Hierarchical Coordination of Economic Agents

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Abstract

This paper discusses the formation of organizational knowledge of boundedly rational Economic agents and studies the necessity of hierarchical coordination of economic agents. We consider a firm that consists of a management and N subordinated shops. The problem of the firm is to observe a signal from the environment, forecast future demands and distribute the correct amount of a good to each of the shops. There are two uncertainties involved: The aggregate demand follows a Brownian motion and the distribution of the aggregate demand to the shops varies stochastically. At the beginning of the simulation the agents are ignorant about their actions. They learn how to choose their actions by probabilistic update. We study the importance of the organizational structure as a function of the uncertainties the agents are facing. It turns out that there is no need for a management if the environment is purely deterministic or if only the aggregate demand varies stochastically. However, if the disaggregate environment is stochastic, the management as a coordinator for the shops becomes important.

1 Introduction

1.1 Information Integration in the Firm

Economic agents are boundedly rational, i.e., their capacity for computation and communication is finite.[1] As a consequence the data collecting and computing activities necessary for directing the activities of a larger firm are distributed and the managers in charge communicate according to specified lines. Traditionally, microeconomics has assumed that the form of this network is hierarchical, where the result of a computation is only passed to several immediate subordinates or to one agent on the next higher level, respectively.

[2] Indeed, it can be demonstrated that a hierarchical organizational form has appealing features when the firm is viewed at as an *information processing system*. Bolton/Dewatripont ([1]), for instance, show that under rather general assumptions about the cost of computation and communication hierarchical designs for distributed computing dominate non-hierarchical ones in the sense that a set of environmental messages can be processed in shorter time. There, the algorithms to be used are given, only the way how they are distributed can be varied.

Clearly, besides speed also the quality of the thus computed organizational action is important, i.e., the decisions computed by the different agents must be coordinated. The classical approach to this problem is to assume that management has a general model of the environment and the organization and on this basis derives the decision rules for the agents. For instance, Cremer states: "The organizational problem found by the firm is the following: It must tell each of the agents which observations it should make ... and the

[1] Computers and telecommunication clearly increase these capacities tremendously. Nevertheless, complexity theory shows that there is the large class of NP-complete problems, for which exact solutions can only be found for small problem instances (see [4]). Furthermore, the cost of finding a suitable model, developing the algorithm and transferring data into digital form still remains.

[2] Williamson, for instance, titles his book about transaction cost economics "Markets and Hierarchies", equating firm with hierarchy (see [13]).

decision that it should take given this observation" ([3]). Thus *structure follows strategy* and once set up the organization behaves like a mechanical computing device.

If the actions of agents on lower hierarchies can be perfectly observed so that deviant behavior can be punished, such a mechanism also works when the agents in the organization have different goal functions. Interesting agency theoretic problems arise when perfect monitoring is not possible and factors additional to the action of the agent that cannot be observed without noise influence the result of an agent's actions. In such cases incentive systems based on profit-sharing are a good method of achieving vertical coordination ([11]). Other interesting problems arise when one examines the tradeoff between costly communication and coordination quality under a common team goal function. Marschak, Radner ([10]) investigate the effects of replacing an information item with its conditional expected value given the other information an agent has and find, for instance, that "Management by Exception", where only "unusual" observations are communicated, solves this tradeoff well.

1.2 Previous Work

Despite the importance of organizational learning, most works on this subject are exploratory and based on case studies rather than on quantitative models. Consequently, many issues are not well understood. Lounamaa/March, for instance, note on this subject: "The failure to specify the mechanisms of adaptation with greater precision makes discussions of organizational learning as a form of intelligence somewhat difficult to evaluate." ([8]) Also, Kagono et.al. write: "A most serious shortcoming typical in Japan is that the H model (i.e., organizational learning) is not sufficiently understood and not a systematic management approach. The system and the process, themselves, spontaneously emerged, but it is not a well-articulated, systematic approach to management." ([7])

First interesting formal models are developed in [9] and [8]. In [9] Marengo models a firm that consists of three agents that in each period have to decide which product to produce and to implement compatible production processes. There, a coordinating agent observes the market and predicts the product to be produced; two producing agents implement the work schedule necessary to produce a product, each one being in charge of half of the activities. Each agent is modeled as a classifier system ([6]), and the effects of different information systems that provide the respective conditions is investigated. The following results are noteworthy:

- partial observation of the organizational action inhibits learning:
  Organizational learning in an organization without a coordinating agent does not converge to the profit maximizing product. If both production agents observe the market and implement their production decision, they cannot build a meaningful relation between their action and the result, as this is confounded by the action of the other agent, which is not known. Introducing the coordinator, who makes a forecast and communicates it to both producing agents remedies this situation.
- irrelevant information distracts learning:
  Marengo shows that when the market changes randomly, information about it given to the producing agents additional to the forecast made by the coordinator causes a non-convergence to the stable optimal decision rule. Thus, while in the information processing paradigm irrelevant information just causes unnecessary costs, meaningless information distracts learning and can cause the learning of spurious cause-effects or prohibit the learning of stable rules. Empirical evidence of this fact is described in [5].
- observing and communicating the same fact can be beneficial:
  However, the same information improves learning when it contains a meaningful functional relationship. This contradicts team theory, where it makes no sense to both communicate and observe the same information. In fact, as Clark/Marshall show, common observation is a powerful mechanism for achieving mutual knowledge, which otherwise cannot be deduced as this leads to an infinite regress ([2]). In light of these findings, it becomes clear why empirical literature on product development postulates that production people should take part from the beginning of the project when the market oriented product concept is developed by analyzing market data and visiting customers: it will allow them to build a mental model of the market so that communication of equivocal concepts is easier latter on when the product concept is transferred into technical specifications to obtain the product plan.

Also Lounamaa/March show that "in the absence of calibrating heuristics, experience becomes a poor teacher and learning fails." ([8]) Using a model of two learners (e.g. divisions), whose payoff is connected via an interaction parameter that is controlled by a third learner (e.g. headquarter), they show that:

- when all agents learn concurrently, the coordinator becomes confused: he learns spurious effects of his actions when a small change of his control is followed by a large change in performance, which is caused by learning of the agents and not by the change of his parameter. Due to this feedback, he will then increase his parameter, which can lead to non-convergence with bad results. Consequently, Lounamaa/March suggest to make changes of the control parameter only when results decrease and to restrict their size.

- when observations are noisy, the coordinator should only act periodically based on averaged values. Also changes of the control parameter should be larger in order to be distinguished from noise by the other agents.
- it is not always good to have a high learning rate, as then observations become unreliable because of the effects of noise and multiple simultaneous changes and the system can move out of control while it is still observed.

However, as Sterman et.al ([12]) show, reducing the simultaneity of learning can have pitfalls of its own. Using a detailed case study and a systems dynamics model of an US electronics manufacturer they show that a successful TQM implementation in operations can have severe negative economic consequences for the firm as a whole. The company under study made the rational choice of starting to learn and improve in operations as there, contrary to product development, the systems are more modular and experiments can be made easily and fast so that the early successes necessary to promote TQM can be achieved. However, management did not understand the interaction between productivity gains in operations, unchanged productivity in new product development and an unchanged accounting rule of adding a fixed mark-up percentage on operative costs to obtain the selling price of a product: as operative costs went down as a result of learning, the unchanged mark up percentage caused the prices to be charged to go down too, and with no new products out demand could not rise accordingly. The combined effect was a fall of profits, which necessitated layoffs, which then severely impeded further TQM-efforts.

2 Coordination of Economic Agents

We consider a simple model of the coordination problem a firm is facing. The outcome for the organization depends on the actions of boundedly rational agents. In our setting the agents try to do their best to increase the value of the firm, i.e., we do not consider agents with interfering incentives. The firm consists of a central management and S subordinated shops. The agents are facing the following problem: At time t each shop $s = 1 \ldots S$ has to forecast its disaggregate demand for the next time step and order a certain amount of a good y_s. At the end of each period the amount of the good $x_s(t+1)$ actually needed is known and is compared to the number of goods ordered. Each shop then receives a payoff $\Pi_s(t+1)$ that depends on the difference between y_s and $x_s(t+1)$. If the amount ordered is lower than actual demand, the shop will be out of stock and receives a negative payoff. If it exceeds actual demand, the good not sold is dumped resulting in a negative payoff as well. We use the same payoff function as Marengo ([9]) where the shop's payoff equals 5 if the forecast was correct and $-|y_s - x_s(t+1)|$ otherwise. The total payoff of the firm is given by the sum over the shop's payoffs.

The job of the management is to forecast the aggregate demand $x(t+1) = \sum x_s(t+1)$ by observing $x(t)$. The payoff function is the same as for the shops, but with the corresponding aggregate variables.

In the demand process there are 2 uncertainties involved. The aggregate demand $x(t)$ follows an autoregressive process bounded between x_{max} and x_{min}.

$$x(t+1) = (x(t) + S + \epsilon_t - x_{min}) \, mod \, x_{max} \; + x_{min} \quad (1)$$

The noise term ϵ_t is ± 1 with probability p_1.

The distribution of the aggregate demand to the shops varies stochastically. The disaggregate demand of the shops $x_s(t)$ is given by $x_s(t) = 1/S * x(t) + \delta_t$ with $\delta_t = \pm 1$ with probability p_2.

The problem of the agents is to observe the demand at time t and forecast the demand of the next period. At the beginning the agents are ignorant about their actions. They learn how to choose their actions by probabilistic update: An agent receives an input signal $i(t)$ ($x_s(t)$ for the shops and $x(t)$ for the management), takes some action $a(t)$ and gets a payoff Π dependent on his action. The payoff serves as a reinforcement signal. An agent consists of a transition matrix T that is set to zero at the beginning. After receiving the payoff for its action a the transition matrix T is updated:

$$T(i,a) = T(i,a) + \Pi \quad (2)$$

The transition probability $p(i,a)$ for taking action a given input i is given by:

$$p(i,a) = (T(i,a) - \min_{a\prime} T(i,a\prime)) / \sum_a T(i,a) - \min_{a\prime} T(i,a\prime) \quad (3)$$

3 Simulation Results

We now compare the performance of two different organizational structures. The *decentralized* structure consists of two shops that act independent of each other and that do not exchange any information. Each shop receives its disaggregated demand $x_s(t)$, tries to forecast future demand, and receives a payoff $\Pi_s(t)$.

The *centralized* structure consists of a management agent and 2 shops. The management agent can only observe the aggregate demand $x(t)$ and sends its forecast of the aggregate demand to the shops. The shops receive the signal from management and take their actions. The payoff of the management is a function of the management's forecast and actual aggregate demand of the next period. The aggregate demand (1) varies between 2 and 14 with increments of 2. For this simple setting it would be easy to give the correct solution to the problem. The agents just would need to increment their observed input value by one modulo the boundary condition. However, we are not interested in optimal solutions but want to study the importance of coordination.

If the environment was purely deterministic, both, the *centralized* and the *decentralized* structure would be able to forecast the demand perfectly after some time of adaptation. However if demand becomes stochastic, the organizational structure becomes important. Figure (3) displays the cumulative payoffs, averaged over 100 repetitions, for both structures as a function of the probability for noise in aggregate demand. The probability p_1 for noise in the distribution to the shops, p_2 is zeros. In the *centralized* structure the management agent tries to forecast the aggregate demand and sends it to the shops. Therefore the shops have to adapt to a deterministic process only whereas they receive the noisy signal in the case of the *decentralized* structure. However, there is a tradeoff between the two structures. In the *centralized* structure shops receive a simpler signal but the management itself takes time to forecast the aggregate demand correctly. In the *decentralized* structure the shops have to adapt to a stochastic signal but there is no management that interferes with their learning process. For all values of p_2 the cumulative payoff after 1000 iterations is higher for the *decentralized* structure (see Figure (3)). Therefore, in the case of uncertainty in the aggregate demand only, there seems to be no need for a management agent that coordinates the shops.

Figure (3) shows the cumulative payoff after 1000 Time steps averaged over 100 repetitions as a function of the probability p_2. The aggregate demand is purely deterministic. If p_2 is zero, each agent receives 50% of the aggregate demand and the maximum payoff would be 10. However, starting from complete ignorance, the agents first have to adapt to the changing demand. For small values of the disturbance of the distribution the decentralized structure is able to adapt faster than the centralized structure. Therefore, for small uncertainties there is no need for a management to forecast the aggregate demand. However, when the probability for disturbances in the distribution becomes large, the centralized structure performs better. In this case the management can stabilize the decision problem for the shops by transmitting the aggregate forecast.

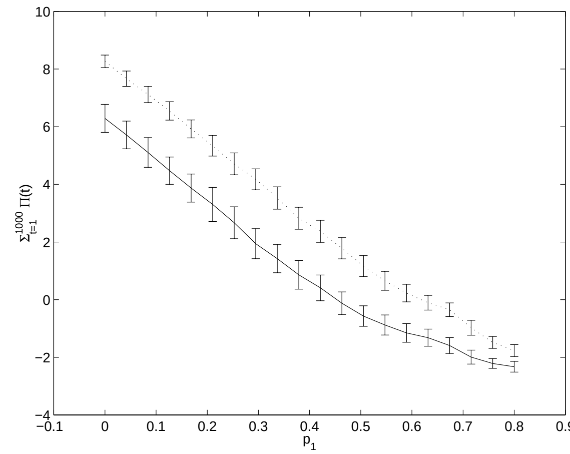

Figure 1. The cumulative payoff Π of the *decentralized* (dotted) and the *centralized* structure as a function of the randomness in the aggregate demand.

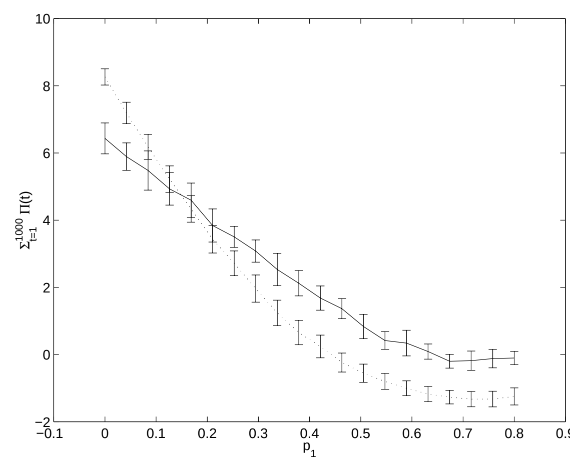

Figure 2. The cumulative payoff Π of the *decentralized* (dotted) and the *centralized* structure as a function of the randomness in the distribution of the demand to the shops.

4 Conclusions

We suggested a model of organizational learning and studied the impact of different organizational structures on the capability of decision making under changing demand. Two structures were compared: A *centralized* structure consists of a management agent observing an aggregate view of the environment and subordinated shops. In the *decentralized* structure the shops take past histories of disaggregate demand as a basis for their decision making process.

Based on our simulations we found the following implications for an organization: For regularly changing environments decentralized decision making is preferred. As for deterministic environments the forecasting task is simple the subordinated agents are able to solve the problem on their own. A management that tries to support the shops by adapting to the process itself only disturbs the signal for the agents and thus slows down their learning process.

In the case of uncertainty on the aggregate level only, there is still no need for a management. Although the management facilitates the task for the shops, the interference of the learning processes outweighs this advantage for all levels of uncertainty. However, for increasing uncertainty the difference between the two organizations decreases.

If the environment is characterized by uncertainty on the disaggregate level, the tradeoff of the management between supporting the shops and interfering with the shop's learning process persists. Contrary to uncertainty on the aggregate level, in this case, the *centralized* organization outperforms the *decentralized* structure even for moderate levels of uncertainty in demand.

The key advantage of our approach is that we model uncertainty on different levels of aggregation. Therefore, one can distinguish between external and internal uncertainty. We found, that a tradeoff between coordination and interfering learning signals exists for both types of uncertainty. Our results indicate the necessity of a management as a coordinator in the case of high uncertainty within the organization.

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