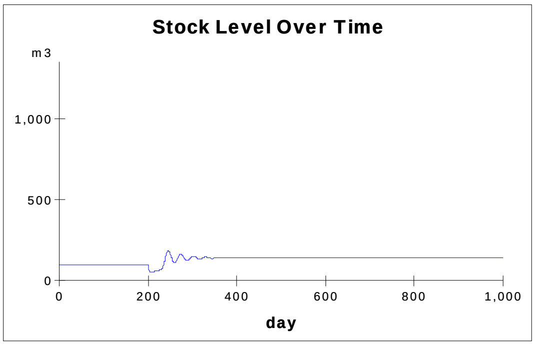
In forestry, a cubic metre of lumber does not become a cubic meter of sawn timber. There is significant wastage along the supply chain, and multiple products at the end. Here we are looking at the underlying effects of the supply chain rather than the actual numerical output, so we have assumed a single product and zero wastage. It would be possible to make multidimensional arrays to cover different wood products, with scaling factors to represent wastage, but that is not the issue we are concerned with here. The lessons learned would be the same, albeit harder to see. This also has the advantage that in equilibrium all the stocks should be at the same level.

RESULTS

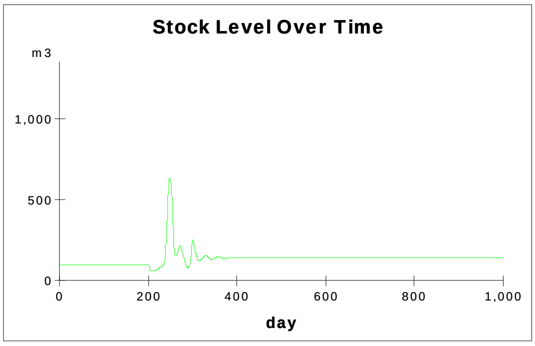
Demand driven bullwhip effect.

The first test is the classic test of a sudden step increase in demand, which is expected to create a bullwhip effect. We will model for 1000 days, and on the 200th day the demand will jump from 50m^3/day^{-1} to 70m^3/day^{-1}. The coverage is set at 2 days, all transport and harvesting delays are set at 5 days, and the reference span at a week.

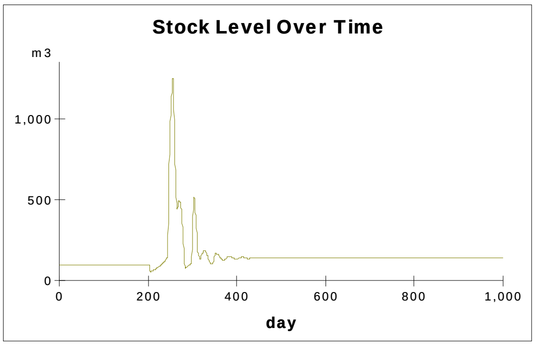
Figure 4 shows how the stock levels vary. When the increase in demand occurs, all stocks take a sudden dive, which prompts a period of oscillations as the system settles to its new equilibrium. These oscillations are more marked further up the supply chain. The feedback loops in Figure 3 are all acting to return to equilibrium, but as a consequence are issuing larger orders to the tiers above. This impedes that tier's ability to settle, and the disturbance amplifies up the chain.



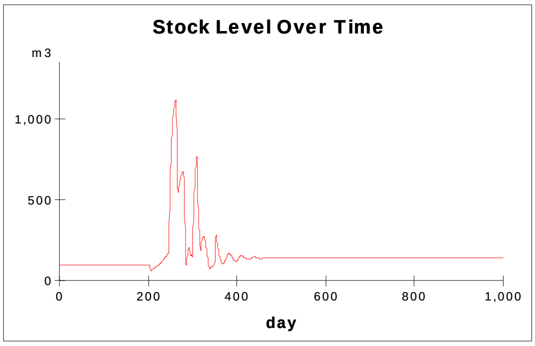
Retail Stocks



Secondary Processing Stocks



Mill Stocks



In-Forest Stocks

Figure 4 – Stock levels in demand-driven Bullwhip effect

Demand driven Bullwhip effect with a limited supply

The previous experiment had the assumption of an unlimited supply. This is acceptable for some industries, but forestry is limited by sustainability and logistics, and supply is run as close to the maximum as possible. Harvesting orders received must have a maximum imposed. If the demand is constant and the supply sufficient, equilibrium will persist. Should the demand exceed the supply, all tiers will rapidly exhaust their stocks and drop to a level equal to the daily supply. Figure 5 shows the traces where the supply is limited to 60m^3/day^{-1}, with the same demand jump from 50m^3 to 70m^3 used in the previous experiment. Notice how the stocks all drop from 100m^3 (equilibrium at two days' coverage) to 60m^3.

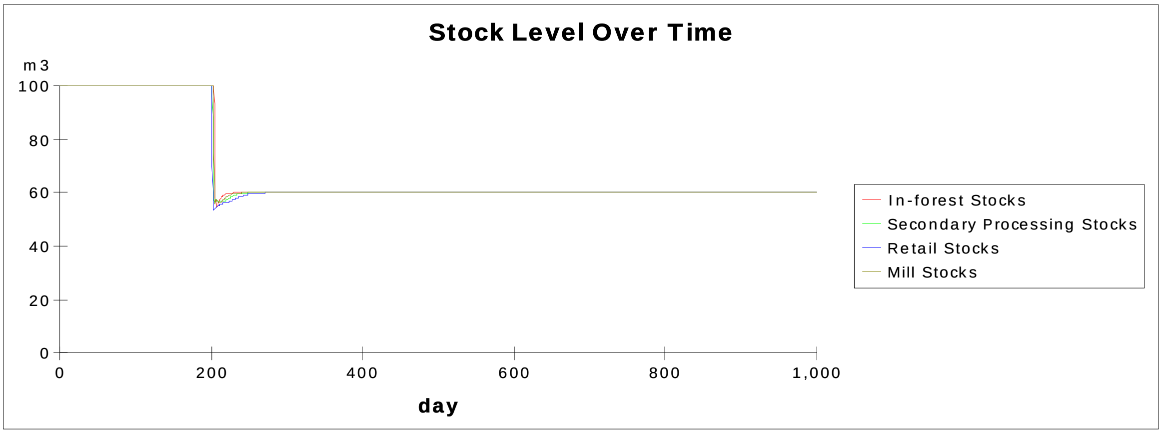


Figure 5 – Stock levels in demand-driven Bullwhip effect with limited supply of 60m^3

If the supply is sufficient, but limited, a new equilibrium will be found but it may take longer. Figure 6 shows the case when the supply is limited to 80m^3. We see the same oscillations, but this time it takes almost a year for the increase in demand to be accounted for (compare Figure 4, where the system was in equilibrium in around 250days).

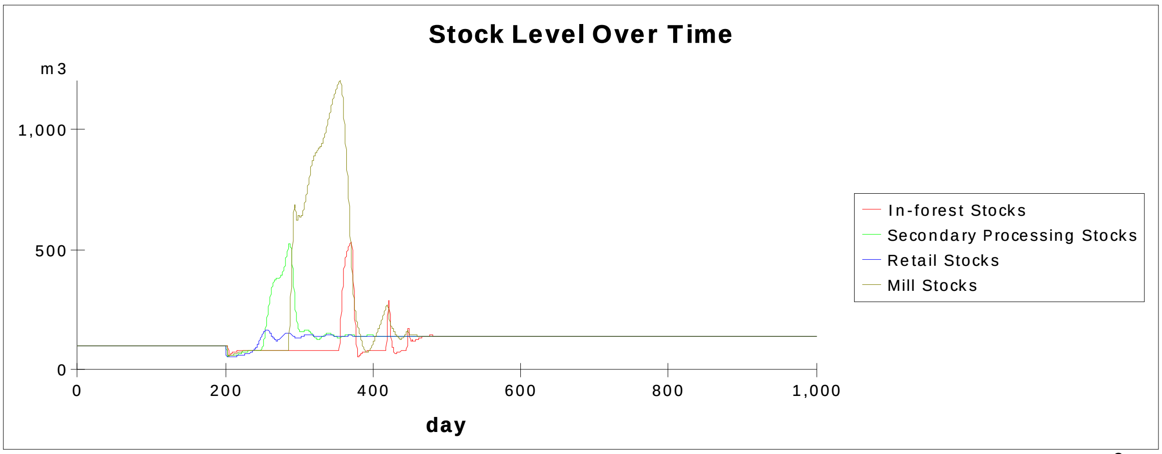


Figure 6 – Stock levels in demand-driven Bullwhip effect with limited supply of 80m^3

Supply driven Bullwhip effect.

Using exactly the same model, we will now examine the case where demand is constant, but the supply suddenly increases from 50m^3 to 70m^3. The traces are given in Figure 7. Unsurprisingly, equilibrium persists. This is because supply was always sufficient, so an extra amount of supply is great, but not needed so amounts to nothing. More interesting is the case where supply *decreases* 20m^3 from 50m^3 to 30m^3. This is shown in Figure 8.

Here we see the stocks fall in rapid succession as demand outstrips supply, and arrives at a new level of 30m^3. This new level is not an equilibrium, even though it appears to be. The system is not 'at rest', as all stocks are deemed to be in a shortage, and order backlogs are increasing year upon year. If this were reality, the state could not persist for long before the chain broke up and the mill looked for a new supplier.

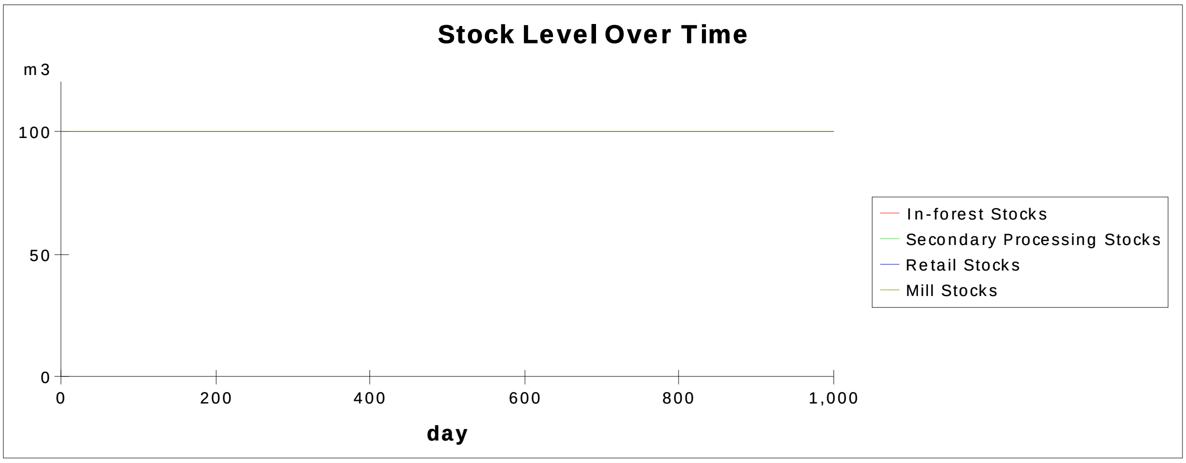


Figure 7 – Stock levels in with supply increase to 70m^3

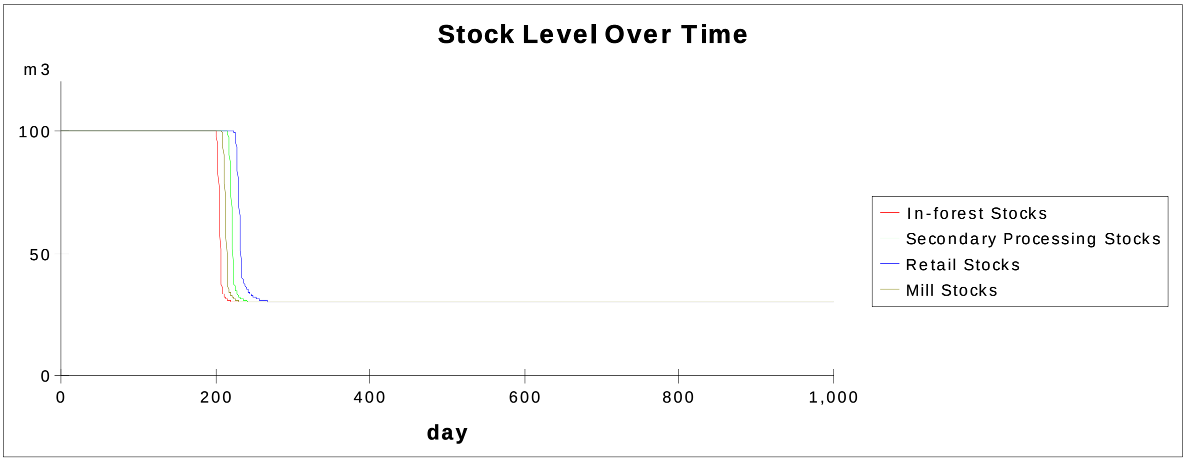


Figure 8 – Stock levels in with supply decrease to 30m^3

What is apparent in Figure 8 is that there is no bullwhip effect. There cannot be any over-ordering as there is not the capacity to support it. It may be more fair to try a situation where there is a large supply (100m^3, twice the required volume), but on day 200 it momentarily drops to 30m^3, before resuming 100m^3 on day 201. This could represent the breakdown of equipment, a strike or unfavourable weather conditions. This allows the capacity for overshoot, and possibly a bullwhip effect. Figure 9 shows the trace, and though the in-forest stocks drop momentarily, there is evidently no bullwhip effect.

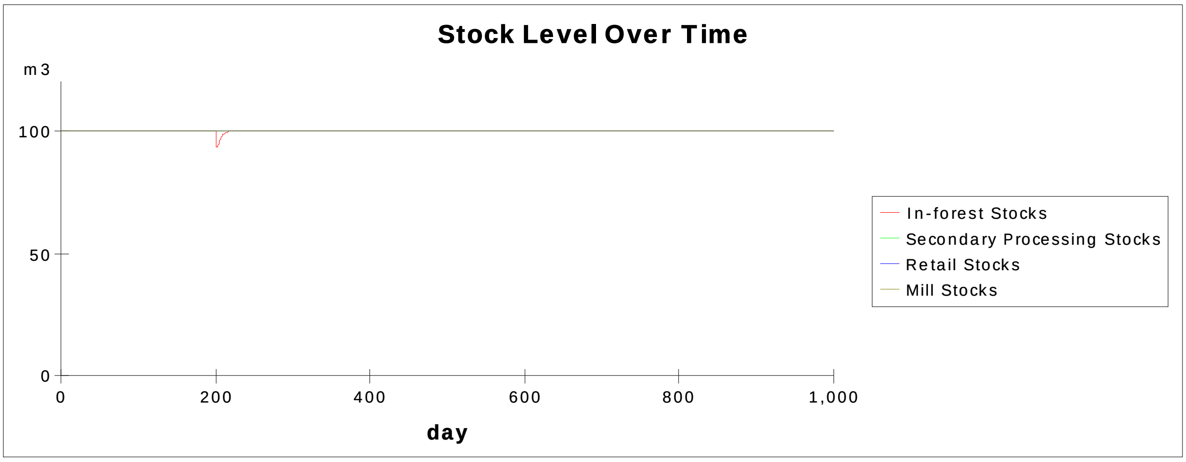


Figure 9 – Stock levels in with a spike supply decrease to 30m^3

Many other scenarios can be trialled, but it is apparent that the bullwhip effect cannot be induced purely through a variation in supply. If there is a variation in supply and demand, the bullwhip due to the demand variation will always swamp out the small blip due to the supply.

Discussion

We have shown that the bullwhip effect, whilst prevalent for demand variation, does not occur for supply variation.

So why is this? At first glance, Figure 1 appears almost symmetrical, with the flow of goods downwards and orders upwards, yet the dynamics vary dramatically with direction.

The difference is in the negative feedback loops that ordinarily keep the system under control. Each body along the chain has its own feedback circuit: when stocks get low, an order is placed with the supplier. When delivered, these goods fill the shortage. This is shown in Figure 10.

If there were no delay in obtaining goods, then the negative feedback loops would keep all of the stocks at the perfect level throughout, and it would be possible to run the stocks to almost zero without disrupting flow. All flows would be equal to the demand, just as in the case of a limiting supply, all flows equal the supply. Unfortunately, there is always a delay between the order being placed and the goods arriving; this is shown by the double diagonal lines in the diagram. This delay is multiplied by the number of tiers the goods must pass through to fill the deficit, so is much greater for an increase in demand than a shortage in supply.

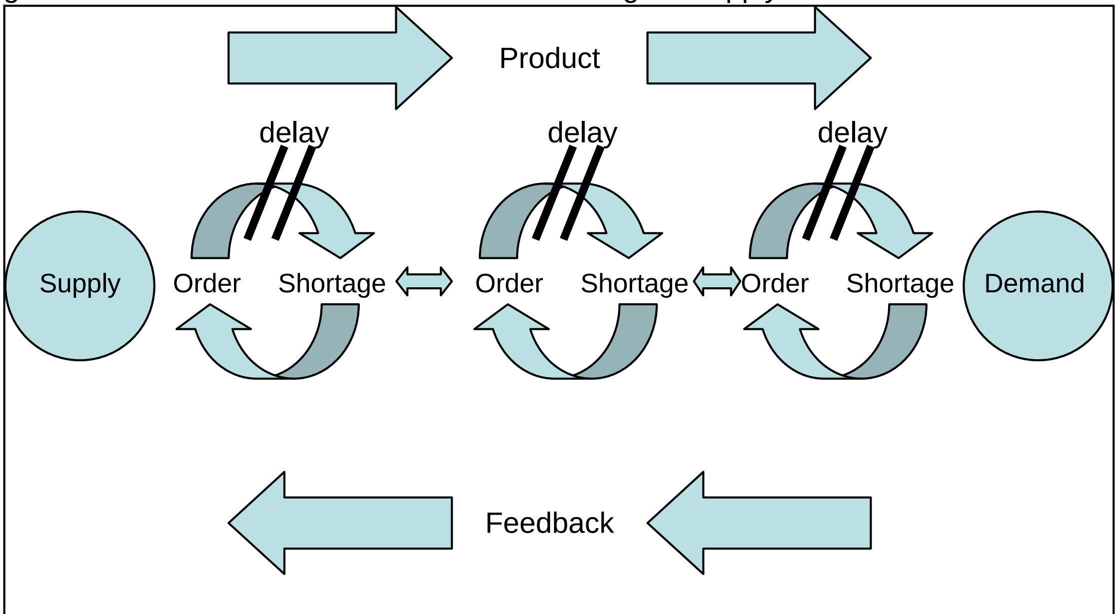


Figure 10 – Feedback loops in a simple supply chain

Conversely, the correcting feedback running up the chain is almost instant, and it is this that causes the over- and under-shoot of the bullwhip effect. Orders will be placed on the instantaneous value of the stocks, but the stocks react on a much slower differential. A shortage in supply can be corrected for before the stocks even begin to react, and even a serious shortage can be absorbed by a series of stocks that only react to the orders from below. For the retailer to correct for a change in demand however, they must wait the full delay of the chain before they can even begin to correct the problem, by which time it can be much worse.

Figures 11 and 12 show the chain of events following a short term demand decrease in a simpler two-tier chain of mill → retail, and demonstrates how quickly the feedback passes the deficit up the supply chain, causing disruptions at all levels. Figures 13 and 14 show the same for a supply decrease.

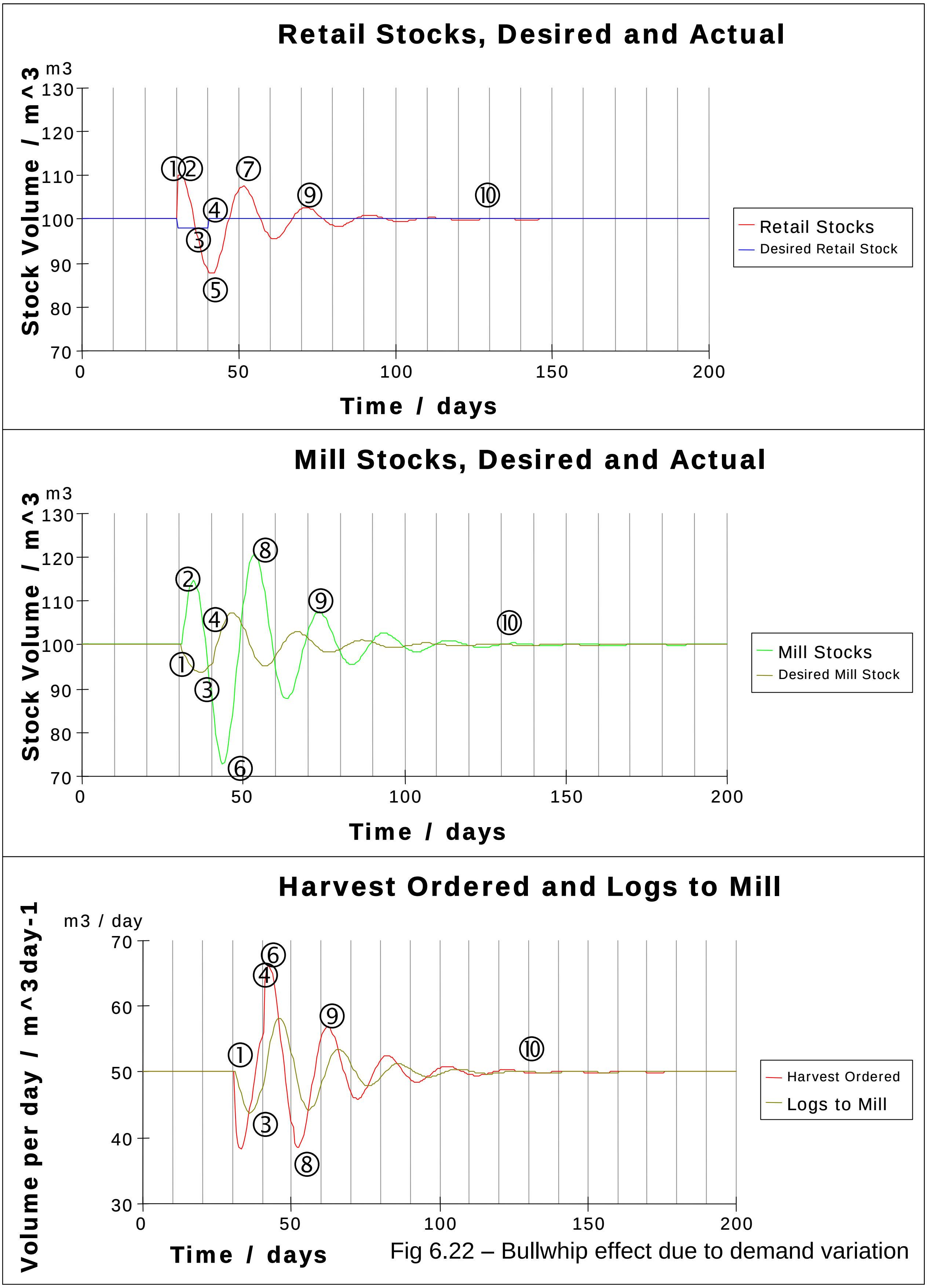


Figure 11 – Bullwhip effect due to demand variation, sequence of events (c.f. figure 12)

①

- Demand, and hence sales, drop below the baseline.
- Retail stocks increase immediately, whilst desired retail stock drops due to reduced average sales
- Retail orders less from mill, so mill stocks start to rise.
- Desired mill stocks decrease, and actual mill stocks rise.
- Harvest ordered decreases to counter this excess, whilst logs to mill is slower to react due to delay.

②

- Demand and sales return to normal.
- Retail stocks pause at higher rate temporarily, as demand meets supply and reduced orders are yet to make it to retail.
- Mill stock continues to rise due to lag in receiving reduced orders.

③

- Reduced orders from mill reach retail, and stocks decline back to desired level.
- Reduced orders from the forest also reach the mill, so mill stocks decline below the desired level.
- This means that orders from retail and mill go above the baseline level, as the stocks are low but the average sales are increasing.

④

- After the reference period on average sales (here 10 days) is over, the average retail sales return to normal.
- This shows as an inflexion point on all traces.

⑤

- The retail stocks reach their lowest point, due to the combination of a lower desired stock level, and delayed under-estimated orders.

⑥

- Shortly after the retail hits the lowest point, the mill does too.
- This is matched by a peak in the harvest ordered.

⑦

- Through heavy ordering, the retailer manages to bring the stock back to baseline – and above. The subsequent peak in retail stock occurs 21 days after the original spike.

⑧

- As before, the peak in retail stock is followed by a subsequent peak in mill stock, as the mill is still receiving orders from when it was in deficit.

⑨

- The following peak in retail and mill stocks is attenuated due to the fact that the delays are not pure pipeline delays – once an increased order is placed, a small fraction of that increase will arrive the next day, but it will take the full delay time for the whole amount to arrive. This smoothing applied decelerates the fastest order rates, which in turn limits ~~to~~ the range the stock can grow to. Thus we now see the oscillations tailing off.

⑩

- Around 100 days after the spike, the system can be considered to have returned to equilibrium

Figure 12 – Bullwhip effect due to demand variation

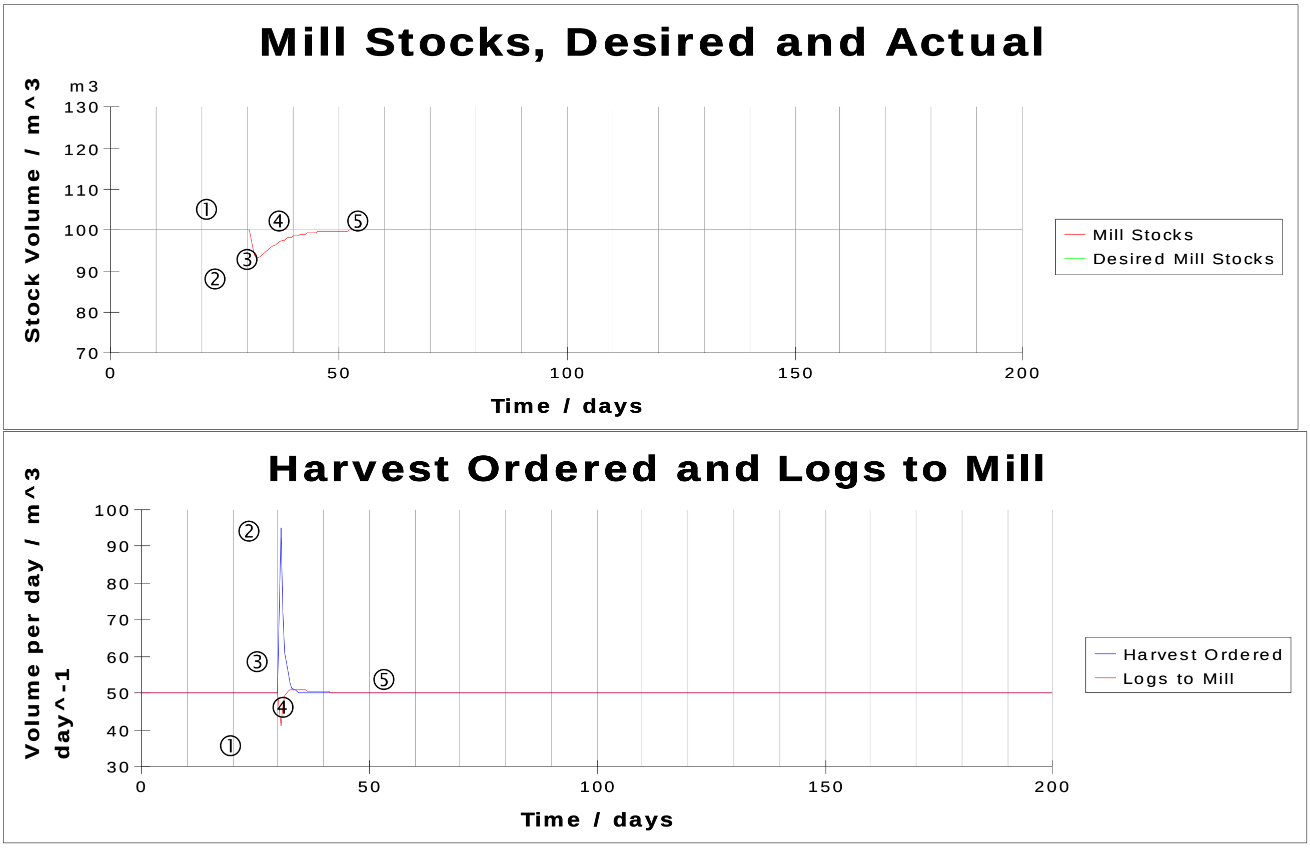


Figure 13 – lack of Bullwhip effect due to supply variation

① Supply is short, so mill uses some of its stocks to fill that day's order. Shipments to the retailer, and hence expected sales, do not change, so the desired mill stocks stay the same.

② The mill places a larger order to fill the deficit in its stocks, whilst still filling the retailer's orders as usual.

③ The increased stocks start making it through to the mill, so they subsequently reduce their orders.

④ The mill reduces its orders as the stock begins to arrive, to the point where the extra orders and the shortage both tend to zero at the same point.

⑤ Equilibrium resumes.

Figure 14 – Lack of Bullwhip effect due to supply variation

CONCLUSION

We have conclusively proved that the bullwhip effect does not occur for variation in supply. Whilst this is a null result, null results can often be extremely enlightening[20]. We see that the dynamics of a supply chain prioritise demand variation greatly above that of supply variation. If supply variation is the main concern there is no underlying phenomenon, such as the bullwhip, that must be understood before the chain can be assessed. The stocks held on each tier can be a function of the reliability of the tier above and the delay in receiving goods.

There is no universal rule for good supply chain management; each real-world case must be considered on its own grounds. Delays should be reduced and infrastructure simplified wherever possible, and information on orders and stock levels should be shared throughout the chain. This must be assessed on a local scale, and there have been many studies showing the success of such practice..[4,13,18,21,30] It is extremely important to be aware of the bullwhip effect in supply chain management, and also we have shown that efforts to minimise it are best targeted at the later stages of the chain. Activities that induce demand variation – e.g. batch ordering, mid-chain 'hidden' uncertainty (such as unknown grades in a log) and over-ordering should all be examined as possible targets for improving supply chain dynamics

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APPENDICES

Powersim Equations

Name	Unit	Definition
Supply		100+PULSE(-70,200<<@day>>,1500<<day>>)*1<<day>>
Mill Cover	day	2
Mill transport Delay	day	5
Secondary Processing Cover	day	2
Secondary Processing transport Delay	day	5
Forest Cover	day	2
Retail Cover	day	2
Transportation Delay	day	5
Harvesting Delay	day	5
Mill Order Backlog	m^3	50
Mill Order Policy	m^3	MAX(0<<m3>>,'Mill Shortage'-'Transit from Forest'+'Av Mill Orders Filled'*1<<day>>)
Mill Shortage	m^3	'Desired Mill Stocks'-'Mill Stocks'
Desired Mill Stocks	m^3	'Av Mill Orders Filled'*('Mill Cover'+'Mill transport Delay')
Mill Stocks	m^3	100
Transit from Forest	m^3	250
Secondary Processing Order Backlog	m^3	50
Secondary Processing Order Policy	m^3	MAX(0<<m3>>,'Secondary Processing Shortage'-'Transit from Mill'+'Av Secondary Processing Orders Filled'*1<<day>>)
Secondary Processing Shortage	m^3	'Desired Secondary Processing Stocks'-'Secondary Processing Stocks'
Desired Secondary Processing Stocks	m^3	'Av Secondary Processing Orders Filled'*('Secondary Processing Cover'+'Secondary Processing transport Delay')
Secondary Processing Stocks	m^3	100
Transit from Mill	m^3	250
Desired Retail Stocks	m^3	'Av Retail Sales'*('Retail Cover'+1<<day>>)
Retail Shortage	m^3	'Desired Retail Stocks'-'Retail Stocks'
Retail Stocks	m^3	100
Transit from Secondary Processing	m^3	500
Retail Order Policy	m^3	MAX(0<<m3>>,'Retail Shortage'-'Secondary Processing Order Backlog'+'Av Retail Sales'*1<<day>>)
Forest Harvest Policy	m^3	MAX(0<<m3>>,'Forest Shortage'-'Wood in Harvesting'+'Av Forest Orders Filled'*1<<day>>+1<<m^3>>)
Forest Shortage	m^3	'Desired Forest Stocks'-'In-forest Stocks'
Desired Forest Stocks	m^3	'Av Forest Orders Filled'*('Forest Cover'+'Harvesting Delay')-1<<m^3>>
Forest Order Backlog	m^3	50
In-forest Stocks	m^3	100
Wood in Harvesting	m^3	250
Mill Orders Sent	m^3/day	MAX('Mill Order Policy',0<<m3>>)/ 1 <<day>>
Secondary Processing Orders Sent	m^3/day	MAX('Secondary Processing Order Policy',0<<m3>>)/ 1 <<day>>
Harvest Ordered	m^3/day	MIN(supply*1<<m3>>,MAX('Forest Harvest Policy',0<<m3>>))/ 1 <<day>>
Wood to Secondary Processing	m^3/day	MIN('Mill Stocks','Mill Order Backlog') / 1<<day>>
Product to Mill	m^3/day	'Transit from Forest'/'Mill transport Delay'
Mill Backlog Orders Filled	m^3/day	'Wood to Secondary Processing'
Av Mill Orders Filled	m^3/day	SLIDINGAVERAGE('Mill Backlog Orders Filled',7<<day>>,'Mill Backlog Orders Filled')
Wood to retail	m^3/day	MIN('Secondary Processing Stocks','Secondary Processing Order Backlog') / 1<<day>>
Product to Secondary Processing	m^3/day	'Transit from Mill'/'Secondary Processing transport Delay'
Secondary Processing Backlog Orders Filled	m^3/day	'Wood to retail'
Av Secondary Processing Orders Filled	m^3/day	SLIDINGAVERAGE('Secondary Processing Backlog Orders Filled',7<<day>>,'Secondary Processing Backlog Orders Filled')
Av Forest Orders Filled	m^3/day	SLIDINGAVERAGE('Forest Backlog Orders Filled',7<<day>>,'Forest Backlog Orders Filled')
Av Retail Sales	m^3/day	SLIDINGAVERAGE(Sales,7<<day>>,Sales)
Retail Orders Sent	m^3/day	MAX('Retail Order Policy',0<<m3>>)/ 1<<day>>
Sales	m^3/day	MIN('Retail Stocks',Demand*1<<day>>) / 1<<day>>
Wood received	m^3/day	'Transit from Secondary Processing'/'Transportation Delay'
Wood to Mill	m^3/day	MIN('In-forest Stocks','Forest Order Backlog') / 1<<day>>
Logs to Skid	m^3/day	'Wood in Harvesting'/'Harvesting Delay'
Forest Backlog Orders Filled	m^3/day	'Wood to Mill'
Demand	m^3/day	50<<m^3/day>>+STEP(20<<m^3/day>>,200<<@day>>)