Research Article

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Teamwork Efficiency and Company Size

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Abstract: We study how ownership structure and management objectives interact in determining the company size without assuming information constraints or any explicit costs of management. In symmetric agent economies, the optimal company size balances the returns to scale of the production function and the returns to collaboration efficiency. For a general class of payoff functions, we characterize the optimal company size, and we compare the optimal company size across different managerial objectives. We demonstrate the restrictiveness of common assumptions on effort aggregation (e.g., constant elasticity of effort substitution), and we show that common intuition (e.g., that corporate companies are more efficient and therefore will be larger than equal-share partnerships) might not hold in general.

Keywords: team, partnership, effort complementarities, firm size
JEL Classifications: D2, J5, L11, D02

1 Introduction

Many human activities benefit from collaboration. For instance, writing papers in Economics with a coauthor is often much more efficient and fun than writing them *solo*. But it is very infrequent that an activity benefits from the universal participation of the whole human population – a moderate finite group suffices for almost every purpose. So what determines the size of the productive company? When do the gains from cooperation balance out the costs of overcrowding? Williamson (1971) writes:

> The properties of the firm that commend internal organization as a market substitute would appear to fall into three categories: incentives, controls, and what may be referred to broadly as "inherent structural advantages."

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We concentrate on the inherent structural advantages of groups of different sizes. We study a model of collaborative production that demonstrates that the answer critically depends on the properties of the production function in a very specific way. Our main contribution is to summarize a generic but hard-to-use *effort aggregation* function that maps the agents' individual efforts to the aggregated effort spent on production with a simpler *teamwork efficiency* function that measures the comparative efficiency of a team of N workers against one worker. We demonstrate that many tradeoffs arising from employing different managerial criteria can be characterized by the interplay of the production function, which transforms aggregated effort into output, and the teamwork efficiency function. For instance, to determine what company size maximizes the effort made by the company's employees, one needs to study the balance between the returns to teamwork efficiency and the behavior of the marginal productivity of the total effort. We compare the predictions for two types of *companies*:

team: workers determine their effort independently, and the product is split evenly; and

firm: the residual profit claimant sets the effort level with the optimal contract.

We attempt to make as few assumptions as possible about the shape of production functions, which pre-empts the chance to obtain closed-form solutions. However, we are able to obtain comparative static results regarding the change in the optimal size of the firm due to changes in the marginal costs of effort, ownership structure (going from a worker-owned to capitalist-owned firm and back), and managerial criteria (maximizing individual effort versus maximizing surplus per worker). We demonstrate that the difference in the sizes chosen by different owners under different managerial criteria are governed by the direction of change in the elasticity of the production function, and therefore results obtained under the assumption of constant elasticities are misleading. The premise that elasticities are constant is natural in parametric estimation, but, as we show, assuming constant elasticities rules out economically significant behavior.

We assume away monitoring, transaction and management costs, direct and indirect, to ensure that they do not drive our results. We believe they are an important part of the reason why firms exist, but they are complementary to the forces we discuss, and their effects have been extensively studied. Our point is that even in the absence of these costs, there may still be a reason for cooperation – and a reason to limit cooperation. Ignoring most of the issues about incentives and controls allows us to obtain strong predictions, providing an opportunity to test empirically for the comparative importance of incentives in

organizations[1]. Our framework allows one to make judgements about the direction of change in the company's size due to changes in the institutional organization based upon the values of elasticities of certain functions, which can be estimated empirically. Heywood and Jirjahn (2009) show that, in German data, the amount of profit sharing in the company is not perfectly related to the company size, whereas one would presume that profit sharing would be next to meaningless in a large enough company. Their literature review contains similar studies, demonstrating both the positive and negative connection of the company size and prevalence of the profit-sharing in incentives in different countries. This line of study is still active: one of the most recent studies, Long and Fang (2013) show that in Canadian firms, an increase in the proportion of profit-sharing in remuneration is associated with increased efforts, especially for industries with team-based production. Other channels of possible explanation are investigated, too: Cornelissen, Heywood, and Jirjahn (2014) shows that some of the heterogeneity can be explained by the reciprocity in particular industries. Our model, however, shows that one can reconcile the observed mixed evidence without sophisticating the model.

We now review the relevant literature. In Section 2, we introduce the model and solve for the effort choice in both the team and the firm. In Section 3, we discuss how to identify the optimal size of the company. The conclusion follows. The mathematical Appendix contains proofs, elaborates on the characterization of the teamwork efficiency function, and discusses the single-peakedness of our size-choice problems.

1.1 Literature Review

The paper contributes to two strands of the literature. The moral hazard in teams literature was introduced by Holmstrom (1982), who showed that the provision of effort in teams will be generally suboptimal due to externalities in effort levels and the impossibility of monitoring individual efforts perfectly. Legros and Matthews (1993) showed that the problem of deviation from efficient level effort may be effectively mitigated if the sharing rules are well-designed.[2] Kandel and Lazear (1992) suggest peer pressure to mitigate the $1/N$ effect: the increase in the number of workers lowers the marginal payoff from higher effort. When the firm gets larger, the output is divided between a larger quantity

1 See Bikard, Murray, and Gans (2015) as an example in team efficiency estimation. This paper also contains a vast review of other empirical papers that estimate collaboration effects, such as in writing comic books, Broadway musicals and research papers.

2 Winter (2004) argues that, frequently, the uniform split of surplus is not necessarily a good outcome. We keep treating workers equally for analytical tractability.

of workers, while they bear the same individual costs. Hence, the effort of each worker should grow less as firms grow larger, and the peer pressure should compensate for this decline.[3]

Adams (2006) showed that the $1/N$ effect may not occur if the efforts of workers are complementary enough. Because he uses a CES production function with constant returns to scale, the determinant of sufficient complementarity is the value of the elasticity of substitution. McGinty (2014) extends this argument to power production functions. In this framework, two outcomes are generic: either to always increase, or always to reduce the firm size. By generalizing, we obtain a nontrivial optimal company size. This allows us to contribute to the firm size literature too. Theories of firm boundaries are classified as technological, organizational and institutional (see Kumar et al. 1999). The technological theories explain the firm size by the productive inputs and the ways in which the valuable output is produced. Basically, five technological factors are taken into account in describing the firm size: market size, gains from specialization, management control constraints, limited workers' skills, and loss of coordination. For example, Adam Smith defined the firm size by benefits from specialization limited by the market size. By his logic, workers can specialize and invest in a narrower range of skills, hence economizing on the costs of skills. Becker and Murphy (1992) focus on the tradeoff between specialization and coordination costs. The larger the firm, the larger the costs of management to put them together to produce the valuable output.

Williamson (1971), Calvo and Wellisz (1978) and Rosen (1982) use loss of control to explain the firm size. Williamson points out that the size of a hierarchical organization may be limited by loss of control, assuming that the intentions of managers are not fully transmitted downwards from layer to layer. Calvo and Wellisz (1978) show that the effect of the problem largely depends on the structure of monitoring. If the workers do not know when the monitoring occurs, the loss of control doesn't hinder the firm size, but it may do so if the monitoring is scheduled. Rosen (1982) highlights the tradeoff between increasing returns to scale in management and the loss of control. Because highly qualified managers foster the productivity of their workers, able managers should have larger firms. However, the attention of managers is limited, hence having too many workers results in loss of control and substantially reduces the

3 In the same spirit of taking peers' responses into account, Heywood and McGinty (2012) replace the Nash equilibrium concept with the Consistent Conjectures approach: each agent, instead of assuming that other agents do not respond to agent's deviation, believes that there is a (locally linear) best response. This yields more effort in outcomes when complementarities are high enough.

productivity of their team. The optimal firm size in this model is reached when the value produced by the new worker is less than the losses due to attention being diverted from his teammates.

In this literature, Kremer (1993) is the paper closest to ours, because this is one paper that obtains the optimal size of the firm based solely on the firm's production function. This paper focuses on the tradeoff between specialization and the probability of failure associated with low skill of workers. He assumes that the the value of output is directly proportional to the number of tasks needed to produce it. A larger number of workers – and hence tasks tackled – allows for the production of more valuable output, but each additional worker is a source of the risk of spoiling the whole product. Hence, the size of the firm is explained by the probability of failure by the workers, which correlates with the worker's skill.

Acemoglu and Jensen (2013) analyze a problem similar to ours. Agents pariticipate in an *aggregative* game, where the payoff of each agent is a function only of the agent himself and of the aggregate of the actions of all agents, and they establish existence and comparative statics results for games of this type. Nti (1997) offers a similar analysis for contests. We allow general interactions, but under certain assumptions we can summarize these interactions in a similar way, which does not depend on additive separability. In addition, Acemoglu and Jensen (2013) and Nti (1997) study comparative statics for this general class of games with respect to the number of players, whereas we go a step beyond, looking at the optimal number of players from the perspectives of different managerial objectives. Jensen (2010) establishes the existence of pure strategy Nash equilibrium in aggregative games, but does not explore the symmetry of the equilibrium or the comparative statics.

2 The Model

In this part, we introduce the model of endogenous effort choice by the company workers as a reaction to the size of the company. We define the equilibrium, determine how the amount of effort responds to the change in the company size N, and obtain comparative statics results.

Company workers contribute effort for production. The efforts of individual workers $\{e_1, ..., e_N\}$ are transformed into *aggregated effort* by the *effort aggregator* function:

$$g(e_1, ..., e_N \mid N) : \mathbf{R}_+^N \to \mathbf{R}_+, \tag{1}$$

where $g(\cdot \mid N)$ changes with N. The aggregated effort is then used for production via $f(\cdot)$, the *production function*[4]. Exercising effort lowers the utility of a team member by the effort cost $c(e)$. Obviously, the choice of effort depends upon other members' effort choice.

The team members split the fruits of their efforts equally. The worker's problem in the team is therefore to choose effort e to maximize

$$u(e \mid e_2, ..., e_N, N) = \frac{1}{N} f(g(e, e_2, ..., e_N \mid N)) - c(e). \tag{2}$$

The firm of size N, following the literature, acknowledges the strategic complementarities between workers' efforts, and provides each worker with a contract that makes this worker implement the first best effort level. We assume that the residual claimant collects all the surplus; results do not change if the residual claimant collects only a fixed proportion of the surplus, with the rest of the surplus going to the government, to employees as a fixed transfer, or to waste. The effort aggregator and the production function are the same.

We introduce a number of assumptions in order to obtain useful characterizations.

Assumption 1 *$f(\cdot)$ is strictly increasing and twice continuously differentiable.*

This is a technical assumption on the production function. We do not require for now that $f(\cdot)$ has decreasing returns to scale or that it is positive everywhere. We use this assumption in all characterizations of the behaviour of optimal effort.

Assumption 2 *$g(\cdot \mid N)$ is symmetric in e_i, twice continuously differentiable, strictly increasing in each argument, concave in one's own effort, and homogenous[5] of degree 1 with respect to $\{e_1, ..., e_N\}$. Normalize $g(1 \mid 1)$ to 1.*

This assumption states that the identities of workers do not matter, and only the amount of effort does. This assumption is the cornerstone of our analysis, since we are considering symmetric equilibria.

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4 This does not have to be a production function. If, for instance, g denotes the amount of effort spent, $q(g)$ delivers the quantity produced from employing g efforts, and $P(q)$ is the inverse demand function, $f(g) \equiv q(g)P(q(g))$ would be the revenue function, which can easily be not concave. We omit this discussion for brevity, and continue to call $f(\cdot)$ the production function.

5 Homogeneity of degree of exactly 1 is not a very restrictive assumption: if one has $g(\cdot)$ which is homothetic of degree y, one can use $\tilde{g}(\cdot) = g(\cdot)^{1/y}$ and $\tilde{f}(x) = f(x^y)$. They produce the same composition, but $\tilde{g}(\cdot)$ is homogenous degree 1.

One of the consequences of this assumption is that $g_1'(e_1, e_2, .., e_N \mid N)$ is homogenous degree 0. This, in turn, implies that in a symmetric outcome

$$g''_{11}(e, e, .., e \mid N) + g''_{12}(e, e, .., e \mid N) + ... + g''_{1N}(e, e, .., e \mid N) = 0 \Leftrightarrow$$
$$g''_{11}(e, e, .., e \mid N) = -(N-1)g''_{1i}(e, e, .., e \mid N) \quad \forall i \in \{2..N\}, \tag{3}$$

which by the concavity in one's own effort means that in symmetric outcomes, not necessarily everywhere, the efforts of members are strategic complements.

Assumption 3 *$c(\cdot)$ is increasing, convex, twice differentiable, $c(0) = c'(0) = 0$.*

This immediately implies that every team member exerts a positive amount of effort, since $f(g(\cdot))$ is assumed to be strictly increasing at zero. Without this assumption, one would need caveats about what happens when no workers expend any effort.

Example 1 (based on McGinty 2014) Let $g(e_1, .., e_N \mid N) = \left(\sum_{i=1}^{N} e_i^{\rho}\right)^{1/\rho}$, $f(x) = x^{\alpha}$, *$c(x)$ is increasing, twice differentiable and concave, and $c'(e)e^{1-\alpha}$ is increasing*[6]. *Therefore, agent 1 solves*

$$\max_{e_1} \frac{1}{N}\left(\sum_{i=1}^{N} e_i^{\rho}\right)^{\alpha/\rho} - c(e_1),$$

that which, assuming a symmetric outcome, produces $e_1 = ... = e_N = e^*(N) = z(N^{\frac{\alpha-2\rho}{\rho}})$, where $z(x)$ is the inverse of $c'(z)z^{1-\alpha}/\alpha$. Hence, $e^*(N)$ is increasing in N if and only if $\rho \in (0, \alpha/2)$. The effort aggregator therefore needs to be closer to Cobb-Douglas to have effort increasing in step with team size.

Even for a well-behaved aggregation function such as CES it is hard to obtain a well-defined $\operatorname{argmax}_N e^*(N)$, and for other maximands, it is even harder, for instance, the utility of a representative agent. This goes against the data: most companies operate with a limited workforce, whatever the maximand they pursue. In order to understand better what kind of interaction can deliver nontrivial predictions (neither 1 nor $+\infty$), we need to characterize the changes in $e^*(N)$. The first-order condition of the worker's problem is

$$f'(g(e_1, ..., e_N) \mid N))g'_1(e_1, ..., e_N \mid N)/N - c'(e_1) = 0. \tag{4}$$

Solving the first-order condition is sufficient to solve for the maximum when

6 Particularly, $\alpha \leq 1$ suffices. McGinty (2014) takes $c(e) = k\frac{e^2}{2}$, and restricts α to less than 2.

$$f''(g(e_1, ..., e_N \mid N))(g'_1(e_1, ..., e_N \mid N))^2/N + f'(g(e_1, ..., e_N \mid N))g''_{11}(e_1, ..., e_N \mid N)/N - c''(e_1) < 0 \tag{5}$$

for every $\{e_2, ..., e_N\}$. Denote $\varepsilon_q(x) = q'(x)x/q(x)$, the elasticity of $q(\cdot)$ with respect to x. By dividing the second-order condition by the first-order condition and multiplying by e_1, with a slight abuse of notation one can obtain

$$\varepsilon_{f'}(g(e_1, ..., e_N \mid N))\varepsilon_g(e_1, ..., e_N \mid N) + \overbrace{\varepsilon_{g'_1}(e_1, ..., e_N \mid N)}^{<0} - \varepsilon_{c'}(e_1) < 0, \tag{6}$$

which will hold whenever (5) holds.

Assumption 4 *(5) holds for every* $\{e_1, ..., e_N\}$ *for every N.*

This assumption guarantees that the first-order condition has a unique solution. Instead, one can assume that $f(\cdot)$ features decreasing returns to scale, and the aggregator function $g(\cdot)$ is concave in each argument. Alternatively, one can require that $c(\cdot)$ is convex enough.

2.1 Effort Choice in a Team: Equilibrium Outcome

The equilibrium is a collection of the efforts of agents $\{e_1^\star, ..e_N^\star\}$ such that each worker i solves his problem (2) treating the efforts of the other peers as given:

$$e_i^\star = \text{argmax}_e \frac{1}{N} f\left(g(e, e^\star_{-i} \mid N)\right) - c(e),$$

where $e^\star_{-i}$ denotes the values of $\{e_1^\star, .., e_N^\star\}$ omitting $e_i^\star$.

Assumption 5 *A unique symmetric equilibrium with nonzero efforts exists.*[7]

Let $e^\star(N)$ be the function that solves

$$f'(g(e^\star(N), .., e^\star(N) \mid N))g'_1(e^\star(N), .., e^\star(N) \mid N)/N = c'(e^\star(N)). \tag{7}$$

7 We can obtain this assumption as a result by imposing additional assumptions on $f(\cdot)$ and $g(\cdot)$, such as supermodularity and Inada conditions. The pure strategy equilibrium exists because the game we consider here is a potential game; see Monderer and Shapley (1996), Dubey, Haimanko, and Zapechelnyuk (2006) and Jensen (2010). To secure the existence and uniqueness of the symmetric outcome, one can impose additional assumptions on $f \circ g(\cdot)$, $c(\cdot)$, direct (concavity) or indirect (profit single-crossing, compactness of strategy space), but such outcomes are clearly quite common. We opt to avoid the discussion of restrictiveness of these additional assumptions, and concentrate on the interesting case.

Homogeneity of degree 1 for $g(\cdot)$ helps us to study the behavior of $e^*(N)$. Define

$$h(N) \equiv g(1, .., 1 \mid N).$$

This function represents the efficiency of coworking. Observe that

$$h(N) = \frac{eg(\overbrace{1, 1, 1, .., 1}^{N \text{ times}} \mid N)}{eg(1 \mid 1)} = \frac{g(\overbrace{e, e, e, .., e}^{N \text{ times}} \mid N)}{g(e \mid 1)};$$

that is, $h(N)$ measures how much more efficient is the team of agents that the efforts of a single person, holding effort level unchanged. Henceforth we will call this *the teamwork efficiency function*. For instance, if it is linear, the working team is as efficient as its members applying the same effort separately. By Euler's rule and the symmetry of $g(\cdot)$,

$$h(N) = \frac{d(h(N)e)}{de} = \frac{dg(e, e, .., e \mid N)}{de} = g_1'(e, .., e) + g_2'(e, .., e) + .. + g_{N'}(e, .., e) = Ng_1(e, .., e \mid N).$$

Therefore, (7) can be rewritten as

$$f'(e^*(N)h(N))h(N)/N^2 = c'(e^*(N)). \tag{8}$$

Equation (8) is the incentive constraint that defines $e^*(N)$ as a function of N.

2.2 Effort Choice in a Firm: First Best

Following Holmstrom (1982), we assume that the residual claimant provides the employees with contracts that implement the first-best choice of effort.

Assumption 6 *The first-best choice of effort is positive and symmetric.*[8]

The residual claimant would choose the effort size $e^P(N)$ to implement by maximizing

$$\max_{e_1, ..e_N} f(g(e_1, e_2, .., e_N \mid N)) - \sum_{i=1}^{N} c(e_i),$$

which, assuming a symmetric outcome, leads to the first-order condition

$$f'(e^P(N)h(N))h(N)/N = c'(e^P(N)). \tag{9}$$

8 This Assumption is a shortcut in a spirit similar to Assumption 5; see Footnote 5.

The solution of (9), $e^P(N)$, is greater than the solution of (8), $e^*(N)$, as long as $N > 1$. The reason is that in equilibrium, the marginal payoff for the individual effort does not take into account the complementarities provided to other workers. Even if the product $f(\cdot)$ were not split N ways, but instead were non-rivalrous,[9] the additional $1/N$ in the marginal benefit of the team worker would persist.

2.3 Second-Order Conditions and Uniqueness

Equation (6), the second-order condition of (8), in the equilibrium can be rewritten as

$$\varepsilon_{f'}(e^*(N)h(N))\frac{1}{N} + \overbrace{\varepsilon_{g'_1}(e^*(N),..,e^*(N)\,|\,N)}^{<0} - \varepsilon_{c'}(e^*(N)) < 0. \tag{10}$$

This is because $\varepsilon_g(e^*(N),..,e^*(N)\,|\,N) = \frac{(h(N)/N)e^*(N)}{e^*(N)h(N)} = \frac{1}{N}$. Let

$$\varepsilon_{f'}(e^*(N)h(N)) - \varepsilon_{c'}(e^*(N)) < 0 \tag{11}$$

hold; then (10) is satisfied automatically. If $c(x)$ is *more convex* than $f(y)$ at every $x \geq y$, this condition is satisfied. Similar math is used to compare the risk-aversity of individuals: for every $u(x)$, $\varepsilon_{u'}(x)$ is just the negative of Arrow-Pratt measure of relative risk aversion.

The second-order condition for (9) is

$$f''(e^P(N)h(N))h^2(N)/N - c''(e^P(N)) < 0,$$

which, after dividing by the first-order condition, can be rewritten as

$$\varepsilon_{f'}(e^P(N)h(N)) - \varepsilon_{c'}(e^P(N)) < 0. \tag{12}$$

Observe that it is very similar to (11): but the effort level in the argument is different. One would be sure that both (11) and (12) hold if one were sure that $c(\cdot)$ is *at every point* "convexer" than $f(\cdot)$ *at every point above*: $\varepsilon_{f'}(y) < \varepsilon_{c'}(x)\,\forall y > x$. This can be simpler to verify if additional assumptions are imposed on $\varepsilon_{f'}$ or $\varepsilon_{c'}$:

Result 1 *If either $\varepsilon_{f'}(x)$ or $\varepsilon_{c'}(x)$ is weakly decreasing, $\varepsilon_{f'}(x) < \varepsilon_{c'}(x)$, and $h(N) \geq 1$, (11) and (12) are satisfied.*

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9 For non-rivalrous goods, consumption by one agent does not prevent or worsen the consumption of the same unit of good by another agent. Think of coauthoring a paper: the fact of eventual publication contributes to both authors as much as they would derive if there was only one author, at least in the opinion of some promotion committees.

Second-order conditions hold at maxima automatically, but if they hold everywhere, the solution of the corresponding FOC has to be unique. Result 1 thus provides sufficient conditions for the uniqueness of the pure strategy outcome.

$\varepsilon_{f'}(x)$ being decreasing has the following interpretation. When $\varepsilon_{f'}(x)$ is constant and equal to α, it means that $f'(x) = Kx^{\alpha}$, which makes $f(x)$ a power function, where K is an integration constant (unless $\alpha = -1$, in which case $f'(x) = K \ln x$). The decreasing $\varepsilon_{f'}(x)$ implies the "lower power", or "less convexity" of $f(\cdot)$ in larger arguments.

3 The Optimal Size of the Company

For now, $h(N)$ has been defined only for $N \in \{1, 2, 3, ...\}$. Algebraically, the problem of the optimal firm size with distinct nonatomary agents lies in the discreteness of the firm size, which comes from having an integer quantity of arguments in $g(\cdot)$. However, using symmetry, homogeneity and the function $h(N)$, we alleviated this mathematical problem. With a heroic leap of faith, we extend the definition of $h(N)$ to real positive semi-axis.[10] The discussion of how to choose a proper $h(N)$ from knowing $g(\cdot)$ is in Appendix 5.1. With differentiable $h(N)$, we can take derivatives with respect to N, and expect $e^{\star}(N)$ and $e^{P}(N)$ defined with (8) and (9) to be continuous and differentiable.

In order to conduct the comparative statics with respect to N, we apply the usual implicit function apparatus.[11] Knowing how the workers of the company of size N choose their effort, we can characterize the consequences of various company managerial objectives on its hiring policy.

Assumption 7 *The Problems we study are single-peaked, that is, there is a unique interior maximum point; the derivative of every Problem's Lagrangean is strictly positive below this point, and strictly negative above this point.*

Our results extend to the case when intersections are multiple in a manner similar to the way that comparative statics with multiple equilibria are treated.

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10 For $g(e_1, e_2, ..e_N \mid N) = \sqrt{e_1^2 + .. + e_N^2 + \alpha \sum_{i \neq j} e_i e_j}$, $\alpha \in [0, +\infty)$ yields $h(N) = \sqrt{\alpha N^2 + (1-\alpha)N}$, with $\varepsilon_h(N) = 1 - \frac{1-\alpha}{2\alpha N + (1-\alpha)}$, an increasing function of N when $\alpha < 1$ and a decreasing function when $\alpha > 1$. Many papers impose an ad hoc $g(\cdot)$ without any discussion; Kremer (1993) argues for Cobb-Douglas, Rajan and Zingales (1998) goes for linear additive; McGinty (2014) uses CES; see Dubey, Haimanko, and Zapechelnyuk (2006), p. 86 and Jensen (2010), p. 16 for other examples.

11 We can use it because the necessary condition for its use is that the SOC for choosing $e(N)$, which is either (11) or (12), holds for every N by Assumptions 4 and 5.

We concentrate on the single-crossing case for brevity: Appendix 5.2 elaborates on single-peakedness.

3.1 Team Size that Maximizes Effort

This may be a concern in industries where learning-by-doing is important, and therefore the decisionmakers would like to increase efforts even though this might hurt their immediate profits. Workers may be willing to participate in teams of a size that maximizes their effort to combat their long-term/short-term decisionmaking inconsistency issues. This subsection is crucial to understanding the further analysis. We have therefore sought to keep the analysis in this part very explicit. Other problems will be dealt with in a similar fashion, therefore we relocate the repetitive parts to the Appendix.

From (8) one can deduce $e^*(N)$, well-defined and differentiable over $N \in \mathbb{R}_+$.

Problem 1 *Characterize* $N_1 = \arg\max_N e^*(N)$.

Take elasticities with respect to N on both sides of (8) to get:

$$\varepsilon_{f'}(e^*(N)h(N))[\varepsilon_{e^*}(N) + \varepsilon_h(N)] + \varepsilon_h(N) - 2 = \varepsilon_{c'}(e^*(N))\varepsilon_{e^*}(N).$$

Solve this to obtain

$$\varepsilon_{e^*}(N) = \frac{\varepsilon_h(N)\left(\varepsilon_{f'}(e^*(N)h(N)) + 1\right) - 2}{\varepsilon_{c'}(e^*(N)) - \varepsilon_{f'}(e^*(N)h(N))}. \tag{13}$$

From (13) one can immediately see that the N that maximizes $e^*(N)$ has to satisfy

$$\varepsilon_h(N)\left(\varepsilon_{f'}(e^*(N)h(N)) + 1\right) = 2. \tag{14}$$

The denominator of (13) is positive: it is a second-order condition of the effort choice problem, (11). Therefore, whenever $\varepsilon_h(N)\left(\varepsilon_{f'}(e^*(N)h(N)) + 1\right) > 2$, $e^*(N)$ is increasing in N, and otherwise it is decreasing in N.

In the space of $(x, y) = (\varepsilon_h(\cdot), \varepsilon_{f'}(\cdot))$, Equation (14) simplifies to:

$$\Phi_1 = \{(x, y) \mid x(y + 1) = 2.\}$$

Solving out the equilibrium will produce a function $e^*(N)$, and therefore a sequence of values of $(\varepsilon_h(N), \varepsilon_{f'}(e^*(N)h(N))$. We depict an example of this path in Figure 1a. Denote

$$\Gamma_1 = ((\varepsilon_h(N), \varepsilon_{f'}(e^*(N)h(N))) \mid \text{Equation (8) holds}).$$

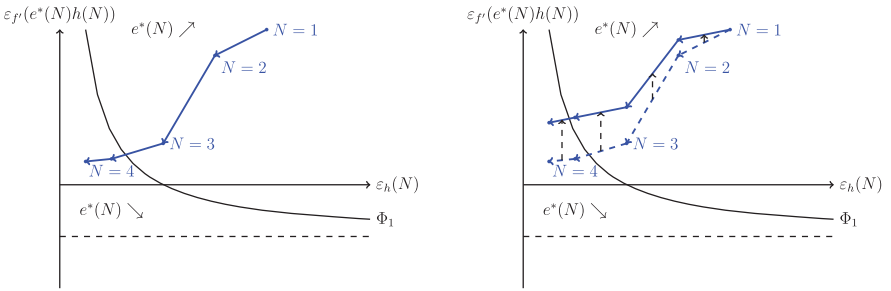


Figure 1: The choice of N to maximize effort in a team; and the Result 2 logic.

For the sequence depicted in the Figure 1, one can observe that $e^*(N)$ is increasing at $N \leq 3$, and decreasing for $N \geq 4$. Therefore, the optimal "continuous" N (denote it N_1) is between 3 and 4, and the integer N that delivers the maximum effort is either 3 or 4.

The assumption that $g(\cdot)$ is CES makes $\varepsilon_h(N)$ constant; the assumption that $f'(\cdot)$ is a power function makes $\varepsilon_{f'}(\cdot)$ constant. Example 1 predicts that whether $e^*(N)$ is increasing or decreasing everywhere depends upon the elasticity of substitution of $g(\cdot)$ precisely because, in the world of Example 1, $f(x) = x^{\alpha}$ and $g(\cdot)$ is CES. Γ_1 is a single point in these assumptions. Therefore, in order to have a nontrivial prediction about the optimal effort size, one needs either a decreasing $\varepsilon_h(N)$, or a decreasing $\varepsilon_{f'}(\cdot)$, or both. Obtaining values in the general case in inherently complicated, but one can make comparative statics predictions without knowing the precise specification of relevant functions.

Result 2 *When $\varepsilon_{f'}$ is decreasing, an increase (decrease) in the marginal costs of effort leads to an increase (decrease) in N_1. When $\varepsilon_{f'}$ is increasing, an increase (decrease) in the marginal costs of effort leads to a decrease (increase) in N_1.*

The purpose of this Result is to illustrate that the effort choice comparative statics are governed by the variation in $\varepsilon_{f'}$. This illustrates that a simplifying assumption, such as constant elasticity, for the production function is not innocuous. Even assumptions such as the concavity of f can restrict the economically important behavior:

Example 2 *(based on Rajan and Zingales 1998, Lemma 2, p. 398) Let $g(e_1, ..e_N \mid N) = \sum_{i=1}^{N} e_i$, and let $f(x)$ be concave. Then*

$$\varepsilon_{f'}(x) = \frac{f''(x)x}{f'(x)} < 0, \qquad h(N) = N \Rightarrow \varepsilon_h(N) = 1,$$

and, therefore, for every N, $\left(\varepsilon_h(N), \varepsilon_{f'}(e^*(N)h(N))\right) < (1,1)$, no matter what $c(\cdot)$ is. The individual effort decreases with N for every N.

3.2 Firm Size that Maximizes Effort

As in the previous part, this problem occurs in industries where learning-by-doing is important, and long term planning may motivate to increase workers' effort by manipulating the number of workers. We assume that when the firm designs a contract, it tries to implement the first-best, which takes into account the agents' complementarities in $g(\cdot)$. If the social planner were choosing the effort for the agents, his FOC would suggest a higher effort for a given N (see the discussion of the $1/N$ effect on p. 12). Since $c'(\cdot)$ is increasing, this immediately implies that $e^P(N) \geq e^*(N)$, with equality at $N = 1$, and therefore the effort-maximizing sizes of a firm and a team do not have to coincide.

Problem 2 *Characterize* $N_2 = \arg\max_N e^P(N)$.

The first-order condition[12] becomes

$$\varepsilon_h(N)\left(\varepsilon_{f'}(e^P(N)h(N)) + 1\right) = 1. \tag{15}$$

Again, if the left-hand side is larger than the right-hand side, the effort is increasing in N, and the reverse holds when the left-hand side is smaller than 1. The change of the managerial objective affects multiple components of the optimal size problem:

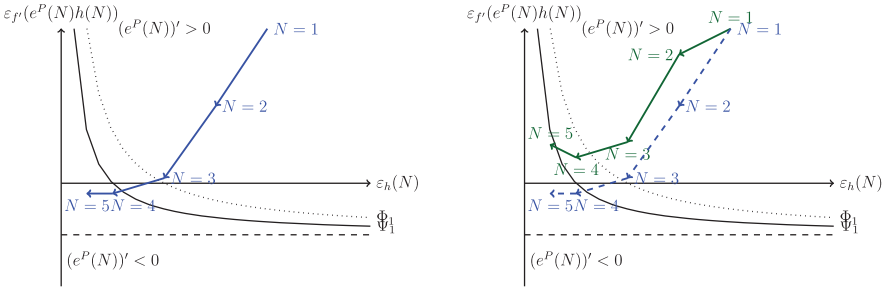
– The threshold that governs when the firm is big enough, Φ_1, is now replaced by

$$\Psi_1 = \{(x,y) \mid x(y+1) = 1\}.$$

The reason why 2 in the definition of Φ_1 is replaced by 1 in the definition of Ψ_1 is exactly because the marginal $1/N$ effect, which appeared because the individual marginal benefit did not include the benefits provided to the other participants, went away.

– Since $e^P(N) > e^*(N)$ for almost every level of N, the values of $\varepsilon_{f'}(e^P(N)h(N)) \neq \varepsilon_{f'}(e^*(N)h(N))$, unless $f(\cdot)$ is a power function in the relevant domain.

12 See Appendix for the derivation of solutions for Problems 2–4.



(a) If $e^*(N)$ were equal to $e^P(N)$ (b) $e^*(N) < e^P(N)$, and $\varepsilon_{f'}(x)$ is increasing

Figure 2: Choosing N to maximize effort, the firm case.

Figure 2b demonstrates the difference, assuming that $\varepsilon_f{}'(\cdot)$ is an increasing function. Since $h(N)$ did not change, abscissae are the same for different values of N for both Φ_1 and Ψ_1. It is plain that the two effects are at odds: since the threshold is further away, larger firms become more efficient. However, the change in $\varepsilon_f{}'(\cdot)$ due to higher efforts for each firm size might lower the optimal firm size.

Result 3 *If $\varepsilon_{f'}(x)$ is weakly increasing, firms that maximize employees' effort will be larger than teams that choose their team size to maximize the efforts of the members ($N_2 > N_1$).*

Proof See Appendix. □

3.3 Team Size that Maximizes Utility

Would team members invite more members to join the team? If this increases the utility of each team member, yes. Thus, the team size that maximizes the utility of a member of the team is the team size that would emerge if teams were free to invite or expel members.

Problem 3 *Characterize* $N_3 = \arg\max_N \frac{1}{N} f(h(N)e^*(N)) - c(e^*(N))$.

N_3 should solve the following first-order condition:

$$\varepsilon_f(e^*(N)h(N))\left(\varepsilon_h(N) + \frac{N-1}{N}\varepsilon_{e^*}(N)\right) = 1. \tag{16}$$

Again, at values of N where the left-hand side is larger (smaller) than 1, the utility is increasing (decreasing) in N. Let Φ_2 be the set of locations where (16) holds with equality. This line, evaluated at $N = N_1$, is plotted over Γ_1 and Φ_1 on Figure 3.

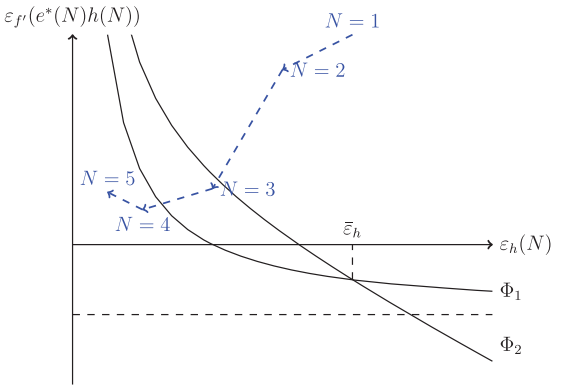


Figure 3: Choosing N to maximize individual utility.
Note: Below both graphs both efforts and profits increase as the size of the firm gets larger. Above both graphs both efforts and profits decrease with N. Between graphs, when $\varepsilon_h(N) < \bar{\varepsilon}_h$, efforts increase with N, but profits decrease; the reverse holds when $\varepsilon_h(N) > \bar{\varepsilon}_h$.

One can immediately see that:

- There is a unique intersection of Φ_1 and Φ_2, which happens at $\bar{\varepsilon}_h = 1/\varepsilon_f(e(N_1)h(N_1))$.
- The path of Γ_1 intersects Φ_1 above $\Phi_1 \bigcap \Phi_2$ if and only if $N_1 < N_3$. In general, when two different maximands are used, different answers are to be expected, but our result makes issues clearer: the only thing necessary to establish whether $N_1 < N_3$ is the value of $\varepsilon_h(N_1)$ and of $\varepsilon_f(e^*(N_1)h^*(N_1))$.

Result 4 *If* $\varepsilon_{f'}(e^*(N_1)h(N_1)) + 1 < (>)\, 2\varepsilon_f(e^*(N_1)h(N_1))$, N_3 *is larger (smaller) than* N_1.

Proof See Appendix. □

Therefore, if the elasticity of $f(\cdot)$ at the size of the team chosen by team members N_3 is too small, it is likely that the team will be too large to implement high efforts ($N_3 > N_1$).

Observe that the local monotonicity of $\varepsilon_f(x)$ is informative about the comparison between $\varepsilon_{f'}(x) + 1$ and $\varepsilon_f(x)$:

$$\big(\varepsilon_f(x)\big)' = \big(\varepsilon_{f'}(x) + 1 - \varepsilon_f(x)\big)\frac{\varepsilon_f(x)}{x}.$$

In particular, $f(x) > 0$ implies $\big(\varepsilon_f(x)\big)' > 0 \Leftrightarrow \varepsilon_{f'}(x) + 1 > \varepsilon_f(x)$, and the condition in Result 4 means that the elasticity of $f(\cdot)$ is either not decreasing too fast, or that it is decreasing quite quickly. Since adding and subtracting constants to the

production function does not change $\varepsilon_{f'}(x)$, but does change $\varepsilon_f(x)$, both cases ($N_1 < N_3$ and $N_1 > N_3$) are generic.

In teaching, many lecturers assign home assignments for group work. Some lecturers use fixed group sizes, other lecturers allow students to form groups of their own choosing. If higher effort is desirable (for instance, because effort in the classroom is valuable on the labor market, which is not fully understood by students), it may be a good idea to restrict the group size, notwithstanding the complaints of students. If the elasticity of $f(\cdot)$ at N_1 is greater than $\frac{1}{2}(\varepsilon_{f'}(\cdot)+1)$ at the same N_1, students will yearn for an increase of the size of the group, and they will complain that the required group size is too large otherwise.[13] Instead of assigning the group sizes, a teacher who wants to implement teamwork projects can manipulate the group's payoff implied by the project design, to make sure the maximal effort group size is close to the maximal utility group size.

3.4 Firm Size that Maximizes Utility

When the principal extracts all surplus from the workers, maximizing the payoff per worker translates to maximizing profit per worker. The principal maximizes the surplus per worker, not the total surplus, because the principal can own more than one firm, as fast food franchisers do.

Problem 4 *Characterize* $N_4 = \arg\max_N \frac{1}{N} f(h(N)e^P(N)) - c(e^P(N))$.

At N_4, the following holds (see Appendix for derivation):

$$\varepsilon_f(e^P(N)h(N))\varepsilon_h(N) = 1 \tag{17}$$

When $\varepsilon_f(e^P(N)h(N))\varepsilon_h(N) > 1$, the utility of each member of the firm increases with the size of the firm, and the utility is reduced otherwise.

One can see the difference between (15) and (17); they have to be equal only when $\forall x, \varepsilon_f(x) = \varepsilon_{f'}(x) + 1$, which implies that $f(x)$ is the power function.

Result 5 *If* $\varepsilon_f(x)$ *is increasing (decreasing),* $\varepsilon_{f'}(x) + 1 > (<)\ \varepsilon_f(x)$, *and therefore* N_4 *is larger (smaller) than* N_2.

Proof See Appendix. □

13 If one believes that the teachers do not split the payoff equally, but with the rule of $1/\beta(N)$ per person with $\beta(N) > 0$, one can instead of $\frac{1}{2}$ in the footnoted sentence use $\frac{\varepsilon_\beta(N_1)}{1+\varepsilon_\beta(N_1)}$.

This Result helps to establish why people do not work efficiently in different environments. The problem is not so much in the returns to scale of the production function; the relevant threshold is the comparison of the first and second derivatives of the production function, which is known if it is known that the elasticity of the production function is locally increasing or decreasing. Those employee-owned companies whose employees feel that they would be more motivated and would work harder had they had more collaborators have $\varepsilon_f(e^P(N)h(N)) < \varepsilon_{f'}(e^P(N)h(N)) + 1$. The curvature of their production function is increasing.

Result 6 *If $\varepsilon_f(x)$ is decreasing, N_4 is smaller than N_3. If $\varepsilon_f(x)$ is increasing, and $2\varepsilon_f(e^*(N_1)h(N_1)) < \varepsilon_{f'}(e^*(N_1)h(N_1)) + 1$, N_4 is larger than N_3.*

Proof See Appendix. □

This Result shows that the issue of which companies are bigger, teams or firms, boils down to the properties of the production function, and the only limitations for the rest of the fundamentals (such as the cost function and effort aggregation function) is to guarantee that assumptions hold. The precise shape of $h(\cdot)$ determines the *value* of N_3 and N_4, but is not always needed to establish which one is bigger. Obviously, there's plenty of $f(\cdot)$ whose elasticities are not monotone, but (a) the part that is harder to observe, the teamwork efficiency function, may not require estimation, and (b) the monotonicity is only important locally, for company sizes near N_3 and N_4.

Results for other managerial objectives can be obtained in a similar fashion: for instance, a residual claimant that collects a fixed proportion of the total surplus of the firm will employ *more* than N_4 workers as long as (12) holds. We reserve these for future research.

3.5 The Quagmire of Constant Elasticities

The previous analysis showed that at least one of two elasticities cannot be constant in order to obtain a well-defined optimal company size. However, even holding one of two elasticities constant can mislead. In the following example, we assume that $\varepsilon_h(N)$ is decreasing from a large enough value to 0, and the production function is a power function.

Example 3 *Let $f(x) = x^\alpha$ and $c(e) = e^\beta$. Let $\beta > \alpha > 0$, then the relevant Assumptions and (11) are satisfied. For general but convenient $h(\cdot)$, where $\varepsilon_h(\cdot)$ is decreasing, the first-best $e^P(N)$ chosen by the firm satisfies*

$$\alpha(e^P(N)h(N))^{\alpha-1}\frac{h(N)}{N}=\beta(e^P(N))^{\beta-1}\Rightarrow$$

$$e^P(N)=\exp\left[\frac{\ln\alpha-\ln\beta}{\beta-\alpha}+\frac{\alpha}{\beta-\alpha}\ln h(N)-\frac{1}{\beta-\alpha}\ln N\right].$$

The effort size $e^*(N)$ chosen by the members of the team satisfies

$$\alpha(e^*(N)h(N))^{\alpha-1}\frac{h(N)}{N^2}=\beta(e^*(N))^{\beta-1}\Rightarrow$$

$$e^*(N)=exp\left[\frac{\ln\alpha-\ln\beta}{\beta-\alpha}+\frac{\alpha}{\beta-\alpha}\ln h(N)-\frac{2}{\beta-\alpha}\ln N\right].$$

Let us order firm sizes chosen with different managerial objectives. When $\varepsilon_h(N)$ is decreasing,

1. N_1, the team size that maximizes the effort when the effort level is chosen simultaneously and independently, satisfies $\varepsilon_h(N_1)=2/\alpha$;
2. N_2, the firm size that maximizes the effort when the effort level is chosen according to the first best, satisfies $\varepsilon_h(N_2)=1/\alpha$;
3. N_3, the team size that maximizes the team member's utility when the effort level is chosen simultaneously and independently, solves $\varepsilon_h(N)=\frac{1}{\alpha}+\frac{N-1}{N\beta-\alpha}$, the right-hand side of which is monotone and converges to $\frac{1}{\alpha}+\frac{1}{\beta}$ from below;
4. N_4, the firm size that maximizes the utility per worker[14] when the effort level is chosen according to the first best, satisfies $\varepsilon_h(N_4)=1/\alpha$.

Example 3 supplies the following intuition for different maximands (see Figure 4):

1 & 2 The effort-maximizing size of the firm is greater than the effort-maximizing size of the team. This is a consequence of $f(\cdot)$ being a power function (see Result 3), and need not hold in general.

1 & 3 The company size chosen by the team when the decision to hire is in the hands of the team members is greater than the company size chosen to maximize the effort size. This is not a general result, but a consequence of a close connection between $\varepsilon_f(\cdot)=\alpha$ and $\varepsilon_{f'}(\cdot)=\alpha-1$. Compare (14) and (16): when N is such that (8) is satisfied, (16) suggests that the utility of each participant increases with the size of the team.

14 This coincides with the revenue per worker if the first best contract provides 0 utility to the worker.

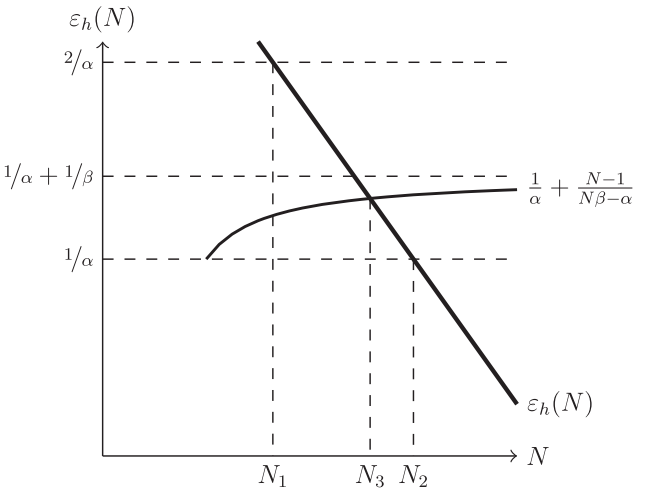


Figure 4: Ordering solutions from Example 3.

2 & 4 The size of the firm that maximizes employees' utilities is maximizing their effort as well. This is not a general result, but a direct consequence of $f(x) = x^\alpha$: conditions (15) and (17) coincide algebraically.

3 & 4 When a self-organized team becomes incorporated, it will become larger. This, however, is not a general result, but a consequence of a power production function.

This exercise demonstrates many spurious findings arising simply from the desire for closed form solutions. Some of the strong predictions are generalizable, but most are a consequence of the power function assumptions.

4 Conclusion

In this paper, we stepped away from the common assumptions about production functions to study the effects of scale on the optimal size of a company, from many perspectives. We found ways to circumvent the inherent discontinuity in hiring when complementarities are important. Our contribution is to characterize the effects of changes in the management of the company, such as the incorporation of a partnership, or going from private to public, on hiring or firing, and whether employees' effort will suffer from overcrowding or from insufficient specialization. We found that teams do not have to be larger or smaller than firms that use the same production function. The analytic framework that we

suggest is very general, and can be modified to include uncertainty, non-trivial firm ownership (for instance, one worker can be the claimant to the residual profit, with nontrivial implications on the effort choice), non-trivial wage schedules (for instance, imperfect observability of effort, total or individual, can call for the design of an optimal wage schedule), or profit-splitting schemes from cooperative game theory, for instance the Shapley value.

The homogeneity of workers is important in our analysis. We have obtained results for a heterogenous workforce, where some workers are capable (can choose a positive effort value), and others incapable (those who can only choose zero effort). We can show that it might be the case that the incapable workers are employed along with the capable ones: this happens if the effort aggregation function is such that the employment of an extra person provides teamwork efficiency externalities for the capable workers, whereas additional effort from one hired capable person would diminish the productivity of other capable employees.

Appendix

Proofs

Solution of Problem 1 in text, on page 14.

Solution of Problem 2 To choose the firm size that maximizes the level of effort, take the derivative of both sides of

$$f'(e^P(N)h(N))h(N)/N = c'(e^P(N))$$

with respect to N. The values of N where $(e^P(N))' = 0$ will be the one we are looking for. The derivative looks like

$$\begin{aligned} &f''(e^P(N)h(N))[h(N)(e^P(N))' + h'(N)e^P(N)]h(N)/N \\ &+ f'(e^P(N)h(N))[h'(N)/N - h(N)/N^2] = c''(e^P(N))(e^P(N))'. \end{aligned}$$

Divide by the first-order condition to obtain

$$\frac{f''(e^P(N)h(N))[h(N)(e^P(N))' + h'(N)e^P(N)]h(N)/N + f'(e^P(N)h(N))[h'(N)/N - h(N)/N^2]}{f'(e^P(N)h(N))h(N)/N} =$$

$$= \frac{c''(e^P(N))(e^P(N))'}{c'(e^P(N))}.$$

Rearrange to obtain

$$\left[\frac{c''(e^P(N))e^P(N)}{c'(e^P(N))} - \frac{f''(e^P(N)h(N))h(N)e^P(N)}{f'(e^P(N)h(N))}\right]\frac{(e^P(N))'N}{e^P(N)} = \frac{h'(N)N}{h(N)}\left[1+\frac{f''(e^P(N)h(N))}{f'(e^P(N)h(N))}\right]-1.$$

Rewrite:

$$\varepsilon_{e^P}(N) = \frac{\varepsilon_h(N)\left(\varepsilon_{f'}(e^P(N)h(N))+1\right)-1}{\varepsilon_{c'}(e^P(N)) - \varepsilon_{f'}(e^P(N)h(N))}.$$

When $\varepsilon_h(N)\left(\varepsilon_{f'}(e^P(N)h(N))+1\right)>1$, effort increases with the size of team, and effort decreases otherwise.

Solution of Problem 3 To choose the team size that maximizes utility, solve

$$\max_N \frac{1}{N} f\left(h(N)e^*(N)\right) - c(e^*(N)),$$

where $e^*(N)$ is such that (8) holds. The first-order condition is:

$$f'(e^*(N)h(N))\left(e^*(N)h'(N)+(e^*(N))'h(N)\right)/N - f(e^*(N)h(N))/N^2 - c'(e^*(N))(e^*(N))' <> 0,$$

with a $>$ sign when the utility of each team member is increasing with the membership size, with a $<$ when the utility of each member is decreasing with the membership size, and with equality at optimum. Substitute (8):

$$f'(e^*(N)h(N))\left(e^*(N)h'(N)+(e^*(N))'h(N)\right)/N - f(e^*(N)h(N))/N^2 - \left(f'(e^*(N)h(N))h(N)/N^2\right)(e^*(N))' <> 0.$$

Group the variables and divide by $f(e^*(N)h(N))/N^2>0$ to obtain

$$\frac{f'(e^*(N)h(N))(e^*(N)h(N))}{f(e^*(N)h(N))}\left(\frac{e^*(N)h'(N)N+(e^*(N))'h(N)(N-1)}{(e^*(N)h(N))}\right)-1<>0,$$

$$\varepsilon_f(e^*(N)h(N))\left(\varepsilon_h(N)+\frac{N-1}{N}\varepsilon_{e^*}(N)\right)-1<>0.$$

Solution of Problem 4 To maximize the utility of each member of the team when their effort is imposed to deliver the first best outcome, the size of the firm should be chosen to solve

$$\max_N f(e^P(N)h(N))\frac{1}{N} - c(e^P(N)),$$

subject to (9). The first-order condition of this problem is

$$f'(f(e^P(N)h(N)))[e^P(N)h'(N)+h(N)(e^P(N))']\frac{1}{N}-\frac{1}{N^2}f(e^P(N)h(N))$$
$$-c'(e^P(N))(e^P(N))'<>0.$$

Divide by $f(e^P(N)h(N))/N^2$ and rearrange to obtain

$$\frac{1}{f(e^P(N)h(N))/N^2}\left(\varepsilon_f(e^P(N)h(N))\varepsilon_h(N)-1\right)<>0. \tag{18}$$

Result 1: If $\varepsilon_{f'}$ is decreasing, then for every level of effort e,

$$\varepsilon_{f'}(eh(N))\le\varepsilon_{f'}(e)<\varepsilon_{c'}(e).$$

If $\varepsilon_{c'}$ is decreasing, then for every level of effort e,

$$\varepsilon_{f'}(eh(N))<\varepsilon_{c'}(eh(N))\le\varepsilon_{c'}(e).$$

Substituting the relevant effort levels completes the proof. □

Lemma 1: *Let $\tilde{e}(N)>e(N)$. If $\varepsilon_{f'}(\cdot)$ is weakly decreasing (increasing), the effort-maximizing team size under $\tilde{e}(N)$ is lower (higher) than the effort maximizing team size for $e(N)$.*

Proof of Lemma 1: Let N_1 and $\tilde{N}_1$ be solutions to team effort maximizing problems with effort functions $e(N)$ and $\tilde{e}(N)$ respectively. If $\varepsilon_{f'}(\cdot)$ is weakly decreasing, since $e(N)<\tilde{e}(N)$

$$\varepsilon_h(\tilde{N}_1)\left(\varepsilon_{f'}(e(\tilde{N}_1)h(\tilde{N}_1))+1\right)-2\ge\varepsilon_h(\tilde{N}_1)\left(\varepsilon_{f'}(\tilde{e}(\tilde{N}_1)h(\tilde{N}_1))+1\right)-2=0.$$

Since we assumed that the problem is single-peaked, this implies that the effort is increasing with N for $e(N)$ at $N=\tilde{N}_1$, or that $N_1>\tilde{N}_1$. The result for increasing $\varepsilon_{f'}(\cdot)$ is proven similarly. □

Result 2: Suppose the marginal costs decrease to $\tilde{c}'(x)\le c'(x)$ for any x. Consider symmetric equilibrium efforts $e(N)$ for the initial problem and $c(\cdot)$ costs, and $\tilde{e}(N)$ under modified costs $\tilde{c}(\cdot)$. By necessary conditions $e(N)$ and $\tilde{e}(N)$ solve (7) with marginal cost functions $c'(x)$ and $\tilde{c}'(x)$ respectively. Therefore,

$$f'(e(N)h(N))h(N)/N^2-\tilde{c}'(e(N))\ge 0=f'(\tilde{e}(N)h(N))h(N)/N^2-\tilde{c}'(\tilde{e}(N)).$$

This, combined with second order conditions and single crossing, implies $\tilde{e}'(N)\ge e(N)$. Applying Lemma 1, we obtain the result. □

Result 3: Let $\tilde{N}_1$ solve

$$\varepsilon_h(\tilde{N}_1)\left(\varepsilon_{f'}(e^P(\tilde{N}_1)h(\tilde{N}_1))+1\right)-2=0.$$

Then $\tilde{N}_1 \le N_2$ by single-peakedness assumption for Problem 1. Moreover, by Lemma 1, $\tilde{N}_1 \ge N_1$ as $e^P(N) \ge e^*(N)$ for each N. Hence, $N_2 \ge \tilde{N}_1 \ge N_1$. □

Result 4: Evaluate (16) at N_1:

$$\varepsilon_f(e^*(N_1)h(N_1))\varepsilon_h(N_1) < > 1.$$

We know that

$$(\varepsilon_{f'}(e^*(N_1)h(N_1))+1)\varepsilon_h(N_1)=2.$$

When $2\varepsilon_f(e^*(N_1)h(N_1)) > \varepsilon_{f'}(e^*(N_1)h(N_1))+1$,

$$2\varepsilon_f(e^*(N_1)h(N_1))h(N_1) > 2 \Rightarrow \varepsilon_f(e^*(N_1)h(N_1))h(N_1) > 1,$$

meaning by the single-peakedness of Problem 3 that $N_3 > N_1$. The proof in the opposite direction is identical. □

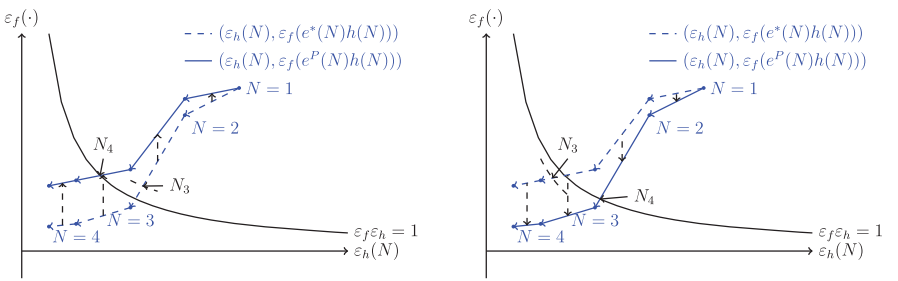
Result 5: $\varepsilon_f(x) \ge \varepsilon_{f'}(x)+1$ means

$$\varepsilon_f(e^P(N_2)h(N_2))\varepsilon_h(N)-1 \ge (\varepsilon_{f'}(e^P(N_2)h(N_2))+1)\varepsilon_h(N)-1=0$$

Workers' utility increases at N_2; hence, by the single-peakedness of Problem 4, $N_2 \le N_4$. The proof in the opposite direction is identical. □

Result 6: N_3 is governed by Equation (16), N_4 is governed by Equation (17).

If $\varepsilon_f(\cdot)$ is decreasing, $\varepsilon_f(e^*(N)h(N)) > \varepsilon_f(e^P(N)h(N))$ for every N, and therefore the path in the space $(\varepsilon_f(), \varepsilon_h())$ for $e^*()$ is above the path for $e^P()$; see Figure 5b for illustration. The intersection of the solid path, that is the outcome of the first-



(a) When $\varepsilon_f()$ is increasing (b) When $\varepsilon_f()$ is decreasing

Figure 5: Result 6 logic.

best effort choice outcome, with the $\varepsilon_f(\cdot)\varepsilon_h = 1$ locus provides N_4. The intersection of the dashed path, that is the outcome of the team-member effort choice, with $\varepsilon_f(\cdot)\varepsilon_h = 1$ locus would provide N_3 if N_1 were equal to N_3: then ε_{e^*} would be equal to zero. In this case, we would argue, $N_4 < N_3$: if the intersection happened for the dashed path, the solid path has already intersected the solid threshold, because it is below the dashed line. However, because $\varepsilon_f(\cdot)$ is decreasing, $\varepsilon_f(\cdot) > \varepsilon_{f'}(\cdot) + 1$, and by Result 4, N_3 happens *before* the dashed path intersects with $\varepsilon_f(\cdot)\varepsilon_h = 1$ locus. Therefore, $N_3 < N_4$.

If $\varepsilon_f(\cdot)$ is increasing, $\varepsilon_f(e^*(N)h(N)) < \varepsilon_f(e^P(N)h(N))$ for every N, and therefore the path in the space $(\varepsilon_f(), \varepsilon_h())$ for $e^*()$ is below the path for $e^P()$; see Figure 5a for illustration. The intersection of the solid path, that is the outcome of the first-best effort choice outcome, with the $\varepsilon_f(\cdot)\varepsilon_h = 1$ locus provides N_4. The intersection of the dashed path, that is the outcome of the team-member effort choice, with $\varepsilon_f(\cdot)\varepsilon_h = 1$ locus would provide N_3 if N_1 were equal to N_3: then ε_{e^*} would be equal to zero. In this case, we would argue, $N_4 > N_3$: if the intersection happened for the dashed line, the solid line cannot yet intersect with the threshold, because it's above the dashed line. However, because of Result 4, we know that N_1 is smaller than N_3 when $2\varepsilon_f(e^*(N_1)h(N_1)) < \varepsilon_{f'}(e^*(N_1)h(N_1)) + 1$, and by single-peakedness of Problem 1, this means that at the intersection of the dashed path and the threshold, ε_{e^*} is negative. Therefore, N_3 is a point *before* the threshold, further ensuring that $N_4 > N_3$. □

The Choice of $h'(\cdot)$

If one knows $f(\cdot)$, $h(\cdot)$, and $c(\cdot)$, one can conduct the analysis above. However, $h'(N)$ is not a fundamental, at least not in non-integer values. It suffices to know $h(N)$ to evaluate e^*, e^P, ε_f, $\varepsilon_{f'}$ and ε_c at integer Ns. The optimum characterizations, however, depend upon $h'(N)$ as well. $h'(N)$ values at integer points would suffice, since optimization requires checking whether the value of the elasticity of $h(\cdot)$ is above or below a certain threshold. How can one choose the value of $h'(N)$ at integer points if one knows only $h(N)$ at integer points? Obviously, arbitrary choices of $h'(N)$ can position the points everywhere in the space of $(\varepsilon_h, \varepsilon_{f'})$. One can impose a refinement over the possible derivatives of $h(N)$, such as:

$$h'(N) \in [\min(h(N+1) - h(N), h(N) - h(N-1)),\ \max(h(N+1) - h(N), h(N) - h(N-1))]. \tag{19}$$

To connect integer points, assume that between two neighboring integers, $h'(N)$ is monotone. This implies that the extrema of $h(N)$ are found only at integer points. Obviously, this preserves concavity, convexity and monotonicity, if $h(N)$ defined over integers had had these properties. This limitation greatly helps to characterize the

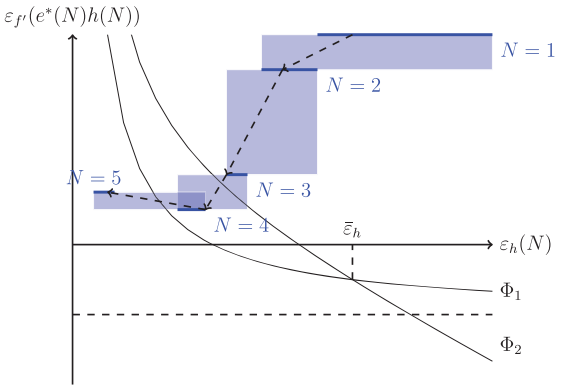


Figure 6: Applying restriction (19) to characterize N_1 when continuous $h(\cdot)$ is not available. Note: The solid lines represent the possible values for the path Γ_1 at integer Ns under the restriction of (19). Shaded region represent possible places for the path of Γ_1 over non-integer values of N. Arrows follow a sample path.

optimal paths. Consider Figure 6, which is similar to Figure 3, but instead of *points* along the path of Γ_1, we plot *sets* for every value of $\varepsilon_{f'}(e^*(N)h(N))$ that is consistent with some value of $h'(N)$ restricted by (19) at integer values, and then impose monotonicity for $h(\cdot)$ across the path to connect the integer values. On Figure 6, one can see that the intersection with Φ_1 happens between $N=3$ and $N=4$, whereas for the Φ_2 intersection with Γ_1 is found between $N=4$ and $N=5$. Therefore, for $f(\cdot)$ and $g(\cdot)$ behind Figure 6, the self-organizing team will be too large to maximize efforts.

The reverse problem of obtaining $g(\cdot)$ if one knows $h(\cdot)$ but not $g(\cdot)$ is surprisingly easy.

Result 7: *For every* $h(N)$,

$$g(e_1,..,e_N \mid N) = h(N)(e_1e_2...e_N)^{1/N} \text{and } g(e_1,..,e_N \mid N) = h(N)/N^{1/\rho}\left(\sum_{i=1}^{N} e_i^{\rho}\right)^{1/\rho}$$

for $\rho<1$ *have properties necessary to apply the analysis above.*

Proof: It is straightforward to see that, for $g(e_1,..e_N) = h(N)(e_1e_2...e_N)^{1/N}$, one obtains

$$g(1,1,..,1 \mid N) = h(N)(1\times 1\times 1\times ..\times 1)^{1/N} = h(N),$$

and homogeneity degree 1 is trivial. Since the function is Cobb-Douglas conditional on N, $g'_i(\cdot \mid N) = \frac{1}{N}\frac{g(\cdot \mid N)}{e_i} > 0$ and $g''_{ii} = -\frac{N-1}{N^2}\frac{g(\cdot \mid N)}{e_i^2} < 0$, therefore, Assumption 1 is satisfied. The CES case is proven similarly. □

This result emphasizes the comparative importance of $h(N)$ over the complementarities in $g(\cdot)$: many different families of $g(\cdot)$ functions can supply mathematically identical $h(N)$ functions. $g(\cdot)$ should provide enough complementarity for the effort choice problem to have a unique solution. The marginal effects of effort complementarity are less important than the scale effects of teamwork for the question of efficient firm size. This, of course, is a consequence of the homogeneity of $g(\cdot)$.

When Our Problems are Single Peaked

In general, the solutions of our Problems characterize two areas in the space of two elasticities: one where the maximand is increasing with company size, and another where the maximand is decreasing with company size. Consider Problem 1. For single-peakedness, we need the path of elasticity values (such as the one depicted with arrows in Figure 1) for our specific Problem to cross the boundary once. Therefore, the path must start from above the boundary, and should end below the boundary.

Moreover, the path should intersect the boundary at most once. Guaranteeing this is hard: since effort might be decreasing in N, the elasticity of f or of f' might reverse the direction, as soon as the boundary was crossed.

Result 8: *Problem 1 is single-peaked if*

- $\varepsilon_h(N) > 2$,
- $\varepsilon_h(N)$ *is weakly decreasing, and* $\varepsilon_{f'}(x)$ *is weakly decreasing*,
- $\varepsilon_h(1)(\varepsilon_{f'}(e^*(1)) + 1) \geq 2$,
- *and the limit points of* $\varepsilon_h(N)(\varepsilon_{f'}(e^*(N)h(N)) + 1)$ *as* $N \to +\infty$ *are less than 2.*

Proof: The last two conditions are to guarantee that teams of size infinity and teams of size of less than 1 are not optimal. The second condition makes sure that the path of elasticity values can cross the boundary only from above. Finally, the first condition makes sure that $e(N)h(N)$ is an increasing function:

$$\text{Differentiate } f'(e^*(N)h(N))\frac{h(N)}{N^2} = c'(e^*(N))\{\text{wrt to N} \Rightarrow$$

$$f''(e^*(N)h(N))\frac{h(N)}{N^2}\frac{de^*(N)h(N)}{dN} + f'(e^*(N)h(N))\left(\frac{h'(N)}{N^2} - 2\frac{h(N)}{N^3}\right) =$$

$$= c''(e^*(N))\frac{de^*(N)}{dN} = \frac{c''(e^*(N))}{h(N)}\frac{de^*(N)h(N)}{dN} - c''(e^*(N))\frac{h'(N)}{h(N)}e^*(N).$$

Divide by the FOC:

$$\frac{\varepsilon_{f'}(e^*(N)h(N))}{e^*(N)h(N)}\frac{de^*(N)h(N)}{dN} + \left(\frac{h'(N)}{h(N)} - \frac{2}{N}\right) = \frac{\varepsilon_{c'}(e^*(N)h(N))}{e^*(N)h(N)}\frac{de^*(N)h(N)}{dN} - \varepsilon_{c'}(e^*(N)h(N))\frac{h'(N)}{h(N)}.$$

$$\underbrace{\frac{\frac{de^*(N)h(N)}{dN}N}{e^*(N)h(N)}}_{\varepsilon_{e^*h}} = \frac{\varepsilon_h(N)(1+N\varepsilon_{c'}(e^*(N))) - 2}{\varepsilon_{c'}(e^*(N)h(N)) - \varepsilon_{f'}(e^*(N)h(N))}.$$

□

For CES effort aggregation function, $g(e_1, e_2, .., e_N) = \left(e_1^\rho + e_2^\rho + ... + e_N^\rho\right)^{1/\rho}$, $h(N) = N^{1/\rho}$, and $\varepsilon_h(N) = \frac{1}{\rho}$, so this condition mean that ρ must be in $(0, \frac{1}{2}]$.

Similarly,

$$\frac{\frac{de^P(N)h(N)}{dN}N}{e^P(N)h(N)} = \frac{\varepsilon_h(N)(1+N\varepsilon_{c'}(e^P(N))) - 1}{\varepsilon_{c'}(e^P(N)h(N)) - \varepsilon_{f'}(e^P(N)h(N))}.$$

Therefore, for the single-peakedness of Problem 2, one can impose similar conditions, with the only difference that $\varepsilon_h(N) > 1$, which is a weaker requirement, would suffice instead; we omit the derivation and the formal statement for brevity.

The difference between the boundaries of Problem 2 and Problem 4 is that $\varepsilon_f(\cdot)$, not $\varepsilon_{f'}(\cdot)$, should be decreasing, so conditions 2–4 change. There are obviously plenty of functions that have decreasing elasticities of both $f(x)$ and $f'(x)$, for example, $f(x) = -Ax^2 + Bx + C$ with $A > C > 0$ and $B > 0$ when $x \in [0, \frac{B}{2A}]$, that is, when $f(x)$ is increasing. In any case, one can supply the sufficient conditions for the single-peakedness of Problem 4 in the spirit of Result 8 by modifying the first condition.

The single-peakedness of Problem 3 is harder to obtain, because it involves ε_{e^*}. As with the approach about Problem 4, we can impose an assumption about $\varepsilon_f(\cdot)$ being decreasing. However, it is harder to show that the boundary (16), which should be intersected, is decreasing: the equation is not defined in the space of two elasticities. Even if one were sure that $\varepsilon_{e^*}(N)$ is decreasing as a function of N, one could not be sure that Problem 3 is single-peaked: the weight attached to elasticities changes with N. Explicit derivation will yield such objects as $\varepsilon_{f'''}$ and $\varepsilon_{c'''}$, which have no well-established intuition.

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