Modeling Coordination in Organizations and Markets

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MODELING COORDINATION IN ORGANIZATIONS AND MARKETS*

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This paper describes a simple set of coordination structures that model certain kinds of information processing involved in organizations and markets. Four generic coordination structures are defined: product hierarchies, functional hierarchies, centralized markets, and decentralized markets. Then tradeoffs among these structures are analyzed in terms of production costs, coordination costs, and vulnerability costs. This model is unusual in that it includes detailed definitions of the structures at a micro-level and mathematical derivations of comparisons among them at a macro-level. In the final section of the paper, several connections are made between these formal results and previous work on organizational design.
(ORGANIZATIONAL STRUCTURE; ORGANIZATION DESIGN; COORDINATION; INFORMATION PROCESSING)

Human organizations and markets are possibly the most complex entities on our planet. Their complexity can be viewed from many different perspectives, each emphasizing some factors and neglecting others. This paper emphasizes one perspective: analyzing these structures in terms of the information processing involved in coordination. This perspective appears particularly promising for understanding how information technology may affect organizational structure because coordination processes are critical in determining organizational structure, and because they are likely to be directly affected by information technology.

We first develop detailed definitions of several structures that represent common ways of coordinating human activity—various forms of markets and hierarchies. These definitions are based on micro-level assumptions about how tasks are selected and assigned. Then we analyze and compare these structures in terms of macro-level characteristics such as production costs and coordination costs. In the final section of the paper, we suggest some connections between these formal models and previous generalizations about organizational design. Clearly there are many important aspects of human organizations and markets that are not captured by these simple coordination structures. However, we have been surprised at the range of issues this modeling approach helps illuminate (e.g., see Malone and Smith 1984; Malone 1986; Malone, Yates, and Benjamin 1987; Crowston, Malone, and Lin in press).

The formal models draw heavily on work by Baligh and Richartz (1967), Baligh and Damon (1980), and Baligh and Burton (1981, 1984). The models also draw implicitly on analogies between the information processing done by people and the information processing done by computers (see Malone and Smith 1984; Malone in press). While people and computers differ in many ways, this "cognitive" approach has been useful in many of the social sciences (e.g., March and Simon, 1958; Norman 1981) and appears to have unrealized potential for analyzing human organizations.

Background

There is a large body of literature about organizational design, and since there are already a number of integrative summaries of this work (e.g., Mintzberg 1979; Gal-

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braith 1977; Hax and Majluf 1981), we will only briefly review here several of the formal mathematical models that bear most directly on the questions with which we are concerned.

Our central problem was formulated in very general mathematical terms by Marschak and Radner (1972). In their formulation of "team theory," each member of a group of *actors* has some initial information about the world and some ability to control certain actions in the world. A team also has some shared *payoff function* that determines, for a given state of the world, the value team members attach to the results of the different possible actions. Since, in general, the team members who must take actions do not possess all the relevant information about the world, there must be some *information structure* that determines how members perceive and communicate information, and there must also be some *decision function* that determines how members decide what actions to take based on the information they receive. The goal of an organizational designer may be thought of as choosing an information structure and a decision function that maximize the *net payoff* to the team members, i.e., the gross payoff less the cost of communicating and deciding.

Unfortunately for our purposes, the range of possible formal assumptions and parameter values that can be used within Marschak and Radner's general framework leads to a multitude of highly conditional results. Almost all the Marschak and Radner theorems depend on the assumption that the payoffs are determined by a quadratic function of the action variables. While this is, of course, a very general mathematical formulation, it is not at all clear what substantive processes in the real world can be represented in this manner or how to interpret the results.

Other theorists have used somewhat more easily interpretable models of the relationship between payoffs and coordination. For example, Jonscher (1982) and Beckman (1982) model the efficiency of production processes as simple functions of the amount of coordination resources applied to them. Burton and Obel (1984) assume that the coordination process in organizations is in some ways similar to iteratively approximating the solution of an optimization problem. Accordingly, they formulate linear programming problems and iterative solution methods that correspond to various organizational forms (e.g., grouping by product or function) and various control mechanisms (e.g., budgets vs. internal prices). Then they use the solutions that would result from a few iteration steps to model the efficiency of the different organizational structures. Mackenzie (1986a, b) describes a detailed set of models and methodologies for studying and representing the tasks, structures, and coordination methods of specific organizations. For instance, he shows how a sequence of tasks can be represented as a process and how tasks and coordinating processes can be analyzed at a series of different levels of abstraction.

The modeling approach we emphasize views each activity as a task that must be performed by some processor (either a person or a machine) and the performance of which requires some amount of time. This view, therefore, highlights the importance of assigning tasks to processors as one of the fundamental components of coordination and it highlights delay time and processing capacity as important components of overall output or cost. Several previous theorists have analyzed organizational coordination from this general point of view. For example, Kochen and Deutsch (1980) analyze queuing delays for tasks in evaluating the desirability of various kinds of decentralization in service organizations.

Perhaps the most extensive analyses of these issues is the work on vertical market structures by Baligh and Richartz (1967). Baligh and Richartz assume that a commodity-like product is being exchanged between a number of buyers and sellers in a market. Their analyses emphasize the conditions under which there are incentives for various numbers of middlemen to enter the market. They analyze a variety of factors including queuing delays, costs for exchanging messages, rebate strategies, and inventory carrying costs. In the next section, we describe how our models build on certain aspects of theirs.

Model

We define a *coordination structure* as a pattern of *decision-making and communication* among a set of *actors* who perform *tasks* in order to achieve *goals* (cf., Baligh and Damon 1980; Baligh and Burton 1981; Baligh 1986). For example, a coordination structure used by an automobile manufacturing company might be thought of as having a set of goals (e.g., producing several different lines of automobiles) and a set of actors, or "processors," (people and machines) to perform the tasks (e.g., engineering, manufacturing, and sales) necessary for achieving those goals. The various forms of markets analyzed by Baligh and Richartz (1967) can also be viewed as coordination structures with goals (e.g., satisfying consumer demands), actors (e.g., buyers, sellers, and middlemen), and tasks (e.g., filling orders). For the sake of concreteness, we will usually refer to "goals" as "products."

We will focus here on three kinds of costs for these coordination structures: *production costs*, *coordination costs*, and *vulnerability costs*. We include in production costs the costs of production capacity and the costs of delays in processing tasks. We include in coordination costs the costs of maintaining communication links (or "channels") between actors and the costs of exchanging "messages" along these links. By vulnerability costs, we mean the unavoidable costs of a changed situation that are incurred before the organization can adapt to a new situation. We model these costs in terms of the expected costs that result when actors fail to perform their tasks (e.g., when actors fail to fill orders or make decisions).

Our analysis of production and coordination costs is quite similar to that by Baligh and Richartz (1967), though our detailed assumptions differ in a few cases. We have extended Baligh and Richartz's analysis in two ways. First, they did not analyze vulnerability costs at all, and that constitutes an important part of our analysis. Second, they explicitly analyzed only market structures. We extend their analyses to include two coordination structures that resemble those found in hierarchical organizations.

Figure 1 shows the coordination structures we consider: product hierarchies, functional hierarchies, decentralized markets, and centralized markets. The lines and symbols in the figure summarize the patterns of decision-making, communication, and task processing described in the next section. More detailed formal descriptions of each structure are provided by Malone (1986) using a framework adapted from Baligh and Damon (1980) and Baligh and Burton (1981, 1984). While there are certainly many other possible coordination structures, these four represent a wide range of patterns that seem to be common in collective human activity. The extent to which these structures reflect the processes in real organizations and markets is, of course, an empirical question. However, we have attempted to define formal structures that capture the essence of some of the intuitive ways people use these terms.

Alternative Coordination Structures

Product Hierarchy. In a product hierarchy, there are separate divisions for different product lines. We use the term "product hierarchy" here, even though the groupings are sometimes made along other "mission-oriented" lines such as geographical regions or market segments. Each division has a manager (whom we will call a "product manager") and its own separate departments for different functions such as marketing, manufacturing, and engineering. General Motors was one of the earliest and best known examples of this general form with its separate divisions for Chevrolet, Pontiac, Cadillac, and other product lines (see Chandler 1962). This form is sometimes called the "multi-divisional" form (Chandler 1962) or the "*M*-form" (Williamson 1975).

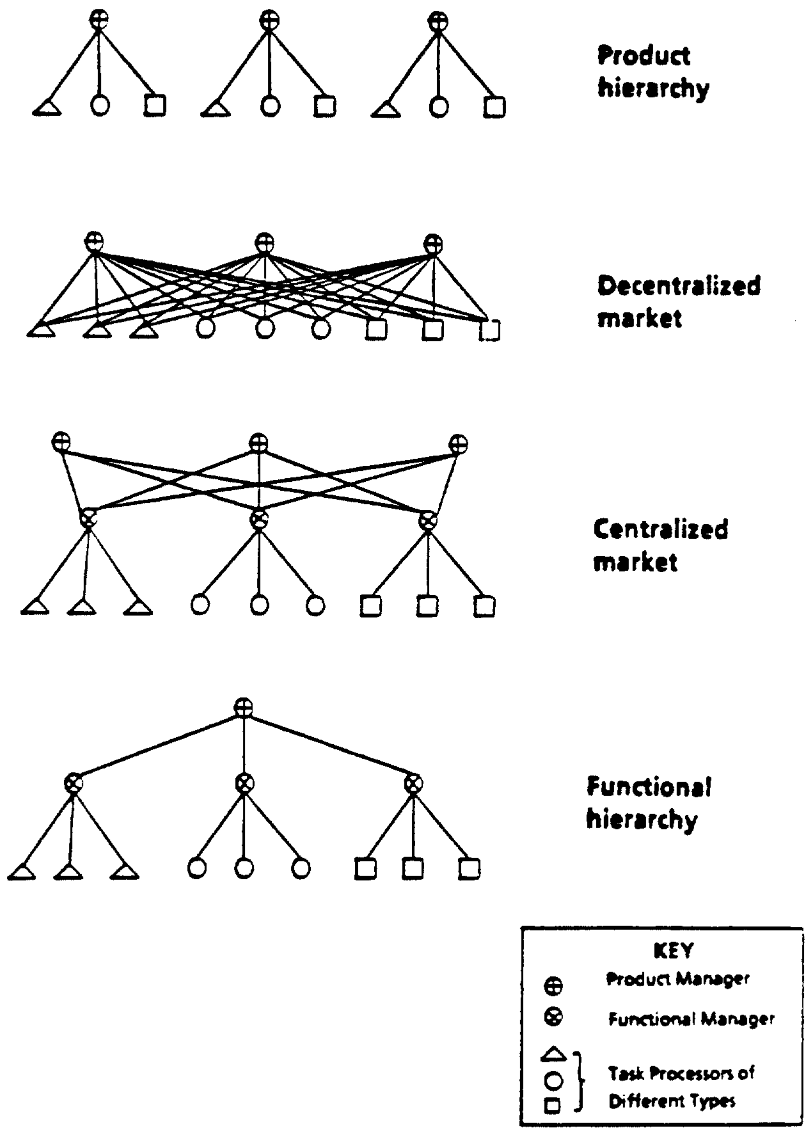

FIGURE 1. Alternative Coordination Structures.

We represent this form by the following coordination structure: Each division has a product manager and a specialized processor (e.g., a department) for each different type of task. The product manager decides what tasks need to be done to produce a product (or, more generally, to achieve some goal). As each task arises, the product manager assigns it to the processor for that type of task. For example, if General Motors used this structure for coordinating engineering tasks, the general manager of the Chevrolet division would expect all new Chevrolet models to be designed by the engineering department in the Chevrolet division. (We will use General Motors as a source of examples throughout this section. Here, and in the rest of this section, *these examples are hypothetical illustrations only, not actual descriptions of General Motors.* General Motors is an attractive choice for illustration because the names of its product divisions are household words for most readers.)

We assume that one "message" is required to assign a task to a processor, and that one "message" is required to notify the product manager that the task is complete. This means that there must be communication links between each of the product managers and their own processors, but not with any of the other divisions. We further assume that when a processor fails, the product division in which the failure occurs is disrupted, but the other divisions are not affected. For example, a major mechanical failure at a factory that produced only Chevrolets would not have any direct effect on the other divisions. A failure by the Cadillac marketing department to correctly predict what their customers would want in next year's models would not necessarily affect the other divisions, either.

Since the "product hierarchy" coordination structure does not include any interactions between the divisions, it could also be used to model a holding company or, indeed, a set of separate companies that do not share any resources.

Functional Hierarchy. In a functional hierarchy, a number of processors of similar types are pooled in functional departments and shared among products. This sharing of processors may reduce duplication of effort and may allow processing loads to be balanced over all products. For example, General Motors might need less manufacturing capacity if instead of providing enough capacity in each division to meet peak demands it had a central manufacturing department and balanced heavy demands for one product against lighter demands for other products. (The functional hierarchy is also sometimes called the "unitary" form or "*U*-form" (Williamson 1975).)

In the coordination structure we use to represent this organizational form, processors of the same type are grouped into functional departments, each of which has a "functional manager." There is also an "executive office" that decides what tasks need to be done to produce all the products of the organization (or, more generally, to achieve all the overall goals of the structure). The executive office, therefore, plays the role of "product manager" for all products. Assigning tasks in this structure is somewhat more complicated than for the product hierarchy because an extra layer of management is involved (cf., Burton and Obel 1984, Chapter 4). We assume that whenever a task of a certain type needs to be done, the executive office delegates the task to the functional manager of the appropriate type who, in turn, assigns the task to one of the processors in the functional manager's department. In order to make this assignment intelligently, the functional manager needs to keep track of the loads and capabilities of the processors in the department. For example, if General Motors used this coordination structure for manufacturing, a central manufacturing department would manage all the manufacturing plants. The vice-president of manufacturing and his or her staff would be responsible for coordinating the sharing of these facilities to produce all the different kinds of cars for all the different product lines.

In defining this coordination structure, we assume that four messages are required to assign a task: one to delegate the task to the appropriate functional manager, one to assign it to a processor, and two to notify the functional manager and the executive office, respectively, that the task is complete. In order to exchange these messages, the executive office must have a communication link to each functional manager, and each of the functional managers must have a link to the processors in their department.

When an individual task processor fails in this structure, the tasks it would have performed are delayed until they can be reassigned to another processor in the same department. For example, if General Motors had a single centralized sales and distribution department for all its products, it could shift car allocations from poorly performing dealerships to more successful ones. If GM had a pure product hierarchy, on the other hand, it would be difficult to shift sales volume of Cadillacs into dealerships that handled only Chevrolets.

There is another kind of failure, however, to which the functional hierarchy is much more vulnerable. When a functional manager or the executive office fails, instead of just an individual task processor, the processing of the entire organization may be disrupted. For instance if the vice-president in charge of all manufacturing performed very poorly, the manufacturing of all products could be excessively costly or delayed and these effects would be felt throughout the organization.

Markets. So far we have considered two hierarchical structures for coordinating task assignments. One of the important insights from the literature of organizational theory and economics (e.g., see Williamson 1975) is that the same tasks can, in principle, be coordinated by either a market or a hierarchy. For example, General Motors does not need to make all the components that go into its finished products. Instead of manufacturing its own tires, for instance, it can purchase tires from other suppliers. When it does this, it is using a market to coordinate the same activities (i.e., tire production) that would otherwise have been coordinated by hierarchical management structures within General Motors.

If General Motors used an extreme form of this coordination structure, the vice president in charge of the Chevrolet division might have only a small staff and all the basic tasks of product design, manufacturing, and sales would be performed by outside suppliers. This form of subcontracting as a coordination structure is already common in some industries (e.g., construction).

Decentralized Market. We distinguish here between two kinds of markets: decentralized and centralized. In the "pure form" of a decentralized market, all buyers are in contact with all possible suppliers and they each make their own decisions about which transactions to accept. This is the case Baligh and Richartz (1967) analyze as a market without middlemen.

In defining the coordination structure to represent this kind of market, we assume that the suppliers are task processors for various types of tasks and that there are "buyers" for each type of product to be produced (or for each overall goal of the structure). The buyers thus play the role of "product managers." We assume, like Baligh and Richartz (1967, Chapter 2), that each buyer has a communication link with each potential supplier and that all buyers exchange messages with all suppliers. Baligh and Richartz assume that each supplier receives "orders" randomly from different buyers (pp. 113–114). With our model of task processing, it seems more plausible to assume that, if buyers exchange messages with all suppliers, buyers will know enough to choose the "best" supplier and will not just send their orders to a random supplier. Therefore, we depart from Baligh and Richartz by assuming that tasks are not randomly assigned to suppliers, but instead are sent to the "best" supplier (e.g., the supplier who can start processing the order soonest). We model this process as one in which buyers send some form of "request for bids" messages to all suppliers of the appropriate type and then select a supplier from among all the "bids" received. If there are m suppliers, this requires $2m$ messages per task. Two additional messages are also used: one to assign the task to the "best" bidder, and one to notify the buyer that the task is complete.

We assume that when a processor fails in a decentralized market, the task it was to have performed is reassigned to another processor of the same type. For example, if one independent dealer for General Motors cars failed to achieve a satisfactory sales volume, that dealer's contract might be terminated and another dealer selected.

Centralized Market. In a centralized market, buyers do not need to contact all possible sellers because a broker is already in contact with the possible sellers. This centralization of decision-making means that substantially fewer connections and messages are required compared to a decentralized market. One of the best known examples of a centralized market is the stock market. People who want to buy a particular stock do not need to contact all the owners of shares of that stock; they only need to contact a broker who is also in contact with people who want to sell the stock.

Our model for this coordination structure resembles Baligh and Richartz's model of a market with a "middleman as a pure coordinator" (1967, pp. 123–126). In addition to the buyers and suppliers present in a decentralized market, we assume that there is also a "broker" (or middleman) for each type of task processor. Each broker coordinates all the task processors of a given type and thus plays the role of a "functional manager." Like Baligh and Richartz, we assume that (1) the broker has a communication link to each buyer and each supplier of the appropriate type and (2) tasks are assigned to the "best" available supplier. We also assume that four messages are required to assign tasks in this structure: one from the buyer to notify the broker that the task needs to be done, one from the broker to assign the task to a processor, and two to notify the broker and the buyer, respectively, that the task is complete.

The centralized market and the functional hierarchy structures are thus quite similar in the patterns of messages they use. We assume that they are also similar in their responses to failures of processors. Both can often reassign tasks when a task processor fails, and in both cases, the production of all products is disrupted when one of the central schedulers (i.e., a broker or a functional manager) fails. The difference between the two structures is that in the centralized market, one of the general contractors can fail without disrupting the production of the other products, but in the functional hierarchy, if the executive office fails, the production of all products is disrupted.

Tradeoffs among Coordination Structures

Now that we have distinguished among these generic coordination structures, one of the most important questions we can ask is what are the relative advantages of each. In particular, we will focus on the tradeoffs between *efficiency* and *flexibility* in the different structures. We will view efficiency as being composed of two elements: *production costs* and *coordination costs*. Coordination costs are also a component of flexibility, since the amount of re-coordination necessary to adapt to new situations helps determine how flexible a structure is. The other component of flexibility we consider is *vulnerability costs*, or the unavoidable costs of a changed situation that are incurred before the organization can adapt to the new situation.

As shown in Table 1, we can compare the different coordination structures on the dimensions of production costs, coordination costs, and vulnerability costs. All the dimensions shown in the chart are represented as costs, so in every column low is

TABLE 1
Tradeoffs Among Alternative Coordination Structures

Coordination Structure	Evaluation Criteria		
	Efficiency	Flexibility	
	Production Costs	Coordination Costs	Vulnerability Costs
Product hierarchy	*H*	*L*	*H*
Functional hierarchy	*L*	*M*−	*H*+
Centralized market	*L*	*M*+	*H*−
Decentralized market	*L*	*H*	*L*

Note. *L* = Low costs ("good")
M = Medium costs
H = High costs ("bad").
Comparisons apply only within columns, not between rows.

"good" and high is "bad". The comparisons apply only within columns, not between rows. Primes are used to indicate indeterminate comparisons. For example, H' is more than L, but it may be either more or less than $H+$ or $H-$. In the next two sections, we present justification for these comparisons, first informally, and then formally.

Informal Justifications for Coordination Structure Comparisons

The key assumptions necessary to compare the different coordination structures are summarized in Table 2. We compare the structures separately for each of the dimensions analyzed: production costs, coordination costs, and vulnerability costs.

Production Costs

Our primary assumption about production costs is that they are proportional to the amount of processing capacity in the organization and the average delay in processing tasks. We assume that tasks of a given type arrive at random times and that processing each task takes a random amount of time. We also assume that processing capacity for a given organizational form is chosen to minimize the total costs of capacity and delay time.

The product hierarchy has the highest average delay in processing tasks because it uses processors that are not shared. The decentralized market, centralized market, and functional hierarchy all have a somewhat lower average delay time because they are able to take advantage of the "load leveling" that occurs when tasks are shared among a number of similar processors. For example, processors that would otherwise be idle can take on "overflow" tasks from busy processors thus reducing the overall average delay.

Coordination Costs

Our primary assumption about coordination costs is that they are proportional to the number of connections between agents and the number of messages necessary to assign tasks. Table 2 summarizes our assumptions about the number of connections and messages required.

The product hierarchy requires the least number of connections since each processor must only be connected to its division manager. This form also requires the least number of messages for task assignment since each task is simply assigned to the processor of the appropriate type in the division in which the task originates.

TABLE 2
Definition of Alternative Coordination Structures

Coordination Structure	Processors Shared Among Products	No. of Connections Required Between Actors[a,b]	No. of Messages Required to Assign a Task[a]	Results of Failure of: Task Processor	Functional Manager	Product Manager
Product hierarchy	No	m	2	1 product disrupted	—	1 product disrupted
Decentralized market	Yes	mn	$2m + 2$	Task reassigned	—	1 product disrupted
Centralized market	Yes	$m + n$	4	Task reassigned	All products disrupted	1 product disrupted
Functional hierarchy	Yes	m	4	Task reassigned	All products disrupted	All products disrupted

[a] m = Number of task processors of functional type being analyzed; n = number of products.
[b] Number required per functional type.

The centralized market and functional hierarchy require more connections since the functional managers (or brokers) must be connected not only to the processors they supervise, but also to the product managers (or clients) who originate tasks. These two forms also require more scheduling messages since an extra layer of management is involved in assigning tasks to the proper processor.

The decentralized market requires the most connections of all because it requires each buyer to be connected to all possible suppliers. This form also requires the most messages since assigning each task requires sending "requests for bids" to all possible processors of the appropriate type and then receiving bids in return.

Vulnerability Costs

Our primary assumption about vulnerability costs is that they are proportional to the expected costs due to failures of task processors and managers. We assume that both processors and managers sometimes fail (i.e., with probabilities greater than 0). Our assumptions about the consequences of different kinds of failures in different organizational forms are summarized in Table 2. We assume that when a task processor fails in a market or in a functional hierarchy, the task can be reassigned to another processor of the same type. When a task processor fails in a product hierarchy, however, there is no other processor of the same type available, so the entire production of the product in question is disrupted. The entire production of a product is also disrupted if the product manager fails, or in the case of the market, if the client who supervises that product fails. Finally, the production of all products is disrupted if a centralized market broker, or a functional manager, or an executive office fails.

We assume that the cost of delaying a task in order to reassign it is less than the cost of disrupting all the production for a given type of product and that this cost is, in turn, less than the cost of disrupting the production of all products.

Given these assumptions, the decentralized market is the least vulnerable to component failure since if one processor fails, the task is only delayed until it can be transferred to another processor. The centralized market and functional hierarchy are more vulnerable since not only can tasks be delayed by the failure of individual processors, but also the entire system will be disrupted if a centralized functional manager or broker fails. The functional hierarchy is somewhat more vulnerable than the centralized market because the functional hierarchy can also be completely disrupted if the executive office fails. The product hierarchy is more vulnerable than the decentralized market because when a processor fails, tasks cannot be easily transferred to another similar processor. Whether the product hierarchy is more or less vulnerable than the functional hierarchy and the centralized market cannot be determined from our assumptions alone. It depends on the relative sizes of costs and probabilities for failures of product managers and functional managers.

Formal Justifications for Coordination Structure Comparisons

The bases for the qualitative comparisons of coordination structures in Table 1 are summarized in Tables 3 and 4 and explained below. Table 3 lists the variables used in this section and Table 4 shows the values for production costs, coordination costs, and vulnerability costs in the different organizational forms. The following abbreviations are used: *PH* for product hierarchy, *FH* for functional hierarchy, *CM* for centralized market, and *DM* for decentralized market. We let m be the number of processors of the functional type being analyzed, n be the number of products, and k be the number of functions. In all cases, we assume that

(A0) Costs not explicitly modeled are the same in all organizational forms.

TABLE 3

Symbol Table

Variable	Definition
Total Costs	
$P_{PH}, P_{FH}, P_{CM}, P_{DM}$	= production costs per task for the various organizational forms
$C_{PH}, C_{FH}, C_{CM}, C_{DM}$	= coordination costs per task for the various organizational forms
$V_{PH}, V_{FH}, V_{CM}, V_{DM}$	= vulnerability costs per task for the various organizational forms
Component Costs	
c_C	= cost of production capacity (cost per unit of processing capacity capable of processing 1 task per time unit)
c_D	= cost of delay (or waiting) for tasks to be processed (cost of delay of 1 task for 1 time unit)
c_L	= cost of maintaining a connection (or link) between processors (cost per time unit)
c_M	= cost of sending a message (cost per message)
c_T	= cost of reassigning a task to another processor (average cost attributed to this function per reassignment)
c_P	= cost of disrupting production of 1 product (average cost per disruption)
c_A	= cost of disrupting production of all products (average cost per disruption)
Probabilities	
p_T	= probability of task processor failure (per time unit)
p_F	= probability of failure of a functional manager or broker (per time unit)
p_P	= probability of failure of a product manager or buyer (per time unit)
p_E	= probability of failure of an executive office (per time unit)
Other quantities	
m	= number of processors of this type for all products combined
n	= number of products
k	= number of functions
λ	= number of tasks per time unit of this type for each product μ
μ	= average processing rate of each processor

Production Costs

For all coordination structures, we make the following assumptions:

(A1) Tasks of a given type are generated randomly according to a Poisson process that is the same for each product and has arrival rate $m\lambda$ for the system as a whole.

(A2) Individual tasks are assigned to the first available processor of the appropriate type and are processed, in the order of arrival, at a rate μ on each processor. The processing times are exponentially distributed.

(A3) Production costs are proportional to the amount of processing capacity in the organization and the amount of time that tasks are delayed.

(A4) The processing capacity μ of each processor is chosen to minimize total production costs.

We let c_C be the cost of a unit of processing capacity (measured in dollars per time unit per unit of processing capacity; where a unit of processing capacity can process one

TABLE 4

Evaluation Criteria for Alternative Coordination Structures

Coordination Structures	Production Costs	Coordination Costs	Vulnerability Costs
Product hierarchy	$2m(c_D c_C \lambda)^{1/2} + m\lambda c_C$	$mc_L + 2m\lambda c_M$	$mp_T c_P + np_P c_P$
Functional hierarchy	$2m(c_D c_C \lambda)^{1/2}$	$(m + 1)c_L + 4m\lambda c_M$	$mp_T c_T + p_F c_A + p_E c_A$
Centralized market	$2m(c_D c_C \lambda)^{1/2}$	$(m + n)c_L + 4m\lambda c_M$	$mp_T c_T + p_F c_A + np_P c_P$
Decentralized market	$2m(c_D c_C \lambda)^{1/2}$	$mnc_L + (2m + 2)m\lambda c_M$	$mp_T c_T + np_P c_P$

task per time unit). We also let c_D be the cost of delay for tasks that have been generated but not yet completed (measured in dollars per task per unit of time task remains uncompleted). With these assumptions, the total production costs per unit of time are $P = m\mu c_C + Ac_D$ where A is the average number of uncompleted tasks in the system at any given time. In this and the other cost expressions, we are concerned only with relative costs of different organizational forms, so by assumption A0, we may omit all other (constant) costs. When tasks are not shared among processors, the tasks arrive randomly at each processor with arrival rate λ. The processing characteristics in this case are the same as the market without middlemen analyzed by Baligh and Richartz (1967). They show (pp. 113–118) that the capacity that minimizes this cost is $\mu^* = (c_D\lambda/c_C)^{1/2} + \lambda$ and that total production costs are then $P = 2m(\lambda c_D c_C)^{1/2} + m\lambda c_C$.

When tasks are shared among the processors, we have the case that Baligh and Richartz analyze as a market with a "middleman as pure coordinator". In this case, orders are assigned to the best processor, and the system behaves as if the processors were m servers for the overall queue of tasks. Baligh and Richartz show (pp. 123–125) that the optimal capacity, in this case, is $\mu^* = (c_D\lambda/c_C)^{1/2}$ and the total production costs are $P = 2m(\lambda c_D c_C)^{1/2}$. The latter result holds exactly only in the limit as m becomes large.

These two production cost results are the basis for the production cost expressions in Table 4: Product hierarchies have processors with separate streams of tasks; the other organizational forms are able to share tasks among processors.

Comparisons. Using the expressions for production costs P shown in Table 4, it is clear that $P_{PH} > P_{FH} = P_{CM} = P_{DM}$ as reflected in Table 1.

Coordination Costs

Assumptions. We make the following assumption about coordination costs:

(A5) Coordination costs are proportional to the number of communication paths (or links) between actors and the number of messages sent over these links.

We let c_L be the cost per time unit of maintaining a link and c_M be the cost of sending a message.

Comparisons. Using assumption A5 and the values given in Table 2 for the number of messages and links in the different organizational forms, it is a simple matter to calculate the costs shown in Table 4. If $n > 1$ and $m \geq 1$, then the following inequalities for coordination costs, C, follow immediately: $C_{PH} < C_{FH} < C_{CM} < C_{DM}$.

Vulnerability Costs

Assumptions. We make the following assumptions about vulnerability costs:

(A6) Vulnerability costs are proportional to the costs of reassigning tasks and the costs of disrupting products due to the failures of processors or managers.

(A7) Processors and managers sometimes fail (i.e., with probability greater than 0), and they do so independently at constant rates according to a Poisson process.

(A8) Product managers that manage more than one product (i.e., with centralized product decisions) fail at least as often as other product and functional managers.

(A9) The cost of reassigning the tasks from one processor to another processor is less than the cost of disrupting a product.

(A10) The cost of disrupting one product is less than the cost of disrupting all products.

We let p_T, p_F, and p_P be the failure rates of task processors, functional managers, and product managers, respectively, and we let p_E be the failure rate for executive offices. According to assumptions A7 and A8, $p_T, p_F, p_P > 0$, and $p_E \geq p_F, p_P$. We let c_T be the expected cost of reassigning the tasks from a failed processor to another processor, c_P be the expected cost of having the production of one product disrupted, and c_A be the expected cost of having all the products disrupted. From assumptions A8 and A9, we know that $c_T < c_P < c_A$.

Comparisons. Given these assumptions, the expressions for failure costs F in Table 4, and the following inequalities all follow immediately: $F_{DM} < F_{CM} < F_{FH}$, and $F_{DM} < F_{PH}$.

Alternative Assumptions

Production Costs. Malone and Smith (1984) examine the consequences of removing the assumption that in all organizational forms, processing capacity is optimally chosen to minimize total production costs. They assume instead that all organizational forms have the same processing capacity. This alternative assumption does not change our results.

Malone and Smith (1984) also analyzed alternative forms of functional hierarchies and centralized markets that include one large scale processor for a function instead of several small scale processors. The large scale organizational forms have lower production costs, but higher vulnerability costs, than their small scale counterparts.

Coordination Costs. Malone (1986) considers several alternative sets of assumptions about coordination costs. The most important of these alternatives involves the role of prices in the decentralized market. In its "pure" form, this structure requires connections and messages between all possible buyers and all possible suppliers. One might argue that in a market with a functioning price mechanism, buyers would only need to contact a few potential suppliers, since most suppliers would have approximately the same price anyway. Malone (1986) shows, however, that as long as the number of suppliers contacted by buyers is, on the average, at least two, this organizational form still has the highest coordination costs of all the forms considered.

Malone (1986) also considers the fixed costs of keeping coordinating processors (i.e., managers, brokers, and clients) in a structure. Introducing these costs into the models does not lead to results that directly contradict the main results in Table 1, but, depending on the size of the fixed costs, it does render some of the comparisons indeterminate. It seems plausible to assume that, in the long run, the number of messages to be processed will be the major determiner of the number of coordinating processors needed. Accordingly, the main results presented here ignore the fixed costs of coordinating processors and focus on the costs of maintaining communication links and the variable costs of processing messages.

Malone and Smith (1984) consider only the message processing costs of coordination and ignore the costs of communication links. With this assumption, functional hierarchies cannot be distinguished from centralized markets in terms of coordination costs.

Vulnerability Costs. Malone and Smith (1984) ignore the possibility of failures of "product coordinators" (e.g., product managers) and the "executive office." When these possibilities are ignored, we cannot distinguish between functional hierarchies and centralized markets in terms of vulnerability costs.

Size of the Structure

The tradeoffs shown in Table 1 assume that the size of the structure being modeled is fixed, that is, that the number of processors, the number of products, and the total number of managers generating tasks are all constant. As the number of processors increases, the relative rankings of the alternative coordination structures do not change on any of the evaluation criteria. However, the values change much faster for some structures and criteria than for others. Thus simply changing the size of the structure, even without changing any other parameter values, may change the relative importance of different criteria and therefore change the "optimal" coordination structure. The relative rates of change for the different criteria are summarized in Table 5. The different numbers of pluses in the table represent the different rates of change. For example, as the size of an organization increases, vulnerability costs increase more rapidly for product hierarchies than for the other forms, and coordination costs increase most rapidly for decentralized markets.

To justify the results in Table 5, we assume that

(A11) As the size of the organization increases, the number of products n and the number of processors m increase.

To determine the effect of these increases on the different kinds of costs, we examine the partial derivatives with respect to m and n. Table 6 shows these partial derivatives. The assignment of varying numbers of pluses for the values in Table 5 all follow immediately from the relative sizes of the partial derivatives in Table 6.

Discussion

We have now analyzed four generic coordination structures that are intended to capture some of the intuitive ways people describe different kinds of organizations and markets. These definitions suggest many empirical questions about how coordination actually occurs in real organizations and markets. At a micro-level, questions of the following sort arise: What actors are involved in deciding which tasks to do and who will do them? What information do they communicate in order to make these decisions? How do they make decisions using this information? Our models are obviously extreme simplifications of the complexities that occur at this level, but this general approach may help suggest and organize micro-level empirical observations (e.g., see Crowston, Malone, and Lin, in press).

Regardless of the detailed validity of the micro-level models, our results also suggest and help organize macro-level hypotheses about the relative advantages of different kinds of structures. For instance, one simple test of how well our formal definitions match the terms people use intuitively is whether our results correspond to previous generalizations about organizational design. Certainly, the qualitative comparisons shown in Table 1 do not begin to include all the factors discussed by organizational design theorists (e.g., Mintzberg 1979; Galbraith 1977; March and Simon 1958; Gulick and Urwick 1937; and Hax and Majluf 1981). However, in the cases where our model addresses issues considered previously, the comparisons in the table do appear to be consistent with previous work. Three examples are summarized below.

Tradeoffs between production costs and coordination costs. March and Simon (1958, p. 29) summarize the problem of departmentalization as a tradeoff between self-containment and skill specialization: "[Functional] departmentalization generally takes greater advantage of the potentialities for economy through specialization than

TABLE 5
Changes in Costs as Size of Structure Increases

	Production Costs	Coordination Costs	Vulnerability Costs
Product hierarchy	+	+	+++
Functional hierarchy	+	++	+
Centralized market	+	+++	++
Decentralized market	+	++++	++

Note: Different numbers of pluses indicate relative rates of change (more pluses mean faster change).

TABLE 6

Rates of Change of Evaluation Criteria as Size of Structure Increases

Coordination Structures	Production Costs		Coordination Costs		Vulnerability Costs	
	$\frac{\delta}{\delta m}$	$\frac{\delta}{\delta n}$	$\frac{\delta}{\delta m}$	$\frac{\delta}{\delta n}$	$\frac{\delta}{\delta m}$	$\frac{\delta}{\delta n}$
Product hierarchy	$2(c_D c_C)^{1/2} + \lambda c_C$	0	$c_L + 2\lambda c_M$	0	$p_T c_P$	$p_P c_P$
Functional hierarchy	$2(c_D c_C)^{1/2}$	0	$c_L + 4\lambda c_M$	0	$p_T c_T$	0
Centralized market	$2(c_D c_C)^{1/2}$	0	$c_L + 4\lambda c_M$	c_L	$p_T c_T$	$p_P c_P$
Decentralized market	$2(c_D c_C)^{1/2}$	0	$n c_L + 2\lambda c_M(2m + 1)$	$m c_L$	$p_T c_T$	$p_P c_P$

does [product] departmentalization; [product] departmentalization leads to greater self-containment and lower coordination costs. . . ."[1] Table 1 reflects this tradeoff with the "economies of specialization" in functional hierarchies being represented as lower production costs, and the advantages of self-containment in product hierarchies being represented as lower coordination costs.

Organizational structure and flexibility. It is commonly claimed that product hierarchies are more flexible in rapidly changing environments than functional hierarchies (e.g., Galbraith 1973, pp. 113–116; Mintzberg 1979, p. 415; Ansoff and Brandenburg 1971, p. 722). Our model reflects this but goes on to suggest an important distinction between two kinds of flexibility: *adaptability* and *vulnerability*. According to our model, product hierarchies are indeed more *adaptable*, in the sense that their coordination costs for re-coordinating in new environments are less than for functional hierarchies.

But our models suggest that product hierarchies are not necessarily less *vulnerable*, in the sense of the losses suffered when unexpected changes occur. For example, Mintzberg, quoting Weick, observes that: ". . . the [product hierarchy] spreads its risk. '. . . if there is a breakdown in one portion of a loosely coupled system then this breakdown is sealed off and does not affect other portions of the organization' (Weick 1976, p. 7). In contrast, one broken link in the operating chain of the functional structure brings the entire system to a grinding halt" (Mintzberg 1979, p. 415).

Table 1 suggests, however, that the overall vulnerabilities of the product and functional hierarchies may not necessarily be different. While a failure in one product division may, indeed, be limited in its effect to that division, the failure of a single processor may bring the entire division to a halt. The failure of an equivalent processor in a functional hierarchy, on the other hand, might be less costly since other processors of the same type are pooled in a central department and shifting tasks between them is presumably easier than shifting tasks between product divisions. The real vulnerability of the functional hierarchy is to failures of the functional managers themselves, because a failure there does indeed disrupt the entire organization. Without more information about the relative frequency and costs of these two kinds of failures, however, we cannot say *a priori* whether the product or functional hierarchy is more vulnerable.

Comparison between markets and hierarchies. There is a growing body of literature concerned with the relative advantages of markets and hierarchies as coordination structures (e.g., Coase 1937; Williamson 1975, 1981). As Williamson (1981, p. 558) summarizes, ". . . trade-offs between production cost economies (in which the market

[1] We have substituted "functional" and "product" for the terms used in the original: "process" and "purpose," respectively.

may be presumed to enjoy certain advantages) and governance cost economies (in which the advantages may shift to internal organization) need to be recognized." Table 1 reflects this result in the following way: Separate firms that "make" products internally are represented by the separate divisions of a product hierarchy. Separate firms that pool their demands and "buy" products in a market are represented by either the centralized or decentralized markets. As the table shows the market structures have lower production costs, but higher coordination costs.

Conclusion

In this paper, we have defined and mathematically analyzed four generic coordination structures. The models are unusual in the degree to which they (a) link micro- and macro-level hypotheses, (b) are formal and mathematical, (c) integrate organizational and market models, and (d) include measures of vulnerability costs along with production and coordination costs.

The models are also interesting because of the surprising range of questions they help illuminate. For instance, elsewhere (e.g., Malone and Smith 1984; Malone 1986; Malone, Yates and Benjamin, in press; Crowston, Malone, and Lin, in press) we have suggested how the models can be used to (a) help understand major changes that have occurred in the structure of American businesses during the last century, (b) make speculative predictions about the possible consequences that the widespread use of information technology may have for organizational structures, and (c) help analyze and predict design options for computer processing networks.[2]

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