SUPPLY CHAIN DYNAMICS, THE "BEER DISTRIBUTION GAME" AND MISPERCEPTIONS IN DYNAMIC DECISION MAKING

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Keywords: Supply chain, stock management, anchoring and adjustment, distribution game, Beer Game, behavioral decision theory, dynamic decision-making, experimental economics

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Summary

Studies in the psychology of individual choice have identified numerous cognitive and other bounds on human rationality, often producing systematic errors and biases. In a dynamic management setting, such systematic errors and biases can be primary causes of mismanagement. A widely known example of such a system is supply chain management and its typical oscillatory dynamics. This paper first describes a generic model of stock management and then adapts it to a well-known supply chain management game, the "beer distribution game." Subjects manage a simulated supply chain system that contains multiple actors, feedbacks, nonlinearities, and time delays. The interaction of individual decisions with the structure of the simulated firm produces aggregate dynamics that systematically diverge from optimal behavior. An anchoring and adjustment heuristic for stock management is proposed as a model of the subjects' decision processes. Econometric tests show the rule explains the subjects' behavior well. The estimation results identify several 'misperceptions of feedback' that account

for the poor performance of the subjects. In particular, subjects are shown to be insensitive to the feedbacks from their decisions to the environment. Finally, the generality of the results is considered and implications for behavioral theories of aggregate social and economic dynamics are explored.

1. Introduction

Experimental studies in economics and the psychology of individual choice have identified numerous cognitive, informational, temporal, and other limitations that bound human rationality, often producing behavior that differs from the predictions of rational models. Yet for the most part models of aggregate phenomena in management science and economics are not consistent with such micro-empirical knowledge of individual decision-making. In a 1981 review Hogarth laments the "insufficient attention" paid "to the effects of feedback between organism and environment." By feedback is meant not merely outcome feedback but changes in the environment, in the conditions of choice, which are caused, directly and indirectly, by an agent's past actions. For example, a firm's decision to increase production feeds back through the market to influence the price of goods, profits, and demand; greater output may tighten the markets for labor and materials; competitors may react – all influencing future production decisions. Such multiple feedbacks are the norm rather than the exception in real problems of choice. Consequently, the focus of much research in behavioral decision theory on individual choice in static and discrete tasks has limited the penetration of psychological perspectives in theories of aggregate dynamics such as the behavior of firms, industries, and the economy. Thus, more empirical investigation is needed to secure micro-level data about how individual agents make their decisions. But securing such micro-level data is not sufficient. What is further needed is an investigation of how the decisions of the individual actors lead to the behavior of the aggregate system, that is, the generation of macro behavior from microstructure.

This paper applies the experimental methods used effectively in the study of individual behavior to the generation of macro dynamics from microstructure in a common managerial context, supply chain management. The paper first describes a generic model of stock management and its dynamics. The model is then adapted to a well-known supply chain management game, the "beer distribution game." In the experiments subjects manage a simulated industrial production and distribution system. The decision-making task is straightforward: subjects seek to minimize total costs by managing their inventories appropriately in the face of uncertain demand. But the simulated environment is rich, containing multiple actors, feedbacks, nonlinearities, and time delays. The interaction of individual decisions with the structure of the simulated firm produces aggregate dynamics that diverge significantly and systematically from optimal behavior. An anchoring and adjustment heuristic for stock management is proposed as a model of the subjects' decision processes. Econometric tests show the rule explains the subjects' behavior well. Analysis of the results shows that the subjects fall victim to several 'misperceptions of feedback.' Specifically, subjects failed to account for control actions that had been initiated but not yet had their effect. Subjects were insensitive to feedbacks from their decisions to the environment. The majority attributed the dynamics they experienced to external events, when in fact these dynamics were internally generated by their own actions. Further, the subjects' open-loop mental model, in which dynamics arise from exogenous events, is hypothesized to hinder learning and retard evolution towards greater efficiency. Finally, the generality of the results is considered and implications for behavioral theories of aggregate social and economic dynamics are discussed.

2. The Stock Management Problem

One of the most common dynamic decision-making tasks is the regulation of a stock or system state. In such a task, the manager seeks to maintain a quantity at a particular target level, or at least within an acceptable range. Stocks cannot be controlled directly but rather must be influenced by changes in their inflow and outflow rates. Typically, the manager must set the inflow rate so as to compensate for losses and usage and to counteract disturbances that push the stock away from its desired value. Often there are lags between the initiation of a control action and its effect, and/or lags between a change in the stock and the perception of that change by the decision maker. The duration of these lags may vary and may be influenced by the manager's own actions.

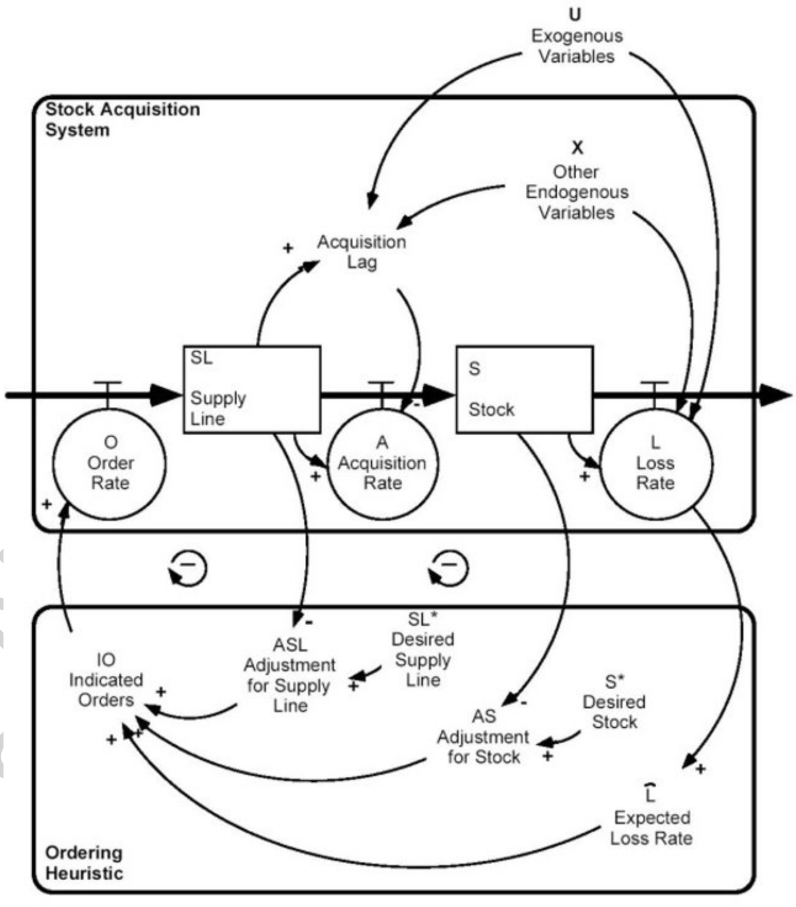

Figure 1. The generic supply chain management system.

Stock management problems occur at many levels of aggregation. At the level of a firm, managers must order parts and raw materials so as to maintain inventories sufficient for production to proceed at the desired rate, yet prevent costly inventories from accumulating. They must adjust for variations in the usage and wastage of these materials and for changes in their delivery delays. At the level of the individual, people regulate the temperature of the water in their morning shower, guide their cars down the highway, and manage their checking account balances. At the macro-economic level, the Federal Reserve seeks to manage the stock of money to stimulate economic growth and avoid inflation, while compensating for variations in credit demand, budget deficits, and international capital flows.

The generic stock management control problem may be divided into two parts: (i) the stock and flow structure of the system; and (ii) the decision rule used by the manager (Figure 1). Considering first the stock and flow structure, the stock *S* is the accumulation of the acquisition rate A less the loss rate *L*:

$$S_t = \int_{t_0}^{t} (A_\tau - L_\tau) d\tau + S_{t_0} \qquad (1)$$

Losses here include any outflow from the stock and may arise from usage (as in a raw material inventory) or decay (as in the depreciation of plant and equipment). The loss rate must depend on the stock itself – losses must approach zero as the stock is depleted – and may also depend on other endogenous variables *X* and exogenous variables *U*. Losses may be nonlinear and may depend on the age distribution of the stock.

The acquisition rate depends on the supply line SL of units that have been ordered but not yet received, and the average acquisition lag . In general, may depend on the supply line itself and on the other endogenous and exogenous variables. The supply line is simply the accumulation of the orders that have been placed *O* less those which have been delivered:

$$SL_t = \int_{t_0}^{t} (O_\tau - A_\tau) d\tau + SL_{t_0} \qquad (2)$$

The structure represented by Figure 1 and Eq. (1)-(2) is quite general. The system may be nonlinear. There may be arbitrarily complex feedbacks among the endogenous variables, and the system may be influenced by a number of exogenous forces, both systematic and stochastic. Table 1 maps common examples into the generic form. In each case, the manager must choose the order rate over time so as to keep the stock close to a target. It is interesting to note that the characteristic behavior modes of many of these systems include oscillation and instability.

In most realistic stock management situations the complexity of the feedbacks among the variables precludes the determination of the optimal strategy. The order decision model proposed here assumes that managers, unable to optimize, instead exercise control through a heuristic that is locally rational. The model thus falls firmly in the tradition of bounded rationality as developed by Herbert Simon (1982), Cyert and March (1963), and others. Cognitive limitations are recognized, as are information limitations caused by organizational structures such as task factoring and sub goals.

The hypothesized decision rule utilizes information locally available to the decision maker and does not presume that the manager has global knowledge of the structure of the system. Managers are assumed to choose orders so as to: (1) replace expected losses from the stock; (2) reduce the discrepancy between the desired and actual stock; and (3) maintain an adequate supply line of unfilled orders.

System	**Stock**	**Supply Line**	**Loss Rate**	**Acquisition Rate**	**Order Rate**	**Typical Behavior**
Supply Chain management	Inventories	Goods on order	Shipments to customers	Arrivals from supplier	Orders for goods	Business cycles
Capital investment	Capital plant	Plant under construction	Depreciation	Construction completion	New contracts	Construction cycles
Equipment	Equipment	Equipment on order	Depreciation	Equipment delivery	New equipment orders	Business cycles
Human resources	Employees	Vacancies & trainees	Layoffs and quits	Hiring rate	Vacancy creation	Business cycles
Cash management	Cash balance	Pending loan applications	Expenditures	Borrowing rate	Loan application rate	Cash flow cycles
Marketing	Customer base	Prospective customers	Defections to competitors	Recruitment of new customers	New customer contacts	Boom and bust in customer base
Hog farming	Hog stock	Immature and gestating hogs	Slaughter rate	Maturation rate	Breeding rate	Hog cycles
Agricultural commodities	Inventory	Crops in the field	Consumption	Harvest rate	Planting rate	Commodity cycles
Commercial real estate	Building stock	Buildings under development	Depreciation	Completion rate	Development rate	Real estate booms and busts
Cooking on electric range	Temperature of pot	Heat in coils of range	Diffusion to air	Diffusion from coils to pot	Setting of burner	Overcooked dinner
Driving	Distance to next car	Momentum of car	Friction	Velocity	Gas and brake pedals	Stop-and-go traffic
Showering	Water temperature	Water temp. in pipes	Drain rate	Flow from showerhead	Faucet settings	Burn then freeze

Personal energy level	Glucose in bloodstream	Sugar and starch in GI tract	Metabolism	Digestion	Food consumption	Cycles of energy level
Social drinking	Alcohol in blood	Alcohol in stomach	Metabolism of alcohol	Diffusion from stomach to blood	Alcohol consumption rate	Drunkenness

Table 1. Examples of the Stock-Management System

To formalize this heuristic, first observe that orders in most real-life situations must be nonnegative:

$$O_t = \text{MAX}(0, IO_t) \qquad (3)$$

where *IO* is the indicated order rate, the rate indicated by other pressures. Order cancellations are sometimes possible and may sometimes exceed new orders (e.g. the U.S. nuclear power industry in the 1970s). Cancellations are likely to be subject to different costs and administrative procedures than new orders and should be modeled as a distinct outflow from the supply line rather than as negative orders.

The indicated order rate is based on the "anchoring and adjustment heuristic." Anchoring and adjustment is a common strategy in which an unknown quantity is estimated by first recalling a known reference point (the anchor) and then adjusting for the effects of other factors which may be less salient or whose effects are obscure, requiring the subject to estimate these effects by what Kahneman and Tversky call 'mental simulation.' Anchoring and adjustment has been shown to apply to a wide variety of decision-making tasks. Here the anchor is the expected loss rate $\hat{L}$. Adjustments are then made to correct discrepancies between the desired and actual stock (*AS*), and between the desired and actual supply line (*ASL*):

$$IO_t = \hat{L}_t + AS_t + ASL_t. \qquad (4)$$

Expected losses may be formed in various ways. Common formulations include static expectations $\hat{L}_t = L^*$ (a constant or equilibrium value), regressive expectations $\hat{L}_t = \; L_{t-1} + (1- \;)L^*$, $0\leq \; \leq 1$, adaptive expectations $\hat{L}_t = \; L_{t-1} + (1- \;)\hat{L}_{t-1}$, $0\leq \; \leq 1$, and extrapolative expectations, $\Delta\hat{L}_t = \; _i \; \Delta L_{t-i}$, where Δ is the first difference operator and $_i \geq 0$.

The feedback structure of the heuristic is shown in the bottom part of Figure 1. The adjustment for the stock *AS* creates a negative feedback loop which regulates the stock. For simplicity the adjustment is linear in the discrepancy between the desired stock S^* and the actual stock:

$$AS_t = \; _S(S^*_t - S_t), \qquad (5)$$

where the stock adjustment parameter $_S$ is the fraction of the discrepancy ordered each period. The adjustment for the supply line is formulated analogously as

$$ASL_t = \; _{SL}(SL^*_t - SL_t), \qquad (6)$$

where SL^* is the desired supply line and $_{SL}$ is the fractional adjustment rate for the supply line. The desired supply line in general is not constant but depends on the desired throughput * and the expected lag between ordering and acquisition of goods:

$$SL^*_t = \hat{\lambda}_t \; ^*_t. \qquad (7)$$

The longer the expected delay in acquiring goods or the larger the throughput desired, the larger the supply line must be. For example, if a retailer wishes to receive 1000 widgets per week from the supplier and delivery requires six weeks, the retailer must have 6000 widgets on order to ensure an uninterrupted flow of deliveries. The adjustment for the supply line creates a negative feedback loop which adjusts orders so as to maintain an acquisition rate consistent with the desired throughput and the acquisition lag. Without such a feedback orders would be placed even after the supply line contained sufficient orders to correct stock shortfalls, producing overshoot and instability. The supply line adjustment also compensates for changes in the acquisition lag. If the acquisition lag doubled, for example, the supply line adjustment would induce sufficient additional orders to restore the desired throughput. As in the formation of expected losses, there are a variety of possible representations for $\hat{\lambda}$ and *, ranging from constants through sophisticated forecasts.

In terms of anchoring and adjustment, expected losses form an easily anticipated and relatively stable starting point for the determination of orders. Loss rate information will typically be locally available and highly salient to the decision maker. Replacing losses will keep the stock constant at its current level. Adjustments are then made in response to the adequacy of the stock and supply line. No assumption is made that these adjustments are optimal or that managers actually calculate the order rate using the equations. Rather, pressures arising from the discrepancies between desired and actual quantities cause managers to adjust the order rate above or below the level that would maintain the status quo.

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Biographical Sketch

John D. Sterman is the Jay W. Forrester Professor of Management at the MIT Sloan School of Management and Director of MIT's System Dynamics Group. His research includes systems thinking and organizational learning, computer simulation of corporate strategy, and the theory of nonlinear dynamics. Author of many scholarly and popular articles on the challenges and opportunities facing organizations today, including the book *Modeling for Organizational Learning*, and the award-winning textbook *Business Dynamics*, he has presented his work before corporate, financial, and government audiences worldwide.

Prof. Sterman's research centers on improving managerial decision making in complex systems. He has pioneered the development of "management flight simulators" of corporate and economic systems. These flight simulators are now used by corporations and universities around the world. His recent research ranges from the dynamics of organizational change and the implementation of sustainable improvement programs to experimental studies assessing public understanding of global climate change.

Prof. Sterman has twice been awarded the Jay W. Forrester Prize for the best published work in system dynamics, won the 2001 Accenture Award for the best paper of the year published in the *California Management Review* (with Nelson Repenning), has five times won awards for teaching excellence from the students of the Sloan School, and was named one of the Sloan School's "Outstanding Faculty" by the 2001 *Business Week Guide to the Best Business Schools*. He has been featured on public television's *News Hour*, National Public Radio's *Marketplace*, CBC television, *Fortune*, the *Financial Times*, *Business Week*, and many other newspapers and journals for his research work and innovative use of interactive simulations in management education and corporate problem solving.