EXPERIMENTING WITH INDUSTRIAL DYNAMICS IN THE FOREST SECTOR – A BEER GAME APPLICATION

Erlend Ystrøm Haartveit
Norwegian Forest Research Institute
Høgskoleveien 12, N-1432 Ås, Norway
erlend.haartveit@skogforsk.no
+ 47 64 94 90 95

Dag E. Fjeld
Swedish University of Agricultural Sciences
Faculty of Forestry,
SLU, 901 83 Umeå, Sweden
dag.fjeld@ssko.slu.se
+ 46 90 786 58 56

Abstract

Two games, called "Wood Supply Games", are developed based on the structure and dynamics of the Beer Game. The games are intended as student exercises in forestry logistics courses. By introducing divergent and convergent flows in the supply chain, the relevance to the forest sector is increased. Results from pilot experiments of the games are presented and discussed in terms of how different degrees of complexity in supply chain structures may affect their efficiency. Measures of efficiency are accumulated costs, amplification of demand and the sample variance of order rates. Results indicate that supply chain performance is negatively affected by increasing rigidity of constraints at points of divergence. Furthermore, lower degrees of efficiency and predictability are observed as complexity of supply chain structure increases. Testing of results and proposed hypotheses can be accomplished by running numerous replications of the games, or alternatively, by development of appropriate simulation models.

Key words (max 10)

Supply chain structure, divergent flows, multiple feedback systems, demand amplification, educational application.

Introduction

Lehtonen (1999) identifies two general supply chain strategies in the Nordic paper industry and names these the efficient and the flexible strategy. The main competitive advantage of the efficient strategy is low cost through economies of scale, favouring high volumes of standardized products (Lehtonen 1999). In contrast, the main competitive advantages of the flexible strategy are described as low inventories and high customer service, requiring higher flexibility, and favouring customized and non-standard products. The two strategies are associated with different control principles; production “push” for the efficient strategy and market “pull” for the flexible strategy.

The potential consequences of demand uncertainty and pull control in industrial supply chains, termed *industrial dynamics*, were first analysed by Forrester (1958). Using simulation models, Forrester (1958) demonstrated how small variations in final customer demand may be amplified upstream in the supply chain, initiated by slow order handling, lack of downstream sales information and immediate corrective actions for inventory discrepancies. The degree of amplification and typical cycles vary from sector to sector. Increasing the degree of market pull control in the forest sector will make knowledge of industrial dynamics potentially more useful.

Material flows can be classified according to their degree of convergence and divergence (Machbeth and Ferguson 1994). Most logistics research is undertaken for flows with convergent (A-type) material flows, exemplified by the audio-visual industry where a large number of components are assembled into few products. Forestry and forest industries have a large degree of diverging (V-type) material flows where few raw materials create a greater variety of products. Demand amplification has been studied in single branches of the forest industries, such as the paper industry (Hameri 1996, Hameri and Nikkola 1999).

The ”Beer Distribution Game”, developed by Sloan School of Management as a part of Jay Forrester’s research on industrial dynamics (Sterman 1984), is used in many university-level logistics programs to empirically demonstrate demand amplification in a simple context. In a four-stage distribution chain, order levels going upstream from each stage are controlled by pull-principles. The Beer Game convincingly demonstrates to the players how instability can arise in managerial systems as a result of decisions made by individuals and the structure of the system (Sterman 1989). In its standard formulation the exercise is built on a straight (I-type) material flow where final customer demand may be amplified by 10-15 times by the time they reach the raw material supplier. The game has since its origination become a sort of a generic laboratory for various types of investigations including applications of business process redesign (van Ackere *et al.* 1993) and analysis of decision making in chaotic environments (Mosekilde and Larsen 1988, Sterman 1988, 1989).

A primary characteristic of wood procurement and sawmilling is the sorting of the raw material into a number of quality classes for further processing to products or product components. An adaptation of the Beer Game's material flow to a divergent pattern, therefore, gives forestry students an environment more relevant to forest industries. This also enables comparison between straight and diverging material flows, giving a better basic understanding of how theory of industrial dynamics may apply to the forest sector, where consumers require an increasing degree of customisation.

Most models of supply chains are unable to take into account effects from network structures in supply chains as they often represent straight (I-type) flows (e.g. Forrester 1958 van Ackere *et al.* 1993, Towill 1996, Mason-Jones and Towill 1997, 1998, 1999, Fowler 1999). To study such effects, diverging or converging flows resulting from branching of the chain must be included in the model. In this paper, branching is included in two different divergent-flow variants of the Beer Game, referred to as Wood Supply Games. Results from the Wood Supply Games are presented and compared to the standard structure of the Beer Game. Due to high variability in results produced by the game, a large number of replications are required for valid statistical analyses.

Goal

The goal of this paper is to generate hypotheses regarding oscillations and demand amplification in diverging environments compared to straight I-type flows. This is accomplished by comparing empirical results from pilot studies of the Wood Supply Games with earlier results from the Beer Game.

Methods

A complete description of the Beer Distribution Game, its rules, operation and debriefing hints can be found in Sterman (1984). The Beer Game consists of four stages that supply consumers with beer according to their demand (Figure 1). Starting from the raw materials, the first position is the brewery, which produces and delivers beer to a distributor (second position). The distributor, in turn, supplies a wholesaler (third position), who supplies a retailer (fourth position). Finally, the retailer sells beer to consumers according to their demand.

Figure 1 – Structure of the Beer Game

Since the positions have different names in the Beer Game and the Wood Supply Games the positions are numbered from first to fourth, where the first position denotes the position furthest upstream in the supply chain, which is the brewery and the wood supply group, respectively. The Wood Supply Games also have four stages (Figure 2), and are based on a chain with a common source for raw materials (the forest). At the first position (wood supply group), the flow diverges into two branches, as pulpwood and sawlogs are distributed to a paper mill and a sawmill. The two mills correspond to the distributor position in the Beer Game (second position), and supply wholesalers and retailers with their respective products. This first variant of the Wood Supply Game is referred to as the divergent variant (Figure 2).

Figure 2 - Structure of the divergent Wood Supply Game

The second variant of the Wood Supply Game was developed to further increase the game's relevance to forest industries. Although having the same basic structure as the divergent variant, chips are separated from lumber products at the sawmill (second position), creating an additional point of divergence for the lumber chain (Figure 3). Chips are thereafter delivered to the paper mill, and mixed with pulpwood for paper production, creating a point of convergence in the flow. This game is referred to as the integrated variant.

Figure 3 – Structure of the integrated Wood Supply Game.

Playing the games

Prior to the game, each chain is supplied with a deck of cards representing the final consumer demand. All experiments with the Wood Supply Games used a sequence of consumer demand identical to the Beer Game: 4 units per week for the first four weeks and 8 units per week for all the remaining weeks of the game. One card is lifted each week and it may only be seen by the fourth position (retailers). Due to delays in transfer of order and shipments of products, there is a four-week lead time between positions, except for the first position, (brewery and wood supply group) which faces a three-week lead time. The game is normally played for 35 order cycles (weeks), where the same operations are repeated once a week. To prevent players from reducing inventories at the end of the game, students are informed that the game lasts for 50 weeks. Weekly orders and inventory levels (inventory or unfilled orders) are recorded for every position. The following three rules should be noted:

1. There is total visibility of inventory levels and goods in transit.
2. The players may only see orders from their immediate customers. Information on order levels is secret and may not be shared with other players. This also accounts for final consumer demand, which is only observed by the fourth position (retailers).
3. All orders must be satisfied, implying that if a player has insufficient inventory to deliver an order, the backlog must be delivered as soon as possible.

The results of the game are judged in terms of total supply chain costs. Cost assumptions for the Wood Supply Games are identical to the ones used in the Beer Game. The cost drivers are inventory and unfilled orders, the latter carrying penalty costs twice as high as the former. Each position seeks to minimize costs based on their estimation of available supply, requirements for inventory and expected demand. Statistical measures of the sequence of orders placed by the players, and changes in inventories are used to describe the dynamics in the chain, thereby indicating supply chain efficiency.

Most positions in the supply chain handle only one product so the only relevant aspect for players is to order quantities sufficient to meet demand. Exceptions from this concern the points of divergence and convergence, which handle two products.

- The first position (wood supply group) in the Wood Supply Games (Figure 2 and 3) experiences restrictions concerning the product mix flexibility, since the percentages of sawlogs and pulpwood delivered from the forest is are subjected to limitations of range.
- The sawmill (second position) in the integrated variant (Figure 3) delivers two products, lumber and chips, and must order sawlogs based on demand for both products.
- The paper mill (second position) in the integrated variant (Figure 3) has certain requirements concerning the mix of the two raw materials in production, and must order appropriate volumes of both raw materials (pulpwood and chips) to be able to produce paper.

The constraints applied to the points of divergence and convergence in the pilot experiments of the Wood Supply Games are presented in Table 1.

Table 1. The variants of the game played, and the restrictions put on the point of divergence

Results

Results from the Wood Supply Games are adjusted for the larger volumes demanded for the first and second positions before comparisons with the Beer Game. Three runs of the Wood Supply Games have been conducted for each of the variants.

Supply Chain Costs

The total supply chain costs from earlier studies of the Beer Game are on average USD 2028 for the 35-week playing period (Sterman 1988, 1989). Our results indicate that the average total costs are somewhat higher for the divergent variant (USD 2260) and highest for the integrated variant (USD 5728). When comparing the individual positions of the games, differences between the structures are largest for the first position (wood supply group / brewery) and smallest for the fourth position (retailers) in the chain (Figure 4). The costs for each position in the divergent variant are similar to costs from the Beer Game, except for the first position (wood supply group), which has approximately twice the costs of the corresponding position in the Beer Game (brewery). The experiments with the integrated variant produced considerably higher costs for the first, second, and third position (Figure 4).

Figure 4. Total supply chain costs

Demand amplification

When studying how demand is amplified, two measures of the weekly order rates are used: the demand amplification and the sample variance of the 35 orders placed by each position. Demand amplification for a position is estimated using the observed increase in demand (the peak order less the initial order) relative to the increase in consumer demand in the game (Sterman 1989). Consumer demand increases from 4 to 8. Hence, demand amplification if placing orders identical to consumer demand is 100%. Figure 5 compares the average demand amplification observed for the Beer Game (N=11), the divergent variant (N=3), and the integrated variant (N=3) of the Wood Supply Game. In the Beer Game, demand amplification has the low values for the fourth position (retailer). Upstream in the chain demand amplification increases, and the highest values occur for the second (distributor) and the first (brewery) positions. For the first position (wood supply group) of the divergent Wood Supply

Game, demand amplification was 1400%, compared to 700% for the first position (brewery) of the Beer Game. For the other positions results from the divergent variant were similar to the Beer Game. The highest observed values were found for the integrated variant, where the first position revealed demand amplification of 1850%. Also for the other positions of the integrated variant, results seem to be higher than observed for the Beer Game (Figure 5).

Figure 5. Demand amplification

Contrary to measurements of demand amplification, the sample variance of the orders placed by each position takes all the observations into account when used as a measure of oscillations. Figure 6 shows that the variance of order rates in the Beer Game increases from the fourth position ($s^2 = 13$) close to the market, to the first position ($s^2 = 72$) (Sterman 1989). The variances of order rates found for the positions 2-4 are somewhat higher (20-75%) for the divergent variant compared to the Beer Game. For the first position (wood supply group), which is the point of divergence, the variance in order rates for the divergent variant is 5 times the result for the corresponding position in the Beer Game (Figure 6). The highest variance of order rates was observed for the integrated variant of the Wood Supply Game, where the variance for the fourth position (retailer) was 5.5 times, and the variance for the first position (wood supply group) was more than 9 times the level observed for the corresponding positions in the Beer Game (Figure 6).

Figure 6. Sample variance of order rates.

All the presented measures of supply chain efficiency show the same ranking of the supply chain structures. Results from the original Beer Game indicate the highest efficiency. In our pilot studies, the divergent variant of the Wood Supply Game produced results on an intermediate level, and the integrated variant had the highest values for the performance measures, indicating the lowest supply chain efficiency.

The effect of constraints in the Wood Supply Game

As shown in Table 1, the divergent variant has been run with different constraints at the point of divergence. Increasing the product-mix flexibility at the point of divergence appears to reduce the impact of the diverging structure. This is reasonable, since playing the divergent variant without restrictions put on the point of divergence is equivalent to two independent runs of the Beer Game.

The integrated variant has also been run with different constraints at the point of divergence (Table 1). The differences used were small, and hence, no indication of the effect of constraints at the point of divergence can be proposed.

Two replications of the integrated variant were run simultaneously. Even though the sets of constraints were identical, the two systems developed differently with respect to costs and accumulation of inventory and backlog. For example, when studying inventory at the sawmill for the two groups, one group experienced problems with accumulation of finished products of lumber, whereas the other group had similar problems with chips.

Discussion

Based on the background of pilot experiments with the divergent variant, the following hypothesis is proposed:

H_1: In a supply chain with a diverging material flow, increasing the rigidity of constraints applied to the point of divergence will negatively influence supply chain performance.

This hypothesis results from the considerable differences found when running the divergent variant allowing different levels of product mix-flexibility from the forest. When relaxing constraints at the point of divergence (Table 1), results produced by the players did not indicate differences from the beer game. Fjeld (2001) suggests that without flexibility at the point of divergence costs will magnify for the first position. This can be derived from the fact that reduction of product mix flexibility at the point of divergence increasingly forces the player to order raw materials for both branches even when inventories would suffice to satisfy demand from one of the branches.

Results from the integrated variant, using relatively strict constraints at the point of divergence, also produced lower performance than would be expected from the Beer Game. This does not necessarily result from the constraints at the point of divergence, as the integrated variant (Figure 3) has a more complex structure than the divergent variant (Figure 2). Three runs of the integrated and one run of the divergent Wood Supply Game used strict constraints at the point of divergence (Table 1). These runs produced costs for operations more than twice the costs for any other observation (the Beer Game included), thereby not contradicting H_1.

The increased level of interdependencies in the integrated variant seems to imply that if one of the branches in the supply chain is not managed well, costs may increase for both branches, particularly for the upstream positions (the first and second positions). This is likely a result of the points of divergence at the first and second positions (wood supply group and sawmill), and partly an effect of the convergence at the second position (paper mill). It is not possible, given the data, to estimate the two effects separately. Results for runs of the integrated variant seem to be difficult to predict, since two games run under the same conditions produced very different results for the two branches.

Based on the background of the pilot experiments using the integrated variant, the following hypothesis is proposed:

H_2: Increasing the complexity by increasing the degree of dependency between actors in a supply chain will decrease predictability of the system.

This hypothesis is vague due to limited experience with the Wood Supply Games. The three replications of the integrated variant resulted in large variations in total costs, and in the distribution of costs along the supply chain. It was observed that actions by one player of the system might have a large effect on costs in other parts of the chain, and even on costs for the other branch. When, for example, increasing orders in the paper branch, this also has an effect on costs for operating the sawmill, all else being equal. This is a result of the trade-off the sawmill continuously must consider: meeting orders for chips, thereby accepting increased costs for inventory of lumber, or accepting costs for chips backlog by postponing deliveries of chips.

Wilding (1998) argues that changing the structure of a supply chain from linear to divergent (e.g. a distribution system) will increase the degree of deterministic chaos in the system, making the system less predictable. Furthermore, Wilding (1998) analysed the effects of *parallel interactions*[1] in a supply chain, and found that poor performance by one vendor may have an impact on other vendors delivering products to the same manufacturer. For example, failing to meet a delivery date may force the manufacturer to reschedule production, thereby changing orders to other vendors. Similarly, Waters-Fuller (1996) notes that suppliers delivering to Just-in-time production systems, regardless of structures in material flows, often experience increased inventories if they are not themselves able to implement Just-in-time techniques. These effects can be found in the integrated Wood Supply Game, when for example, poor performance for one actor in one branch may affect the result for actors in other parts of the system. Increasing inventories may buffer the effects of parallel interactions, but increased inventory cover has also been observed to increase demand amplification (Wilding 1998). Parallel interactions are not considered when models concern supply chain structures without branching such as convergence or divergence.

[1] Defined as: "*interactions occurring between different channels of the same tier in a supply network*".

What creates dynamics in supply chains?

According to Sterman (1989), oscillations and demand amplifications in the Beer Game are created as a result of players failing to take relevant information into account when placing orders. The size of each order should be determined from expected loss, discrepancies in inventory from target inventory, and discrepancies in the supply line from the target supply line, where players often fail to take the latter into account (ordered but not yet received goods) (Sterman 1989). This is, however, hardly surprising since the supply line, contrary to inventories, is never recorded. Due to the time delays between players, it is difficult to keep track of what is actually on order. Although the Beer Game illustrates the dynamics in chains, it is likely other factors that induce demand amplification in real world supply chains (Metters 1997). Lee *et al.* (1997b), contrary to Sterman (1989), argue that demand amplification is the result of rational behaviour rather than misperceptions of information. Lee *et al.* (1997b) identify four causes of demand amplification:

- Forecasts are based on sales (or incoming orders) at each actor, rather than on the quantities actually sold in the consumer market.
- Order batching created by inventory management using re-order-point systems and high transaction costs.
- Fluctuating prices, resulting from batch production and sales campaigns, induce fluctuating sales, which thereafter amplify upstream in the supply chain.
- Rationing and shortage gaming, where shortage gaming is exemplified by artificially high orders placed to remedy vendors' inability to deliver complete orders. Rationing is proposed as the cause of shortage gaming since suppliers, when unable to fulfil orders, ration their deliveries across customers so that all customers receives less than ordered.

In the Beer Game, as well as in real supply chains, time delays between actors in the chain contribute to oscillations (Forrester 1958, Towill 1996, Metters 1997). According to Metters (1997), mitigating demand amplification potentially increases profitability, depending on the time between demand spikes, their amplitude and predictability.

The Wood Supply Games provide initial insights with respect to how different structures affect costs in a supply chain. It is worth emphasising that the structure of the games, with multiple direct feedback loops, time delays and results affected by actions from individual players, makes it difficult to predict the result of individual games. In that respect, Sterman (1992) mention that it is not unusual for total costs to exceed USD 10,000, which is higher than that found in any of the experiments using divergent structures. Consequently, pilot experiments on games with similar structure as the Beer Game may be used to get a first impression, from which hypotheses can be generated. To test such hypotheses, however, a considerable number of replications must be obtained. Effects of using different constraints for the actors in the chain are more appropriately analysed using analytical models (e.g. simulation models). For these purposes methodologies for quantifying the effects of demand amplification (referred to as "*the bullwhip effect*") can be found in Metters (1997). Considerable research has been conducted in order to discover remedies for demand amplification (see e.g. van Ackere *et al.* 1993, Hameri 1996, Towill, 1996, Lee *et al.* 1997b, Mason-Jones and Towill 1997, 1998, 1999, Taylor 2000). None of these, however, consider effects of branching in material flows.

Relevance of game structure for the forest sector

Fowler (1999) points out that the pull-oriented systems are actually adaptations of generic feedback control systems where the basic instability is a result of a combination of time lag and operator gain. The longer the period between observed changes in system state and corrective measures (time lag), and the weaker the reactions to these changes (operator gain), the lower the possibility to successfully correct the situation (e.g. low inventory levels). Even worse, long lags combined with a high operator gain result in instability. A series of cascading feedback loops, such as in a supply chain, makes correction to steady state even more difficult.

In terms of simulating instability in the forest sector system with the Wood Supply Games, the realism of both the assumed time lag between positions and operator gain should be examined. Average times for wood procurement from stump to mill for a large forest owner may vary between two and four weeks (Skoog 2000). Communication of new demands and revision of delivery plans may require two additional weeks giving a lead time of 4 to 6 weeks. Average lead times for 6 paper mills used in a study by Hameri and Nikkola (1999) varied between 3 and 8 weeks. In the Wood Supply Games, the delays in transfer of orders and material result in a lead time of four weeks, provided that the ordered quantity is in stock. This is slightly shorter than would be realistic for the forest sector.

Competitive advantage in the forest sector is often determined by low cost production, using large plants with capital intensive technology requiring high and even capacity utilization. With this strategy, maximum volume flexibility is relatively low. Forest harvesting production, however, may be varied by up to 30 % (Helstad 2000, Helstad *et al*. 2001). The games have no restrictions concerning the volume flexibility in forest operations, making the operator gain assumed in the Wood Supply Games greater than realistic values for the forest sector.

Several restrictions have been applied at the point of divergence (Table 1). In wood procurement, product mix flexibility (percentage of sawlogs or pulpwood) may be changed by up to 30-40 % for a monthly period (Nilsson 2000, Helstad *et al*. 2001). Assuming 40% pulpwood in the total delivery as normal, this indicates that the percentage of pulpwood delivered from the forest could be varied between 25% and 54% on a monthly level. The constraint producing the best approximation of the observed values of product mix flexibility in Nilsson (2000) and Helstad *et al.* (2001) requires that weekly deliveries from the forest have a percentage of pulpwood between 30% and 50%, corresponding to a product-mix flexibility of 25% for pulpwood and 17% for sawlogs. At the second point of divergence (sawmill) 50% of the sawlogs is converted to chips, which is somewhat higher than commonly observed for Norwegian sawmills (approximately 35%). Constraints on transport operations have not been considered.

During the development of the games the goal was to increase the relevance to the forest sector by introducing divergent material flows, and only to change rules and methods from the original Beer Game when strictly required. The game is, therefore, still played using the same costs assumptions, demand patterns and delays in orders and transportation as found in the Beer Game. Similarly, the Wood Supply Games has four stages from the forest to the consumer. Real world supply chains shows variation with respect to the number of stages in a supply chain. For furniture production, the number may be larger than four, whereas for direct deliveries to construction sites, there may be less than four stages.

In addition to making constraints a better reflection of the real world, increased relevance to forest industries can be achieved by using demand patterns according to what is observed for different forest products, and by introducing seasonality and random events (e.g. reduction or stop in supplies from the forest due to poor weather conditions). One drawback associated with these changes is that from an educational point of view, it is no longer possible to show that even a simple pattern of demand will be distorted when communication in a supply chain is lacking. A second drawback is the increased complexity introduced by further modifications, making the game more difficult to run and participate in. Future development of Wood Supply Games must, therefore, carefully consider the trade off between realism and simplicity.

Conclusions

The Wood Supply Games provide opportunities for forestry students to experience industrial dynamics within a relevant framework. The most complex variant considers the problem faced by paper mills requiring an adequate mix of chips and pulpwood for paper production. This game also takes into account that lumber and paper production result in main products and by-products, making it possible to apply different assumptions concerning the yield of these processes. The games constitute one of the few ways, for students or managers, to experience almost a whole years' wood procurement in the course of a few hours.

The same games may be used to quantify industrial dynamics for sectors with divergent flow. Two hypotheses are suggested that may be tested by students within such a framework. Testing may be based on student games entirely, or alternatively, combined with development of computer simulation models.

Further development of the games should consider increasing the realism of assumptions and constraints to better reflect the forest industries. Introducing further restrictions, or otherwise increasing the complexity of the game will, however, make the game more difficult to learn and less entertaining for student use.

References

Andries, B. and L. Gelder. 1995. Time-based manufacturing logistics, Logistics Information Management, Vol. 8, No. 3, pp. 30-36.

Fjeld, D. E. 2001. The Wood Supply Game as an educational application for simulating industrial dynamics in the forest sector. In: Sjöström, K. and L-O. Rask, (*Ed*s). 2001. Supply Chain Management for Paper and Timber Industries. Timber Logistics Club, pp. 241-252.

Forrester, J. W. 1958. Industrial dynamics – a major breaktrhough for decision makers. Harward Business Review, July-August, 1958.

Fowler, A. 1999. Feed-back and feed-forward as systematic frameworks for operations control. International Journal of Operations & Production Management, Vol. 19, No. 2, pp. 182-204.

Hameri, A-P. 1996. A method to avoid demand amplification in bulk paper distribution. Paperi ja Puu – Paper and timber, Vol. 78, No. 3, pp. 102-106.

Hameri, A-P. and J. Nikkola. 1999. Demand amplification in supply chains of mills close to and far from main markets. Paperi ja Puu – Paper and Timber, Vol. 81, No. 6, pp. 434-438.

Helstad, K. 2000. Skiftformer för framtidens råvaruförsörjning – flexibilitet, kostnader och arbetsmiljö. MSc. Thesis, Swedish University of Agricultural Sciences, Div. of Forest Technology, Umeå.

Helstad, K., A. E. Nilsson, and D. E. Fjeld (2001). Volume flexibility in wood procurement – costs and constraints for adjusting supply chain strategy. In: Sjöström, K. and L-O. Rask, (*Ed*s). 2001. Supply Chain Management for Paper and Timber Industries. Timber Logistics Club, pp. 143-162.

Lee, H. L., V. Padmanabhan and S. Whang. 1997a. The Bullwhip Effect in Supply Chains. Sloan Management Review, Vol. 38, No. 4, pp. 93-102.

Lee, H. L., V. Padmanabhan and S. Whang. 1997b. Information Distortion in a Supply Chain: The Bullwhip Effect. Management Science, Vol. 43, No. 4, pp. 546-558.

Lehtonen, J-M. 1999. Supply chain development in process industry. Acta Polytechnica Scandinavica IM No. 4.

Machbeth, D. K. and N. Ferguson. 1994. Partnership Sourcing – An Integrated Supply Chain Management Approach. Pitman Publishing.

Mason-Jones, R. and D. R. Towill. 1997. Information enrichment: designing the supply chain for competitive advantage. Supply Chain Management, Vol. 2, No. 4, pp. 137-148.

Mason-Jones, R. and D. R. Towill. 1998. Time compression in the supply chain: information management is the vital ingredient. Logistics Information Management, Vol, 11, No. 2, pp. 93-104.

Mason-Jones, R. and D. R. Towill. 1999. Using the Information Decoupling Point to Improve Supply Chain Performance. The International Journal of Logistics Management, Vol. 10, No. 2, pp. 13-26.

Metters, R. 1997. Quantifying the bullwhip effect in supply chains. Journal of Operations Management, Vol. 15, pp. 89-100.

Mosekilde, E. and E. R. Larsen. 1988. Deterministic Chaos in the beer production-distribution model. System Dynamics Review, Vol. 4 Nos. 1-2, pp. 131-147.

Nilsson, A. E. 2000. Möjligheter och kostnader för flexibel virkesförsörjning. MSc. Thesis, Swedish University of Agricultural Sciences, Div. of Forest Technology. Umeå.

Skoog, E. 2000. Leveransprecision och ledtider - två nyckeltal för styrning av virkesflödet. Institutionen för skoglig resurshushållning och geomatik, Sveriges Lantbruksuniversitet, Umeå.

Sterman, J. D. 1984. Instructions for running the Beer Distribution Game D-3679, Systems Dynamics Group, MIT, E60-383, Cambridge, MA 02139.

Sterman, J. D. 1988. Deterministic chaos in models of human behaviour: methodological issues and experimental results. System Dynamics Review, Vol. 4, Nos. 1-2, pp. 148-178.

Sterman J. D. 1989. Modelling managerial behaviour: misperceptions of feedback in a dynamic decision making experiment. Management Science, Vol. 35, No. 3, pp. 321-339.

Sterman, J. D. 1992. Teaching Takes Off - Flight Simulators for Management Education. "The Beer Game". OR/MS Today, October 1992, pp. 40-44.

Taylor, D. H. 2000. Demand amplification: Has it got us beat? International Journal of Physical Distribution & Logistics Management, Vol. 20, No. 6, pp. 515-533.

Towill, D. R. 1996. Time compression and supply chain management – a guided tour. Supply Chain Management, Vol. 1, No. 1, pp. 15-27.

van Ackere, A., E. R. Larsen and J. D. W. Morecroft 1993. Systems thinking and business process redesign: an application to the beer game. European Management Journal, Vol. 11, No. 4, pp. 412-423.

Waters-Fuller N 1996. The benefits and costs of JIT sourcing. A study of Scottish suppliers. International Journal of Physical Distribution & Logistics Management, Vol. 26, No. 4, pp. 35-50.

Wilding, R. 1998. The supply chain complexity triangle – Uncertainty generation in the supply chain. International Journal of Physical Distribution & Logistics Management, Vol. 28, No. 8, pp. 599-616.

Figures and Tables

Figure 1 – Structure of the Beer Game

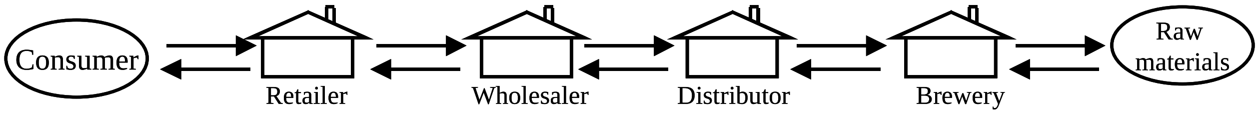

Figure 1. Standard structure for the Beer Distribution Game. The demand signals move from left to right while the flow of products move from right to left.

Figure 2. Structure of the divergent Wood Supply Game

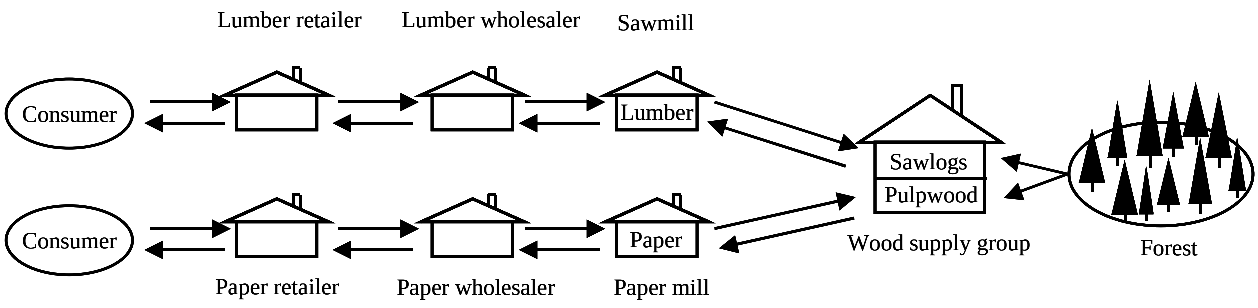

Figure 2. The divergent variant of the Wood Supply Game is producing two types of products. The flow of demand signals (from left to right) converge at the wood supply group. The flow of products (from right to left) diverge at the wood supply group.

Figure 3. – Structure of the integrated Wood Supply Game

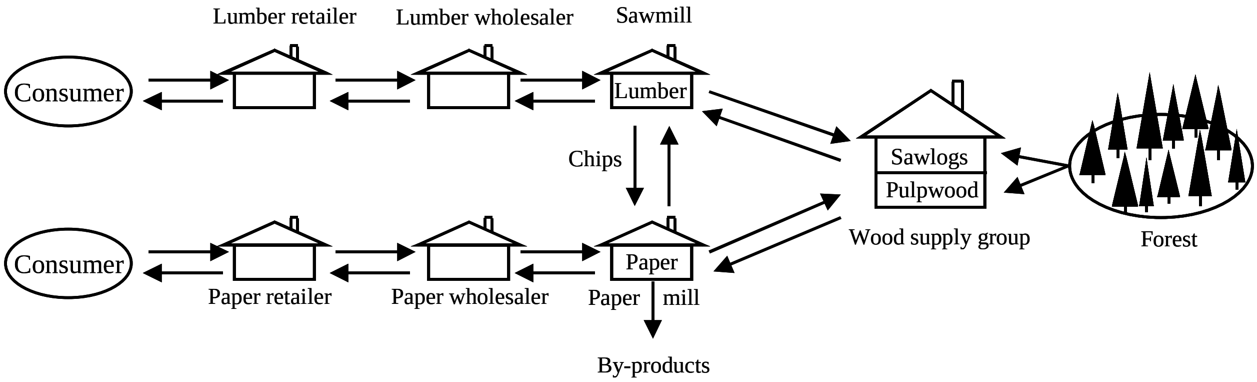

Figure 3. The integrated variant of the Wood Supply Game produces two types of products, and associated by-products. The structure is similar to the divergent variant, but a second point of flow divergence is introduced at the second position (sawmill), and a point of convergence is introduced in corresponding position in the other chain (paper mill).

Figure 4. Total supply chain costs

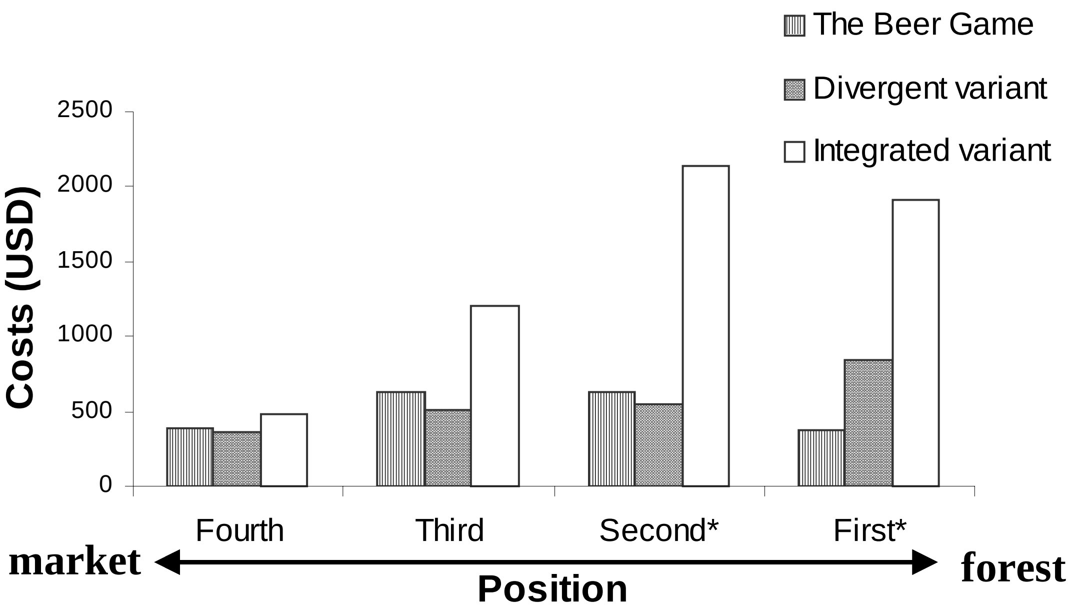

Figure 4. Comparison of costs for the positions in each game. First position denotes the wood supply group and the brewery. Fourth position denotes retailers. (* = the results for this position have been adjusted to account for the larger volumes in the flows in the Wood Supply Games).

Figure 5. Demand amplification

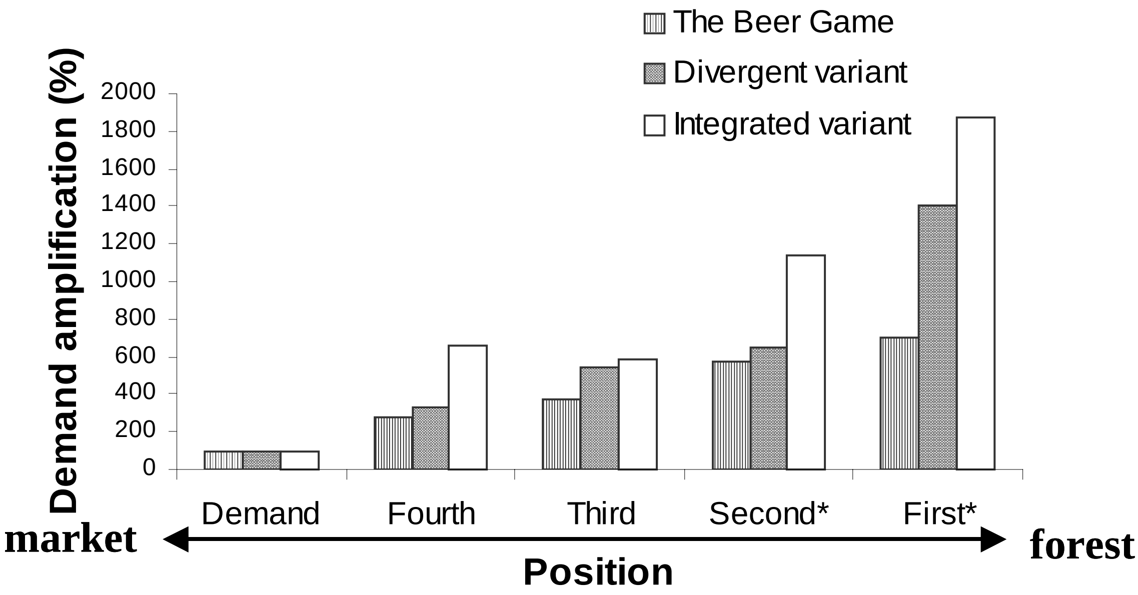

Figure 5. Average demand amplification ((peak order - initial order)/(peak demand - initial demand)) for the positions in the different games. First position denotes the wood supply group and the brewery. Fourth position denotes retailers. (* = the results for this position have been adjusted to account for the larger volumes in the flows in the Wood Supply Games).

Figure 6. Sample variance of order rates.

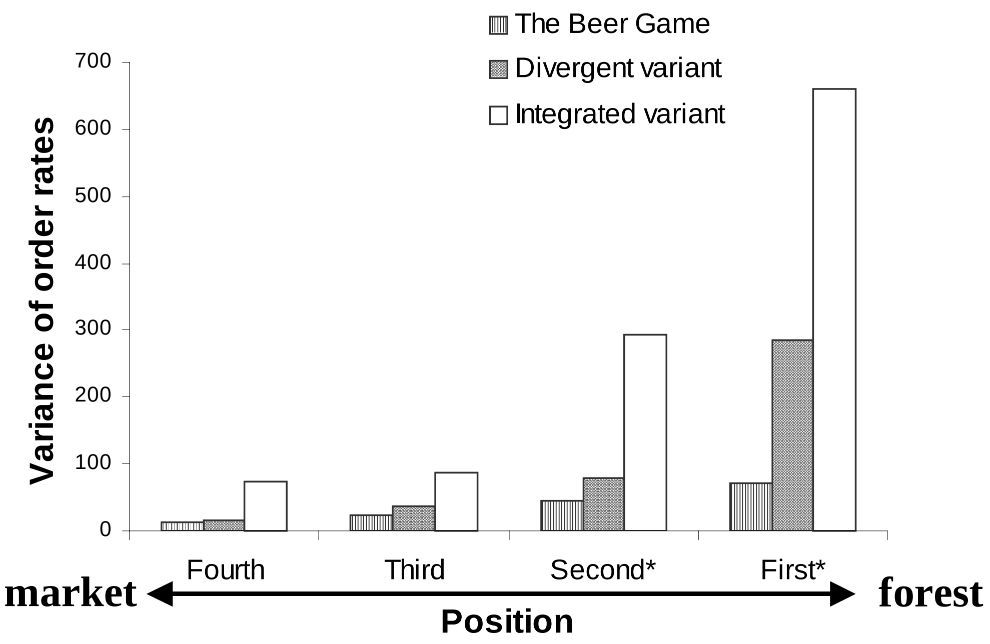

Figure 6. Average sample variance for each position in the different games. First position denotes the wood supply group and the brewery. Fourth position denotes retailers. (* = the results for this position have been adjusted to account for the larger volumes in the flows in the Wood Supply Games).

Table 1. The variants of the game played, and the restrictions put on the points of divergence and convergence

Variant	N	Restriction forestry		Yield lumber		Mix in paper mill		Yield Paper	
Divergent variant	1	Sawlogs Pulpwood	50% 50%	n/a		n/a		n/a	
Divergent variant	2	Sawlogs Pulpwood	30% - 70% 30% - 70%	n/a		n/a		n/a	
Integrated variant	1	Sawlogs Pulpwood	50% - 70% 30% - 50%	Lumber Chips	50% 50%	no constraints		n/a	
Integrated variant	2	Sawlogs Pulpwood	60% - 70% 30% - 40%	Lumber Chips	50% 50%	Chips Pulpwood	40% - 60% 40% - 60%	Paper By-products	50% 50%

s