**Coordination in an agent-based division of labor model**

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This paper compares the performance of coordination by decentralized and centralized mechanisms in a division of labor model, where there are returns to specialization. My primary hypothesis is that central coordination is a superior mechanism for organizing systems that display complex webs of interdependency between participants. The model demonstrates that centralized coordination provides efficiency benefits over decentralized systems when duplication of effort is costly and close synchronization of effort is required; that centralized coordination can be more efficient than decentralized coordination even in the absence of opportunism; and that redundancy is a necessary element of decentralized systems.

The comparison of centralized and decentralized systems in economic production has a long history in economics. Coase [1937] first pointed out that economic agents incur an unseen cost when they rely on decentralized markets. Hayek [1944] argued that decentralized systems have information processing advantages since economic agents acting on local information could process more information than a central coordinator. Most recently, Williamson [1975, 1985] proposed that hierarchical organizations arise to solve bargaining problems when production involves investments by one agent that are specialized to another economic agent.

This model demonstrates the advantages of central coordination in overcoming synchronization and assignment problems [Milgrom and Roberts, 1992]. Synchronization problems arise when many participants in a joint process must time their contributions precisely; in this situation agents acting on their own behalf may not synchronize their actions properly. Assignment problems, on the other hand, arise when redundancy is particularly costly. For instance, if ambulances were dispatched through a decentralized market, then several emergency vehicles might respond to a call requiring just one team, leaving the system unprepared for the next emergency. These advantages of centralized coordination of production have not been closely explored, probably because they are dynamic and do not lend themselves to analytical modeling.

This paper uses an agent-based computer model to compare the advantages of centralized and decentralized coordination in conditions that share many of the characteristics of synchronization and assignment problems. The model requires synchronization, since all the steps of the production process must be performed in every round or the product will not be produced. Thus when an agent exits the simulation, all its trading partners are reset to solo production since they have lost the steps that a partner provided. In addition, the model is an example of the assignment problem in reverse, since it demonstrates the problems of decentralized systems when they lack sufficient redundancy.

## Model

In the simulation, each agent can produce a single product by performing $n$ steps in a round. Each agent earns a welfare score from its production, which is calculated as $n$ (the number of steps) minus the number of transitions between steps (so each move from one step to the next imposes a cost on the agent). Thus there are returns to specialization, and agents receive a greater payoff if they specialize in fewer steps of production. Agents may trade steps with one another to increase their specialization. In each round agents attempt one trade and then they produce. The production of each agent must contribute to a finished product in that round, and an agent will revert to solo production if its trading network will not produce a complete final product.

In one set of simulations, agents are completely decentralized. They trade with neighbors to specialize in certain steps of the model. To trade, they randomly select a neighbor and search for two steps in common: if they have two steps in common they swap so that each of them performs twice a single step in the production process. In another set of simulations, certain agents act as central coordinators who split the production steps between members of their group. Each coordinator begins with one agent in its group. During the trading stage, it selects an agent at random to invite into the group. If the new agent and the group will be better off by sharing production, the agent joins the group. In the centralized model, the coordinator does not contribute to output but shares the value of production, so maximum possible welfare is less than in the decentralized system.

**Results**

The two systems were compared first in a static setting then in a dynamic setting. In the static setting, the decentralized system converged to its final state more quickly and reached a higher level of average welfare than the centralized system. In the dynamic setting, agents exit the model at random. When an agent exits, its trading partners revert to solo production. In this setting, the decentralized system achieved lower average welfare per agent because many more agents were affected when an agent exited the simulation. In the centralized simulation, at most n-1 trading partners were reset to solo production. In the decentralized simulation, resetting the agent’s trading partners had a cascading effect, because its trading partners performed the same production step for several different production networks. All these interdependent networks would be reset to solo production, and then other production networks that overlapped with them would be reset as well. This would sometimes lead the entire set of agents in the simulation to revert to solo production when a single agent exited.

The results of the simulation strongly support the proposition that hierarchy is a more robust coordination mechanism for highly interdependent systems of production. When turnover is introduced into the model, the welfare of agents in both systems becomes much more unstable. Neither model converges to a stable solution, and neither model even approaches the levels of welfare in a static model. Comparing the average welfare in centralized and decentralized systems over 10 runs of this system, the centralized system shows significantly higher average welfare than the decentralized system. For larger values of *n*, the advantages of the centralized mechanism are greater because the interdependence between agents is greater.

**Discussion**

The simulation results confirm several aspects of centralized and decentralized systems of coordination that have been suggested in the literature. First, as Simon [1982], Williamson [1975], and others have pointed out, central coordination offers advantages when the actions of the members of a system are very interdependent. In the simulation, central coordinators economize on interdependence, linking only the minimum number of agents necessary to achieve full specialization. Thus in the dynamic model, the advantages of central coordination as the interdependence of agents increased (as the number of production steps rose). In addition, the model illustrated the brittleness of decentralized systems in dynamic situations demanding synchronized contributions from multiple members. When agents exited the simulation, centralized agents experienced less disruption in cooperation and thus higher average welfare than decentralized agents.

The model also sheds new light on redundancy in decentralized markets. Not only is duplication of resources a *possible* (and costly) outcome of decentralization, as Milgrom and Roberts argue, but it is a necessary cost of decentralization. In the simulation, the decentralized trading system was very fragile when a simple dynamic of turnover was introduced into the model. The effect of turnover on the variation and average welfare of agents suggests that a high level of redundancy of actions is required to mitigate the brittleness that decentralized systems face in an environment of extensive interdependence between agents. This finding runs counter to the traditional emphasis on slack resources in organizations as compared to markets [Cyert and March, 1963].

The model also provides an example of the role of centralized coordination in the absence of opportunism. It suggests that while the presence of bargaining problems and opportunism explains many aspects of organizations, it does not completely account for the need for centralized coordination. In the simulation, hierarchical coordination minimized the interdependence of agents while still achieving full economies of specialization. In a dynamic setting with turnover, the centralized trading system led to better overall outcomes for agents despite the substantial penalty imposed on agents in the form of the administrative cost of a non-productive member of the group (the coordinator). An important caveat is that this model does not specifically address issues of organizational boundaries that are the focus of most transaction cost economics. In many complex production systems, central organizations act as coordinators of inputs purchased over markets from separate organizations.

**Possible extensions**

I am planning four extensions to this model to shed further light on the comparison of decentralized and centralized systems of coordination. These modifications will: 1) allow both centralized and decentralized agents to trade with any other agent in the simulation (now the decentralized agents search for partners locally, while centralized coordinators search over the whole system); 2) enable decentralized traders to use the payoff from specialization to invest in inventory or buffers by performing extra steps that would be useful in the case of departure of a trading partner (allowing me to explore the extent of redundancy required for the decentralized system to match the performance of the centralized system); 3) test the model in dynamic situations other than turnover of agents – such as when synergies appear between steps in the production process, so one agent can do the work of two agents by combining steps; and 4) combine both types of coordination into a single model, to see under what conditions groups of agents would be likely to trade with one another.

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