

Adaptive Organizations*

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Abstract

This paper is concerned with the three-way trade-off between *coordination*, *specialization* and *adaptation*, and its implications for organizational design. Every organized activity gives rise to two conflicting requirements: the division of labor into manageable tasks and the coordination of these tasks to ensure harmonious execution. In a stable environment, however, coordination can be trivially achieved by letting employees blindly stick to a set of prescribed guidelines. Thus, the demand for coordination is endogenous and depends on how ‘adaptive’ the organization is to an uncertain environment. We show how this endogenous demand for coordination results in strong complementarities between organizational decision variables: task specialization, employee discretion, the quality of horizontal coordination, and the size of management. Moreover, in contrast to previous claims in the literature, the degree of task interdependence and improvements in communication technology are shown to have a decidedly ambiguous impact on specialization and the division of labor.

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I. INTRODUCTION

Every organized activity - from making pins to placing a man on the moon - gives rise to two opposing requirements: the division of labor into various tasks and the coordination of these tasks to accomplish the activity. Thus, as argued by Becker and Murphy (1992), the benefits of specialization and the division of labor are limited by the need to coordinate these specialized activities.¹ Nevertheless, as long as the organizational environment is predictable or adaptation to this environment is not an organizational goal, coordination can be trivially achieved by letting all employees blindly stick to a set of prescribed guidelines. In practice though, the success of organizations depends to a large extent on how well they can respond to particular market conditions (demand may be higher or lower than expected,) operational conditions (a worker may be ill, an unexpected delay may occur), and how efficiently it can customize its products or services to particular consumer characteristics or changing consumer needs. In the presence of this desire for adaptation, how does an organization achieve coordination amongst its members?

In this paper, we propose a novel team-theoretic model in which production involves the combination of a number of interdependent tasks and which neatly captures the trade-off between *adaptation*, *coordination*, and *specialization*. This model allows us to endogenize the (i) the *specialization* of workers, that is the variety of tasks assigned to them, (ii) the *standardization* of these task, that is, how much flexibility is embodied in the training and instructions workers receive, (iii) the quality and intensity of the *horizontal communication and coordination* between workers, and (iv) the extent of *vertical coordination* and the *size of management*, who may update the task instructions of production workers in a coordinated fashion.²

Central in our paper is the notion that the demand for coordination in an organization

¹Also the qualitative management literature has identified and paid considerable attention to this trade-off. Indeed, according to Rivkin and Siggelkow (2002) “the [qualitative management] literature is unified in what it perceives as the central challenge of organizational design: to divide the tasks of a firm into manageable, specialized jobs, yet coordinate the tasks so that the firm reaps the benefits of harmonious action.” For an early reference on the statement of the problem see March and Simon (1958, pages 22-30.)

²Our list of organizational design variables correspond very well with the coordinating mechanisms considered in the management literature. In a classic management text, Mintzberg (1979), for example, discusses the following coordination mechanisms: (i) *Mutual adjustment* through informal communication, (ii) *Direct supervision* in which one person coordinates by giving instructions and (iii) *Standardization* of work processes, outputs, skills and norms.

is endogenous and depends on the ‘adaptiveness’ of this organization – that is the extent to which its members are given flexibility and exert discretion to adjust their tasks to local circumstances.

Endogenizing the need for coordination has important implications for the *trade-off between coordination and specialization*. As mentioned above, Becker and Murphy (1992) argued that the extent of specialization in organizations is limited by the importance of coordination. In contrast, we show that specialization and the division of labor often *increase* when tight task coordination becomes essential. Intuitively, when tight coordination becomes more important, organizations respond by becoming less adaptive, reducing the need for coordination and, hence, the cost of specialization. Similarly, organization scholars and economist have argued that improvements in communication technology, such as email and cell phones, will unambiguously result in more specialization as better communication allows for a better coordination of specialized tasks.³ As communication technology improves, however, organizations also tend to become more adaptive, increasing the need for ex post coordination. Therefore, improvements in communication technology may actually result in *less* specialization.

The same force which is responsible for the tenuous trade-off between coordination and specialization - the elasticity of the demand for coordination - also results in *strong complementarities between the different elements of organizational design*, establishing a sense in which organizations are ‘single-dimensional’. Roughly speaking, we show that organizations are naturally characterized by increasing returns to being adaptive and coordinated ex post. Thus, a change in any organizational design variable towards more flexibility or a better ex post coordination increases the returns to change all other design variables in the same direction. As a result, organizations tend to fall in two categories: First, organizations which exhibit specialized task assignments are typically also characterized by limited task flexibility and limited employee discretion and they rely on a large middle management to coordinate their activities as opposed to horizontal communication between workers. In contrast, organizations in which employees have significant flexibility and discretion tend to be characterized by broad task assignments, a strong horizontal communication network, and a small management.

Consider first the complementarities between *broad task assignments*, *high quality horizontal communication* and *substantial task flexibility* and *employee discretion*. Intuitively, a broader task assignment or a higher quality of horizontal communication increases the returns

³For example, the trade-off between specialization and communication costs is at the center of Bolton and Dewatripont (1994) and Garicano (2000).

to boost employee discretion and task flexibility, as tasks are better coordinated. Conversely, the resulting increase in the ‘adaptiveness’ of the organization increases the need for broader task assignments and more extensive horizontal communication, as ex post coordination is now more important.⁴ It follows that an increase in the quality of ex post coordination in one part of the organization, through its impact on employee discretion and flexibility, increases the returns to coordination throughout the entire organization.

Consider now the *role of management* in improving coordination and adaptation by updating ex ante task guidelines in a changing environment. The more employees exert discretion and deviate from such prescribed guidelines, the less useful it is to install a costly managerial hierarchy whose aim it is improve the quality of these guidelines. Conversely, the more accurate are these ex ante task guidelines, the less need there is for employee discretion, task flexibility and ex post coordination. It follows that a large management and extensive vertical coordination is complementary to extensive task specialization, limited task flexibility and limited horizontal communication.

The complementarity between the different elements of organizational design implies that the latter tend to move up and down together in response to environmental changes, as any change that favors increasing one design variable also favors increasing all the other design variables. This result sheds light on proclaimed trends in organizational structure towards *reengineering* (more task-bundling), *empowerment* (more task flexibility and employee discretion), *team work* and *job rotation* (better horizontal communication), and *flatter organizations* (reduction in middle-management).⁵

⁴There is a growing literature (for example, Aghion and Tirole (1997) and Dessein (2002)), which looks at employee discretion from a contractual perspective: who has decision rights for a particular action. Given that incentives play no role in our model, there is no need to specify such decision rights. In contrast, employee discretion is an equilibrium phenomenon: how much do workers adhere to ex ante task guidelines or, in contrast, tailor their actions to local circumstances.

⁵For example, Osterman (1994)’s study of 694 US Manufacturing establishments find that 50 percent used self-directed work teams and 56 percent job rotation practices in 1992. Of these establishments, respectively 40 percent and 35 percent introduced these workplace practices in the years between 1987 and 1992. Similarly, Ichniowski et al. (1996) claim that “new work practices have become increasingly common among US businesses in recent years”, and according to Brickley, Smith and Zimmerman (2001), state that “Recently, there has been a trend towards creating jobs [...] that are less specialized and where employees have broader decision authority” (p286). Aoki (1990), finally, writes that “the tendency towards delegation of decision-making authority to the lower levels of organizational hierarchies, where economically usefull on-the-spot-information is available, as well as non-hierarchical communication among operating units, is becoming a more discernable phenomena on a world-wide scale, wherever conditions permit.”

Consider, for example, the impact *information technology* on organization design. Several organization scholars have argued that improvements in information technology over the last decades (extensive databases, expert systems, computerized processes and controls) have made it easier to give employees more flexibility to adapt their tasks to changing circumstances.⁶ A decrease in the cost of IT thus directly affects task flexibility and employee discretion. Indirectly, however, this makes it also optimal for the organization to increase task bundling and improve horizontal communication, reinforcing further increases in task flexibility and employee discretion. Consistent with this prediction of our model, Brynjolfsson and Hitt (1997) and Bresnahan, Brynjolfsson and Hitt (2002), in a sample of 300 large U.S. firms, have identified a strong correlation between the use of information technology and ‘new workplace organization practices’ involving (i) more discretion for employees in how to complete their tasks, (ii) the use of self-managing teams, team building activities and teamwork as a promotion criterion (more horizontal communication), (iii) broader job-classifications and (iv) higher human capital and human capital investments such as training and preemployment screening.⁷ In addition, they find that these workplace practices are also strongly correlated with each other, suggesting that they are complements.⁸ Our paper thus shows how these robust empirical correlations between the occurrence of new workplace practices can be traced back to a unique driving force: the elasticity of the demand for coordination. Hence, our model provides a theoretical underpinning for the central thesis of Bresnahan, Brynjolfsson and Hitt (2002) that the impact of IT on the demand for high-skilled labor mainly stems from its complementarity with *high-skill biased workplace reorganizations*.

Our model, however, points also to a number of alternative causes for the above mentioned organizational trends. For example, an increase in the *instability or variability of the of the business environment* also result in more task bundling, more task flexibility and an emphasis on coordination by horizontal communication as opposed to managerial direction. Similarly, our model predicts a shift to these ‘new work organization’ practices as a response

⁶These improvements in *information technology* which makes it easier for employees to exert discretion and adapt their tasks to local circumstances should be distinguished from improvements in *communication technology* such as e-mail. As argued previously, improvements in communication technology have a decidedly ambiguous impact on organizational design.

⁷Note that a higher demand for high-skilled workers is consistent with broader task assignments, less standardized tasks, and attempts to improve horizontal communication. Hence, Bresnahan et al (2002) refers to ‘skill biased organizational change’.

⁸Similarly, Ichniowski, Shaw and Prennushi (1997), which study the same new workplace practices (but not IT) in the steel industry, find substantial evidence that the latter are strongly complementary.

to an *increase in demand for adaptation and responsiveness to consumer needs*.⁹

Related Literature. The theoretical literature studying organizational design originated with the theory of teams of Marschak and Radner (1972) and, building on this, Cremer (1980).¹⁰ Whereas this literature studies the coordination of tasks when specialization implies that information is necessarily disperse, the present paper is one of very few who endogenizes the division of labor which causes these coordination problems. Cremer, for example, studies the optimal grouping of technological interdependent production units, but takes the number of units which are bundled together as given. A notable exception is Geanakoplos and Milgrom (1991), who offers a partial characterization of the optimal level of task bundling in a setting a la Cremer. However, their model, in which managers have limited time to process and collect information about a number of units, has very different implication than ours. In particular, more task uncertainty results in more specialization as collecting information is then more important. Another important exception is Garicano (2000), which studies vertical specialization in knowledge acquisition, that is, what range of problems is solved by production workers and what range of problems is solved by management. Unlike the present paper and Cremer (1980), however, there is no need to coordinate the tasks of production workers or subunits, as there are no interdependencies between problems. As Geanakoplos and Milgrom (1991), Garicano's main focus is on the characteristics of the vertical hierarchy. Finally, the trade-off between specialization and coordination is also emphasized in Becker and Murphy (1992). The latter paper, though, does not model neither the sources of the coordination costs that specialization would bring nor any form of communication within the parties or the role of management, so their model has limited organizational design implications. They emphasize the impact of growth in human capital on the extent of specialization and we touch, albeit slightly, on this issue here as well.¹¹

To the best of our best knowledge, this paper is also the first to simultaneously analyze

⁹The former comparative static may be consistent with the finding of Osters (1994) that new workplace practices are more prevalent in markets which face a lot of international competition, a factor which is often blamed for increasing the instability of the business environment. As for the latter prediction, Osters (1994) finds that new workplace practices are correlated with firms using 'high road' strategies which emphasize variety, service and quality as opposed to cost.

¹⁰A strand of this literature is concerned with the optimal design of information processing organizations (e.g. Radner (1993), Van Zandt (1999), Bolton and Dewatripont (1994), and Vayanos (2002)). With the exception of Vayanos (2002), these papers focus on situations in which there exist no interdependencies among tasks and, hence, they are less related to the present paper.

¹¹Lindbeck and Snower (2000) is a more recent addition to this literature.

vertical and horizontal coordination. Aoki (1985), building on Cremer (1980), compares the efficiency of vertical and horizontal coordination of interdependent tasks and relates these to U.S. and Japanese work-practice. Unlike the present paper, however, his analysis of these two organizational structures yields no insight as to whether the latter are complements or substitutes, nor does he endogenize the optimal level of task bundling, and the extent of specialization.

Finally, mainly based on case studies and inductive grounds, the qualitative literature on organizations has extensively argued that elements of organizational design and structure are strongly complementary, that is they have to ‘fit’ with one another.¹² This notion of ‘strategic fit’ was made concrete in the economics literature by Milgrom and Roberts (1988, 1990), who use the mathematics of complementarity or ‘supermodularity’ to discuss the shift from mass production to modern manufacturing. While we also make of supermodularity our main analytical tool to study complementary elements of organizational design, our approach differs from Milgrom and Roberts in that we derive this complementarity in an explicit model of production. Thus, whereas Milgrom and Roberts posit a reduced form profit function and make assumptions about cross-derivatives which imply supermodularity, we propose a specific team-theoretic model of production and show that, in equilibrium, the expected profit function is supermodular. In addition, the main focus of Milgrom and Roberts is on elements of manufacturing strategy as opposed to organizational design. Thus, Milgrom and Roberts (1988) concentrate on interdependencies between the breadth of the product line, the levels of finished goods inventories and the choice of make-to-stock versus make-to-order, whereas Milgrom and Roberts (1990) focus on the complementarities between the choice of technology, capital investments, and operating systems. Our analysis of organizational design in the present paper connects with this study of modern manufacturing strategy in its treatment of task flexibility, which is affected by falling costs in flexible manufacturing equipment.¹³ An important paper which does explicitly analyze complementarities between elements of organizational design is Holmstrom and Milgrom (1994). Their focus, however, is on the complementarities between

¹²See, however, Rivkin and Siggelkow (2002) for a model which tries to provide a rationale for why and how these interdependencies arise in general. Unlike ours, their model, does not rely on supermodularity but uses simulations in which the modeler dictates the particular pattern of interaction among decisions.

¹³In an overview paper, Milgrom and Roberts (1995) briefly discuss how some elements of human resource management policies are related to this modern manufacturing strategy, including horizontal communication and worker autonomy. They simply outline the assumptions on the cross-derivates of the reduced form profit function which are sufficient and necessary to guarantee the complementarity, however, without motivating these assumptions.

worker discretion, high-performance incentives and worker ownership of assets.

Outline. The paper proceeds as follows. Section II introduces the model and Section III analyzes the behavior and performance of a given organizational structure. Section IV shows then that resulting expected profit function of an organization is supermodular in the appropriately signed organizational design variables and a number of exogenous variables. This result allows to obtain strong comparative statics results. Section V introduces management in our model and generalizes the supermodularity result and comparative static analysis.

In Section VI, we report on the influential study of Van de Ven, Delbecq, and Koenig (1976), which is, to the best of our knowledge, the only empirical study of coordination modes inside organizations. These authors surveyed the organization of a large employment security agency and offer striking quantitative evidence on the coordination modes adopted by the different units inside the agency. In particular they show that as uncertainty decreases, these units turn from a “horizontal” coordination mode, based on the mutual adjustments of workers, to a “vertical” mode based on rules and procedures and managerial intervention. Finally, Section VII concludes. Proofs are contained in the Appendix.

II. THE MODEL

In this section, we present a new team theoretic model of production, in which workers take actions after observing some local information and after having communicated with other workers involved in production. Organizational design will determine the effectiveness of these actions through its impact on the productive efficiency of workers and the information available to the workers. Before we present our specific production function in Section II.D, we first discuss the objectives of the organization, and the different organizational design variables which determine how efficiently these objectives can be realized. In Section V we extend this model to incorporate the role of management in production. Table 4 at the end of the paper summarizes our extensive notation.

II.A Adaptation and Coordination

Production, in our model, requires the combination of n tasks, where the profits of the organization depends on (i) how well each task is *adapted* to the organizational environment and (ii) how well each task is *coordinated* with the other tasks.

Adaptation.— Task i consists of undertaking a primary action, a^{ii} , whose effectiveness depends

on how well it is adapted to the local environment. Thus, adaptation calls for the use of *local information*, which exclusively pertains to a particular task and can only be observed by the worker assigned to it. This local information, a random variable θ^i with mean $\hat{\theta}^i$ and a common variance σ_θ^2 determines the optimal primary action. In particular, to achieve perfect adaptation, the primary action a^{ii} should be set equal to θ^i . The realization of the local information is independent across tasks.¹⁴

Coordination. – In addition, in order to ensure that task i is coordinated with all tasks $j \neq i$, the employee in charge of task i must perform a string of $n - 1$ actions $\{a^{i1}, a^{i2}, \dots, a^{in}\}$ who are complementary to the primary actions of task $j \neq i$. In particular, to achieve perfect coordination between task i and j , action a^{ij} of task i should be set equal to the primary action a^{jj} .

For example, if the organization consists of two tasks, then profits are maximized by minimizing the distance between the following two matrices

$$\begin{pmatrix} a^{11} & a^{12} \\ a^{21} & a^{22} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \theta^1 & a^{11} \\ a^{22} & \theta^2 \end{pmatrix}$$

where the diagonal elements pertain to the adaptation objective and the off-diagonal elements to the coordination objective.

II.B Organizational Design: Task Specialization and Task Standardization

An important objective of organizational design is to partition the totality of tasks into smaller *jobs* and assign them to specific individuals or groups. Jobs have at least two important characteristics: *task specialization* or the variety or number of tasks that a particular worker is asked to complete, and the *flexibility* which workers have in determining how best to complete those tasks. Both task specialization and task flexibility will affect how efficient or good an employee will carry out a task. For conciseness, we will think of the organizational problem as the assignment of jobs to workers. The analysis of the assignment of jobs to subunits under the direction of a subunit manager, is formally identical.

Task Specialization. – Each task is assigned to exactly one employee, but an employee may have

¹⁴In this paper we are interested in the effect of bundling tasks on task of flexibility and the quality of the communication network inside the organization. If the local information were to be correlated across tasks, this would introduce an additional motive for (un)bundling that, though interesting, is not the primary focus of this paper.

several tasks assigned to him. We denote by $\mathcal{T}(i)$ the set of tasks bundled with task i . To simplify the analysis we restrict the organization of production to be symmetric, that is, all workers inside the organization have an identical number t of tasks assigned to them. That is, we exclusively consider organizations where $t \in \mathcal{J} = \{t \in \mathbb{N} \text{ such that } \frac{n}{t} \in \mathbb{N}\}$.

Task variety is costly in the usual specialization sense: as in Adam Smith's Pin Factory, the larger the number of tasks assigned to an employee, the lower his degree of specialization and, as a consequence, the lower his productivity. Specifically, we assume that the income the organization generates is a decreasing function of the number of tasks per agent,

$$I(t, \alpha) \quad \text{with} \quad I_t < 0 \quad \text{and} \quad I_{t\alpha} < 0. \quad (1)$$

Here α governs the gains from specialization. The higher this parameter, the higher the returns to decrease the number of tasks per agent.

Task Standardization.— For the same reasons as there are productivity gains in letting workers perform a limited number of tasks, productivity can further be improved by training worker to perform a given task in a specific way: task standardization. Indeed, as this makes tasks much simpler, it is less time-consuming or costly to train workers and/or the task can be performed by a less skilled work-force. The benefits of task standardization, for example, were at the center of the Scientific Management method or Taylorism, which aimed to improve productivity by exactly specifying which movements a worker must make, in what order and in how much time. By specializing workers to perform tasks in a particular way, however, task standardization has the drawback that workers tend to be very inefficient if adaptation requires a different course of action. For example, a low-skilled teacher which is trained to teach economics by the letter of a particular textbook, may be very bad at tailoring his lectures to the specific characteristics of his students or to current events in the economy. In contrast, by increasing task flexibility - that is, by giving workers a more general training and/or by hiring higher-skilled workers which are better able to correctly apply general, non-specific, instructions - the organization can make the adaptation of a task to local information less costly. We model the standardization of task i as the *level of flexibility or discretion* a worker has around an *organizational guideline* r^{ij} for all actions a^{ij} , $j = 1, \dots, n$. Formally, we assume that the cost of taking an action a^{ij} is given by

$$\frac{(a^{ij} - r^{ij})^2}{x^{ij}} + \lambda f(x^{ij}) \quad (2)$$

where $f'(\cdot) > 0$, $f(0) = 0$, x^{ij} is the level of flexibility and λ is a parameter which characterizes the returns to standardization. From (2), task standardization (x^{ij} small) is ex post optimal

if and only if a^{ij} is sufficiently close to r^{ij} . The larger is λ , the more costly it is to provide flexibility. To simplify the analysis, we posit that the organization must choose the same level of standardization x^m for all primary actions a^{ii} , $i = 1, \dots, n$, and, similarly, the same level of standardization x^c for all complementary actions a^{ij} , $j \neq i$.

Besides returns to specialization, task flexibility may be costly for two other reasons.

(i) First, the adaptation of a task to local information may not only require flexible human capital, but also *versatile physical capital*. A similar trade-off obtains in the case of human capital. As long as only standardized products or services are produced in a standardized way, inflexible single-purpose tools and machines tend to be more efficient or cheaper than flexible machines. Single-purpose machines, however, often result in big switching or retooling costs if product or service specification change. Empirically, a proxy for λ will thus be the availability and cost of flexible machine tools and programmable equipment.

(ii) Secondly, task standardization may be useful in reducing *moral hazard* by employees. Intuitively, by exactly specifying what workers should do, the organization can, at a low cost, tightly monitor the inputs or effort provided by workers.¹⁵ It is in this sense that task flexibility is related to *employee empowerment*. The impact of task standardization on moral hazard was already recognized by the scientific management method. As Frederic Taylor, the ‘father of Scientific Management’ wrote: “Hardly a competent worker can be found who does not devote a considerable amount of time to studying just how slowly he can work and still convince his employer that he is going at a good pace.”¹⁶

II.C Modes of Coordination: Task Bundling, Standardization and Communication

In breaking down the production processes into a series of uncomplicated tasks, the organization may make the jobs themselves much simpler (benefits of specialization), but the coordination of the people performing those jobs becomes far more complicated. Indeed, each worker only observes his own actions and the local information which pertains to the tasks assigned to him. In our basic organization, coordination can be achieved in three ways:

¹⁵In contrast, when workers receive a lot of flexibility to adapt their tasks to local information, the measurement of the inputs provided by the workers tends to be much more costly or even impossible, as workers can hide behind the discretion accorded to them. In order to reduce moral hazard, the organization must then resort to output monitoring, which is less precise than input monitoring. See Prendergast (2002) for a formal argument along these lines.

¹⁶Frederic Taylor, *The Principles of Scientific Management* (New York and London Harper, 1929), as cited by Milgrom and Roberts (1992).

Limiting task specialization.— A straightforward way to avoid any coordination problem is to assign all tasks to one agent. More generally, by limiting the specialization of agents, the organization ensures an optimal coordination of all the tasks assigned to a particular employee. The cost of achieving coordination in this way, however, is that the organization forsakes returns to specialization.

Limiting task flexibility.— Alternatively, even in the presence of full specialization (each agent performs one task), perfect coordination can be achieved through an extensive task standardization, which fixes all primary actions *ex ante*, and ensures that all complementary actions are perfectly coordinated with these primary actions. The cost of this form of coordination, however, is that the organization cannot be adaptive to *ex post* realizations of the local information.

Improving communication.— Finally, to improve coordination between specialized tasks, workers can *communicate* the choice of their primary action to other workers prior to its actual implementation. Such communication, however, will often be imperfect due, for example, to limitations on the employee’s ability to hold unscheduled meetings or simply because of the lack of a shared language that facilitates the quick transmission of information. As a result, an employee may not understand what the particular choice of a primary action by another employee implies for the corresponding complementary action under his control. In particular, if task i and j are assigned to different employees, then with a probability $1 - p$, the message concerning the primary action of task j will be pure noise for the employee in charge of task i . In contrast, with a probability p , the agent in charge of task i perfectly understands what the choice of action a^{jj} means for the optimal choice of the complementary action a^{ij} . We will refer to p as to the effectiveness or *quality of the communication channels* between two non-bundled tasks.¹⁷

Importantly, we posit that the quality of these communication channels are an *organizational design variable*: p is chosen endogenously by the organization at a cost $\delta g(p)$ per communication channel, where $g_p > 0$ and δ is a positive constant. Given a level of task bundling t , the total cost of the communication network thus equals

$$n(n - t)\delta g(p)$$

One can interpret $\delta g(p)$ as the opportunity cost to the organization of having workers engaged

¹⁷Our assumption that the quality of the communication channels is identical for all task pairs is without loss of generality given the symmetry of our model.

in regular meetings designed to exchange information rather than in production itself, the provision of the information technology for workers, like intranet, and the computer terminals to facilitate it. Similarly, the organization can improve communication channels by job-rotation, team-events or by hiring employees with knowledge or skills which span across job-boundaries. Obviously, if task i and j are assigned to the same employee then employees perfectly understand what the choice of primary action a^{ii} means for the choice of secondary actions of other tasks assigned to them.

We make the following two technical assumptions about the communication process: First, if agent 1 controls both task i and j , but task k is controlled by agent 2, then whether communication is successful between task i and task k is independent of the success of the communication between task j and task k . Intuitively, a particular choice of a primary action for task k is likely to have different implications for task i and task j . Hence, if agent 1 understands the implication of a^{kk} for a^{jk} , this does not imply that he understands what it means for action a^{ik} . While this assumption simplifies the analysis, it is not essential for our results. Secondly, an employee never knows if his communication with other agents was successful. Thus, when deciding upon a primary action a^{ii} , he takes into account that with a probability p , the employee in charge of a^{ji} will be influenced by his communication on a^{ii} . Again, this greatly simplifies both the analysis and exposition, but it does not affect our main results.

II. D The Production Function

We will define $\bar{a}^i = (a^{1i}, a^{2i}, \dots, a^{ni})$ as the vector consisting of the primary action of task i , a^{ii} , and the string of actions belonging to task $j \neq i$ who are complementary to this primary action of task i . We define $\bar{r}^i = (r^{1i}, r^{2i}, \dots, r^{ni})$ as the vector of organizational guidelines associated with \bar{a}^i . Given this, we can write the organization's profit function as

$$I(t, \alpha) = \sum_{i=1}^n C^i(\bar{a}^i, \bar{r}^i, x^m, x^c, p, t \mid \theta^i) \quad (3)$$

where:

$$C^i(\bar{a}^i, \bar{r}^i, x^m, x^c, t \mid \theta^i) = \phi(a^{ii} - \theta^i)^2 + \frac{(a^{ii} - r^{ii})^2}{x^m} + \lambda f(x^m) \quad (4)$$

$$+ \frac{1}{n-1} \sum_{j \neq i} \left\{ \beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^c} + \lambda f(x^c) \right\} \quad (5)$$

$$+ (n-t)\delta g(p) \quad (6)$$

As pointed out previously, the term $I(t, \alpha)$ represents the revenues of the organizations, who are an increasing function of the specialization of the employees: $I(t, \alpha)$ is decreasing in t , the number of tasks per employee.¹⁸ The higher is α , the larger are the returns to specialization. The term C^i represents all the costs incurred by the organization who are related to the primary action of task i and to the actions of task $j \neq i$ who are complementary to this primary action. As shown in expression (4), the effectiveness of the primary action a^{ii} depends on how close it is set to the local information θ^i , capturing the need for *adaptation* of task i to the organizational environment, whereas as seen in line (5), the effectiveness of the complementary actions a^{ji} , $j \neq i$, depend on how close they are set to the choice of a^{ii} , capturing the need for *coordination* between the primary action of task i and the other tasks. The parameter ϕ reflects the importance of adaptation, whereas the parameter β determines the importance of coordination. In addition, both the cost of undertaking the primary actions and the cost of undertaking the complementary actions depend on the level of task flexibility, x^m and x^c , in a way which reflect the trade-off between flexibility and standardization. The weight $1/(1-n)$ in front of line (5) implies that if $\beta = \phi$, then adaptation is as important as coordination. Finally, the term in line (6) represents the cost of building and maintaining the quality of the communication channels which inform the tasks not carried out by the employee in charge of task i , about the primary action of task i .

II.E Timing

The timing of our model goes as follows:

(i) *Organizational design stage*: The organization determines the number of task per agent, t , the quality of the communication channels, p , the guidelines r^{ij} for all tasks, and the standardization of these tasks as characterized by x^m and x^c .

(ii) For all $i = 1, 2, \dots, n$, The local information θ_i is realized and observed by the employee in charge of task i .

(iii) *Communication stage*: Workers communicate their intended choice of primary actions to each other. With a probability p these communications are successful.

(iv) *Action stage*: For all $i = 1, 2, \dots, n$, the employee in charge of task i chooses actions a^{ij} , $j = 1, 2, \dots, n$, in such a way as to maximize the objective function (3), subject to his information constraints and taking the organizational structure as given.

¹⁸Obviously, our results would not be affected if, instead, we assumed that costs were a decreasing function of specialization.

III. ORGANIZATIONAL ACTIONS AND PERFORMANCE

Production requires the combination of n tasks; each of these involves the choice of a primary action that needs to be adapted to local information, and $n - 1$ complementary actions who must ensure coordination with the $n - 1$ primary actions of other tasks. We start by characterizing the choice of actions as a function of a particular organizational design in Lemma 2 and then evaluate the costs associated with that particular organizational design in Lemma 3.

It is easy to see that it will always be optimal to set the guideline r^{ji} for task a^{ji} equal to the mean of the local information variable θ^i .¹⁹

Lemma 1 Optimal guidelines are characterized by

$$r^{ji} = \widehat{\theta}^i \quad \text{for all } j, i = 1, 2, \dots, n.$$

Assuming such optimal guidelines, equilibrium actions are characterized as follows:

Lemma 2 Given a particular organizational design, $\{x^m, x^c, p, t, r^{11}, r^{12}, \dots, r^{nn}\}$, where $r^{ji} = \widehat{\theta}^i$, there exists a unique equilibrium in which workers, faced with a vector of local information $(\theta^1, \theta^2, \dots, \theta^n)$, choose the following primary and complementary actions:

$$a^{ii} = \widehat{\theta}^i + \left(\frac{\phi}{\phi + 1/x^m + B} \right) (\theta^i - \widehat{\theta}^i) \quad (7)$$

$$a^{ji} = \begin{cases} \widehat{\theta}^i + \left(\frac{\beta x^c}{1 + \beta x^c} \right) (a^{ii} - \widehat{\theta}^i) & \text{when task } j \text{ learns } a^{ii} \\ \widehat{\theta}^i & \text{when task } j \text{ does not learn } a^{ii} \end{cases}, \quad (8)$$

where

$$B = \left(\frac{\beta}{n-1} \right) \left[(t-1) \left(\frac{1}{1 + \beta x^c} \right) + (n-t) \left\{ p \left(\frac{1}{1 + \beta x^c} \right) + (1-p) \right\} \right]. \quad (9)$$

Equation (7), which gives the choice of the primary action, has two terms. The first one is the action suggested by the organizational guideline. The second term captures the need for adaptation to local information, θ^i , limited by the term $\phi + (1/x^m) + B$. The latter expression

¹⁹This result is intuitive. Minimization of the quadratic cost function is identical to the standard minimization of the mean square error, which is achieved by setting the guidelines r^{ji} equal to mean value of the action, $E(a^{ii})$. But clearly $E(a^{ii}) = \widehat{\theta}^i$, and Lemma 3 follows.

summarizes the costs of tailoring closely the primary action to the local information due to both lack of flexibility as well as coordination failures. Henceforth, we will refer to

$$\frac{\phi}{\phi + 1/x^m + B} \tag{10}$$

as the *equilibrium level of discretion* exercised by employees, that is how strictly do employees adhere to task guidelines or, in contrast, tailor their actions to local information.

Specifically, the first component, $1/x^m$, measures the decrease in the adaptation that is related to the flexibility built in task i . If the worker is given little flexibility (x^m is low), then the costs of deviating from a prescribed action is high, reducing the scope for adaptation.

The second component, B , given in expression (9), measures the limits to adaptation that result from the need to maintain some coordination with other tasks. B is increasing in β , which captures the overall importance of maintaining coordination in the organization: the greater is β , the lower the adaptation to local information. There are two terms in B . The first captures the coordination with tasks which are bundled with i and depends, as before, on the flexibility associated with these tasks. Recall that if two tasks are bundled, then the worker who is assigned to them observes perfectly the primary actions of each task. In contrast, the second term captures the fact that for those tasks that are assigned to a different job, $j \notin \mathcal{T}(i)$, coordination is hindered by communication failures. If the worker in this alternative task observes the primary action of task i , which occurs with probability p , then his choice of action will balance the need for coordination with a^{ii} with the cost of exercising discretion. If, in contrast, he does not observe a^{ii} , which occurs with probability $1 - p$, then it is optimal to fully adhere to the guidelines and choose $a^{ji} = r^{ji} = \hat{\theta}^i$.

B neatly summarizes the limits to adaptability which are due to coordination failures. It is therefore interesting to see how B is affected by changes in organizational design. Consider first the sensitivity of B^i to changes in the specialization of agents, that is the number of elements in $\mathcal{T}(i)$. Increasing this number improves coordination through a direct informational effect as workers now get to observe the local information of the additional bundled tasks. This effect can be directly seen in expression (9), where additional task bundling mechanically translates into upgrading the communication success probabilities to one. It follows that B is decreasing in t , the number of tasks per agent: a reduction in specialization results in primary actions that are more adaptive to the local information as now the worker can rely on a better coordination with the additional tasks under his control

Secondly, B is decreasing in p : increasing the quality of the communication channels naturally improves coordination as now complementary actions are based on better informa-

tion. This results in more adaptive primary actions because the employees can feel confident that these actions are more likely to be understood by other agents in the organization. Finally, an increase in the level of flexibility of complementary actions, x , yield primary actions that are better tailored to the local environment as now employees can be sure that whatever information gets through will be met by a stronger response by part of the other workers in the organization.

We summarize the many effects on B of changes in the organization design variables as

$$B_{\bar{t}} - B_{\underline{t}} < 0 \quad B_p < 0 \quad B_{x^m}^i < 0 \quad \text{and} \quad B_{x^c}^i < 0, \quad (11)$$

where $\underline{t}, \bar{t} \in \mathcal{J}$. Lemma 21 characterizes the organizational actions for a given realization of the local information and a given organizational form. As a result, the cost associated with a particular organizational form will depend on the realization of the local information. The next lemma provides a tractable expression for the average cost associated with a particular organizational form:

Lemma 3 The expected cost function for task i is given by

$$E \left[\min_{\bar{a}^i} C^i (\bar{a}^i, x^m, x^c, p, t \mid \theta_i) \right] = \lambda f(x^m) + \lambda f(x^c) + \delta(n-t)g(p) \quad (12)$$

$$+ \phi \left(\frac{1/x^m + B}{\phi + 1/x^m + B} \right) \sigma_\theta^2. \quad (13)$$

The first two terms in (12) capture the costs associated with a particular choice of flexibility and the third the quality of the communication channels in the organization. Expression (13) captures the costs that the organization suffers due to a lack of coordination and adaptability. Intuitively, it is proportional to the variance of the local information, σ_θ^2 . The higher the variance in the task environment, the larger the coordination and adaptation failures.

IV. ORGANIZATIONAL DESIGN

The problem of organizational design consists of the choice of the number of tasks per agent, the level of flexibility employees have in executing these tasks, and the quality of the communication channels between tasks assigned to different agents. In this section, we characterize the interactions among these organizational design variables, as well as the comparative statics with respect to the many technological parameters that determine the particular organizational form adopted in equilibrium.

For this purpose, we will make use of the concept of *supermodularity*. Roughly speaking, a function is supermodular in its arguments if the returns to increasing one of the arguments are higher the higher the other arguments. Supermodularity thus formalizes the idea of ‘complementarity’ or ‘fit’ among choice variables - the idea that the “whole is more than the sum of its parts” - and allows for unambiguous comparative statics. In particular, if a function of a vector of choice variables $y = (y^1, \dots, y^k)$ and an exogenous parameter τ is supermodular, then the maximizers $y^*(\tau)$ will be monotone nondecreasing in the parameter τ . In other words, choice variables tend to move up or down together in response to environmental changes, and any change that favors increasing one variable leads to increases in all the other variables.

IV.A Complementarities between Elements of Organizational Design

Abusing notation we denote by

$$\Pi(x^m, x^c, p, t, \tau) \equiv I(t, \alpha) - \sum_{i=1}^n E \left[\min_{\bar{a}^i} C^i(\bar{a}^i, x^m, x^c, p, t \mid \theta_i) \right]$$

the expected profits of a particular organizational form as a function of a parameter $\tau \in \{\sigma_\theta^2, \phi, \alpha, \lambda, \beta, \delta\}$, keeping all other parameters fixed.

Clearly, $\Pi(x^m, x^c, p, t, \tau)$ is not supermodular on the full support of the organizational design variables. In particular, if the quality of horizontal communication is very low, increasing task bundling (t) and improving horizontal communication (p) are typically *substitutes*. Indeed, a slightly higher quality of communication then typically *increases* the returns to a more extensive task specialization, as tasks are now better coordinated.

In equilibrium, however, high quality horizontal communication channels and task bundling are always *complements*: (i) First, more task bundling increases the level of discretion exerted by employees, as bundled tasks are better coordinated. This increased employee discretion, however, increases the demand for better coordination and communication between tasks which are not yet bundled. Similarly, an improvement in the quality of horizontal communication between two particular tasks, makes it more desirable to bundle each of these task with other tasks. In other words, *an increase in coordination in one part of the organization, increases the returns to also improve coordination in other parts of the organization*. (ii) Secondly, if the quality of communication is optimally chosen given the other organizational design variables, then any further increase in p still reduces coordination problems, but the associated costs to achieve this improved coordination outweigh its benefits. It follows that any increase in the quality of communication between two tasks above its equilibrium level, makes it more attractive to substitute this communication by bundling the two tasks.

In order to restrict our statements about complementarities to *equilibrium values of communication quality*, we will therefore consider the optimized value of profits with respect to the quality of communication p , where this communication quality is restricted by a lower bound \hat{p} :

$$\pi(x^m, x^c, \hat{p}, t, \tau) = \max_{p \geq \hat{p}} \Pi(x^m, x^c, p, t, \tau)$$

Letting this bound \hat{p} replace the quality of communication as the choice variable in our problem, it is clear that this change of variables leaves the optimal values of the other variables unchanged. Moreover, if for any fixed values of the other variables, the corresponding value of p is unique, the highest optimal value of \hat{p} equals the optimal communication quality p . As we will show next, an increase in \hat{p} then always makes it weakly more profitable to also increase task-bundling and task flexibility.

To ensure uniqueness of the optimal quality of communication, we make the following assumption:

Assumption The expected profit function $\Pi(x^m, x^c, p, t, \tau)$ is strictly quasi-concave in p .²⁰

We are now ready to state our first main results

Proposition 4 (i) The expected profit functions

$$\pi(x^m, x^c, \hat{p}, t, \sigma_\theta^2), \pi(x^m, x^c, \hat{p}, t, \phi), \pi(x^m, x^c, \hat{p}, t, -\alpha) \text{ and } \pi(x^m, x^c, \hat{p}, t, -\lambda)$$

are supermodular on the sublattice of $\mathbb{R}_+^3 \times \mathcal{J} \times \mathbb{R}_+$ defined by the restrictions that all the decision variables be non-negative.

(ii) The equilibrium values of the organizational design variables p, t, x^m and x^c are monotone non-decreasing in the parameters σ_θ^2 and ϕ , and monotone non-increasing in the parameters α and λ .

Proposition 4 formalizes the notion of ‘*organizational fit*’ or, equivalently, the notion that organizations are basically ‘*single-dimensional*’: organizations with a low degree of task specialization, are also those where workers are empowered with a lot of flexibility and which

²⁰A (very) sufficient condition for a stronger property of the expected profit function, strict concavity, is that

$$-\delta g''(p) + \frac{2\sigma_\theta^2 \beta^2}{\phi} \left(\frac{1}{n-1} \right) < 0.$$

It is easy to see that this condition will always be verified whenever the number of tasks is large enough.

are characterized by strong horizontal communication channels. Moreover, given the complementarity of the organizational design variables, even a small change in one of the parameters σ_θ^2 , ϕ , α or λ , may result in a dramatic shift in organizational structure, as any change in t , x^c , x^m or p reinforces further changes in all other design variables.

To see the complementarity of these organizational variables, it is useful to refer to the *discretion or empowerment* of employees as the extent to which the latter deviate from prescribed task guidelines in order to tailor their primary actions towards their local information. Importantly, the *demand for ex post coordination is elastic* as it is increasing in this level of employee discretion and empowerment. Thus, an organization which anticipates that its primary actions will become more adaptive to local information, will respond to this by increasing task bundling and improving horizontal communication channels in order to reduce the coordination problems associated with discretionary behavior. Similarly, it will make tasks more flexible, in order to make this discretion less costly. The causality, however, also goes in the other direction. Any improvement in ex post coordination or task flexibility, makes it optimal for employees to exert even more discretion, further increasing the demand for ex post coordination and flexibility. It follows that organizations are naturally characterized by *increasing returns to being adaptive and coordinated ex post*. In particular, any change in one organizational design variable towards more flexibility or a better coordination in one part of the organization, through its impact on employee discretion and empowerment, increases the returns to improve coordination and flexibility throughout the entire organization.

Proposition 4 allows us to make robust comparative static predictions with respect to four exogenous variables that determine t , x^c , x^m or p .

(i) First, *an increase in the uncertainty of the organizational environment*, as characterized by the variance in local information, σ_θ^2 , results in a lower degree of specialization, an increase in workers' flexibility, and improvements in the quality of the communication network inside the organization. Intuitively, as the uncertainty increases, employee discretion becomes more important, as the actions prescribed by the organizational guidelines are much more likely to be far from target. It follows from (11) that such an increased discretion can be achieved by the above mentioned changes in the organizational design variables. Moreover, each change in one of the variables reinforces the effectiveness of a change in the other ones. Obviously, the same argument holds if *adaptation becomes more important* for some other reason, that is, if ϕ increases.

(ii) Second, our model predicts the same shift in all three organizational design variables

if either the *cost of task flexibility*, characterized by λ , and/or the *returns to specialization*, characterized by α , decrease. Intuitively, a decrease in the cost of flexibility will, as a direct effect, make it optimal to increase the flexibility of workers. Due to the complementarity with the other organizational design variables, however, it will then also be optimal to increase task bundling and the quality of the horizontal communication channels. The same argument holds for a decrease in the returns to specialization.

The latter comparative static prediction sheds light on the recent debate on the impact of information *information technology* on organization design. Several organization scholars have argued that improvements in information technology over the last decades (extensive databases, expert systems, computerized processes and controls) have made it easier to give employees more flexibility to adapt their tasks to changing circumstances.²¹ A decrease in the cost of IT thus directly affects task flexibility and employee discretion. Indirectly, however, our model implies that is then also optimal for to increase task bundling and improve horizontal communication, reinforcing further increases in task flexibility and employee discretion. Consistent with this prediction of our model, Brynjolfsson and Hitt (1997) and Bresnahan, Brynjolfsson and Hitt (2002), in a sample of 300 large U.S. firms, have identified a strong correlation between the use of information technology and ‘new workplace organization practices’ involving (i) more discretion for employees in how to complete their tasks, (ii) the use of self-managing teams, team building activities and teamwork as a promotion criterion (more horizontal communication), (iii) broader job-classifications and (iv) higher human capital and human capital investments such as training and preemployment screening.²² In addition, they find that these workplace practices are also strongly correlated with each other, suggesting that they are complements.²³ Our paper thus shows how these robust empirical correlations between the occurrence of new workplace practices can be traced back to a unique driving force: the elasticity of the demand for coordination. Hence, our model provides a theoretical underpinning for the central thesis of Bresnahan, Brynjolfsson and Hitt (2002) that the impact

²¹These improvements in *information technology* which makes it easier for employees to exert discretion and adapt their tasks to local circumstances should be distinguished from improvements in *communication technology* such as e-mail. As we will argue next, improvements in communication technology have a decidedly ambiguous impact on organizational design.

²²Note that a higher demand for high-skilled workers is consistent with broader task assignments, less standardized tasks, and attempts to improve horizontal communication. Hence, Bresnahan et al (2002) refers to ‘skill biased organizational change’.

²³Similarly, Ichniowski, Shaw and Prennushi (1997), which study the same new workplace practices (but not IT) in the steel industry, find substantial evidence that the latter are strongly complementary.

of IT on the demand for high-skilled labor stems to a large extent from its complementarity with *high-skill biased workplace reorganizations*.

IV.B. The Tenuous Trade-off between Coordination and Specialization

Two parameters that are conspicuously absent in Proposition 4, and they are the parameter that controls the overall costs of coordination, β , and δ , which measures the overall costs of building good communication channels inside the organization. The same complementarity of design variables which allowed us to make strong comparative static predictions with respect to ϕ , σ_θ^2 , α and λ , implies that the impact of β and δ is decidedly ambiguous.

Coordination Costs. — Consider first the case of β , which determines the importance of coordination. If coordination becomes more important, then if the adaptation to local information is essential (ϕ is large) and the returns to specialization are not very important (α is not too large), the organization will react by integrating tasks more broadly and improving communication channels. Indeed, this allows the organization to achieve a better coordination while not inhibiting its ability to be adaptive to the local environment. In contrast, if specialization is very valuable and adaptation is only moderately important, an opposite response is likely to be observed. In order to achieve an almost perfect coordination, the organization may then deem it optimal to forego any adaptation to local information, fully specialize its workers and achieve perfect coordination by letting the workers stick blindly to the organizational guidelines. We formalize this intuition with the following limit result:

Proposition 5. (a) Given α there exists a unique $\bar{\phi}$ such that

$$\begin{aligned} \lim_{\beta \rightarrow \infty} t^* &= n & \text{if } \phi > \bar{\phi} \\ \lim_{\beta \rightarrow \infty} t^* &= 1 & \text{if } \phi < \bar{\phi}, \end{aligned}$$

where t^* is the optimal number of tasks per job, and (b) $\bar{\phi}$ is increasing in α .

Proposition 5 should be compared with the intuition advanced by Becker and Murphy (1992), namely, that specialization is limited by the coordination costs incurred when combining a large number of workers rather than by the size of the market. Here, in contrast, if adaptation is not a relevant organizational goal because of a low ϕ , then an increase in the importance of coordination costs, as measured by β , *increases* specialization. The reason is that organizations facing a larger β may respond by exploiting the specialization gains while

reducing the employee discretion and hence achieving coordination by forcing them to adhere to recommended actions.

Communication Technology — A similar result holds for δ , which measures the cost of improving the quality of the communication channels. Obviously, as δ becomes very small, there will be a trend towards full specialization as workers assigned to different tasks can then perfectly coordinate their actions. One may therefore be tempted to conclude that the division of labor will be increasing in the cost of communication. There is, however, an important countervailing force. Indeed, as horizontal communication between workers improves, it also becomes optimal for the organization increase employee discretion, which favors more task bundling in order to reduce coordination failures. Thus, the complementarity between better communication channels, less standardization and more task bundling implies that improvements in information technology have an ambiguous impact on the organization of production.

Consider, for example, a case in which coordination between different tasks is very important, but communication technology is very bad and complete task bundling is very costly. In the latter case, the organization will probably give up any benefits to being adaptive, but instead choose to reap the benefits of extreme task specialization and task standardization. As communication technology improves, however, the organization is likely to change this strategy towards more employee discretion and, hence, more adaptation to the local environment, which it will achieve initially not only by increasing task flexibility and by investing in the quality of communication, but also by increasing task bundling in order to reduce coordination failures. Finally, as horizontal communication becomes very efficient, the benefits of task bundling in terms of reduced coordination failures will become smaller and smaller, and task specialization will eventually increase again. The following proposition gives some weak conditions under which the impact of a better communication technology has a non-monotonic impact on task specialization. It suggests that better horizontal communication is most likely to reduce task specialization in cases where the quality of the communication channels is very poor.

Proposition 6. Assume that for a given set of parameters, σ_θ^2 , ϕ , λ , β , and α , there exists a δ' for which $1 < t^*(\delta') < n$. Moreover assume that $t^* = 1$ in the absence of any horizontal communication between workers, then $t^*(\delta)$ is non monotonic in δ .

The intuition, and proof, for the proposition is immediate. If $t^* = 1$ in the absence of any communication between workers, which occurs for example when the specialization gains α are sufficiently large, then $t^*(\delta)$ is necessarily non-monotonic as the organization will also

resort to complete specialization when there is perfect horizontal communication. Because by assumption $1 < t^* (\delta') < n$, non-monotonicity follows.²⁴

V. THE ROLE OF MANAGEMENT

“The key role of management in organizations is to ensure coordination.”

Milgrom and Roberts (1992), Chapter 4.

V.A What do managers do?

Task standardization and task guidelines have played a key role in our model. But where do task instructions come from?²⁵ How are organizational routines, procedures and rules affected by changes in the organizational environment? In most organizations, it is management - in particular middle-management - who develops the instructions which guide and coordinate the activities of workers and who ensures that these instructions are adjusted appropriately as circumstances change. In this section, we introduce a simple dynamic version of our model in which the role of management is exactly that: updating guidelines and task instructions. We are in particular interested in how management may improve coordination, what determines the number of coordinating managers and how is management size related to the other organizational design variables. For example, if task instructions can be updated frequently, this makes it feasible to ensure tight coordination by means of very specific task instructions and still remain somewhat adaptive to changing circumstances. Hence, a larger management reduces the need for task flexibility and horizontal communication.

In the previous sections, task instructions for the employee carrying out a^{ij} gave the latter some flexibility around an organizational guideline r^{ij} , where r^{ij} was optimally set equal to $\hat{\theta}^j$, the expected value of θ^j . In a dynamic world, however, not only the realizations of θ^j are likely

²⁴This result stands in contrast with those of Garicano (2000) and Geanakoplos and Milgrom (1991) in different but related models. For instance, Garicano (2000) shows that in a knowledge based hierarchy, better communication yields an unambiguous decrease in the scope of production workers, who, in the course of production, generate problems that they may or may not be able to solve, and an unambiguous increase in the span of problem solvers, who have the knowledge to address the problems raised by production that workers cannot solve (see his Proposition 5, page 889.) In Geanakoplos and Milgrom (1991) managers’ span of control should increase with better information systems, where the quality of these systems is defined as the precision with which relevant production parameters are known (see their Propositions 8 and 9, in page 221.)

²⁵Organizational instructions include the training which employees receive, routines and procedures developed by management, task manual which specifies what actions should be undertaken in which situations etc. Depending on how specific or general these instructions are, tasks will be more or less standardized.

to differ every period, but also the distribution of θ^j may change. We assume that management is specialized in observing such changes in the *fundamentals* of the organizational environment. The role of management is then to update the task instructions to better correspond to these changes. Obviously, issuing new task instructions is time-consuming. The larger the size of management, however, the lower this cost and, hence, the more frequently management intervenes.

Formally, we consider a two period model, in which in period 2, θ^i is drawn from a distribution with mean $\hat{\theta}^i + \varepsilon^i$ and variance σ_θ^2 , where ε^i is an i.i.d shock, normally distributed with mean $E(\varepsilon^i) = 0$ and variance σ_ε^2 , which occurs after period 1.²⁶ Thus, the unconditional variance of θ^i in the second period equals $\sigma_\theta^2 + \sigma_\varepsilon^2$. As in our previous sections, only the employee in charge of task i can observe θ^i . Moreover, employees do not have the knowledge to identify changes in the mean $\hat{\theta}^i$ of tasks not allocated to them. In contrast, managers do observe changes in $\hat{\theta}^i$. Intuitively, managers have a more general picture of the organization as they are specialized in designing the instructions for the various tasks. This requires an understanding of the general characteristics of tasks and how they are optimally performed under ‘average circumstances’.

Figure 1 provides a summary of the timing of actions and events: Upon observing the environmental shock ε^i at the beginning of the second period, managers decide whether or not to intervene in production by issuing new instructions. For simplicity, we assume that when instructions for a particular primary action are updated, they are also updated for the actions complementary to this primary action. If no new instructions are issued, the old instructions remain in place.²⁷ We make the natural assumption that issuing new guidelines and retraining employees to apply these new guidelines is costly. Hence, management will only intervene if these changes in the fundamentals are severe enough. The larger the number of managers in the organization the lower the costs of implementing change in a centralized way. Formally, we denote the cost of changing the task instructions for a vector of actions \vec{a}^i by

$$h(m) \quad \text{with} \quad h_m < 0$$

²⁶The assumption on the normality of ε^i is made to simplify the proofs of the propositions and it is much stronger than needed.

²⁷We assume, that even when instructions are updated, management is unable to affect the level of flexibility itself. This is a simplifying assumption which can be easily relaxed and that is not essential for our results. It is realistic, though, if the cost of flexible instructions reflect the required human capital and training of employees. It is easy to see that shocks to the mean of θ^i only affect the optimality of the instructions, but not the other organizational design variables.

where m is the *size of management in the organization*, an endogenous variable. Thus, $h(m)$ measures the ability of the organization to react to aggregate events in a *centralized* way.²⁸

Note, finally, that the impact of new task instructions is twofold. First, new task instructions provide a better estimator of the primary actions taken by other employees. Hence, if one employee does not understand the information communicated by another employee, then the new instructions will improve coordination between the actions of these two employees. Secondly, new instructions provide additional flexibility to adapt to changing circumstances. Indeed, by issuing instructions which better correspond to changing circumstances, managerial intervention makes adaptation to these new circumstances cheaper. Thus, one way to be very adaptive as an organization is to have very flexible instructions. Another way is to have a larger management which frequently updates very specific instructions. Hence, a second role of management is to allow adaptation in the presence of standardized tasks.

V.B Management intervention

Organizational design will take place taking into account the possibility of management intervention to improve coordination and organizational adaptability. The next lemma shows that, quite naturally, management will implement change whenever the shock ε^i is sufficiently large.

Lemma 7. (a) Management updates organizational guidelines in period 2 from $r^{ji} = \widehat{\theta}^i$ to $r^{ji} = \widehat{\theta}^i + \varepsilon^i$ whenever $|\varepsilon^i| \geq b^*$ where

$$b^* = \left[\left(\frac{\phi + 1/x^m + B}{1/x^m + B} \right) \frac{h(m)}{\phi} \right]^{1/2}. \quad (14)$$

(b) b^* is increasing in x^m , x^c , and p and decreasing in m and ϕ . Moreover, $b(\bar{t}) > b(\underline{t})$ for $\underline{t}, \bar{t} \in \mathcal{J}$ and $\underline{t} < \bar{t}$.

Intervention by management in task i is then less likely the larger t , x^m , x^c and p , for $j = 1, 2, \dots, n$. Intuitively, if tasks are very standardized, that is x^m and x^c are small, then agents will adhere strictly to the old organizational guideline, $\widehat{\theta}^i$. In this case, the bounds associated with intervention will narrow as the management can relieve this lack of flexibility by providing new task instructions which are centered around $\widehat{\theta}^i + \varepsilon^i$. Similarly, if p is high, then management can rely on the communication across tasks to implement the necessary

²⁸For simplicity, and without any loss of generality we take $m \in \mathbb{R}_+$.

coordination, making coordination by way of a new organizational guideline $\widehat{\theta}^i + \varepsilon^i$ less useful. Thus, the impact of t , x^m , x^c and p on b^* reflect the two roles of management intervention: improving flexibility to adjust to changing circumstances and improving coordination between workers. In particular, management intervention is a *substitute* to the flexibility embedded in original task instructions, x^m and x^c , and the ability of employees to coordinate their actions using horizontal communication, p . Finally, the larger the number of managers m the more intervention as the less costly it is. In summary then, for a given variance σ_ε^2 , b^* determines the equilibrium occurrence of vertical coordination, that is, the frequency of managerial intervention. For analytical purposes, we will consider b as an organizational design variable, chosen at the organizational design stage. In equilibrium, however, b will always satisfy equation (14).

As in Section III knowledge of the expected cost function is needed in order to characterize organizational design. Let P be the probability that management intervenes in a particular task, that is

$$P = \text{prob} [|\varepsilon^i| > b].$$

The following lemma provides the expected cost suffered by the organization in the second period, that of the first period being identical to the one reported in Lemma 2.

Lemma 8. The expected cost function for task i in period 2 is given by

$$E \left[\min_{\bar{a}^i} C^i (\bar{a}^i, x^m, x^c, p, t, b, -m \mid \theta^i, \varepsilon^i) \right]$$

$$= \lambda f(x^m) + \lambda f(x^c) + \delta(n-t)g(p^{ji}) + \phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) [\sigma_\theta^2 + \sigma_\varepsilon^2] \quad (15)$$

$$+ \omega m + P \left[h(m) - \phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) E [\varepsilon^{i2} \mid |\varepsilon^i| > b] \right]. \quad (16)$$

The term (15) represents the expected second period cost in the absence of any coordination by management. It is identical to the organizational cost expression in Lemma 2, except that the variance of θ^i now equals $\sigma_\theta^2 + \sigma_\varepsilon^2$. Expression (16) represents the impact of management and vertical coordination. First, the presence of management involves a fixed cost ωm , where ω stands for the manager's wage. Second, whenever management intervenes to update \bar{r}^i , which occurs with probability P , the organization suffers a variable cost $h(m)$ but it reduces the "variance" by a term that is proportional to $E [\varepsilon^{i2} \mid |\varepsilon^i| > b]$; it is as if the second period variance of θ^i is only σ_θ^2 as opposed to $\sigma_\theta^2 + \sigma_\varepsilon^2$.

V.C Management and Organizational Design

We are now ready to characterize the relationship between the size of management and the frequency of managerial intervention, and the other organizational design variables. As before, the expected profits of a particular organizational form as a function of a parameter $\tau \in \{\phi, \alpha, -\lambda, \beta, \delta, \omega, \sigma_\theta^2, \sigma_\varepsilon^2\}$, keeping all other parameters fixed is given by

$$\Pi(x^m, x^c, p, t, b, -m, \tau) \equiv I(t, \alpha) - \sum_{i=1}^n E \left[\min_{\bar{a}^i} C^i(\bar{a}^i, x^m, x^c, p, t, b, -m, \tau \mid \theta^i) \right] \quad (17)$$

$$+ I(t, \alpha) - \sum_{i=1}^n E \left[\min_{\bar{a}^i} C^i(\bar{a}^i, x^m, x^c, p, t, b, -m, \tau \mid \theta^i, \varepsilon_i) \right], \quad (18)$$

where (17) corresponds to the profits in the first period and (18) to those in the second period. As in the previous section, we restrict our statements about complementarities to *equilibrium values of communication quality*, which we achieve by investigating the properties of,

$$\pi(x^m, x^c, \hat{p}, t, b, -m, \tau) = \max_{p \geq \hat{p}} \Pi(x^m, x^c, p, t, b, -m, \tau),$$

rather than of $\Pi(x^m, x^c, p, t, b, -m, \tau)$. Similarly, as before as well, we make the following assumption:

Assumption The profit function $\Pi(x^m, x^c, p, t, b, -m, \tau)$ is strictly quasi-concave in p .²⁹

The next proposition generalizes the supermodularity of the expected profit function, put forward in Proposition 4, to include treatment of the role of management. Concretely it implies that an increase in the size of management and the frequency of vertical coordination is a *substitute* for task flexibility, task bundling, and a high quality horizontal communication network.

Proposition 9. (i) The expected profit functions

$$\pi(x^m, x^c, \hat{p}, t, b, -m, -\alpha), \quad \pi(x^m, x^c, \hat{p}, t, b, -m, -\lambda), \quad \pi(x^m, x^c, \hat{p}, t, b, -m, \omega), \quad \text{and} \\ \pi(x^m, x^c, \hat{p}, t, b, -m, \sigma_\theta^2)$$

are supermodular on $\mathbb{R}_+^2 \times \mathcal{J} \times \mathbb{R}_+^3$.

(ii) The equilibrium values of the organizational design variables p, t, x^m, x^c, b and $-m$ are monotone non-decreasing in the parameter σ_θ^2 and ω , and monotone non-increasing in the parameters α and λ .

²⁹It can be easily shown that the condition in footnote 20 is again a sufficient condition for strict concavity in p of the profit function.

The main implication of Proposition 9 is that the returns to increasing the size of management (m) and the frequency of managerial intervention (as measured by b) are increasing in the level of task specialization and task standardization, and decreasing in quality of the horizontal communication network. This result coincides with casual observation that organizations with extensive management forces are associated with the intense specialization of the workers' narrow job descriptions. Intuitively, one way to achieve adaptation is by making it relatively cheap for employees to exert discretion in the way they carry out their task. This goal can be achieved by making horizontal coordination with other tasks easy through task bundling and a strong horizontal communication network and by hiring high-skilled employees who receive general task instructions and training. Alternatively, however, the organization can achieve coordinated adaptation by frequently updating task instructions in a coordinated way. In order to do this efficiently, this requires the presence of a large middle-management. Hence, a large managerial force increases the returns to task specialization and task standardization, as vertical coordination will be able to ensure an adequate adaptation to changes in environmental fundamentals. Similarly, increasing task flexibility and task bundling is a substitute for a larger management, as employees then can easily exert discretion and coordinate their activities without new task instructions.

The complementarity of vertical coordination, task standardization, and task specialization yields an number of direct comparative static implications. First, the size of management and the frequency of managerial intervention will decrease if the returns to specialization decrease (α decreases) or task flexibility becomes easier to implement (λ decreases). Similarly, specialization and task standardization will increase if management becomes more productive or cheaper (ω decreases).

As second set of comparative static results concern the relation between the size of management and the importance of local information, as measured by σ_θ^2 . An increase in the local uncertainty σ_θ^2 is met by organizations with a reduction in the size of the managerial force, m , and with a decrease in the frequency of vertical coordination, that is, an increase in the intervention bound b . The reason is that an increase in local uncertainty makes it optimal to increase task flexibility and task bundling, which decreases the returns to vertical coordination. For instance, if competition forces the organization to tailor its product more closely to the taste of customers, which we can interpret as an increase in σ_θ^2 , then the organization will respond by becoming flatter, increasing the number of tasks to workers as well as giving them more flexibility and stronger horizontal communication channels.

The only ambiguous comparative static concerning task uncertainty is an increase in σ_ε^2 , that is, an increase in the overall uncertainty which is not related to an increase in local uncertainty. Indeed, the direct effect of an increase in σ_ε^2 will be both to increase management, and to increase task flexibility and task bundling. An increase in task flexibility and task bundling, however, makes it less attractive to increase the size of management and vice versa. Hence, depending on the particular circumstances, the impact of an increase in uncertainty which is fully observable by management is ambiguous, and could potentially result in a decrease in the size of management.³⁰

Finally, notice again the ambiguous impact of improvements in communication technology or an increase in the importance of coordination. For the same reasons as in Section IV, an improvement in the communication technology may result in more specialized and more standardized tasks - and, by complementarity, more vertical coordination - as well as in more task bundling and task flexibility and, hence, a smaller managerial force. Similarly, a large increase in the importance of coordination may result in a very specialized organization, in which a large management is the only way to achieve adaptation, or, in contrast, in an organization which is characterized by extreme task bundling and very strong horizontal communication channels, where vertical coordination plays virtually no role.

VI. EVIDENCE AND EXAMPLES

VI.A The organization of an employment security agency

As described above, organizations adapt to local uncertainty by addressing the coordination problems that adaptation itself entails. We saw that, in the context of our model, coordination is achieved by combining four main organizational design variables: specialization, task standardization, managerial intervention, and the quality of the communication channels between agents. In particular, organizations with extensive “horizontal” communication mechanisms, have broader job definitions, and hence lower specialization, make less use of managerial intervention to achieve coordination, and have tasks that are flexibly defined.

Van de Ven, Delbeq, and Koenig (1976) tested these propositions empirically in an influential study of coordination and communication modes in sixteen district offices as well as the headquarter of a large employment security agency.³¹ They collected observations on

³⁰This could occur, for example, if $h(m)$ becomes very convex for larger values of m .

³¹The organization of employment security agencies was subject of an extensive and very detailed study in Blau and Schoenherr (1971). Chapter 2 of their book provides an informal description of employment security

197 formal work units, as officially defined in the organizational chart.³² These units, which are formed by a supervisor and a varying number of agents, face different coordination and adaptation challenges. Van de Ven et al. (1976) measured the degree of uncertainty that each unit faced as well as the degree of “interdependence” among the agents within the unit, that is, the extent to which these agents are dependent upon one another to perform their individual jobs. Similarly, they measured the extent to which different “modes” are used to achieve coordination. According to their classification, coordination can be achieved through the use of “impersonal coordination modes,” which include the use of rules and procedures and that of plans and schedules, “personal coordination modes,” which include both vertical and horizontal communication, and “group coordination mode,” that includes both the use of scheduled and unscheduled meetings.³³

The rules and procedures and plans and schedules are defined as formally or informally understood policies for coordinating work within the unit and it corresponds to the recommended action r^{ji} and the associated flexibility x^{ji} in the context of our model. Vertical coordination channels refer to any coordination mechanism that uses either the supervisor or an assistant unit supervisor as a coordinator. This variable has a direct translation to the frequency of management intervention as determined by the bounds b^i . Horizontal coordination modes include informal communication channels between unit members or through a formally designated work coordinator other than the supervisor. Group coordination modes are self explanatory. Respondents were asked to rank each method in a ten interval scale ranging from 1, meaning “used to no extent,” to 10, “used to a great extent.” Similarly, task uncertainty and interdependence were measured as the average responses to several questions relating to the variability of tasks and their interconnectedness.³⁴ Finally, unit size was measured as the

 agencies, whose responsibilities include everything from placement of unemployed workers to counseling and the distribution of unemployed benefits.

³²More specifically, data was collected from on-site conducted questionnaires to the supervisors and all members of the working units for a total of 197 unit supervisors and 880 workers. Work units were defined as consisting of one supervisor and all non-supervisory personnel reporting to the supervisor.

³³Group modes seem to us to be another form of horizontal communication method and we will interpret it this in what follows.

³⁴For instance, a sample question for task uncertainty was “How much variety in cases, claims, clients, or things do you generally encounter in your normal working day?” As for task interdependence it was measured using two alternative measures. One the one hand, following work by Thompson (1967) respondents were shown several plots showing different “work flow cases” and asked to choose among them. The second measure is due to Mohr (1971) who uses questions like “To what extent do the people in this unit have one-persons jobs: that is, in order to get the work out to what extend do unit members independently accomplished their own assigned

number of people in the unit.

Table I shows the zero order correlation among independent variables and coordination modes. First notice that the correlation between task uncertainty and impersonal modes of communication, which includes rules and procedures and plans and schedules, is strongly negative, whereas it is strongly positive with horizontal communication modes and group coordination modes. Interestingly, vertical channels show no discernible correlation with task uncertainty. Notice as well, that impersonal coordination modes correlate positively with vertical personal modes, that is, those that rely on supervisors for coordination but that they correlate negatively with both the horizontal coordination and the group coordination modes, suggesting that indeed, as shown in the context of the model, rules and procedures move together with managerial intervention as means of coordination at the expense of communication between workers in the organization, either through personal or group modes.³⁵

Table II shows the effect of multiple regressions were the different coordination modes are regressed against task uncertainty, interdependence, and unit size. The results indicate that task uncertainty decreases impersonal modes of coordination, the rules and instructions provided by the organization, whereas it significantly increases horizontal communication modes as well as group coordination mechanisms. These results lend support to the aspects of the model that deal with standardization and communication as ways of achieving coordination in the presence of uncertainty and interdependence.³⁶ In particular they confirm that both inflexible rules and managerial intervention substitute horizontal communication in the presence of significant uncertainty. In contrast flow interdependence, which correlates negatively with impersonal coordination modes and positively with the other coordination modes, only does so significantly for the group mode. Finally, as the unit size increases the use of impersonal coordination mechanisms increases significantly whereas personal modes remain unaffected.

task?" In addition, unit size was measured as well appealing to fiscal records. For a detailed description of the independent variables see the Appendix in page 333 of Van de Ven et al. (1976).

³⁵The idea that rules and procedures are the distinctive features of bureaucracies can, of course, already be found in Weber (1946) who states that "Bureaucratization ... primarily means a discharge of business according to calculable rules and 'without regard for persons.'" Weber was clearly responding to the rise of large organizations that he witnessed during his lifetime. Merton (1963), in contrast emphasized the inefficiencies that standardization entails. For an interesting discussion on these matters and on Weber's and Merton's differing views see Blau and Schoenherr (1971, page 114-5) and March and Simon (1958, 36-40.)

³⁶Cheng (1983) built on Van de Ven et al. (1976) to study in a sample of 127 research units sampled from 33 organizations in Belgium the relation between interdependence and the level of coordination, although how the latter is achieved is left unspecified. See also Tushman (1978) for another empirical study.

While the interpretation of unit size as a measure of the division of labor should be made with caution as it requires some uniformity in the number of tasks across units,³⁷ this last result seems consistent with the model prediction that an increase in the division of labor is associated with a more intensive use of rules and less horizontal communication.

VI.B Coordination in software design

Design of complex systems is perhaps one of those activities where the trade-offs between adaptability and coordination are most obvious, and nowhere are these problems more daunting than in the development of large software projects. For instance, the software design for the management of the Apollo missions in the 1970s contained 23 million lines of code whereas the system governing AT&T's switchboard is "only" 10 million lines.³⁸ The complexity of software design is such that problems in software design are a permanent fixture of this industry.³⁹ Clearly, such systems are beyond the abilities of one person to write and supervise and for this reason the development of large software systems involves several teams of software engineers who are allocated separate modules of the overall design. As Kraut and Streeter (1995) emphasize, though "there is no single cause of the software crisis, a major contributor is the problem of coordinating activities while developing large software systems." Indeed, partition of the software design in modules simplifies its production at the expense of potential problems caused by incompatibilities across these modules.⁴⁰ Failure to properly mesh these modules results in complete breakdowns, as in the famous meltdown of the AT&T long distance system when a "bug" in one of the modules produced failures throughout the whole network.⁴¹ For instance, Crowston (1997) described the organization of a minicomputer

³⁷Unfortunately, we were not able to retrieve information about this from either Van de Ven et al. (1976) or Blau and Schoenherr (1971).

³⁸See Kraut and Streeter (1995), footnote 1.

³⁹Cusumano and Kemerer (1990) state that "[S]oftware has presented problems to managers since the beginning of the industry in the late 1950s, when programmable computers first appeared," and Kraut and Streeter (1995) state that "[S]ince its inception the software industry has been in crisis."

⁴⁰As defined by Zmud (1980), modularity in software development refers to the breakdown of the system into well defined blocks. A cursory look at the literature on software development is plagued with references to coordination problems. For instance Zmud (1980), Curtis, Crasner and Iscoe (1988), Koushik and Mookerjee (1995), Kraut and Streeter (1995), Nidumolu (1995), Crowston (1997), Faraj and Sproull (2000), and Mookerjee and Chiang (2001).

⁴¹The problem of the development of large software systems is acute for complex engineering projects and it has led to a large literature on software engineering and even the foundation of laboratories exclusively devoted to the study of software development. For instance, the Software Engineering Laboratory (SEL) created by

division of a large corporation, in charge of the development of proprietary operating systems, of a size of roughly one million lines of code. Operating systems are broken into several subsystems, such as the process manager, the file system, that are then in turn broken into several modules. Coordination problems arose in the company studied by Crowston because improvements in one of the modules made at later stages in the development process were in occasion incompatible with the existing design of other modules. Coordination problems in software design then have an intertemporal component as adaptive changes in one side of the system have to be consistent with pre-existing design in other subsystems.⁴²

Coordination is achieved by either extensive communication between the software engineers or by the intervention of senior system engineers who assume management roles. As for the latter, Curtis, Crasner and Iscoe (1988, page 1271-2) mention in their study of 17 large software projects, that these engineers had the central role of integrating different perspectives on the development process, and in particular they “were skilled at modeling the interaction of a system’s different functional components.” On the other hand communication among engineers can be either formal, like written specification documents, status review meetings, or automated reporting or informal, personal, peer oriented interaction (Kraut and Streeter (1995)). It is important to emphasize that formal communication, codified in manuals kept in internal documentation libraries which include whatever modification was made to the code, is costly as it requires the developer to devote time and energy to building such a documentation while designing the system. Clearly, if the organization is under pressure to deliver the software in time to the customer, careful documentation is the first likely casualty, which can only come at the expense of severe lack of coordination later down the road.

But, what is the source of uncertainty in software development? First, software design is a non routine activity that is typically tailored to the customer’s needs. As these change, due to fluctuations in business conditions or changes in computer platforms, customers will require updating the obsolete modules. These changes though need to be coordinated with other modules. If those modules are part of the same subsystems they were most probably designed

NASA’s Goddard Space Flight Center “for the purpose of understanding and improving the overall software process and products that were being created within the GSFC Flight Dynamics Division (FDD).” It was created in 1976 and since then has collected data on several software projects to evaluate ways of improving the management process. For an overview of SEL visit <http://sel.gsfc.nasa.gov/website/welcome.htm>.

⁴²Lientz and Swanson (1980) argue that there are three reasons to modify a code: corrective, perfective, or adaptive. In any of the three, problems of compatibility arise and this can only be addressed if proper documentation, which supports communication between different software engineering teams across time, is available.

by a single team and hence coordination is less of a concern. But if these other modules were in turn part of other subsystems then the risk exists that the improvements introduced are incompatible with the non obsolete modules. In one specific example mentioned by Crowston (1997), the word processor kept crashing due to the fact that engineers in charge of its design had chosen a low level system call. This system became incompatible with the operating system when changes in the latter were made by the engineers in charge of updating it, who were not aware of the system call used by the word processing designers. In addition, as Kraut and Streeter (1995) emphasize, software development is uncertain because of the incomplete nature of the specifications. Engineers then have to exercise considerable judgement on which direction to take the development of the project and make sure their interpretation is consistent with others in charge of different modules and subsystems.

To quantify the determinants of coordination modes in software design Kraut and Streeter (1995) collected data on 65 software system or subsystems. Independent variables included project size, as measured by the number of people involved in it, project age, the maximum number of years that any project member worked in the project, planning stage, measured as the percentage of the staff involved on high level software design and architecture, interdependence, defined as in Van de Ven et al. (1976), and, finally, project certainty, that is, whether there was stability on the project specifications, and whether there was a clearly defined body of knowledge guiding the process. As in Van de Ven et al. (1976), coordination modes include formal impersonal coordination techniques, such as written requirements and documentation, formal interpersonal modes, which are essentially code inspection meetings, and, finally, informal interpersonal techniques such as unscheduled review meetings. The translation of these coordination variables to our framework is identical to the previous example. The results are contained in Table III. The more certain the project the more the software development effort relies on formal procedures, again consistent with the theoretical findings. The use of interpersonal communication modes have the right negative sign but they are not significant at the 5% level.⁴³ In addition software projects that exhibit large interdependencies rely more on informal interpersonal procedures to address coordination concerns.

In summary, software development is not only a challenging technical problem but rather it is also a problem that tests to the limit the ability of organizations to coordinate the different engineers while at the same time allowing the flexibility to each to write the best possible code

⁴³Kraut and Streeter (1995) do report neither standard errors nor p-values, but only mark those coefficients that are significant at the 5%, so it is impossible to asses whether thes coefficients are significant at moderate levels.

for the assigned module.⁴⁴

VII. CONCLUSIONS

How can organizations be adaptive and take advantage of dispersed information while achieving coordination among its members? In this paper we show that, under general conditions, adaptive organizations are unidimensional. That is, they either coordinate and adapt by designing jobs narrowly, and hence having workers specialize, by curtailing the flexibility with which they can perform their assigned tasks, by setting strong vertical communication channels, and, finally, by having a large managerial force. Alternatively, organizations can remain adaptive and coordinated by having broad job definitions, where several tasks are bundled in one job and the benefits of specialization are foregone, by empowering workers with extensive flexibility with which to perform their assigned tasks, by creating extensive horizontal communication channels, and by limiting the size of the managerial force. The first type of organization adapts and coordinates through extensive managerial intervention and a frequent updating of the rules and procedures that govern tasks, whereas the second type does it through employee discretion and mutual horizontal adjustment.

The strong complementarity between the organizational design variables may lead to large swings in organizational design because an exogenous change in one of the design variables increases the returns to change, in turn, all the others. In particular, an increase in the uncertainty in the local information yields organizations that are “flatter,” that is, with broader job definitions, lower managerial force,⁴⁵ more intense horizontal communication, and an empowered workforce. A trend towards these type of organizations have been noticed by many observers of business practices.⁴⁶ Similar effects are to be expected whenever adaptation becomes more important, the returns to specialization diminish, or it becomes easier

⁴⁴As Mookerjee and Chiang (2002) note that “developing large software systems remains a technical and managerial challenge. Technical challenges arise from the complex, innovative, and critical nature of software products. Managerial challenges occur because of the need to synchronize the effort of the various professionals involved, including line managers, end-users, subject matter experts, analysts, designers, developers, testers, etc.”

⁴⁵Some empirical evidence on the disappearance of middle management has been recently reported in Rajan and Wulf (2002).

⁴⁶See for instance Hammer (1990) and Hammer and Champy (2001). These authors popularized the expression “reengineering.” For instance, “(W)hen a process is reengineered, jobs evolve from narrow and task oriented to multidimensional. People who one did as they were instructed now make choices and decisions on their own instead.” Hammer and Champy (2001, page 69.) In general reengineered processes have some commonalities: Several jobs are combined into one, workers make decisions, processes have multiple versions, that is they are no

to train workers to perform a wide variety of actions. In particular, many have argued that the proclaimed increase in world competition forces organizations to adapt more to local customers tastes and, as a consequence, the present paper provides a rational for the perceived link between competition and flatter organizations.⁴⁷

Importantly we show that if coordination becomes a more critical organizational goal, one should not necessarily expect a decrease in specialization. Indeed, if adaptation is not an important objective, organizations may respond to a higher demand for coordination by *increasing* specialization. Indeed, a higher need for coordination will often induce organization to reduce the discretion of employees, which increases the returns to specialization. Thus, one of the main insights of this paper is that the trade-off between coordination and specialization cannot be studied without also analyzing the organization's need for adaptation.

In addition, the complementarity of the organizational design variables implies that reductions in the costs of improving the communication technology in place have an ambiguous impact on organizational design. On the one hand, as horizontal communication improves, the organization can increase the extent of specialization in the expectation that coordination will not suffer due to the better communication technologies in place. On the other, as horizontal communication improves, it pays for the organization to increase employee discretion and empowerment. This, in turn, makes task bundling more attractive in order to reduce coordination problems. Improvements in communication technology may thus result in either more employee discretion and less specialization, or less employee discretion and more specialization, depending on which effect dominates.

longer standard, checks and controls are reduced, and hybrid centralized-decentralized operations are prevalent (see Hammer and Champy, 2001, pages 53-66.)

⁴⁷Still, the exact link between competition and organizational design remains an unexplored topic and it is the subject of our current research.

REFERENCES

- Aghion, Philippe and Jean Tirole** (1997) "Formal and Real Authority in Organizations," *Journal of Political Economy*, 105, 1-29.
- Aoki, Masahiko** (1986) "Horizontal vs. vertical information structure of the firm," *American Economic Review*, Vol. 76, no. 5, 971-983.
- Aoki, Masahiko** (1990) "The Participatory Generation of Information Rents and the Theory of the Firm." pp.26-52 in *The Firm as a Nexus of Treaties*,. Aoki, M., B.Gustafsson and O. Williamson (eds.), Sage Publications, London.
- Becker, Gary S. and Kevin M. Murphy** (1992) "The division of labor, coordination costs, and knowledge," *Quarterly Journal of Economics*, Vol. CVII, no. 4, 1137-1160.
- Blau, Peter M. and Richard A. Schoenherr** (1971) *The Structure of Organizations*, Basic Books, Inc., Publishers, New York.
- Bolton, Patrick and Mathias Dewatripont** (1994) "The Firm as a Communication Network," *Quarterly Journal of Economics*, CIX, no. 4, 809-839.
- Bresnahan, Timothy, Eric Brynjolfsson, and Lorin Hitt** (2002) "Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-Level Evidence," *Quarterly Journal of Economics*, CXVII, no 1, 339-376.
- Brickley, J., C. Smith and J. Zimmerman** (2001) *Managerial Economics and Organizational Architecture*. Irwin, Chicago.
- Brynjolfsson, Eric and Lorin Hitt** (1997) "Information Technology and Organizational Design: Evidence from Microdata." MIT Sloan School Working Paper.
- Cheng, Joseph L. C.** (1983) "Interdependence and Coordination in Organizations: A Role System Analysis," *Academy of Management Journal*, Vol. 26, no. 1, 156-162.
- Cremer, Jacques** (1980), "A partial theory of the optimal organization of a bureaucracy," *Bell Journal of Economics*, Autumn, 683-693.
- Crowston, Kevin** (1997) "A Coordination Theory Approach to Organizational Process Design," *Organization Science*, Vol. 8 no.2, March-April, 157-175.
- Curtis, Bill, Herb Krasner, and Neil Iscoe** (1988) "A Field Study of the Software Design Process for Large Systems," *Communications of the ACM*, November, Vol. 31 no. 11, 1268-1287.

- Cusumano, Michael A. and Chris F. Kemerer** (1990) "A Quantitative Analysis of U.S. and Japanese Practice and Performance in Software Development," *Management Science*, Vol. 36 no. 11, November, 1384-1406.
- Dessein, Wouter** (2002) "Authority and Communication in Organizations," *Review of Economic Studies*, October, Vol. 69 (4), 811-838.
- Faraj, Samer and Lee Sproull** (2000) "Coordinating Expertise in Software Development Teams," *Management Science*, Vol. 46 no. 12, 1554-1568.
- Garicano, Luis** (2000), "Hierarchies and the Organization of Knowledge in Production," *Journal of Political Economy*, October, 874-904.
- Geanakoplos, John and Paul Milgrom** (1991) "A theory of Hierarchies based on limited managerial attention," *Journal of the Japanese and International Economies*, 5, 205-225.
- Hammer, Michael** (1990) Reengineering Work: Don't Automate, Obliterate, *Harvard Business Review*, July-August, 104-112.
- Hammer, Michael and James Champy** (2001) Reengineering the Corporation, Harper Business, New York, 2nd ed.
- Holmstrom, Bengt and Paul Milgrom** (1994) "The Firm as an Incentive System," *American Economic Review*, LXXXIV, 972-991.
- Ichniowski, C., T. Kochan, D. Levine, and G. Strauss** (1996) "What Works at Work: Overview and Assessment," *Industrial Relations*, XXXV, 299-333.
- Ichniowski, Casey, Katherine Shaw, and Giovanna Prennushi** (1997) "The Effects of Human Resource Management Practices on Productivity," *American Economic Review*, LXXXVII, 291-313.
- Koushik Murlidhar V. and Vijay S. Mookerjee** (1995) "Modeling Coordination in Software Construction: An Analytical Approach," *Information Systems Research*, 6:3, 220-253.
- Kraut, Robert E. and Lynn A. Streeter** (1995) "Coordination in Software Development," *Communications of the ACM*, March, Vol. 38 no. 3, 69-81.
- Lindbeck, Assar and Dennis J. Snower** (2000) "Multitask learning and the reorganization of work: From Tayloristic to holistic organization," *Journal of Labor Economics*, vol. 18 no. 3, 353-376.
- March, James G. and Herbert A. Simon** (1958) *Organizations*, John Wiley & Sons, New York.
- Marschak, Jacob and Roy Radner** (1972), *Economic Theory of Teams*, Yale University Press, New Haven and London.

- Milgrom, Paul and John Roberts** (1988), "Communication and Inventories as Substitutes in Organizing Production," *Scandinavian Journal of Economics*, 90, 275-289.
- Milgrom, Paul and John Roberts** (1990) "The economics of modern manufacturing: Technology, strategy, and organization," *American Economic Review*, vol. 80 no. 3, 511-528.
- Milgrom, Paul and John Roberts** (1992) *Economics, Organization, and Management*, Prentice Hall, Englewood Cliffs, New Jersey.
- Milgrom, Paul and John Roberts** (1995) "Complementarities and fit: Strategy, Structure, and Organizational Change in Manufacturing," *Journal of Accounting and Economics*, 19, 179-208.
- Mintzberg, Henry** (1979) *The Structuring of Organizations*. Prentice Hall, London.
- Mohr, Lawrence B.** (1971), "Organizational Technology and Organizational Structure," *Administrative Science Quarterly*, Vol. 16 no. 4, December, 444-459.
- Mookerjee, Vijay S. and I. Robert Chiang** (2002) "A Dynamic Coordination Policy for Software System Construction," *IEEE Transactions on Software Engineering*, Vol. 28 no. 6, 684-694.
- Osterman, P.** (1994) "How Common is Workplace Transformation and Who Adopts It?" *Industrial and Labor Relations Review*, Vol. 47 no 2, 173-188.
- Prendergast, Canice** (2002) "The Tenuous Trade-off Between Risk and Incentives," *Journal of Political Economy*, vol. 110, no. 5, 1071-1102.
- Radner, Roy** (1993) "The Organization of Decentralized Information Processing," *Econometrica*, September, 61 no. 5, 1109-1146.
- Radner, Roy and Timothy Van Zandt** (1992) "Information Processing in Firms and Returns to Scale," *Annales D'Economie Et De Statistique*, 25-26, 265-298.
- Rajan, Raghuram G. and Julie Wulf** (2002) "The Flattening Firm: Evidence from Panel Data on the Changing Nature of Corporate Hierarchies," manuscript, Wharton School, University of Pennsylvania.
- Rivkin, Jan W. and Nicolaj Siggelkow** (2002) "Balancing Search and Stability: Interdependencies Among Elements of Organizational Design," manuscript Harvard Business School.
- Smith, Adam** (1976) *An Inquiry into the Nature and Causes of the Wealth of Nations*, Oxford University Press.
- Van de Ven, Andrew H, Andre L. Delbecq, and Richard Koenig, Jr.** (1976) "Determinants of Coordination Modes within Organizations," *American Sociological Review*, Vol. 41 iss. 2, April, 322-338.

- Van Zandt, Timothy** (1999) "Real-Time Decentralized Information Processing as a Model of Organizations with Boundedly Rational Agents," *Review of Economic Studies*, 66 no. 3, 633-658.
- Vayanos, Dimitri** (2003) "The Decentralization of Information Processing in the Presence of Interactions," *Review of Economic Studies*, forthcoming.
- Wilson, James Q.** (1989) *Bureaucracy*, Basic Books.
- Zmud, Robert W.** (1980) "Management of Large Software Development Efforts," *MIS Quarterly*, Vol. 4 no. 2, 45-55.

APPENDIX

Proof of Lemmas 1-3

The results in this section is slightly more general than in the body of the paper. In particular we show the results hold even when the flexibility is different across *actions*. Similarly with the quality of the communication network. We assume that the organization is given generic rules r^{ji} for all $j, i = 1, 2, \dots, n$. We first then solve for the actions.

Choice of a^{ji} for $j \in \mathcal{T}(i)$, $j \neq i$ or $j \notin \mathcal{T}(i)$ but the agent in charge of task j observes a^{ii}

In this case the agents minimize,

$$\min_{a^{ji}} \left\{ \beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^{ji}} \right\},$$

which leads to

$$a^{ji} = \left(\frac{\beta x^{ji}}{\beta x^{ji} + 1} \right) a^{ii} + \left(\frac{1}{\beta x^{ji} + 1} \right) r^{ji}. \quad (\text{A1})$$

Choice of a^{ji} for $j \notin \mathcal{T}(i)$ and the agent in charge of task j does not observe a^{ii}

In this case the minimization is given by,

$$\min_{a^{ji}} \left\{ E \left[\beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^{ji}} \right] \right\},$$

where the expectations operator is relative to the equilibrium distribution of a^{ii} . In this case the first order condition is given by,

$$a^{ji} = \left(\frac{\beta x^{ji}}{\beta x^{ji} + 1} \right) E(a^{ii}) + \left(\frac{1}{\beta x^{ji} + 1} \right) r^{ji}. \quad (\text{A2})$$

Choice of a^{ii}

In this case the minimization is of the the function:

$$\begin{aligned} & \min_{a^{ii}} \left\{ \phi (a^{ii} - \theta^i)^2 + \frac{(a^{ii} - r^{ii})^2}{x^{ii}} + \frac{1}{n-1} \left[\sum_{j \in \mathcal{T}(i), j \neq i} \left\{ \beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^{ji}} \right\} \right. \right. \\ & \left. \left. + \sum_{j \notin \mathcal{T}(i)} \left\{ p^{ji} \left(\beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^{ji}} \right) + (1 - p^{ji}) \left(\beta (a^{ji} - a^{ii})^2 + \frac{(a^{ji} - r^{ji})^2}{x^{ji}} \right) \right\} \right] \right\} \end{aligned}$$

subject to equations (A1) and (A2).

The solution is given by

$$\begin{aligned} a^{ii} &= \left(\frac{\phi}{\phi + \frac{1}{x^{ii}} + B^i} \right) (\theta^i - E(a^{ii})) + \left(\frac{1}{\phi + \frac{1}{x^{ii}} + B^i} \right) \times \\ & \times \left[\phi E(a^{ii}) + \frac{r^{ii}}{x^{ii}} + \left(\frac{\beta}{n-1} \right) \left(\sum_{j \in \mathcal{T}(i), j \neq i} \left(\frac{r^{ji}}{\beta x^{ji} + 1} \right) \right. \right. \\ & \left. \left. + \sum_{j \notin \mathcal{T}(i)} \left\{ p^{ji} \left(\frac{r^{ji}}{\beta x^{ji} + 1} \right) + (1 - p^{ji}) \left(\frac{\beta x^{ji}}{\beta x^{ji} + 1} E(a^{ii}) + \frac{r^{ji}}{\beta x^{ji} + 1} \right) \right\} \right] \right], \end{aligned} \quad (\text{A3})$$

where B^i is given in Lemma 1, and, importantly, it does not depend on \bar{r}^i .

Proof that $r^{ji} = \hat{\theta}^i$ for all $j = 1, 2, \dots, n$

To prove that $r^{ji} = \hat{\theta}^i$ we start by showing that $E(a^{ii}) = r^{ji}$ for all $j = 1, 2, \dots, n$. The result will then trivially follow when taking expectations in equation (A3). First, substitution of equations (A1), (A2) and (A3) in the cost function yields, after trivial but tedious manipulations, the following expression for the expected cost function,

$$E(C^i) = \phi E(a^{ii} - \theta^i)^2 + \frac{E(a^{ii} - r^{ii})^2}{x^{ii}} \quad (\text{A4})$$

$$+ \left(\frac{1}{n-1}\right) \sum_{j \in \mathcal{T}(i), j \neq i} \left\{ \left(\frac{\beta}{\beta x^{ji} + 1}\right) E(a^{ii} - r^{ji})^2 \right\} \quad (\text{A5})$$

$$+ \left(\frac{1}{n-1}\right) E \left[\sum_{j \notin \mathcal{T}(i)} \left\{ p^{ji} \left(\frac{\beta}{\beta x^{ji} + 1}\right) (a^{ii} - r^{ji})^2 \right\} \right] \quad (\text{A6})$$

$$+ (1 - p^{ji}) \beta \left[\left(\left(\frac{\beta x^{ji}}{\beta x^{ji} + 1}\right) E(a^{ii}) + \frac{r^{ji}}{\beta x^{ji} + 1} - a^{ii} \right)^2 \right] \quad (\text{A7})$$

$$+ \left(\frac{\beta x^{ji}}{(\beta x^{ji} + 1)^2} \right) (E(a^{ii}) - r^{ji})^2 \left. \right] \quad (\text{A8})$$

$$+ \lambda f(x^{ii}) + \left(\frac{\lambda}{n-1}\right) \sum_{j \neq i} f(x^{ji}) + \delta \sum_{j \notin \mathcal{T}(i)} g(p^{ji}). \quad (\text{A9})$$

First, inspection of (A4) and (A5) show that the expected cost function is minimized by setting

$$r^{ji} = E(a^{ii}) \quad \text{for} \quad j \in \mathcal{T}(i).$$

As for $j \notin \mathcal{T}(i)$ we show next that *both* the term in p^{ji} and the term in $(1 - p^{ji})$ are separately minimized by setting $r^{ji} = E(a^{ii})$, and that as a consequence joint minimization is also achieved by setting $r^{ji} = E(a^{ii})$. First, once again inspection of (A6) shows that this is indeed the case for the term in p^{ji} . As for the term in $(1 - p^{ji})$, equations (A7) and (A8), cumbersome manipulations show that it can be written as

$$\left(\frac{1}{\beta x^{ji} + 1}\right) E(a^{ii} - r^{ji})^2 + \text{var}(a^{ii}),$$

but inspection of equation (A3) shows that the variance of a^{ii} is independent of \bar{r} , so that the term in $(1 - p^{ji})$ is again minimized by setting

$$r^{ji} = E(a^{ii}) \quad \text{for} \quad j \notin \mathcal{T}(i).$$

Substituting r^{ji} for all $j = 1, 2, \dots, n$ by $E(a^{ii})$ in expression (A3) and taking expectations yields that $E(a^{ii}) = \hat{\theta}^i$, which implies that

$$r^{ji} = \hat{\theta}^i \quad \text{for all} \quad j = 1, 2, \dots, n,$$

which concludes the proof of Lemma 3.

The proof of Lemma 1 is now immediate by substituting $r^{ji} = E(a^{ii}) = \widehat{\theta}^i$ for all $j = 1, 2, \dots, n$ in equation (A3). Finally to obtain the expression for the cost function in Lemma 2 substitute the expressions for the actions found in Lemma 1 in the equation for the expected cost, expressions (A4) to (A9). To obtain the expressions in the paper simply substitute

$$x^{ii} = x^m \quad \text{and} \quad x^{ji} = x^c \quad \text{for all} \quad j, i = 1, 2, \dots, n$$

and

$$p^{ji} = p \quad \text{for all} \quad i = 1, 2, \dots, n \text{ and } j \notin \mathcal{T}(i).$$

This concludes the proof of Lemmas 1, 2, and 3. \square

Proof of Proposition 4

Preliminary notation and basic properties of $B(x^c, p, t)$

Recall that the profit function is defined as,

$$\pi(x^m, x^c, \widehat{p}, t, \tau) = \max_{p \geq \widehat{p}} \left\{ I(t, \alpha) - \sum_{i=1}^n E \left[\min_{\bar{a}^i} C^i(\bar{a}^i, x^m, x^c, p, t, \tau \mid \theta^i) \right] \right\} \quad \text{for } \tau \in \{\sigma_\theta^2, \phi, -\alpha, -\lambda\}$$

The choice of \widehat{p} then does not affect the optimal choice of the other design variables as, given the strict quasiconcavity of the profit function, the highest optimal value of \widehat{p} is always chosen to be equal to $p^*(x^m, x^c, t)$, the unique equilibrium value for the quality of communication. With some abuse of notation, define $\widetilde{p}(x^m, x^c, t, \tau)$ as the value of the constrained maximization of the profit function,

$$\widetilde{p}(x^m, x^c, t, \tau) = \begin{cases} p^*(x^m, x^c, t, \tau) & \text{if } p^*(x^m, x^c, t, \tau) > \widehat{p} \\ \widehat{p} & \text{if } p^*(x^m, x^c, t, \tau) \leq \widehat{p} \end{cases}.$$

Recall as well that we have assumed that $\Pi(x^m, x^c, p, t, \tau)$ is a strictly quasiconcave function of p . $\Pi(x^m, x^c, p, t, \tau)$ is a differentiable function of p and, as a consequence, it follows that $p^*(t)$ is the solution of $\Pi_p(x^m, x^c, p, t, \tau) = 0$, where

$$\Pi_p(x^m, x^c, p, t, \tau) = -\delta n(n-t)g_p(p) - n\phi^2 \frac{B_p(x^c, t)}{(\phi + \frac{1}{x^m} + B(x^c, p, t))^2} \sigma_\theta^2. \quad (\text{A10})$$

In addition, recall that we have assumed that

$$g_p(0) = 0 \quad \text{and} \quad \lim_{p \rightarrow 1} g_p(p) = \infty.$$

It follows that $p^*(x^m, x^c, t, \tau)$ is unique, strictly in the interior of $[0, 1]$, and differentiable with respect to x^m , x^c , and τ . Finally, for ease of notation we denote $\widetilde{p}(x^m, x^c, t, \tau)$ simply, say, by $\widetilde{p}(t)$ when the relevant comparative statics correspond to t . Similarly we denote $p^*(x^m, x^c, t, \tau)$ by $p^*(t)$.

Before we tackle the proof of Proposition 4 it is useful to establish some properties of the function $B(x^c, \widehat{p}, t)$ which play an important role in what follows. Assume first that $\widetilde{p}(x^m, x^c, t, \tau) = \widehat{p}$, then

$$-B_{x^c}(x^c, \widehat{p}, t) = \frac{1}{n-1} \left(\frac{\beta}{1+\beta x^c} \right)^2 [(t-1) + (n-t)\widehat{p}] > 0. \quad (\text{A11})$$

Moreover,

$$B_{\widehat{p}}(x^c, t) = \begin{cases} 0 & \text{if } p^*(x^m, x^c, t, \tau) > \widehat{p} \\ -(n-t) \left(\frac{\beta}{n-1} \right) \left(\frac{\beta x^c}{1+\beta x^c} \right) & \text{if } p^*(x^m, x^c, t, \tau) \leq \widehat{p} \end{cases} \leq 0, \quad (\text{A12})$$

$$B_{x^c \widehat{p}}(x^c, t) = \begin{cases} 0 & \text{if } p^*(x^m, x^c, t, \tau) > \widehat{p} \\ - \left(\frac{n-t}{n-1} \right) \left(\frac{\beta}{1+\beta x^c} \right)^2 & \text{if } p^*(x^m, x^c, t, \tau) \leq \widehat{p} \end{cases} \leq 0. \quad (\text{A13})$$

In addition, one can show immediately that if $t' > t$ and $p' > p$ then

$$B(x^c, p', t') < B(x^c, p, t). \quad (\text{A14})$$

Throughout we write B rather than of $B(x^c, \widehat{p}(t), t)$ unless the omission of the arguments would create confusion and similarly with B_{x^c} , $B_{\widehat{p}}$, and $B_{x^c \widehat{p}}$.

Having established these basics we prove the following Lemma that plays an important role in the proof below.

Lemma I (a) $\widetilde{p}(\bar{t}) \geq \widetilde{p}(\underline{t})$ for $\bar{t} > \underline{t}$, (b) $\widetilde{p}_{x^c} > 0$, and (c) $\widetilde{p}_{x^m} > 0$.

Proof: (a) Clearly it is enough to show that $p^*(\bar{t}) > p^*(\underline{t})$. Then

$$\begin{aligned} 0 &= \Pi_p(x^m, x^c, p^*(\underline{t}), \underline{t}, \tau) \\ &= (n - \underline{t}) \left\{ -\delta n g_p(p^*(\underline{t})) + n\phi^2 \left(\frac{\beta}{n-1} \right) \left(\frac{\beta x^c}{1 + \beta x^c} \right) \frac{\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, p^*(\underline{t}), \underline{t}) \right)^2} \right\} \\ &< (n - \underline{t}) \left\{ -\delta n g_p(p^*(\underline{t})) + n\phi^2 \left(\frac{\beta}{n-1} \right) \left(\frac{\beta x^c}{1 + \beta x^c} \right) \frac{\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, p^*(\underline{t}), \bar{t}) \right)^2} \right\} \\ &= \left(\frac{n - \underline{t}}{n - \bar{t}} \right) \left\{ -\delta n (n - \bar{t}) g_p(p^*(\underline{t})) - n\phi^2 \frac{B_p(x^c, \bar{t})}{\left(\phi + \frac{1}{x^m} + B(x^c, p^*(\underline{t}), \bar{t}) \right)^2} \right\} \\ &= \left(\frac{n - \underline{t}}{n - \bar{t}} \right) \Pi_p(x^m, x^c, p^*(\underline{t}), \bar{t}, \tau), \end{aligned}$$

where the strict inequality follows from the fact that $B(x^c, p^*(\underline{t}), \bar{t}) < B(x^c, p^*(\underline{t}), \underline{t})$, which can be immediately checked from the definition of $B(x^c, p, t)$. The result now follows from the strict quasiconcavity of $\Pi(x^m, x^c, p, t, \tau)$.

(b) and (c) It follows from a basic application the implicit function theorem to expression (A10) and the fact that, at the optimum, $\Pi_{pp} < 0$. \square

Proof of Proposition 4

To prove this proposition we make use of standard results on supermodularity. By Theorem 1 of Milgrom and Roberts (1990),¹ a function $\ell : \mathbb{R}^m \rightarrow \mathbb{R}$ that is supermodular when exclusively considered as a function of two variables y^i and y^j while fixing the remaining ones, $\ell(y^i, y^j, y^{-ij})$, is supermodular. Our strategy of proof is then to show that the cross derivative of the function $\pi(x^m, x^c, \widehat{p}, t, \tau)$ are all positive. Throughout we appeal to the envelope theorem and “ignore” the impact of the variation on, say, x^c on $p^*(x^m, x^c, t, \tau)$ whenever $p^*(x^m, x^c, t, \tau) > \widehat{p}$. Also notice that whenever $p^*(x^m, x^c, t, \tau) \leq \widehat{p}$ the constrained maximization of p sets $\widetilde{p}(x^m, x^c, t, \tau) = \widehat{p}$ and hence, for example,

$$\widetilde{p}_{x^m} = \begin{cases} p_{x^m}^* & \text{if } p^*(x^m, x^c, t, \tau) > \widehat{p} \\ 0 & \text{if } p^*(x^m, x^c, t, \tau) \leq \widehat{p} \end{cases}$$

Complementarity between x^m and x^c

$$\pi_{x^m x^c} = -2n \left(\frac{\phi}{x^m} \right)^2 \frac{B_{x^c} + B_{\widehat{p}} \widetilde{p}_{x^c}}{\left(\phi + \frac{1}{x^m} + B \right)^3} \sigma_\theta^2 > 0,$$

as $B_{x^c} < 0$, $B_{\widehat{p}} < 0$, and $\widetilde{p}_{x^c} > 0$.

¹Milgrom and Roberts (1990) offer a transparent primer on the mathematics of supermodularity. For a textbook presentation see Sundaram (1996).

Complementarity between x^m and \hat{p}

$$\pi_{x^m \hat{p}} = -2nB_{\hat{p}} \frac{\left(\frac{\phi}{x^m}\right)^2}{\left(\phi + \frac{1}{x^m} + B\right)^3} \sigma_{\theta}^2 \geq 0,$$

with equality whenever $p^*(t) > \hat{p}$.

Complementarity between x^m and t

Define

$$\Delta(x^m) = \pi(x^m, x^c, \hat{p}, \bar{t}, \tau) - \pi(x^m, x^c, \hat{p}, \underline{t}, \tau),$$

it follows that

$$\Delta_{x^m} = n \left(\frac{\phi}{x^m}\right)^2 \left\{ \frac{1}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})\right)^2} - \frac{1}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})\right)^2} \right\} \sigma_{\theta}^2 > 0,$$

where we have made use of Lemma I and (A14).

Complementarity between x^m and ϕ

First notice that applying once again the implicit function theorem to (A10) it can be immediately be shown that $\tilde{p}_{\phi} \geq 0$, with strict inequality whenever $p^*(x^m, x^c, t, \tau) > \hat{p}$. Then,

$$\pi_{x^m \phi} = \frac{2n\phi}{(x^m)^2} \left(\frac{1}{\phi + \frac{1}{x^m} + B}\right)^3 \left[\phi + \frac{1}{x^m} - \phi B_{\tilde{p}} \tilde{p}_{\phi}\right] > 0,$$

as $B_{\tilde{p}} \leq 0$ and $\tilde{p}_{\phi} \geq 0$.

Complementarity between x^c and \hat{p}

$$\pi_{x^c \hat{p}} = \frac{n\phi^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(t), t)\right)^2} \left\{ -B_{x^c \hat{p}} + 2 \frac{B_{x^c} B_{\hat{p}}}{\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(t), t)} \right\} \sigma_{\theta}^2 \geq 0,$$

with equality whenever $p^*(t) > \hat{p}$.

Complementarity between x^c and t

Define

$$\Delta(x^c) = \pi(x^m, x^c, \hat{p}, \bar{t}, \tau) - \pi(x^m, x^c, \hat{p}, \underline{t}, \tau).$$

Then

$$\begin{aligned} \Delta_{x^c} &= n\phi^2 \left\{ \frac{[-B_{x^c}(x^c, \tilde{p}(\bar{t}), \bar{t})]}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})\right)^2} - \frac{[-B_{x^c}(x^c, \tilde{p}(\underline{t}), \underline{t})]}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})\right)^2} \right\} \sigma_{\theta}^2 \\ &> \frac{n\phi^2 \sigma_{\theta}^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})\right)^2} [-B_{x^c}(x^c, \tilde{p}(\bar{t}), \bar{t}) + B_{x^c}(x^c, \tilde{p}(\underline{t}), \underline{t})] \\ &> 0. \end{aligned}$$

The first inequality follows from the fact that $-B_{x^c} > 0$ and that $B(x^c, \tilde{p}(\bar{t}), \bar{t}) < B(x^c, \tilde{p}(\underline{t}), \underline{t})$. The second inequality follows from the fact that

$$\begin{aligned}
-B_{x^c}(x^c, \tilde{p}(\bar{t}), \bar{t}) &= \left(\frac{1}{n-1}\right) \left(\frac{\beta}{1+\beta x^c}\right)^2 [(\bar{t}-1) + (n-\bar{t})\tilde{p}(\bar{t})] \\
&> \left(\frac{1}{n-1}\right) \left(\frac{\beta}{1+\beta x^c}\right)^2 [(\bar{t}-1) + (n-\bar{t})\tilde{p}(\underline{t})] \\
&> \left(\frac{1}{n-1}\right) \left(\frac{\beta}{1+\beta x^c}\right)^2 [(\underline{t}-1) + (n-\underline{t})\tilde{p}(\underline{t})] \\
&= -B_{x^c}(x^c, \tilde{p}(\underline{t}), \underline{t})
\end{aligned}$$

Complementarity between x^c and ϕ

$$\pi_{x^c\phi} = -\frac{n\phi\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(t), t)\right)^2} \left[\phi B_{x^c\tilde{p}}\tilde{p}_\phi + 2B_{x^c} \left(\frac{1}{x^m} + B - \phi B_{\tilde{p}}\tilde{p}_\phi \right) \right] > 0.$$

Complementarity between \hat{p} and t

Define

$$\Delta(\hat{p}) = \pi(x^m, x^c, \hat{p}, \bar{t}, \phi) - \pi(x^m, x^c, \hat{p}, \underline{t}, \phi)$$

Notice that if $\tilde{p}(\bar{t}) > \tilde{p}(\underline{t}) \geq \hat{p}$, then, trivially $\Delta_{\hat{p}} = 0$. If instead, $\tilde{p}(\bar{t}) > \hat{p} > \tilde{p}(\underline{t})$, then $\Delta_{\hat{p}} = -\pi_{\hat{p}}(x^m, x^c, \hat{p}, \underline{t}, \phi) > 0$, by the strict quasiconcavity of the profit function and the fact that $\hat{p} > \tilde{p}(\underline{t})$. Assume finally that $\hat{p} \geq \tilde{p}(\bar{t}) > \tilde{p}(\underline{t})$. In this case,

$$\begin{aligned}
\Delta_{\hat{p}} &= \delta n(\bar{t} - \underline{t}) g_p(\hat{p}) + n\phi^2\sigma_\theta^2 \left\{ \frac{-B_{\hat{p}}(x^c, \bar{t})}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \bar{t})\right)^2} - \frac{-B_{\hat{p}}(x^c, \underline{t})}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \underline{t})\right)^2} \right\} \\
&> \delta n(\bar{t} - \underline{t}) g_p(\hat{p}) + \frac{n\phi^2\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \bar{t})\right)^2} \{-B_{\hat{p}}(x^c, \bar{t}) + B_{\hat{p}}(x^c, \underline{t})\} \\
&= (\bar{t} - \underline{t}) \left\{ \delta n g_p(\hat{p}) - \frac{n\phi^2\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \bar{t})\right)^2} \left(\frac{\beta}{n-1}\right) \left(\frac{\beta x^c}{1+\beta x^c}\right) \right\} \\
&= \left(\frac{\bar{t} - \underline{t}}{n - \bar{t}}\right) \left\{ \delta n(n - \bar{t}) g_p(\hat{p}) - \frac{n\phi^2\sigma_\theta^2}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \bar{t})\right)^2} (n - \bar{t}) \left(\frac{\beta}{n-1}\right) \left(\frac{\beta x^c}{1+\beta x^c}\right) \right\} \\
&= \left(\frac{\bar{t} - \underline{t}}{n - \bar{t}}\right) \left\{ \delta n(n - \bar{t}) g_p(\hat{p}) + n\phi^2\sigma_\theta^2 \left(\frac{B_{\hat{p}}(x^c, \bar{t})}{\left(\phi + \frac{1}{x^m} + B(x^c, \hat{p}, \bar{t})\right)^2} \right) \right\} \\
&= -\pi_{\hat{p}}(x^m, x^c, \hat{p}, \bar{t}, \phi) \\
&> 0.
\end{aligned}$$

Complementarity between \hat{p} and ϕ

$$\pi_{\hat{p}\phi} = -2n\phi\sigma_\theta^2 B_{\hat{p}} \left[\frac{\frac{1}{x^m} + B - \phi B_{\hat{p}}\tilde{p}_\phi}{\left(\phi + \frac{1}{x^m} + B\right)^3} \right] \geq 0$$

Complementarity between t and ϕ

Define

$$\Delta(\phi) = \pi(x^m, x^c, \hat{p}, \bar{t}, \phi) - \pi(x^m, x^c, \hat{p}, \underline{t}, \phi)$$

Then

$$\Delta_\phi = n \left\{ \left(\frac{\frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})}{\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})} \right)^2 - \left(\frac{\frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})}{\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})} \right)^2 \right\} \sigma_\theta^2 > 0$$

where we have made use of (A14). This concludes the proof of the proposition. \square

Proof of Proposition 5: As $\beta \rightarrow \infty$ the organization will find it necessary to achieve perfect coordination in equilibrium, that is for all i, j $a^{ji} = a^{ii}$. Given that $p < 1$, this implies that $a^{ji} = r^{ii}$ whenever $t \neq n$. However, whenever $a^{ji} = r^{ii}$ for all i, j , positive returns to specialization imply that it will be optimal to choose $t = 1$. Hence, as $\beta \rightarrow \infty$ either $t = n$ or $t = 1$. Obviously, if ϕ tends to 0, $t^* = 1$ will be optimal, whereas $t^* = n$ will be optimal whenever ϕ tends to ∞ . Moreover, if $t^* = n$ for ϕ' then also $t^* = n$ for $\phi > \phi'$. This proves part (a) of the proposition. Finally, if given $\alpha = \alpha'$ for $\phi = \phi'$, then the organization is indifferent between setting $t^* = 1$ and setting $t^* = n$ then for $\alpha > \alpha'$ the organization must strictly prefer $t = 1$ which implies the second part of the proposition. \square

Proof of Proposition 6: It follows immediately from the comments in the text. \square

Proof of Lemma 7: (a) Let $E(C^i|\varepsilon^i, \text{int})$ the expected cost function associated with task i , conditional on the management's information at the interim stage, that is conditional on ε^i , when management decides to intervene and update the rules. Similarly let $E(C^i|\varepsilon^i, \text{non-int})$ the corresponding expected cost function conditional on the management's information at the interim stage when management decides not to intervene. Clearly, in the case of intervention, $E(C^i|\varepsilon^i, \text{int})$ is given as in Lemma 3,

$$\begin{aligned} E(C^i|\varepsilon^i, \text{int}) &= \phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) \sigma_\theta^2 + \omega m + h(m) \\ &+ \lambda(f(x^m) + f(x^c)) + \delta(n-t)g(p), \end{aligned}$$

where the term $h(m)$ is the cost associated with intervention. If management decides not to intervene and update the rules associated with task i , the organization saves managerial intervention costs $h(m)$, but suffers the costs associated with the bias built in the outdated rules,

$$E(C^i|\varepsilon^i, \text{non-int}) = E(C^i|\varepsilon^i, \text{int}) + \phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) \varepsilon^{i2} - h(m)$$

Management then intervenes in task i , whenever $E(C^i|\varepsilon^i, \text{non-int}) > E(C^i|\varepsilon^i, \text{int})$, that is, management intervenes whenever,

$$|\varepsilon^i| > b \quad \text{where} \quad b = \left[\left(\frac{\phi + \frac{1}{x^m} + B}{\frac{1}{x^m} + B} \right) \frac{h(m)}{\phi} \right]^{\frac{1}{2}},$$

which concludes the proof of Lemma 7. (b) This follows immediately from the expression for b . \square

Proof of Lemma 8: Recall that $P^i = \text{prob}[|\varepsilon^i| \geq b]$, then

$$\begin{aligned} E(C^i) &= (1-P)E(C^i | |\varepsilon^i| < b) + PE(C^i | |\varepsilon^i| \geq b) \\ &= \lambda f(x^m) + \lambda f(x^c) + \delta(n-t)g(p) + \omega m \\ &+ (1-P)\phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) \left(\sigma_\theta^2 + E[\varepsilon^{i2} | |\varepsilon^i| < b] \right) \\ &+ P \left[\phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) \sigma_\theta^2 + h(m) \right], \end{aligned}$$

adding and subtracting

$$P\phi \left(\frac{\frac{1}{x^m} + B}{\phi + \frac{1}{x^m} + B} \right) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| \geq b \right],$$

the results follows. \square

Proof of Proposition 9

Preliminaries

Recall that the second period profit function is given by,

$$\pi(x^m, x^c, \hat{p}, t, b, -m, \tau) = \max_{p \geq \hat{p}} \left\{ I(t, \alpha) - \sum_{i=1}^n E \left[\min_{\bar{a}^i} C^i(\bar{a}^i, x^m, x^c, p, t, b, -m, \tau \mid \theta^i) \right] \right\},$$

for $\tau \in \{\sigma_\theta^2, -\alpha, -\lambda, \omega\}$. The following Lemma, which is given without proof, is the counterpart to Lemma I above and we use it repeatedly in the proof of proposition 9.

Lemma II (a) $\tilde{p}(\bar{t}) \geq \tilde{p}(\underline{t})$ for $\bar{t} > \underline{t}$, (b) $\tilde{p}_{x^c} > 0$ (c) $\tilde{p}_{x^m} > 0$, and (d) $\tilde{p}_b > 0$.²

Proof of Proposition 9

We prove the complementarity of the function

$$\pi(x^m, x^c, \hat{p}, t, b, -m, -\lambda),$$

the rest being identical in the logic and mechanics. Throughout we make use of the characterization of the profit function π found in the proof of the Proposition 4. Recall as well that the optimal level of the quality of the communication, p^* is independent of m , the size of the managerial force, and λ .

Complementarity between x^m and x^c

$$\pi_{x^m x^c} = -2n \left(\frac{\phi}{x^m} \right)^2 \frac{B_{x^c} + B_{\hat{p}} \tilde{p}_{x^c}}{\left(\phi + \frac{1}{x^m} + B \right)^3} \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] > 0.$$

Complementarity between x^m and \hat{p}

$$\pi_{x^m \hat{p}} = -2n \left(\frac{\phi}{x^m} \right)^2 \frac{B_{\hat{p}}}{\left(\phi + \frac{1}{x^m} + B \right)^3} \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] > 0.$$

Complementarity between x^m and t

Define

$$\Delta(x^m) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

Then,

$$\begin{aligned} \Delta_{x^m} &= \left\{ \frac{1}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t}) \right)^2} - \frac{1}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t}) \right)^2} \right\} \\ &\times \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] > 0. \end{aligned}$$

²It follows from inspection of the first order condition for p that p^* is independent of m and parameters like λ .

Complementarity between x^m and b

$$\begin{aligned}\pi_{x^m b} &= \left(\frac{\frac{\phi}{x^m}}{\phi + \frac{1}{x^m} + B} \right)^2 \left\{ -P_b E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] + (1-P) E_b \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right\} \\ &\quad - 2 \left(\frac{\phi}{x^m} \right)^2 \left(\frac{1}{\phi + \frac{1}{x^m} + B} \right)^3 B_{\tilde{p}} \tilde{p}_b \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] \\ &> 0\end{aligned}$$

as $P_b < 0$ and $E_b \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] > 0$ due to our assumption on the normality of ε^i .

Complementarity between x^m and $-m$

$$\pi_{x^m(-m)} = 0.$$

Complementarity between x^m and $-\lambda$

$$\pi_{x^m(-\lambda)} = n f_{x^m} > 0.$$

Complementarity between x^c and \hat{p}

$$\pi_{x^c \hat{p}} = n \left(\frac{\phi}{\phi + \frac{1}{x^m} + B} \right)^2 \left[-B_{x^c \hat{p}} + 2 \frac{B_{x^c} B_{\hat{p}}}{\phi + \frac{1}{x^m} + B} \right] \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] > 0$$

Complementarity between x^c and t

Define

$$\Delta(x^c) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

Then,

$$\begin{aligned}\Delta_{x^c} &= n \phi^2 \left\{ \frac{[-B_{x^c}(x^c, \tilde{p}(\bar{t}), \bar{t})]}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})\right)^2} - \frac{[-B_{x^c}(x^c, \tilde{p}(\underline{t}), \underline{t})]}{\left(\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})\right)^2} \right\} \\ &\quad \times \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] \\ &> 0,\end{aligned}$$

where the argument needed to sign the expression is identical to the one in the proof of Proposition 4.

Complementarity between x^c and b

$$\begin{aligned}\pi_{x^c b} &= -n B_{x^c} \left(\frac{\phi}{\phi + \frac{1}{x^m} + B} \right)^2 \left\{ -P_b E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] + (1-P) E_b \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right\} \\ &\quad + 2n B_{x^c} B_{\tilde{p}} \tilde{p}_b \left(\frac{1}{\phi + \frac{1}{x^m} + B} \right)^3 \left[\sigma_\theta^2 + (1-P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right] \\ &> 0.\end{aligned}$$

Complementarity between x^c and $-m$

$$\pi_{x^c(-m)} = 0.$$

Complementarity between x^c and $-\lambda$

$$\pi_{x^c(-\lambda)} = n f_{x^c} > 0.$$

Complementarity between \hat{p} and t

Define

$$\Delta(\hat{p}) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

The proof that $\Delta_{\hat{p}} > 0$ follows identical steps as those in Proposition 4, with the only substitution of σ_{θ}^2 by

$$\sigma_{\theta}^2 + (1 - P) E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right].$$

Complementarity between \hat{p} and b

$$\pi_{\hat{p}b} = -nB_{\hat{p}} \left(\frac{\phi}{\phi + \frac{1}{x^m} + B} \right)^2 \left\{ -P_b E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] + (1 - P) E_b \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right\} > 0.^3$$

Complementarity between \hat{p} and $-m$

$$\pi_{\hat{p}(-m)} = 0.$$

Complementarity between \hat{p} and $-\lambda$

$$\pi_{\hat{p}(-\lambda)} = 0.$$

Complementarity between t and b

Define

$$\Delta(b) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

Then

$$\begin{aligned} \Delta_b &= - \left[\frac{\frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})}{\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\bar{t}), \bar{t})} - \frac{\frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})}{\phi + \frac{1}{x^m} + B(x^c, \tilde{p}(\underline{t}), \underline{t})} \right] \\ &\times \left\{ -P_b E \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] + (1 - P) E_b \left[\varepsilon^{i^2} \mid |\varepsilon^i| < b \right] \right\} \\ &> 0, \end{aligned}$$

where we have made use of the envelope theorem to ignore the effect of variation in b in \tilde{p} .

Complementarity between t and $-m$

Define

$$\Delta(-m) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

Then

$$\Delta_{(-m)} = 0.$$

Complementarity between t and $-\lambda$

Define

$$\Delta(-\lambda) = \pi(x^m, x^c, \hat{p}, \bar{t}, b, -m, -\lambda) - \pi(x^m, x^c, \hat{p}, \underline{t}, b, -m, -\lambda).$$

Then

$$\Delta_{(-\lambda)} = 0.$$

Complementarity between b and $-m$

$$\pi_{b(-m)} = P_b h_m > 0,$$

³Clearly $B_{\hat{p}}B_{\hat{p}} = 0$ so the term in $B_{\hat{p}}$ can be ignored.

as recall that $h_m < 0$.

Complementarity between b and $-\lambda$

$$\pi_{b(-\lambda)} = 0.$$

Complementarity between $-m$ and $-\lambda$

$$\pi_{(-m)(-\lambda)} = 0.$$

This concludes the proof of Proposition 9. \square

Table I: Zero order correlation among independent variables and coordination modes

(Source: van de Ven, Delbeq, and Koenig (1976))

	1	2	3	4	5	6	7	8	9	10	11
1. Task Uncertainty											
2. Task interdependence	.37										
3. Unit size	-.14	-.12									
4. Impersonal coordination	-.49	-.26	.29								
5. <i>Rules and procedures</i>	-.46	-.22	.16	.78							
6. <i>Plans and schedules</i>	-.36	-.23	.25	.75	.49						
7. Personal coordination	.35	.20	.03	.00	-.05	-.04					
8. <i>Vertical channels</i>	.04	.06	.11	.31	.27	.23	.74				
9. <i>Horizontal channels</i>	.52	.23	-.06	-.30	-.34	-.28	.75	.13			
10. Group coordination	.64	.41	-.15	-.32	-.32	-.26	.42	.11	.52		
11. <i>Scheduled meetings</i>	.59	.41	-.08	-.27	-.27	-.22	.36	.17	.37	.88	
12. <i>Unscheduled meetings</i>	.64	.32	-.16	-.33	-.33	-.28	.35	.02	.51	.89	.66

Table II: Multiple regression analysis*

(Source: Van de Ven, Delbeq, and Koenig (1976))

Dependent Variable	Task uncertainty	Task interdependence	Unit size	R^2 (%)
A. Impersonal mode	-.44 (.06)	-.07 (.06)	.22 (.06)	30
1. <i>Rules and Proc.</i>	-.43 (.07)	-.05 (.07)	.10 (.06)	23
2. <i>Plans and Schd.</i>	-.20 (.07)	-.09 (.07)	.20 (.06)	8
B. Personal mode	-.33 (.06)	.08 (.06)	.07 (.06)	14
1. <i>Vertical chann.</i>	.03 (.08)	.07 (.08)	.13 (.07)	2
2. <i>Horizontal chann.</i>	.51 (.07)	.04 (.06)	.01 (.06)	28
C. Group mode	.57 (.06)	.19 (.05)	-.05 (.06)	45
1. <i>Sched. meetings</i>	.48 (.06)	.23 (.06)	-.03 (.05)	39
2. <i>Unsched. meetings</i>	.60 (.06)	.08 (.06)	-.07 (.06)	43

* Standard errors in parenthesis

Table III: Use of coordination techniques in software design
(Source: Kraut and Streeter (1995))

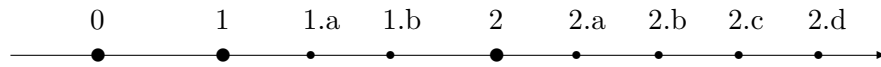
Dependent variable	Formal impers. proc.	Formal interpers. proc.	Informal interp. proc.
Project age	.17	.13	.16
Project size	.32*	.50*	-.20
Planning stage	-.30*	-.05	.27*
Interdependence	-.02	-.18	-.01
Project certainty	.24*	.16	-.08

* significant at the 5% level.

Table IV: Notation

Variables	
t	Number of tasks per job
$\mathcal{T}(i)$	Set of tasks bundled with task i
a^{ii}	Primary action of task i
a^{ji}	Action of task j that needs to be coordinated with task i
p	Probability that the agent in charge of task j understands what action a^{ii} means for a^{ji} for $j \notin \mathcal{T}(i)$
r^{ji}	Guideline for action a^{ji}
x^{ji}	Employee's flexibility around guideline for action a^{ji}
m	Management size
b	Management's intervention rule for action a^{ji} for $j = 1, 2, \dots, n$
Parameters	
n	Total number of tasks
α	Returns to specialization
θ^i	Local information, a random variable of mean $\tilde{\theta}^i$
ε	Shock to the mean of local information observed by management
σ_{θ}^2	Variance of the local information
σ_{ε}^2	Variance of the mean of the local information
λ	Costs of increasing task flexibility
δ	Costs of improving the quality of the communication channels
β	Importance of coordination
ϕ	Importance of adaptation
ω	Manager's wage

Figure 1: Timing of actions



- 0 → Organizational design stage
- 1 → Realization of local information $\theta^i \sim (\hat{\theta}^i, \sigma_\theta^2)$
 - 1.a → Communication round
 - 1.b → Actions taken
- 2 → Realization of $\varepsilon^i \sim (0, \sigma_\varepsilon^2)$
 - 2.a → Management decides to intervene or not
 - 2.b → Realization of $\theta^i \sim (\hat{\theta}^i + \varepsilon^i, \sigma_\theta^2)$
 - 2.c → Communication round
 - 2.d → Actions taken