Complex supply chains: analysis of a Beer Distribution Game Simulation output

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## *Abstract*

This paper reports on an ongoing project that is using the Beer Distribution Game as a vehicle to establish simulation strategies for supply chain systems, using a programming environment based on open source software,and SQL programming. The particular model discussed in this paper was used to develop a rangeo of timeseries data streams, and techniques drawn from the chaos, or non linear, timeseres analysis area have been used to visualise and analyse the data. The model has produced credible output, and the visualization strategies provide useful insight into the dynamics of the system.

## *Keywords*

Chaos, Supply Chain, Simulation, SQL

## *Introduction*

The use of simulation, and agent based modelling; in supply chain management has been the subject of interest in some recent publications. Savings of more than $10m were claimed to be a result of the application of agent based modelling techniques to scheduling at Southwest Airlines (Bonabeau and

Meyer, 2001) Successes have been noted in a number of other locations by Bonabeau (2002, 2003). Areas that have been particularly identified as suitable for an agent based modelling approach have been characterized by the presence of chaos, complexity or emergence. Swarm and Repast are two prominent software systems that enable agent based models to be developed. There are numerous other systems, some that are substantially less complex, and consequently less capable of modelling complex reference systems. Axelrod (1997) suggests that Swarm requires a substantial level of programming knowledge to master, and Swarm appears to be of a similar level of complexity. A result of this complexity is that it may be simpler to approach the problem using a standard software language, and in this paper we describe an approach that has followed this strategy.

The basic concept of this simulation approach is that the complex behaviour of systems containing many agents can be a result of the interaction of those agents, operating autonomously with simple rules. Axelrod (1997) refers to emergent behaviour as large scale effects arising from the local actions of agents in the system. Emergent behaviour has been applied to many fields including organizational studies (Axelrod, 1997; Anderson, 1999; MacIntosh and MacLean, 2001). In this paper we use agent based modelling to examine the behaviour of a simple, widely used system in the teaching of operations management, the Beer distribution game (BDG). The work reported here builds on and extends work reported earlier (Jenkins and Breach, 2004).

The modelling strategy has continued to use software that is 'free'. The software development community distinguishes between different interpretations of 'free' using the metaphors '*free as in speech*' and '*free as in beer*'. Free software is generally accepted to be software that is provided with a license that grants the end user the *freedom* to run the software, the *freedom* to study and modify the software, the *freedom* to redistribute the software, and the *freedom* to make public any changes or improvements that they make. Free Software is, by definition, *free as in speech*. Most free software is also *free as in beer* – that is to say there is no fee or charge for its acquisition ("The Free Software Definition", Free Software Foundation, http://www.gnu.org/philosophy/free-sw.html). Most important in this context was an absence of financial and legal encumbrance by way of commercial software products, and an ability to directly translate the techniques discussed herein into computing environments in common use in business today. The agent based BDG is written in Perl, and stores its operating data and agent parameters in a MySQL database. Graphing and data analysis were carried out using Microsoft Excel, but we intend to translate these routines into Perl in future work.

In previous work (Jenkins and Breach, 2004) we described an agent based modelling approach that depended on the object orientate paradigm that dominates contemporary programming languages, and incidentally, is grounded in earlier simulation languages such as Smalltalk. In this paper we describe a significantly different modelling strategy. We have separated the methods that agents follow from the rules they use to reach decisions. Agents follow methods as defined in a Perl main process program. The decisions the agents make are grounded in a set of rules that are based in database records, accessed by SQL statements. We believe that this will provide a very flexible environment for agent characterization, and rule manipulation as our modelling project addresses more complex supply chain situations.

The Structured Query Language (SQL, formally known as SEQUEL2) is an English keyword based language for defining, manipulating and querying relational databases (Chamberlin et al., 1976). SQL, or some variant thereof, is the language used within the vast majority of modern commercial database systems. The agent based BDG uses SQL to communicate with the MySQL database server. The MySQL database server is 'free' software that is published under both commercial and free licenses. MySQL is designed with speed and stability in mind. The MySQL company "media kit"(http://www.mysql.com/press/index.html) claim that MySQL's success can be gauged by its acceptance by companies that includes the New York Stock Exchange, the University of California, the University of Texas and NASA. MySQL is available for Microsoft Windows, Apple OSX and many versions of the UNIX operating system at http://www.mysql.com.

A further extension to the previous work is the inclusion of extensive data analysis using techniques based on non linear time series analysis. This work is motivated by the desire to achieve a more quantitative appreciation of the nature of the outcomes of different agent behaviours. The techniques used have been drawn from the non linear time series analysis literature (noted as each technique is described) and many have been applied in the supply chain area (see for example Levy, 1995; Macbeth, 2002, and Wilding, 1998)

## *Description of the modelling approach*

Mihram (1972) described the process of developing a model as having five stages of development.

The process used to develop the model reported in this paper will be described within the framework of these five stages.

## 1 Systems analysis

The BDG is well described in the literature (see for example: Sterman, 1989; Forrester, 1992; Senge, 1992; Lee et al, 1997; and in particular Croson & Donahue, 2002) and so the description used for this paper will be very brief. The way in which the game is organized for play is illustrated in fig. 1.

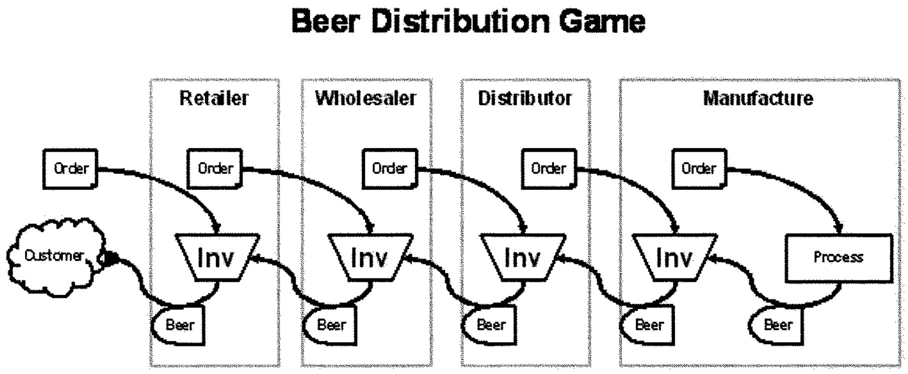


**Figure 1** **Beer distribution game layout**

The game simulates a system of four independent agents within a simple supply chain. A customer, from outside the chain places orders on a *retailer*.

The profile of demand from this agent is an important part of the game. In the first tick, the first two cycles of the game, the customer places orders for 4 units, thereafter the customer orders eight units per tick. This is effectively a steady level of demand, with a single step change in the third tick. The *retailer* supplies the customers with cases of beer, and attempts to maintain their capacity to supply the customer by ordering supplies of more beer from a *wholesaler*. The *wholesaler* operates similarly to the *retailer*, and orders their supply of beer from the *distributor*. The *distributor* is resupplied from a *manufacturer*. The *manufacturer* produces more cases of beer from within their own factory.

When a case of beer is shipped by a supplier it will take two weeks to reach the next agent down the supply chain, similarly, an order will take two weeks to reach the next agent up the supply chain. People playing the game have complete visibility of all products on the playing field, but limited visibility of orders in the system. The agent originating the order nominally knows what each order is. The players are expected to develop strategies that enable them to maintain supply, but at minimum levels of inventory. Unsatisfied orders are ultimately supplied from backorder. Players are expected to operate in 'silos' using only information that is available to them or clearly visible by observing the game area. The players must operate within the rules of the game, and are not able to modify the structure of the supply chain system. Problems related to supply chain structure and agent mindset form the major grounds for the debrief of the game. System analysis for this project is a relatively simple matter. A project that is based in a real situation is never so simple. The advantage of selecting this strategy for this stage of the project is that it allows more attention to be directed at modeling issues; rather than on the scope of the problem and the purpose to which the model's output will be put. Given the highly defined nature of the reference system the next stage of the process is relatively straightforward.

## 2 System synthesis

This refers to the construction of a representation of the reference system that captures the essential logics and interactions that are of interest to the clients of the modeling process. This stage will typically include the collection of data required to establish the parameters of the model. The parameters for this project are set by the published parameters of the game.

The essential aspect of this project is in the selection of the appropriate modeling strategy. Logistics systems, and the BDG, have been modeled previously. Typically a process orientation is taken for the models. In the case of a global crude oil logistics system Jenkins (1995) chose to use *Siman,* a commercial discrete event simulation application, to build the model. Sterman (1989) has developed a series of models of dynamic systems in a programming environment typified by the software package *iThink*, and this also is a modeling environment that has a focus on the process through which entities such as cases of beer pass (iThink in fact provides an interactive model of the Beer Distribution Game in its distribution software). In these software applications the focus is on the process workstations, and the entities that pass through these workstations. These modeling environments can become very difficult to use when the reference situation includes people who are influencing the nature of decisions taken in the reference situation (Jenkins, et al, 1998).

## 3 Verification

System synthesis may produce some form of representation of the reference system. This might be diagrammatic, discursive, or it might be in some structured form such as UML. Mapping this representation into the model's programming environment, such as specific Perl code, used in the modeling framework is a crucial stage. The ease with which the human mind can cope with ambiguity and exception is only realized when a model needs to be written in some form of computer based modeling environment. Verification is the stage where the operation of the code developed is checked until the modeler is satisfied that the model is an accurate expression of the system representation. This of course does not imply that the model is a valid representation of the reference system.

Two main strategies were followed as the BDG model was developed for this paper. The first strategy was the use of an object orientated language and the use of object orientated agents. Entities in the model were developed as agents, and the agents contained methods (in Perl) and properties (in SQL linked tables). This approach enabled verification to be achieved on small sections of the overall model as the model was developed. The second strategy was the use of extensive data retention in the data based tables. This data was available for subsequent process tracing and program debugging.

## 4 Validation

Validation compares the output of the model with data collected from the reference system. Validation is grounded in the work of stage 2; system synthesis. Good levels of interaction between modelers and clients at the system synthesis stage will facilitate effective validation, and if this is not effective then the scope of the model may be quite different to that envisaged at the early stages of the project; validation then becomes very difficult. This is a particularly difficult problem if the reference system contains social agents that are empowered to take autonomous decisions in the process being modeled (Jenkins et al, 1998).

In this paper we argue that our model has captured the non social dimensions of the game. The output of the model reflects, at a face level, the appearance of output from typical students groups that play the game. This paper is however a preliminary paper that establishes the basic model, and its basic validity. Ultimately the model will be used to explore aspects related to the reflexive social agents included in the reference system; we do not claim validity for that aspect of the model at this stage.

## 5 Model use and experimentation

This stage sees the model used to explore some aspect of the reference system. In this paper we report on the use of the model to examine aspect of the BDG. Although other researchers have argued that the BDG reflects aspects of real supply chains (Lee et al, 1997); we do not. Our argument is that the model reflects aspects of the game, and we leave till later work the extension of the model to real systems. We argue in particular, that the high level of SQL functionality in the model will facilitate the extension of the model in further work to the area of real supply chains. Often, simulation models will operate within a self contained system, where data is sourced from dedicated files, and is reported to dedicated files (this is the case, for example, for ProModel, Witness, and iThink; at the time of writing of this paper). This will restrain the model to its own system, making an interface to operating systems difficult. The programming strategy used in this project will enable the model to be readily interfaced to most mainstream operational RDBMS. This will enable real time operation of the model from within the operating system. The benefits of this strategy will flow from the incorporation of a wider range of rules for order calculation, and the addition of standard optimization routines such as simulated annealing and genetic algorithms and function (as described for example by Downsland, 1993 and Ghanea-Hercock, 2003)

In our earlier paper on this project we noted the behavior of a typical group of students as they played the game. The time series plot of inventory will typically have the appearance of that shown in fig. 2. The retailer has an inventory that varies from about 18 to -22. The wholesaler has a wider variance, from about 30 to -38, and the distributor has a further increase variance from about 70 to -20. The factory has a lower variance of about 38 to -18.

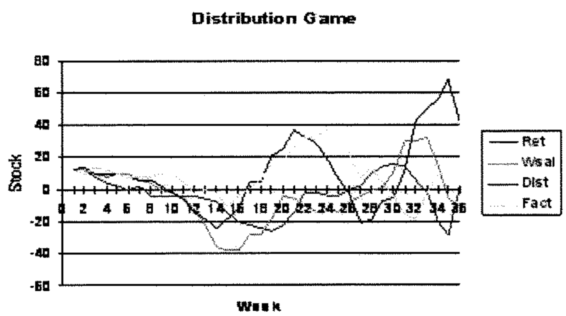


**Figure 2** **Student performance**

This effect is generally referred to as the bullwhip effect and it is an effect that has been observed in real logistics systems (Lee et al, 1997). Lee et al (1997) argued that demand forecasting updating strategies and order batching strategies were one of the main causes of the bullwhip effect: It follows that the range of the bullwhip effect should be reduced if demand forecasting is stabilized, if agents respond to customer demand rather than supply chain agent demand, and finally if order batching strategies can be modified in support of smaller batches. Our model can reproduce the behaviour of the supply chain, and we can demonstrate the impact of alternate policies (see Jenkins and Breach, 2004), but the work reported here is mainly directed at the use of a range of analytical approaches to facilitate more effective representation of the behaviour of the supply chain.

We report the results of five runs and use a range of techniques to visualize and analyse these results. Each run was carried out with, wherever possible, the same conditions. Specific details of the model and its code can be obtained from the first author.

## *Analytical techniques*

The analysis is motivated by a desire to establish the degree of complexity of the data, and the extent to which the data will be inherently predictable given knowledge of the system at some time. This will be done, when the data shows evidence of chaotic character, by estimating the correlation dimension of the time series and the largest Lyapunov coefficient of the data. In order to perform these two analyses we need firstly to establish the period of the data, the time taken for the time series to cover the full domain of the orbit, and we should visualize the data in order to gain some overall perspective on the dynamics. Accordingly we shall use four techniques; autocorrelation, delay plots, correlation dimension, and largest Lyapunov coefficient. Each of these techniques is briefly discussed below:

***Autocorrelation***: the data was initially examined for any relatively obvious periodic behaviour using the autocorrelation function. Data in all cases were normalized to a mean of zero and standard deviation of one. . This is defined by Mullin (1993) as:

$$R(n\tau) = \frac{1}{N-1}\sum_{i=1}^{N-1} x_i x_{i+n\tau}$$

The plot of autocorrelation vs delay (*t*) was used to establish the delay that was applied to the delay plot. The delay was set at the tick corresponding to the first crossing of the X axis, or approximately one quarter of the orbital period (Kantz and Schreiber, 2004).

***Delay plot***: an XY plot is developed for each point in the time series, the X value is for the point corresponding to the current tick - tau ($X_{t-t}$), where tau was established in the autocorrelation plot, the Y value corresponds to the time series value for the current tick ($X_t$). The choice of delay time (tau) will affect the prominence of the different features of the plot, but does not change the fundamental topology of the chart. A common choice of tau is one, and this plots $X_{t-1}$ vs. $X_t$. This strategy can lead to a concentration of points around the diagonal of the chart due to short term correlation in the data (ie where the value of $X_t$ is similar to $X_{t-1}$).

***Correlation dimension:*** The correlation dimension C(r) is calculated using a Visual Basic module that was developed from a program listed in Peters (1991) and based on the work of Grassberger and Procaccia (1983). This measure determines the number of dimensions required by a geometric representation of the attractor for the time series. The nature of this measure is described at a simple level in Peters (1991) and at more technical levels in Farmer and Sidorowich (1987), Grassberger and Procaccia (1983 ), Grassberger et al (1991), and Kantz and Schreiber (2004). The latter work is particularly comprehensive and is supported by a set of software modules that can facilitate many of the techniques in the area on non linear time series analysis. The correlation dimension will be used to represent the relative measure of the complexity of a series, and in order to calculate the Lyapunov exponent.

***Largest Lyapunov Exponent:*** This analysis uses the method developed by Wolf et al. (1985) and modified by Peters (1991) to develop the Visual Basic version of the program. This exponent is a measure of the presence of sensitive dependence on initial conditions - the necessary condition for the presence of deterministic chaos in a system. With positive values for this exponent the series can develop future values from the present that are difficult to predict after a short time. This can be due to the presence of non linearities and feedback in the general formulation of chaotic systems although Handley et al.(1993) report a personal communication from co-author Jaenisch that proposes that the presence of feedback is a sufficient condition for chaotic behaviour.

## Results

Five trials were carried out to explore the behaviour of the system when changes were made to the nature of demand and the ordering rules for the wholesaler and distributor. In all runs the retailer and manufacturer used the same ordering rules, and these were simply to order enough stock, allowing for material already ordered, to return stock levels to a target stock level. The target stock level was set high enough to avoid backordering periods as this led to loss of detail in the behaviour of some parts of the system.

A summary of the runs is set out in table 1.

| Run | Demand | Wholesaler and distributor ordering rules |
|---|---|---|
| 1 | Static 4,4,8,8,8,... | Unresponsive: order enough stock, allowing for material already ordered, to return stock levels to a target stock level |

| | | |
|---|---|---|
| 2 | Static | Forgetful: order enough stock to return stock levels to a target stock level, but forget orders in the system |
| 3 | Static | Responsive; order enough stock to raise stock level to 4 x previous order received. |
| 4 | Static | EOQ: only order in quantities of 20 units |
| 5 | Random: Uniform distribution (4to12) | Unresponsive |

**Table 1** **Summary of simulation runs**

## Run 1 Static unresponsive

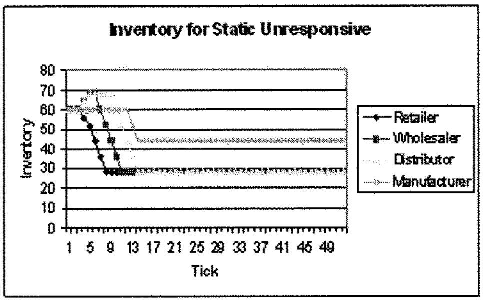


**Figure 3** **Static Unresponsive inventory time series**

This simulation run can be considered a benchmark for a rational, capable set of agents, operating to a rule that ignores external demand and simply orders sufficient to maintain a target inventory. These agents might be considered to have unbounded rationality in that they act on the full range of available information. There is no point in carrying out further analysis on this set of data as the series has no variability after a warm up period.

## Run 2 Static forgetful

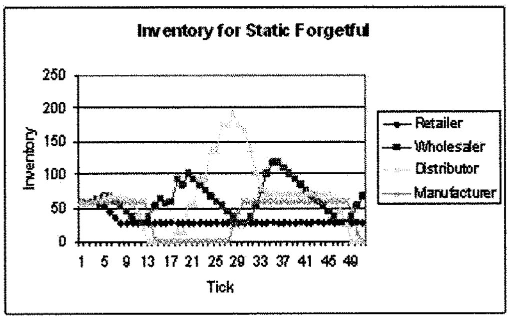


**Figure 4** **Static Forgetful inventory time series**

The output for this simulation shows similar dynamics to that found in the reference system. Within the limits of the timeframe there is variation in inventory that increases for the two central agents of the supply chain. Further analysis was carried out to develop delay plots, correlation dimension and Lyapunov coefficients. Delay plots were developed using a delay of five units based on the autocorrelation function that indicated an orbital period of about twenty units. Visual inspection of the delay plot suggests the presence of complex behaviour in the data and supports the use of further analysis.

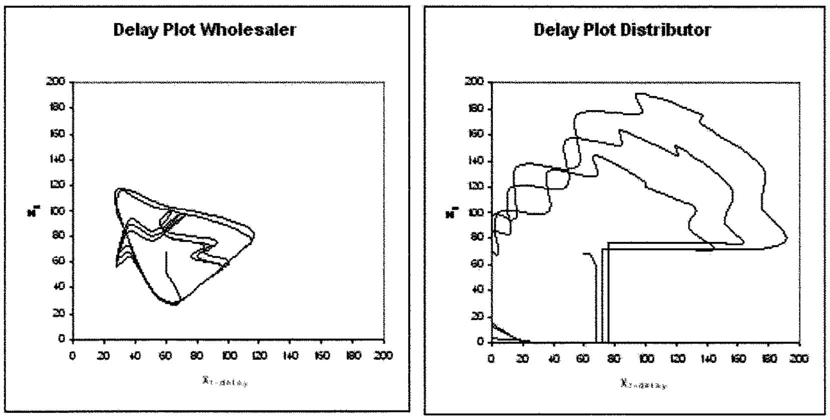


**Figure 5** **Delay plot of Static Forgetful agents**

Correlation dimensions were estimated and the charts are exhibited below.

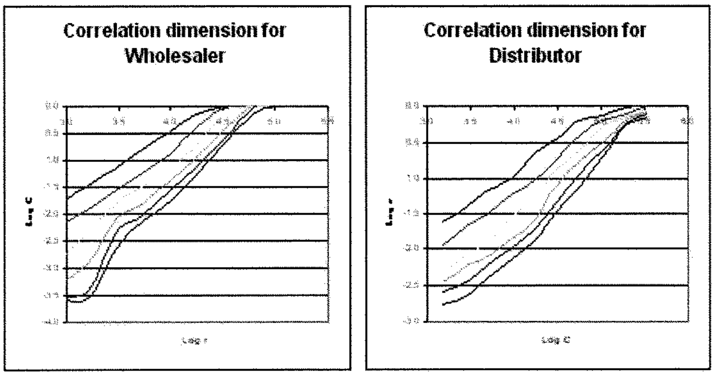


**Figure 6** **Correlation dimension of Static Forgetful agents**

The associated slopes (the Correlation Dimension) of each of these curves are tabulated below. The third case has been listed for a Random time series to illustrate the property of the correlation dimension of random data to increase regardless of how many dimensions are used. The two series chosen for analysis appear to stabilize in the region of five dimensions. This indicates an extremely complex set of forces acting to create the data set.

| | Embedding dimension | | | | | |
|---|---|---|---|---|---|---|
| Series | 2 | 3 | 4 | 5 | 6 | 7 |
| Wholesaler | 0.8 | 1.2 | 1.3 | 1.6 | 1.8 | 1.9 |
| Distributor | 0.8 | 0.9 | 1.1 | 1.2 | 1.2 | 1.3 |
| Random | 1.2 | 1.9 | 2.6 | 3.3 | 4.0 | 4.8 |

**Table 1 Correlation dimension vs embedding dimension for Static Forgetful agents**

The following values were found for the largest Lyapunov exponent (l) of the two time series:

- Wholesaler 0.15

· Distributor 0.30

The size of each of these exponents indicates that predictions of future behaviour of these two variables will be quite difficult. For the distributor for example, after the evolution of ten ticks, and initial difference of one inventory unit will have been magnified to about twenty units(calculated as exp(10xl) see Mullin, 1993 or Wilding, 1998), and this result is consistent with a visual inspection of the delay plot for that agent.

## Run 3 Static Responsive

Inventory in this run showed no variation after a warm up period of about twenty weeks. The time to achieve equilibrium was longer than that required for Static Unresponsive (about fourteen weeks) but this result shows no evidence of uncertainty in the long run inventory levels of agents in this supply chain. No further analysis was carried out on the results from this run.

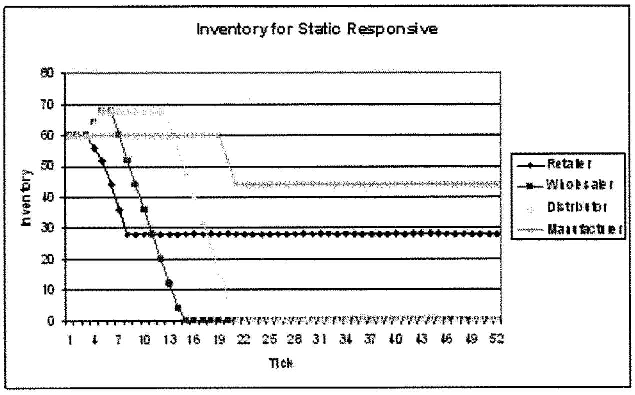


**Figure 7** **Static Responsive inventory time series**

The zero level of inventory reflects the target inventory set point of four times the previous order, for agents in the supply chain that corresponds to the total lead time for the supply of material.

## Run 4 Static EOQ

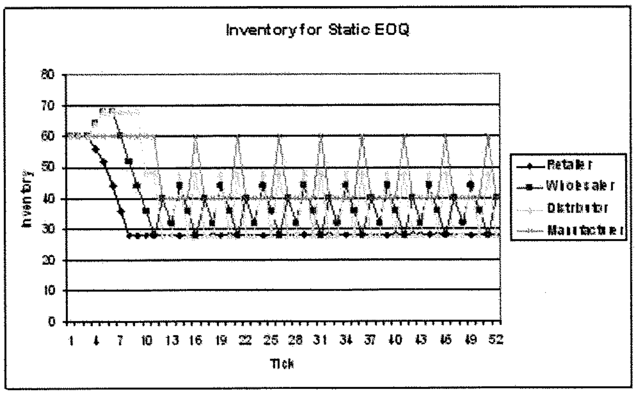


**Figure 8** **Static EOQ inventory time series**

There appears to be substantial levels of variability in inventory, and autocorrelation indicates a period of about four so delay plots were prepared for delay unit of one.

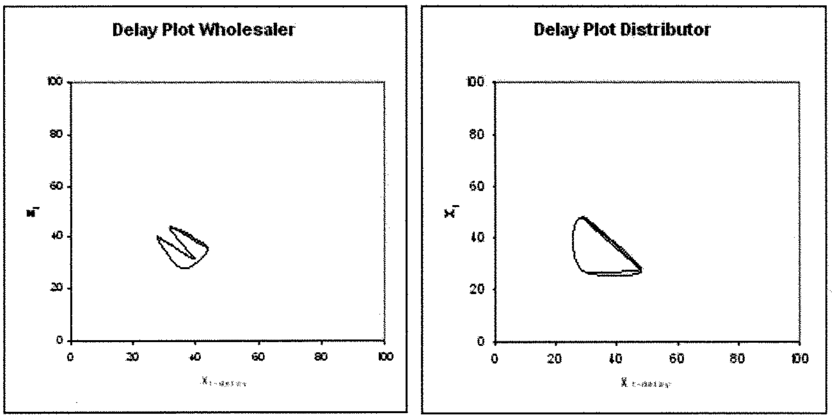


**Figure 9** **Delay plots for Static EOQ agents**

The data is clearly not chaotic in that the series follows the same path through this delay plot. Variability in the delay plot is not as wide as shown in the Static Forgetful model (note that plotting axes are different).

## Run 5 Random demand

Time series plot of inventory shows no evidence of bullwhip. The system is essentially stable, allowing for short term responses to a variable demand.

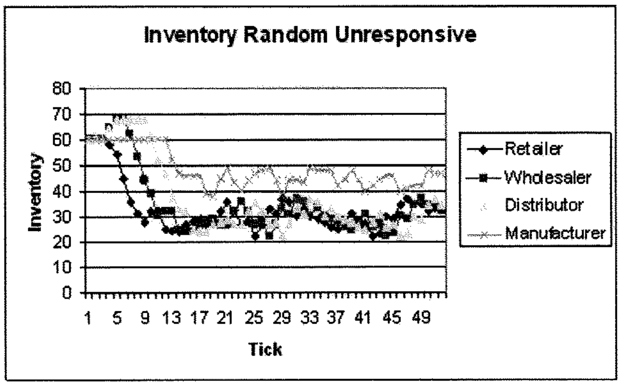


**Figure 10** **Random Unresponsive inventory time series**

Delay plots of wholesaler and distributor show no evidence of structure.

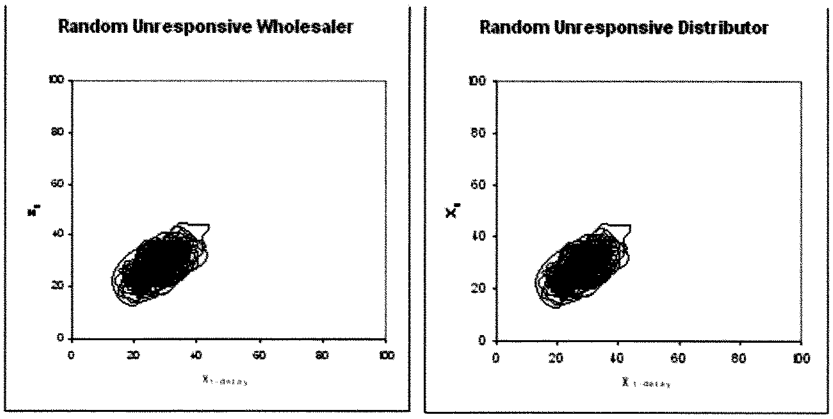


**Figure 11** **Delay plots for Random Unresponsive agents**

The dense trace indicates a multidimensional structure typical of random processes. It is expected that as the trace is developed in further dimensions it will continue to display an undifferentiated structure. No further analysis was carried out on this data.

## Discussion

The behaviour of the model using a range of ordering rules indicates that the model is a fair representation of the BDG. The cyclic character of the EOQ time series is to be expected, and the stable character of the unresponsive agents is also expected. The most striking feature of the game, of the model, and of some reported supply chains is the presence of amplified inventory fluctuation as we pass from customer to manufacturer. The literature usually refers to this as the Bullwhip effect. As noted in the discussion it has been argued that the Bullwhip effect can be reduced by changes to demand forecasting and batching policies (Lee et al., 1997). The model is consistent with this argument. The results of this model also suggest that the nature of the Bullwhip may be related to effective management of ordering data. The single most significant contribution to system stability in this model relates to loss of visibility of orders in the system. The delay plots and time series both indicated variability on the short 50 tick run and long 2000 tick run. Analysis approaches based on non linear time series analyses were useful for the Static forgetful run, but the analyses indicated that other runs were either dominated by stochastic behaviour (related obviously to random level of customer demand in the Random runs) or showed only relatively short lived instability in inventory levels.

While the correlation dimension and the Lyapunov exponents were calculable for the two agents that were at the centre of the Static Forgetful run, it is more likely that the delay plots gave a more credible representation of system behaviour. The amplitude of the plot, and the number of alternate traces gave a compact representation of the complexity of the system, while providing a useful overview of likely extreme values and paths to particular states of the system.

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