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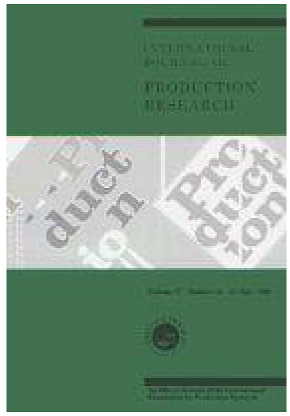

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Abstract

'Bullwhip' is the phenomenon experienced in practice, signifying the propagation and amplification of orders as they pass upstream in a supply chain pipeline. 'Bullwhip' creates uncertainty for managers who then create stock and/or maintain excess capacity leading to increased total costs. A well known descriptor of the phenomenon is the MIT Beer Game simulation.

We use the Beer Game to describe and explore a different phenomenon we term the 'backlash' effect. This is the resulting impact of the 'bullwhip' effect on shipments downstream. The two effects described have analogue with amplitude pressure wave propagation ('bullwhip') and reflection ('backlash') in physical systems such as flow ducts. We use the Fourier Transform method to describe the 'bullwhip' propagation and 'backlash' reflections. We conclude that the 'backlash' effect occurs due to the ready availability of capacity in the whole supply chain and inventory in the final echelon.

Keywords: Supply chain management; Beer Game; backlash effect; simulation, Fourier transforms

1. Introduction

The 'bullwhip' effect is a well documented phenomenon that occurs in real-world supply chains (Lee et al., 1997a and b; Fransoo and Wouters, 2000; Geary et at., 2006). It describes the propagation and amplification of orders from one re-ordering system to another upstream in a supply chain, which, may then be considered as a single pipeline. The 'bullwhip' effect causes uncertainty in supply chain planning and management leading to increased on-costs as organisations in the supply pipeline mitigate against the potential risks in customer service levels by, say, increasing available capacity or increasing stock holding (Metters, 1997). Much research has been undertaken in understanding the fundamental root causes of the 'bullwhip' effect and subsequently in identifying potential solutions. However, the focus of almost all of these studies has been on orders and inventories with its impact on shipments (and consequently on the transport function) being mostly overlooked. For example, there is only a brief mention about demand amplification causing increase in transport costs due to inefficient scheduling and premium transport rates by Lee et al., (1997a) in a seminal paper on bullwhip. Lack of shipment consideration is still evident ten years later. However, for transportation this continues to be a critical issue. Boughton (2003) for example, routinely encountered fleet utilisation decreases on weekly and monthly cycles. According to him shippers operated with the belief that any short term demand changes and uncertainties would be managed by the transport companies. Similarly, Steinke et al. (2003) describe how logistics operators adjust their operations to accommodate amplified shipment requirements. The cost of managing fluctuating dynamics is significant ,which, for production has been estimated to be proportional to the cube of the deviation around the average production level (Stalk and Hout, 1990) and whose reduction could result in increased profitability of between 22% and 53% (Metters,1997). The transport function being similarly capacitated as production and with an additional disadvantage of non availability of buffers therefore faces similar high costs/lower profitability from shipment dynamics (analogues to order dynamics for production) from the need to ramp the capacity up and down as well as from loss of customers/revenue due to poor service. At the moment these costs are being absorbed by the transport companies. However, with the role of transportation becoming increasingly critical in meeting the cost and customer service expectations of customers (Stank and Goldsby, 2000; Gaurav, 2004; Tracey, 2004), a more in depth study of shipment dynamics is required. This is what we attempt to do in this paper by exploring the shipment dynamics associated with the reflection of the orders downstream in the supply chain what we term as the ‘backlash’ effect. Two generic definitions of ‘backlash’ are;

“A sudden or violent backward whipping motion” (Farlex, 2007)

“A movement back from an impact” (Wordreference.com, 2007)

'Backlash' effect arises from 'bullwhip' for which five major sources have been identified in the literature. These are demand signal processing, batching, price fluctuations, shortage gaming (Lee et al., 1997a) and behavioural (Sterman, 1989). The focus of this study is on Demand signal processing induced 'backlash'. Demand signal processing as a cause for 'bullwhip' is considered critical as compared to other causes (Miragliotta, 2006) and has seen a large number of academic as well as practitioner studies. However, none of these studies has studied its impact on shipments which constitutes a gap. In terms of methodology we used a multi method approach in this study. The Massachusetts Institute of Technology (MIT) Beer Game (Sterman, 1989), a popular method for analysing the 'bullwhip' effect (Chen and Samroengraja, 2000; Croson and Donohue, 2003) which controls for all but the demand signal processing and the behavioural causes was used to get evidence of the 'backlash' effect. We were unable to identify any literature where the Beer Game has been used to study the backlash effect of shipments and this also is a novelty of this paper. To increase the validity of our findings, we complimented the Beer Game with a systems dynamics simulation model of the same so as to eliminate the behavioural aspect again a common approach (Hong Minh et al., 2000; Naim, 2006). Finally, from a practitioner perspective we explored the effectiveness of the Fourier transform technique in compactly representing the 'backlash' effect which could subsequently be used for detecting the same.

To summarise, the aim of this paper is to explore the 'backlash' effect or reflection of shipments in response to amplification in orders. We will describe the 'backlash' behaviour and draw analogies with the physical propagation / reflection of waves, determine its dynamic characteristics, reflect on possible causes and discuss its managerial implications. The specific research questions that we are seeking to answer in this study are:

1) Does 'bullwhip' (order amplification) induce a corresponding 'backlash' effect in shipments, and if so, what is the behaviour of the 'backlash' effect and its principal cause?
2) What technique could be used for detecting the 'backlash' effect?

The paper is structured as follows. In the next section we review existing literature on the 'bullwhip' effect and identify any papers that discuss or allude to the 'backlash' effect. Section 3 describes our method, which includes desk and computer based versions of the MIT Beer Game to understand the 'backlash' effect and the use of Fourier transform technique in detecting it. In Section 4 we present our findings. We conclude with Section 5 where we discuss the analysis and highlight the research and practical implications of the 'backlash' effect.

2. Literature Review

The nature of this research being of an exploratory nature, an exhaustive literature search was conducted spanning multiple databases such as ABI Inform, EBSCOHost, Emerald and IngentaConnect. A range of key word searches were made such as 'bullwhip', 'backlash', 'shipment dynamics', 'bullwhip and shipments', 'shipment amplification' and 'bullwhip and transport/freight'. While 'bullwhip' related searches yielded a large number of hits, results from shipment related queries were minimal. For the latter, therefore, we went through papers with 'bullwhip' themes individually to see evidence/explanation of the 'backlash' effect. This also yielded limited success as we discuss in the paragraphs below.

2.1 The 'Bullwhip' Effect

The 'bullwhip' effect defined as the amplification of demand from a downstream site to an upstream site has a direct impact on the shipment dynamics as the orders require to be shipped, though order backlogs also have an influence on this dynamics. 'Bullwhip' has been observed in individual industries as well as at a macroeconomic level for many years and has been the focus of a large number of studies. Two comprehensive recent studies are one by Geary et al. (2006) who carried out a past, present and future analysis and another by Miragliotta (2006) whose review covers its empirical assessment, causes and remedies. There are four main operational causes of the 'bullwhip' effect in a rational decision making environment (Lee et al., 1997a):

1) *Demand Signal Processing and Lead times (Forrester Effect)*: Compounding of forecasts from use of statistical forecasting techniques which get further magnified due to non-zero lead times
2) *Order Batching* - Forridge Effect (Towill, 1997): Batching of orders used to realise scale economies in production and/or transport
3) *Price Fluctuations*: Demand fluctuations from price based promotions
4) *Shortage Gaming*: Excess ordering in shortage situations/capacity bottleneck at suppliers

An additional behavioural cause was suggested by Sterman (1989) which arises from the cognitive limitations of human beings in handling dynamic complexity. In the context of the Beer Game he observed that participants tended to underestimate the supply line and placed orders without taking into account their past orders. This decision bias caused over ordering and the 'bullwhip' effect for upstream players. The existence of the behavioural causes of the 'bullwhip' effect has been demonstrated in a variety of laboratory settings by many researchers (Chen and Samroengraja, 2000; Croson and Donohue, 2003; Croson and Donohue, 2006; Diana and Katok, 2006).

The nature of the 'backlash' could depend on the cause of 'bullwhip' for which we have used the framework suggested by Miragliotta (2006). Price fluctuations, gaming and process reliability act as 'triggers' to the 'bullwhip' effect by disturbing the demand signal/supply chain process and can be effectively filtered by managerial action. On the other hand demand signal processing (Forrester effect), batching and behavioral causes classified as 'determinants' which amplify the demand variance and require significant redesign action are more critical. The 'determinants' therefore require priority focus with regard to studying their impact on the 'backlash' effect from which the batching aspect was recently studied by Disney et al. (2003). This paper is therefore aimed at exploring the 'backlash' in shipments arising from Demand Signal Processing (Forrester Effect). The Forrester effect has been the most extensively studied 'bullwhip' cause among practitioners as well as the academic community and therefore the 'backlash' effect arising from it is very relevant as a means of obtaining consistency in approach in understanding supply chain dynamics behaviour.

2.2 The 'Bullwhip' Effect, Shipments and 'Backlash'

The literature review revealed a large number of studies on the 'bullwhip' effect. However, studies which have explored its impact on material/goods shipments or 'backlash' are very few as seen in Table 1.

Table 1

In many of these studies shipments get only a brief mention with their predominant focus being on the 'bullwhip' effect. Their scope is also narrow and limited to 1 or 2 echelons. Lee et al. (1997b) shows significantly amplified shipments vis-à-vis orders for a single echelon in a food supply chain in the context of price fluctuation induced 'bullwhip'. A similarly amplified supplier to OEM shipment profile is depicted by Taylor (1999) for an automotive supply chain. The context in this case was the 'bullwhip' induced by production batching. This was also the 'bullwhip' context in the study by Hejazi and Hilmola (2004) who depict shipment dynamics for two echelons in an electronics supply chain which is indicative of the 'backlash' effect. The two echelon shipment profiles depicted by Kaipia et al. (2006) also give some evidence of the 'backlash' effect. However, in all these studies there is no discussion, explanation, or analysis about shipments or 'backlash'.

There are a few studies which have discussed shipments/'backlash' explicitly. Holweg and Bicheno (2000) used the case study of a steel supply chain to demonstrate amplified and distorted shipment patterns, what they called 'reverse amplification'. They speculated that it was caused by supply/throughput constraints in response to amplified demand patterns. However, their understanding about this phenomenon was limited for which they recommended further simulation study to understand its causes, its quantification and prediction. Naim et al. (2002) identified via empirical data in the automotive sector, differences between order variance and shipment variance in a logistics triad, namely a customer, supplier and third party logistics provider (3PL). They found that the variance of the shipments from the 3PL to the customer was less than half of that from the supplier to the 3PL though no detailed explanation was provided for the same. However, based on the details of the case one can speculate that it was because of multiple 'bullwhip' operational causes with the dominant impact from the Forrester effect. Similarly, Hines et al. (2000) use the analogy of waves on a beach to analyse what they term as 'splash back'. They considered water flowing up a beach as analogous to information flow, which, when it hits a breakwater, breaks up and "splashes back" in a greatly distorted and magnified form, analogous to material or goods flow. They deduced that such an effect was due to large batch policies of upstream suppliers. However, their approach was conceptual and did not give detailed evidence or explanation. A more quantitative simulation based approach to analyse shipments and supply chain dynamics was used by Disney et al. (2003). They compared different supply chain designs such as traditional, internally consolidated (batching into truck loads) and Vendor Managed Inventory (VMI) from the viewpoint of manufacturing-transport fluctuation tradeoffs and associated cost implications. However, their use of the dyad as the unit of analysis precluded fully studying the 'backlash' effect that we define in this paper.

Overall we find that there is only one study which has done some detailed analysis of the shipment behaviour. However, it was conducted with a limited dyadic scope and had its focus on batching as a factor. The dynamic behaviour of shipments in a multi echelon supply chain arising from the Forrester effect therefore constitutes a research gap which this paper seeks to fill.

3. Method

Limited research on the 'backlash' effect meant that there were few precedents in terms of choosing appropriate methods. However, substantive research on the order and inventory dynamics ('bullwhip' effect) served as a good reference. This has been detailed in Section 3.1 which also explains why the Beer Game was used, its operational details and the need to complement it with a simulation based approach. Section 3.2 gives the details of the simulation model including the ordering rule and parameters used with Section 3.3 describing the methods for detecting the 'backlash' effect and the appropriateness/effectiveness of choosing the Fourier transform.

3.1 Methods for studying dynamic behaviour in supply chains

A range of methods have been used to analyse the dynamic behaviour of supply chains out of which the most widely used are:

Statistical: Studies based on these such as Lee et al. (2000) and Chen et al. (2000) provide insights about the impact and nature of demand (autoregressive parameters, standard deviation) and supply chain characteristics (information flow, lead time) on inventory costs and demand amplification. However, the snap shot nature of output from these studies means that there is limited insight obtained about the cause and effect of system structure and performance. This method is therefore inappropriate for this study whose aim is to understand the 'backlash' effect and its causal mechanism.

Control theory: This method focuses on evaluating and improving supply chain design (Ortega and Lin, 2004; Dejonckheere et al., 2003; Gaalman, 2006). It involves representing the supply chain using mathematical equations based on transfer functions which are then solved to get exact values for performance measures. This method was also not considered for this study because of its linearity requirement, large cumbersome mathematics with multi echelon structures and inability to handle discrete time delays by a certain category of models.

Beer Game: The Beer Game (Sterman, 1989) represents a typical production-distribution system with four echelons (retailer, wholesaler, distributor and factory) where the player managing each echelon enacts the role of an inventory manager and makes decisions on ordering from his/her supplier. The decision environment is complex with a non-stationary demand pattern, time delays in ordering and shipment, uncertainty in behaviour of suppliers and customers, short response times and the need to optimize inventory/backlogs. Despite being a considerable simplification of reality, it still provides a controlled environment to study the 'bullwhip' effect. It is therefore not surprising to find extensive use of the Beer Game in many 'bullwhip' related studies (Croson and Donohue, 2003; Disney et al., 2004; Croson and Donohue, 2006; Diana and Katok, 2006).

Given the extensive use of the Beer Game to understand the causes of 'bullwhip', we have used the same to understand the dynamic behaviour of shipments. Shipments have not been studied in any of the Beer Game studies in the literature. The structure of the game and the protocol that we used in this study is similar to that used by Sterman (1989) as it allows studying the impact of the Forrester effect on shipments in isolation from the other three operational causes identified by Lee et al. (1997a), batching, price promotion and gaming. The only difference in our protocol was that participants were required to record shipments as well as orders, inventory and backlogs. We used a 25 week time period in each game so as to balance between the requirements of gaining adequate insight and efficiency. The participants of the game were Masters Students in logistics at our University who had varied industrial and academic backgrounds and levels of experience. Outputs from 35 games played in the period from 2003 to 2007 were considered in this study.

System Dynamics Simulation: This method was advocated by Forerster (1958) as a method of investigating the dynamical effects in large, complex systems. It has significant advantages vis-à-vis analytical studies in terms of ability to cope with non-linearities and visualization and understanding of cause effect relationships. Because of this it has seen extensive application in understanding supply chain dynamics especially those arising from the 'bullwhip' effect (Angerhofer and Angelides, 2000; Villegas and Smith, 2006; Potter and Disney, 2006). However, there has been only one study which has used system dynamics to explore shipment behaviour. Disney et al. (2003) used systems dynamics to understand the impact of batching on shipments, but, their scope of study was restricted to a dyadic structure.

In this study we have complemented the Beer Game with a system dynamics simulation model of the same so as to methodologically triangulate the findings (Seaker et. al., 1993). Beer Game output is characterized by significant presence of noise as found by Sterman (1989), Croson and Donohue

(2006) and other researchers who found low fitment of ordering regression parameters to the game data. This arises from the irrational or inconsistent behaviour demonstrated by many players in the game. In our Beer Game output also the dynamic behaviour of shipments was not clear as only a small proportion of teams displayed the 'backlash' effect. Using the Beer Game results in conjunction with output from a system dynamics model in which consistent and rational decision rules are used therefore increase the validity of the study findings. The simulated approach also facilitated exploring the impact of alternative decision policies and lead times on the 'backlash' effect which would either have been impossible or cumbersome to conduct in the Beer Game experiments. A similar sequentially combined Beer Game and systems dynamics approach has been used by Hong Minh et al. (2000) in the context of emergency transhipments and centralized stock control dynamics, and by Naim (2006) who, based on Disney et al. (2004), undertook a net present value assessment of e-business impact on supply chains.

System Dynamics simulation can be carried out using different structures, number of echelons, decision rules and parameters. Using common structures and approaches, however, facilitates model validation and comparison of results. The Beer Game structure has been used by a large number of researchers in the context of supply chain dynamics. Ackere et al. (1993) used a system dynamics model of the Beer Game to demonstrate reduction in 'bullwhip' or order amplification from supply chain redesign strategies. Larsen et al. (1999) used a similarly simulated model of the game to demonstrate chaotic behaviour. Recently, O'Donnell et al. (2006) used this model of the Beer Game with genetic algorithms to determine optimal ordering for each supply chain player. Given that the Beer Game despite its simplification is still reasonably representative of real world supply chains (Larsen et al., 1999) and that it has been extensively used by the academic community to study order dynamics, we applied it for doing a simulated study of the dynamics of shipments and the 'backlash' effect.

3.2 System Dynamics model of Beer Game

The key considerations in the continuous simulation (or system dynamics) model of the Beer Game were the ordering rule or heuristics and parameter values. We chose the ordering rule based on John et al. (1994), which is typically applied by the 'best' players of the Beer Game and is given in Figure 1.

Figure 1

This rule has been applied in industry (Evans et al. 1997), in determining the dynamic implications of pipeline control in whole supply chains (Mason-Jones et al. 1997), in vendor managed inventory (Disney and Towill, 2002) and in remanufacturing (Tang and Naim, 2004). In the Beer Game ,however, the rule has been modified to explicitly include shipments and to take into account non-linearities associated with the backlog situation where shipments are set to zero when there is no inventory available and to ensure that when inventory does become available an echelon ships what is ordered plus any backlog that has been accumulated. Table 2 below shows the translation of Figure 1 into difference equations incorporating the non-linearities. The equations have subsequently been incorporated into a Microsoft® Office Excel 2003© spreadsheet. Excel has been used for the sake of convenience though proprietary software packages such as Vensim® or Stella®/I-Think® could also have been used.

Table 2

Different decision policies to assess their impact on shipment dynamics have been applied. These are based on changing the values of the T_i, T_a and T_w parameters which are:

a) T_a or Time to average incoming orders: This determines the length of time used to smooth incoming orders. Higher values of T_a imply greater smoothing which therefore impacts on the degree of 'bullwhip' but this leads to lower sensitivity in picking up changes in demand signals

b) T_i or Time to recover desired inventory: A lower time to recover target inventory results in faster system response, but, causes significant volatility of the order rate leading to higher 'bullwhip'. Higher levels of T_i result in greater inventory recovery times hence affecting customer service

c) T_w or time to recover desired work in progress: Incorporation of T_w in the ordering rule provides pipeline feedback with greater feedback resulting in lower 'bullwhip'. The fraction of feedback is $1/T_w$. The impact on 'bullwhip' is the inverse to that from T_i.

The different policies considered are based on Mason-Jones (1998) and are:

- Hardware analogue "optimum" design - T_i: 3, T_a: 6, T_w: 6: Rational rule based on 'hard' engineering systems (John et al., 1994)
- "Optimum" cost design - T_i: 3, T_a: 1.5, T_w: 3: Rational rule based on optimising total cost (Sterman, 1989) which adequately compensates the order pipeline
- Hardware analogue "optimum" design with greater feedback - T_i: 3, T_a: 2, T_w: 6: Variant of the hardware analogue decision logic with greater order pipeline feedback

Besides assessing the impact of alternative decision policies on the 'backlash' effect we also assessed the latter's sensitivity to shipment lead time changes. Shipment lead time change would impact shipments through change in order amplification and backlogs which would affect the nature of the 'backlash' effect across multi echelons. We analysed the 'backlash' effect with a base shipment lead time value of 2 and ± 50% for all echelons.

3.3 Methods for detecting the 'Backlash' effect

Choosing an appropriate method for detecting the 'backlash' effect was based on its effectiveness in capturing the intrinsic relationship between the 'backlash' and the 'bullwhip' effects. If found effective, this method could then be applied to a new situation, to detect the 'backlash' effect. Typical time series methods for univariate/multivariate analysis include autocorrelation/cross correlation functions in the time domain and fourier/wavelet transforms in the frequency domain (Chatfield, 2004). However, the effectiveness and accuracy of a particular technique depends on the nature of data in the application domain. Data in the supply chain domain typically has a significant seasonal component which arises either exogenously and/or endogenously from time delays and feedback loops in decision making. Fourier transform method is most suited for analyzing such data and operates by decomposing a time series pattern into its constituent sinusoidal components at different frequencies. This well established method is robust to noisy data and capable of bringing out hidden periodicities not apparent in the time domain (Hearn, 1995). Suitability of this method for such an analysis has recently been demonstrated by Thornhill and Naim (2006) who used it in the context of rogue seasonality detection. We therefore tried this method on both the actual and simulated game's order and shipment data to assess its effectiveness in detecting the 'backlash' effect. The Fourier transform analysis was carried out using Matlab®.

4. Results

4.1 Beer Game output analysis

A total of 35 games played by Master's students in our University were analysed out of which 9, found to have errors or evidence of gaming behaviour, were discarded. The overall quality of Beer Game output therefore compares favourably with Sterman (1989) who found only 11 out of 44 games to be error free. Order traces of the players showed the classic 'bullwhip' effect clearly for 11 out of the 26 games. For a further 6 games, 'bullwhip' was apparent though not for all the echelons/players. The order profiles were characterized by increase in variance as well as lags as these propagated upstream from retailer to factory which is consistent with previous research on the Beer Game. However, when we considered the shipment traces we noted quite a different effect, that of upstream echelon traces leading the downstream echelons. This effect was, however, not observed for all games with only 6 of 26 showing it clearly and 9 of 26 showing it partially i.e. only for a few echelons/players. Moreover, the variance in shipments was not consistent across these games with some showing attenuation and others showing constant levels as these are reflected back downstream in the supply chain pipeline. Figure 2 shows the order and shipment traces for a team where the 'bullwhip' and reflected shipment behaviour is clearly evident.

Figure 2

Finally, we considered order and shipment behaviour together so as to assess the correlation between the two. At the overall game level we may expect that games in which 'bullwhip' is apparent (greater order amplification) the reflected shipment behaviour would also be clearly delineated. However, this was not clearly evident from the game outputs. Only 5 game outputs showed clarity in both 'bullwhip' and 'backlash' behaviour with 8 games showing unclear bullwhip with unclear backlash profiles. At the individual echelon/player level we compared maximum orders and shipments for each echelon/player for all game outputs to assess their degree of correspondence. Figure 3 gives the scatter plot of the ratio between maximum order and shipment for each echelon/player for all 26 games.

Figure 3

We can see large variability in the ratio which is not surprising given that players show large differences in their ordering behaviour as found in previous studies (Sterman, 1989). Maximum shipment greater than maximum order was observed for 9 out of 26 games for the retailer,10 out of 26 games for the wholesaler,9 out of 26 games for the wholesaler and 4 out of 26 games for the factory. In the remaining games maximum orders were greater than maximum shipments. Given the mixed nature of observations, conclusive assessment and effective understanding of the order-shipment behaviour was not possible.

Overall, from the evidence of the Beer Game we may conclude that the 'bullwhip' wave is in some way being reflected down the supply chain pipeline, and given the generic definitions of Section 1, we may call this a 'backlash' effect. However, we found this 'bullwhip' 'backlash' relationship to be inconsistent across different game outputs. In some cases while the 'bullwhip' effect was apparent the 'backlash' effect was not. Comparison of maximum orders vis-à-vis maximum shipments also showed an inconsistent relationship. This could have arisen from the conditions of the Beer Game which induce irrational/inconsistent ordering behaviour from the players. Hence, in order to increase the validity of our findings we had the motivation to replicate the Beer Game via computer simulation and attempt to determine whether or not the same 'backlash' effect is observed. If we do observe the same effect then we may deduce that it is due to the same system structure and not merely due to some anomaly created by the players themselves.

4.2 Beer Game simulation analysis

Alternative decision parameters were applied to the system dynamics simulation model of the Beer Game to both validate as well as assess their impact on the 'backlash' effect. Three rational rules were used and involved changing the T_a, T_w and T_i parameter values. The impact of shipment lead time on the 'backlash' effect was also assessed by increasing and decreasing the lead time by one unit for each echelon in the game. Figure 4 shows the order and shipment profiles for different simulation parameters.

Figure 4

In all three traces we note the 'backlash' effect but each with varying characteristics. In Figure 4a) analysis of shipments provides some evidence of attenuation as well as lagged profiles of downstream echelons. Figure 4c) shows that there is no attenuation of shipments but upstream echelons greatly lead downstream echelons. Figure 4b) provides clear evidence of both lagging and attenuation. Hence, the extent of order amplification and shipment attenuation varies with the decision rule with the one having parameters T_i=3, T_a=1.5, T_w=3 showing the lowest values. In terms of relationship between orders and shipments, the latter is more than the former for all echelons except the factory where both are almost equal. At the factory echelon delay is fixed and less than the other echelons which means lower backlogs and faster delivery of material both of which result in minimising the variance between maximum orders and shipments. For the other echelons effective delay for delivery of material is much larger, which, together with backlogs results in shipment surges. This causes maximum shipments to be greater than maximum orders.

In terms of impact of changing the lead time we found that a decrease/increase in shipment lead time caused decrease/increase in maximum orders and shipments for all echelons. The causal loop mechanism for the same is given in Figure 5. Causal loops are conceptual representations of relationships in which arrows are drawn between variables with the one at the tail influencing the one at the head (Sterman, 2000). To distinguish between positive and negative relationships, a plus (+) or minus (-) sign is used.

Figure 5

Reduction in order amplification across echelons by a reduction in lead time is well known and is due to reduction in the Forrester effect with improvements in forecast accuracy and reduction in safety stock. Hence, receipt of material is lower, which, in turn implies that the maximum shipments that could be made are also lower. Also, lower shipment time means that the backlog quantity is also reduced which also reduces the maximum shipments. Therefore, intuitively we would expect maximum shipments to fall with a reduction in lead time and this is what we observe in the simulation analysis. Therefore, overall, the simulation analysis has considerably enhanced our understanding of shipment dynamics or 'backlash'.

4.3 Fourier analysis for 'backlash' detection

The Fourier transform technique was considered because it is suited for processing signals with cyclic features and such features are usually present in supply chain variables. This technique decomposes a time series into sinusoidal components at different frequencies with each frequency represented by its amplitude which gives a measure of the strength or energy of that sinusoidal component and phase which give a measure of its location or shift. Signals are compared at similar frequencies with amplitudes representing the respective signal energies and phase difference indicating whether a time signal is leading/lagging the other signal at that frequency. Phase relationships are usually measured in time periods or radians.

Fourier analysis or forms of it (Thornhill and Naim, 2006; Afify et al., 2007) has previously been used to detect 'bullwhip' and hence has potential for 'backlash' detection. 'Backlash' and 'Bullwhip' are related as given in Figure 5 and therefore if we could profile them together, this could be used as a characteristic signature for detecting the 'backlash' effect. 'Bullwhip' is characterised by amplification in orders as we move upstream with upstream echelons leading downstream echelons. Though for shipments also the upstream magnitudes are greater than that of downstream echelons as discussed in the previous section, the phase relationships are reversed to those for orders i.e. upstream lead downstream echelons for shipments. Therefore, if order and shipment data for all echelons were to be fourier transformed and their amplitudes and phases plotted, we would expect to see a U shaped profile if the 'backlash' effect is present. The appropriate frequency for the plot would be that which corresponds to maximum energy (or amplitude) in orders and shipments for most of the echelons.

In order to test the effectiveness of the above approach, we applied it to the simulated trace shown in Figure 4b and another case with the same decision rule, but, with lead time increased by 1. Both these traces showed the 'bullwhip' and 'backlash' effects in the order and shipment time plots respectively. We also used two outputs from the Beer Game, one which showed the 'backlash' effect and the other which did not show the same in the time domain plots. Figure 6 shows the amplitude- phase plots for the four cases process for which is explained in greater detail below.

Figure 6

Each order and shipment time series profile was fourier transformed to yield amplitude and phase of its constituent sinusoids at various frequencies. Sinusoid with maximum amplitude representing dominant oscillating characteristic was used as the reference for each profile. Each of the order and shipment points plotted in the amplitude (y axes) and phase (x axes) in Figure 6 correspond to this reference. For example, FO or Factory orders in Figure 6a shipment lead time 3 case has a dominant sinusoidal oscillation with amplitude of around 8 units while the corresponding value for DO or Distributor orders is around 4 units. The respective phase values are -2 and -1 which implies that the dominant sinusoid for DO is ahead or leading FO by around 1 radian (Radians can be converted into time units by the relationship 1 time period of sinusoid = 2 π radians)

We see a U shaped profile for both the simulated as well as the role playing version of the Beer game therefore giving clear evidence of the 'backlash' effect. The nature of the U shaped profile for the greater lead time simulated case was wider (greater lead time) and higher (greater amplification in orders and shipments) as expected. As against this the order and shipment points for an actual Beer Game without the 'backlash' effect are scattered and do not form a regular U shaped profile. Therefore, amplitude phase profile of orders and shipments after fourier transform could compactly represent and be an effective basis for detecting the 'backlash' effect. Fourier transforming the data or transformation of the time series data into the frequency domain is fast and easy to implement thereby facilitating adoption of this approach by practitioners.

5. Discussion and Conclusions

In the previous section we have demonstrated the 'backlash' effect in both the desk based and computer simulation versions of the Beer Game. We have demonstrated the use of the Fourier transform method to highlight the dynamic characteristics of the 'backlash' effect vis-à-vis the 'bullwhip' effect. We now relate our findings to previous research and develop propositions for the 'backlash' effect by drawing analogue with the reflection of waves in physical systems. Developing the propositions of the 'backlash' effect will generate further academic endeavour to understand its causes so as to help managers in avoiding/mitigating negative consequences arising from it.

5.1 Understanding the Causative Mechanism

The principal characteristics of the 'backlash' effect as observed in the previous section are:

- Shipment profiles are attenuated as they move downstream in the supply chain, that is, from factory through to the retailer.
- Shipment profiles of upstream echelons lead those of the downstream echelons.

The 'backlash' effect may be attributed to the conditions of the Beer Game. The conditions are exactly the same as those that lead to the 'bullwhip' effect. Hence, as the Beer Game is used as a learning mechanism to understand the causes and potential solutions of the 'bullwhip' effect, the same may be said for the 'backlash' effect. These conditions that lead to both effects are:

- The initial state of the Beer Game, with orders and shipments set at 4 units per week and inventory levels fixed at 12 units, means that as demand at the customer changes from 4 to 8 unites per week, due to the delays in the system, a stock out and hence backlog situation will inevitably occur. Such a backlog situation, combined with the system structure (delays and feedback), exacerbates the inclination for a player to over-order as they see their inventories depleted.
- Each echelon has sufficient capacity and hence there are no constraints in terms of stock holding, shipments or production.
- While backlog situations may occur at any of the four echelons there is also ample availability of raw materials at the factory.

Figure 5 explicitly describes the causal relationship between 'bullwhip' and 'backlash' effects for a single echelon where maximum order quantity equates to 'bullwhip' and maximum shipments equates to 'backlash'. The close loop relationship between the two effects and the role of backlogs in the same is clearly evident. We may also draw an analogue with physical systems for the multi echelon structure. First, we have the 'bullwhip' effect, with a wave that propagates and amplifies, hence gaining energy, as it flows upstream in the pipeline. The wave impacts a 'wall', namely the infinite supply of raw materials, with a resulting transfer of energy as the wave reflects downstream creating a 'backlash'. A loss of energy is evidenced by the attenuation in the wave as it flows downstream.

5.2 Implications for practice

The findings from this research provide experiential and simulation based causal evidence to support the empirical observations of previous research where it was observed that some kind of effect, other than 'bullwhip', was occurring in shipments. While such research maintained the focus on the implications for manufacturing processes and inventory management, this paper additionally considers the service implications of the delivery of goods. The insights from this study are therefore especially relevant to transportation companies. The Fourier transform technique was used for detecting the 'backlash' effect and could be a useful tool for these companies as well as their respective shippers.The shipment dynamics associated with 'backlash' involves fluctuations in distribution capacity requirements. Attenuation in shipments across echelons and the lead characteristics of the attenuation involved require appropriate capacity allocation both temporally and spatially, an aspect highlighted by Hillis (2006). This is especially relevant for small transporters with lower capacities and bargaining power vis-à-vis shippers. In order to continue to provide adequate service in the face of the 'backlash' effect, these companies should explore horizontal collaborative relationships (Naim, et. al., 2007; Mason et. al., 2007) so that spare capacity could be shared. The larger transport companies could explore forming close triadic relationship with the shipper and the customer to optimally manage capacity-service conflict arising out of the 'backlash' effect. It is to be noted that many of these large transport companies manage transport for multiple companies in a supply chain/network and understanding the phased nature of amplified shipments across echelons could help improve planning, acquisition and sharing of assets.

5.3 Conclusions and research implications

This study assessed the impact of demand signal processing (Forrester effect) induced 'bullwhip' on shipments using the well known MIT Beer Game as well as its systems dynamics simulated model. This study fills an important gap in the literature as the focus of most previous studies has been predominantly on order and inventory dynamics. Shipments constitute demand for transport companies and therefore the findings of this study are particularly relevant to them for effective mitigation of the negative cost and performance implications of its dynamics.

The 'backlash' effect characterised by attenuation and phase lags of downstream shipments though evident in a small proportion of actual game outputs was clearly evident in all the simulated outputs where alternative rational decision parameters were used. Analysis of peak orders and shipments for individual echelons also revealed the latter to be greater than the former for all echelons except the extreme upstream factory echelon. This 'backlash' effect arises as a reflection of the order profiles and the associated 'bullwhip' effect because the demand and raw material supply points are located at extreme ends of the supply chain creating an enclosed pipeline. Infinite capacity availability, tendency for backlogs to occur and infinite availability of raw materials explain the principal cause of the 'backlash' effect. 'Backlash' effect depends on the ordering decision rules and the decision rule that minimized shipment amplification was also the same that minimized the order amplification. The impact of shipment lead time on shipments was also analogous to that of orders. Increase in lead time caused increase in peak shipments because of increase in both backlogs as well as orders and receipts. This answers our first research question about generation of the 'backlash' effect in shipments, its behaviour and principal causes. With regard to our second research question about detection of the 'backlash' effect we showed the effectiveness of the

Fourier transform approach. Amplitude-phase plot (after Fourier transform) of orders and shipments for all echelons at the peak frequency form a characteristic U shaped profile when 'backlash' effect is present. The nature of this profile in terms of height and width could also be used to discriminate the severity of this effect. This could be used by transport companies in to formulate effective mitigation strategies.

This research though quite exhaustive, opens up the possibility of still further research. Key research questions that have emerged include the impact of finite capacity and how other alternative demand patterns, both deterministic and stochastic, may impact on the 'bullwhip' and 'backlash' effects as well as their detection. The Fourier transform technique has been used as an example of 'bullwhip' and 'backlash' detection but further testing of this technique and alternatives is still required. There is also a need for empirical studies which would help in assessing the incidence and characteristics of the 'backlash' effect in the real world. Finally, a key aspect that has not been covered and requires further investigation is the impact of cost penalty for late delivery of shipments on the 'backlash' effect. Previous Beer Game studies also have generally ignored this in the context of the 'bullwhip' effect, and the few that have are not comparable as they have used variants of the original game. A more rigorous study to understand the impact of change in penalty costs on 'bullwhip' and 'backlash' effects is required using both the role playing as well as simulated versions of the game, The latter requires explicit relationship between cost penalty and order quantity which could come from the role playing versions of the game.

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Table 1

Studies covering Shipment Dynamics and Backlash

Reference	Industry	No of echelons of Shipment Information	Nature of Analysis	Bullwhip Factor for Shipment amplification	Evidence of Backlash
Lee et al. (1997b)	Food (US)	1 (Mfg --> Distributor)	Brief mention	Price Fluctuation	NA
Taylor (1999)	Automotive (UK)	1 (Supplier --> OEM)	Brief mention as part of case study	Batching – Manufacturing	NA
Hines et al. (2000)	Automotive (UK)	3	Conceptual (waves, beaches, breakwaters)	Batching – Manufacturing	Yes
Holweg and Bicheno (2000)	Steel (UK)	2	Qualitative as part of case study	Batching – Manufacturing and Gaming	Yes
Naim et al. (2002)	Automotive (UK)	2 (2nd tier supplier --> 3PL --> 1st tier supplier)	Qualitative as part of case study	Multiple ,but, primarily Forrester effect	Yes
Disney et al. (2003)	Generic	1 (Mfg --> Distributor)	Simulation (Continuous) Traditional and VMI Supply Chain designs	Batching – Transportation	NA
Hejazi and Hilmola (2004)	Furniture, Electronics (Finland)	Furniture – 1 (Mfg --> Distributor) Electronics – 2 (Component --> Assembly --> Customer)	Qualitative as part of case study	Batching – Manufacturing	Yes
Kaipia et al. (2006)	Electronics (Finland)	2 (Supplier --> OEM --> Channel)	Qualitative as part of case study	Non specific	Yes

Table 2

Difference equations used for simulating the Beer Game

J = Level of the supply chain with J=1, 2, 3, 4 for Retailer, Wholesaler, Distributor and Factory respectively

Incoming Order ^{J} = 4 for t <= 4 for J = 1 (1a)
= 8 for t > 4 for J = 1 (1b)
= Order $^{J-1}$ (t-2) for J = 2 to 4 (1c)

Shipment Received ^{J} (t) = Shipping $^{J+1}$ (t-2) for J = 1 to 3 (2a)
= Order ^{J} (t-3) for J = 4 (2b)

Maximum Shipping ^{J} (t) = Inventory ^{J} (t-1) + Shipment Received ^{J} (t) for J = 1 to 4 (3)

Desired Shipping ^{J} (t) = Backlog ^{J} (t-1) + Incoming Order ^{J} (t) for J = 1 to 4 (4)

Shipping ^{J} (t) = MIN [Desired Shipping ^{J} (t), Maximum Shipping ^{J} (t)] for J = 1 to 4 (5)

Actual Inventory ^{J} (t) = Actual Inventory ^{J} (t-1) + Shipment Received ^{J} (t) - Shipping ^{J} (t) for J = 1 to 4 (6)

Backlog ^{J} (t) = Backlog ^{J} (t-1) + Incoming Order ^{J} (t) - Shipping ^{J} (t) for J = 1 to 4 (7)

Expected Incoming Order ^{J} (t) = Expected Incoming Order ^{J} (t-1) + α [Order ^{J} (t) – Expected Incoming Order ^{J} (t –1)] (8)
for J = 1 to where $\alpha = 1/(1+T_a/\Delta t)$; T_a is the time to average sales or orders for the respective level of the supply chain (assumed equal for all levels in this case); Δt is our simulation time increment set at 1

Desired WIP or DWIP ^{J} (t) = T_p * Expected Incoming Order ^{J} (t) for J = 1 to 4 (9)
where T_p is the lead time between placing an order and receiving the material for the respective supply chain level;

T_p = 3 for J = 1 to 3; T_p = 2 for J = 4 (10)

WIP ^{J} (t) = Order ^{J} (t-1) + Shipping $^{J+1}$ (t-1) + Shipping $^{J+1}$ (t) + Backlog $^{J+1}$ (t) for J = 1 to 3 (11a)
= Order ^{J} (t-1) + Order ^{J} (t-2) for J = 4 (11b)

Error in WIP or EWIP ^{J} (t) = DWIP ^{J} (t) – WIP ^{J} (t) for J = 1 to 4 (12)

Desired Inventory or DINV ^{J} (t) = 12 for J = 1 to 4 for all t (13)

Error in Inventory or EINV ^{J} (t) = DINV ^{J} (t) – Inventory ^{J} (t) (14)

Orders ^{J} (t) = MAX [0, Expected Incoming Order ^{J} (t) + (EINV ^{J} (t) / T_i) + (EWIP ^{J} (t) / T_w)] for J = 1 to 4 (15)
where $1/T_i$ = fraction of inventory feedback and $1/T_w$ = fraction of pipeline or WIP feedback

T_i value for all J's assumed equal; Similarly, T_w value for all J's are also assumed equal

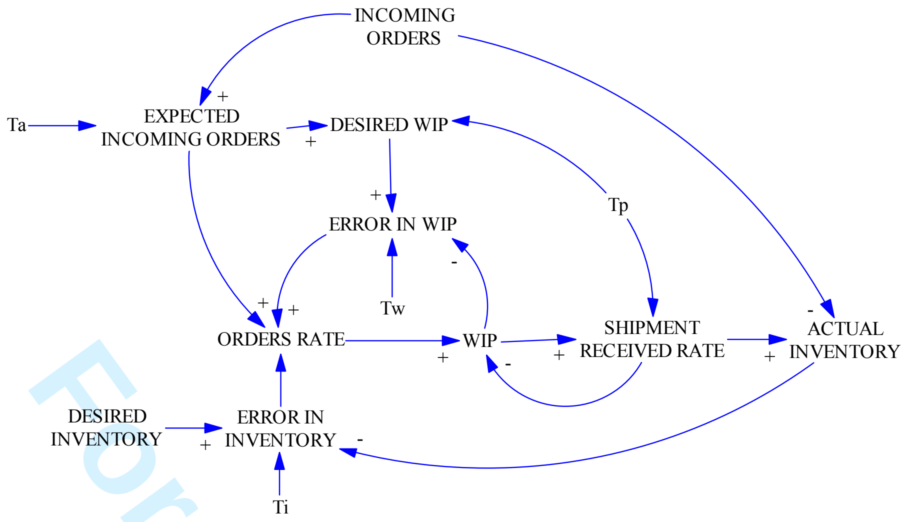


Figure 1

Causal loop of the ordering process of an individual player in the Beer Game

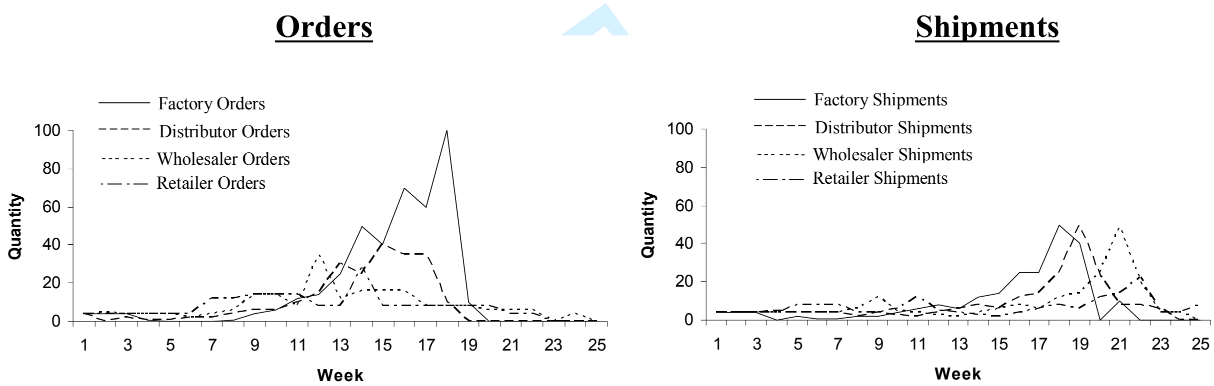


Figure 2

Orders and shipments in actual Beer Game experiments

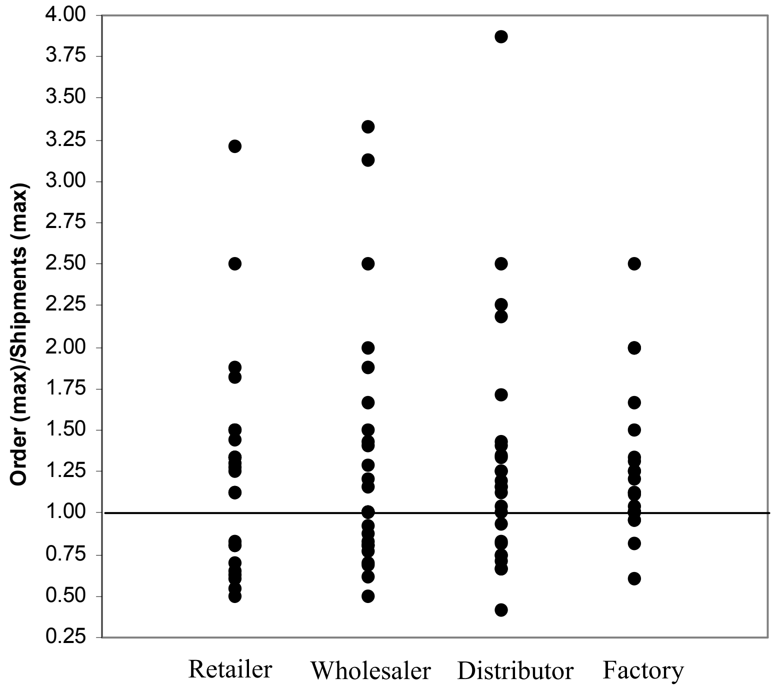
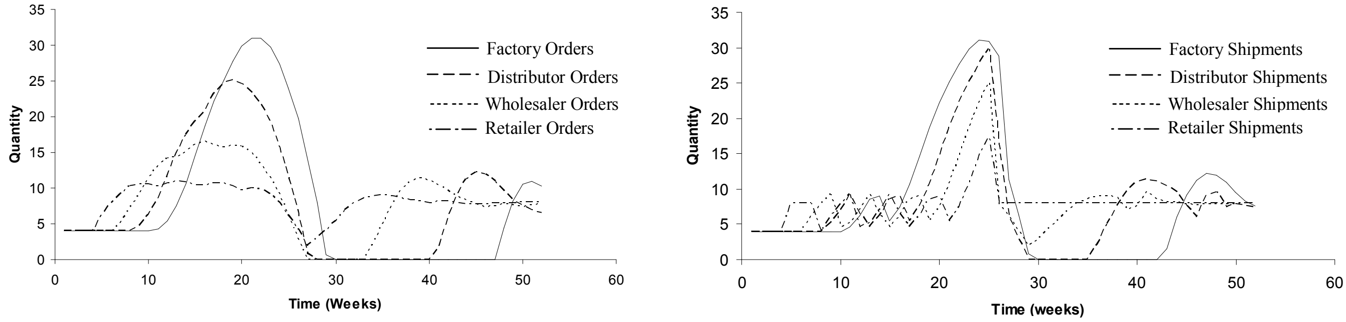
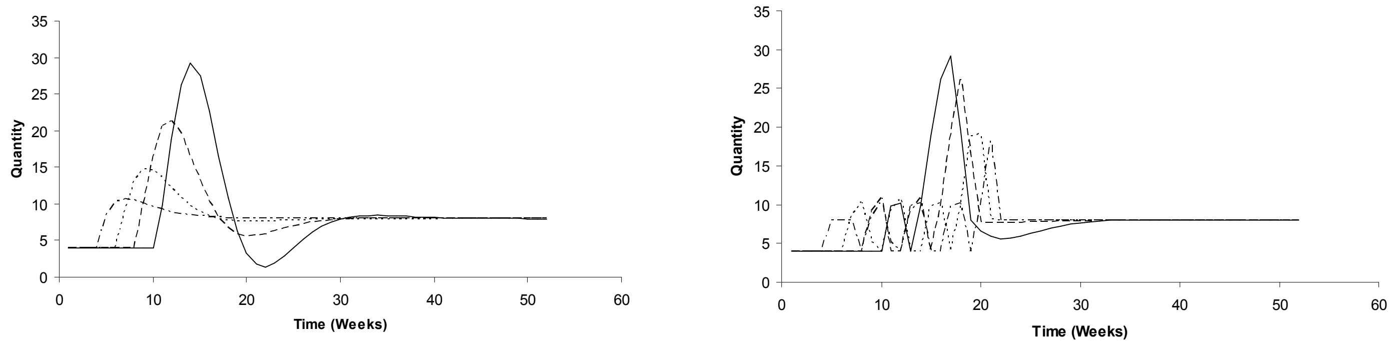


Figure 3
Ratio of Orders (max) and Shipments (max) in actual Beer Game experiments
(Total Games: 26)

a) Parameters used: Tp – 3, Ti – 3, Ta – 6, Tw – 6



b) Parameters used: Tp – 3, Ti – 3, Ta – 1.5, Tw – 3



c) Parameters used: Tp – 3, Ti – 3, Ta – 6, Tw – 2

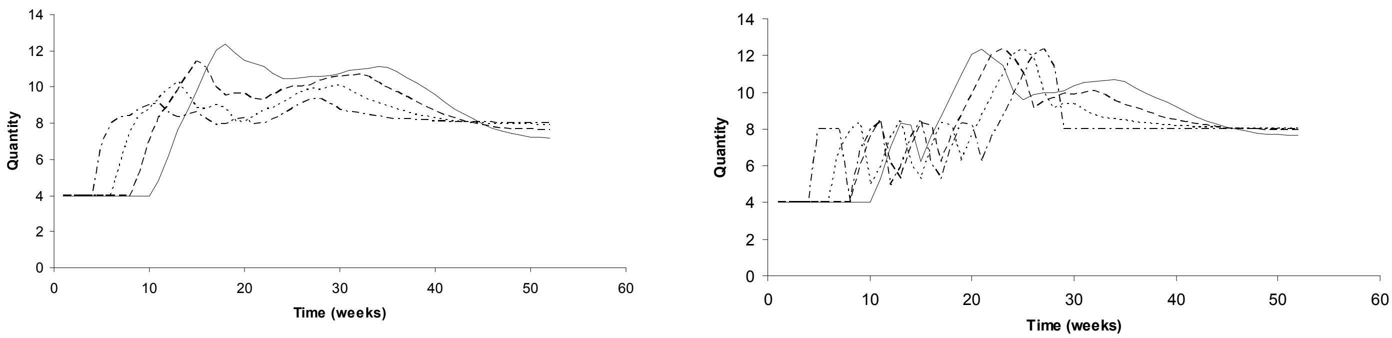


Figure 4

Orders and shipments in simulated Beer Game for select parameter values

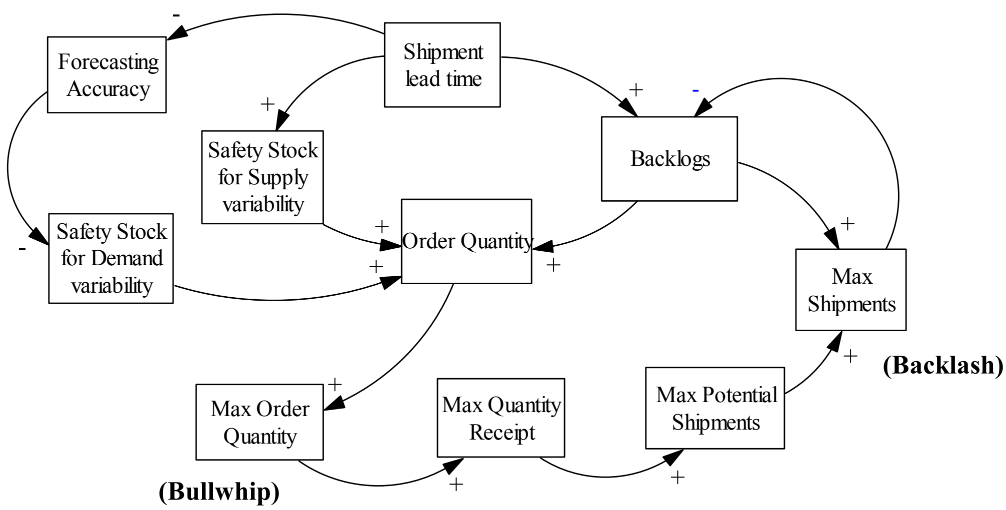
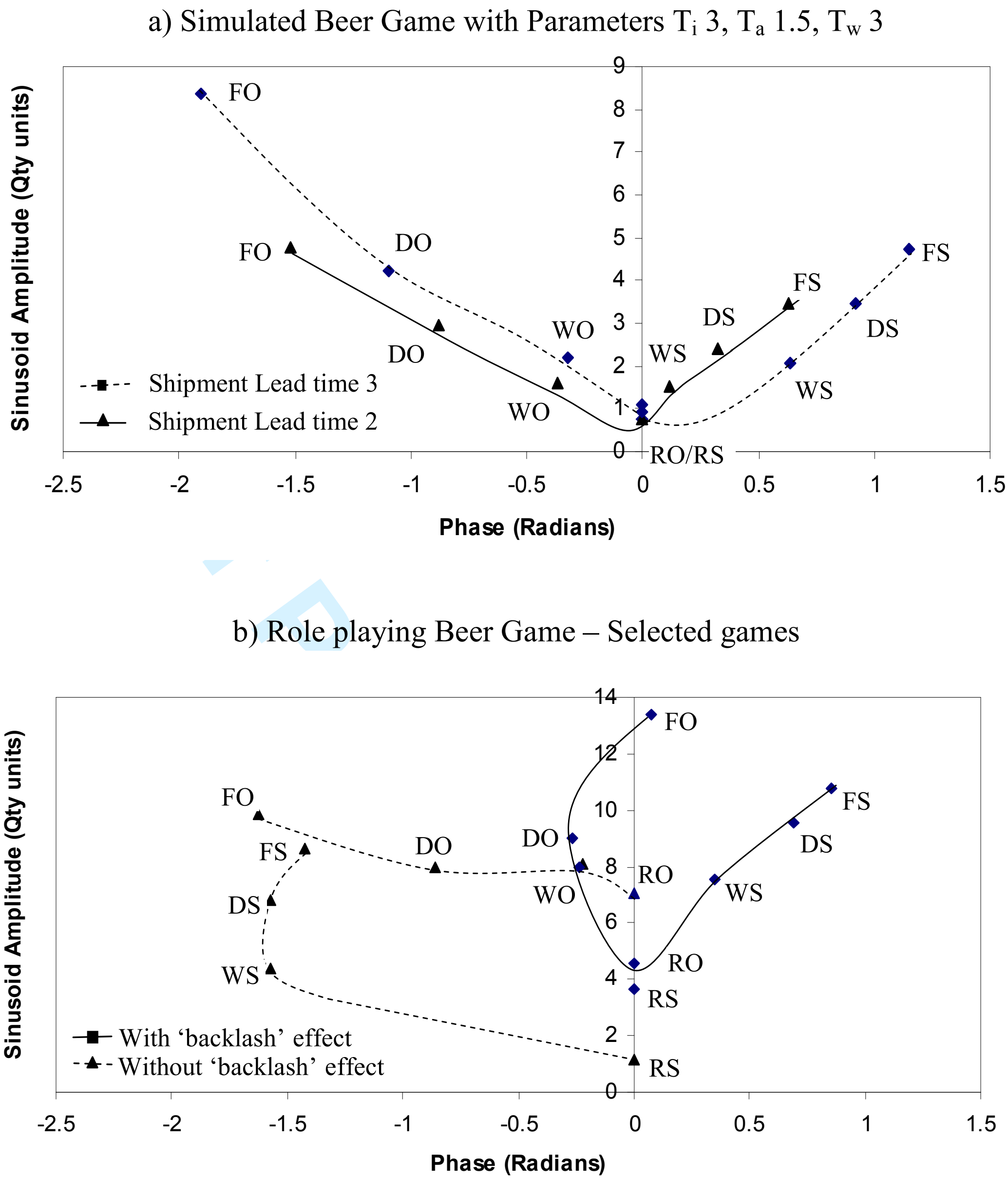


Figure 5
Causal loop for 'Bullwhip' and 'Backlash' Interaction



FO/FS: Factory orders/shipments; DO/DS: Distributor orders/shipments
WO/WS: Wholesaler orders/shipments; RO/RS: Retailer orders/shipments

Figure 6
Amplitude - Phase plot of Orders and Shipments for Backlash Detection