Coordination of internal supply chains in vertically integrated high-tech manufacturing organizations (HTMOs)

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Abstract

This paper uses economic mechanisms to coordinate supply chains within High-Tech Manufacturing Organizations (HTMOs). It models the one-shot initial production and allocation decisions involved in the production and marketing of new technologies; these decisions are driven by the economic objectives of the firm and of the employees with private information—the experts. It analyzes and compares the efficiency of three coordination policies: centralized command and control, centralized revelation, and decentralized revelation. It shows that decentralized policies introduce an additional cost, and it proposes rules of thumb for coordinating supply chains within firms that use many experts. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

HTMOs are large and vertically integrated so as to take advantage of economies of scale and scope, reduce their time to market, and afford periodic large capital investments. HTMOs have several divisions running technologically complex operations. The internal transactions in large and complex organizations are characterized by information asymmetries and lack of market competition [1].

HTMOs are continuously looking for improvements in their overall supply chain efficiencies.

Companies such as Hewlett Packard (HP) and IBM are continuously fine tuning their organizations to better coordinate their internal supply chains. Hewlett Packard (HP) fabricates semiconductors which it subsequently uses to build computers, printers, fax machines, medical devices, etc. In the late 1980s, HP decentralized its organizational structure and created independent business units that were asked to focus attention on improving their cost efficiency and market responsiveness. Similarly, IBM after achieving technological leadership in semiconductor manufacturing expanded their production through forward integration to produce computers and other high-tech products. In the early 1990s, however, IBM had to down size and restructure itself into a less hierarchical organization in pursuit of higher efficiency. The success of HTMOs such as HP and IBM depends
on their technological leadership and the efficient coordination of their supply chains.

This paper evaluates the use of economic market mechanisms to coordinate a HTMO’s production and marketing decisions of a new proprietary technology. In Section 2, We model the coordination of production and allocation decisions during the introduction of a new technology as decisions that are driven by the economic objectives of the firm and of the employees with private information—the experts. We investigate and compare the efficiency of a Centralized Command and Control policy, Section 3; a Centralized Revelation policy, Section 4; and a Decentralized Revelation policy, Section 5. In Section 6, we illustrate the efficiency of the policies analyzed by means of a numerical example consistent with our model. In Section 7, we generalize the efficiency condition for the three policies and show that decentralized policies introduce a decentralized efficiency cost. Finally, we propose some rules of thumb for coordinating internal supply chains in HTMOs.

2. A coordination model for HTMOs

In the remainder of this paper we consider a stylized HTMO consisting of a Headquarters division (HQ) and two vertically integrated production divisions, Division-1 and Division-2. Division-1 produces an intermediate product using state-of-the-art technology, such as integrated circuits; Division-2 uses part of the output from Division-1 to assemble a final product, such as printers, computers, phones, etc. HQ coordinates the divisions using information provided by the division managers, Manager-1 and Manager-2.

We make three important assumptions. First, we assume that the initiative, knowledge, effort, experience, and intuition of the experts play a major role in the development, design, production, and marketing of new technologies. Second, we assume that the productivity of a new technology is uncertain due to its immaturity and workers’ heterogeneity in mastering new technologies. Third, We assume that expert employees are rational, risk neutral, and utility-maximizing decision makers; their objective is to maximize their income and/or to minimize their disutility from effort, which we model as disutility costs.

2.1. Production characteristics

Division-2 uses inputs produced at Division-1 to assemble and market a finished product based on a new technology. The demand for its finished product $d(I, z_2(\theta_2))$, with cumulative probability distribution $F_d(I, z_2)$, has a first-order stochastic dependency on marketing expenditures $I$ and on marketing productivity $z_2(\theta_2)$. Marketing productivity $z_2(\theta_2)$ depends on Manager-2’s private information parameter $\theta_2$, which accounts for Manager-2’s market information, connections, and effectiveness.

Division-1 operates a state-of-the-art production facility with a capacity of $K$ regular production hours per period; of which $k_s$ hours are sold to external customers and $k_p$ hours are used to produce inputs for Division-2. The production of inputs for Division-2, $g(k_p, z_1(\theta_1, \epsilon)) = k_p z_1$, is done by means of a new proprietary technology with uncertain production yield. Productivity $z_1(\theta_1, \epsilon)$ depends on Manager-1’s private information parameter $\theta_1$, and on an uncertain level of production ‘noise’ $\epsilon$. The parameter $\theta_1$ accounts for Manager-1’s experience and effectiveness in bringing new technologies up to production maturity. Production noise $\epsilon$, with cumulative probability

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1 Our objective is not to replicate generic economics results but rather to add structure to the models employed in the economics literature so as to specialize and reinterpret these results in a manufacturing context.

2 Private information represents the knowledge, intuition, experience, and effort of managers and experts; this information is not ex-ante observable by the firm.

3 This result reaffirms the results obtained by Melumad et al. [2] hereafter referred as MMR 1995 – and Vaysman [3]; our model expanded the effect of private information onto the operation decisions which have “supply chain” efficiency connotations.

4 Higher levels of $\theta_2$ are desirable, $\partial z_2(\theta_2)/\partial \theta_2 > 0$.

5 $K$ does not include overtime hours.

6 Higher levels of $\theta_1$ are desirable, $\partial z_1(\theta_1, \epsilon)/\partial \theta_1 > 0$. 

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distribution $F_i(\cdot)$, accounts for all the uncontrollable events that can affect production yields and cycle time.\footnote{Productivity decreases with noise, $\hat{c}z_1(\theta_1, \alpha)/\hat{c}c < 0$.}

2.2. Economic characteristics

HQ’s objective is to maximize firm’s expected profits $E[H_i(\cdot)]$ from the new technology. Corporate revenues result from: selling capacity $k_s$ at a unit profit of $p$ dollars, selling Division-2’s assembled products at a unit price of $p_2$, and salvaging Division-2’s intermediate inputs in excess of demand $(g(k_p, z_1) - d(I, z_2))^+$ at a net unit gain of $h_1$ dollars.$^8$ Corporate costs result from: production $\sum_{i=1}^2 c_i \times d$, penalizing excess demand $(d(I, z_2) - g(k_p, z_1))^+$ at a cost of $s_2$ per excess unit, and from compensating the manager $\Phi_i$. Expected corporate profits before compensating managers are:$^9$

$$E_{d, \alpha}[H(k_s, k_p, I, \tilde{\theta}; \theta)] = pk_s + \left(p_2 - \sum_{i=1}^2 c_i\right)E_{d, \alpha}[d(I, z_2)]$$

$$+ h_1E_{d, \alpha}[\max(g(k_p, z_1) - d(I, z_2), 0)]$$

$$- s_2E_{d, \alpha}[\min(g(k_p, z_1) - d(I, z_2), 0)] - I,$$

In the above equation, price per unit of capacity at Division-1 is positive $p > 0$, price per unit of final product produced at Division-2 is greater than production cost $p_2 - c_1 - c_2 - p/E_i[z_1(\theta_1, \nu)] > 0$, there is an overstock cost in Division-1 for the excess inputs produced for Decision-2 $h_1 < p/E_i[z_1(\theta_1, \nu)]$, and the excess demand penalty cost at Division-2 is non-profitable $s_2 < p_2 - c_1 - c_2 - p/E_i[z_1(\theta_1, \nu)]$.\footnote{Overstock cost does not consider inventory costs because these are negligible.}

Managers are utility maximizers, rational, and risk neutral; the economic utility for the Manager of the $i$th Division is $U_i(\Phi_i, V_i) \equiv \Phi_i - V_i(a_i, \theta_i)$. Managers’ compensations $\Phi_i$ are determined by HQ; their disutility or personal costs $V_i(a_i, \theta_i)$ account for the time, effort, and forgone opportunity costs that a manager with private information parameter $\theta_i$ incurs when assigned production activity $a_i$;\footnote{For weaker conditions see Milgrom and Shannon [4].} $V_i(\cdot)$ is assumed to be monotonic and single crossing in $\theta_i$ to guarantee at least one incentive compatible solution [2]. Sufficiency conditions for monotonicity and single crossing are satisfied when $V_i(\cdot)$ increases with higher levels of production activity $(\partial V_i(a_i, \theta_i)/\partial a_i > 0)$; decreases with higher levels of private information $(\partial^2 V_i(a_i, \theta_i)/\partial a_i \partial \theta_i < 0)$; decreases marginally in production activity and private information $(\partial^2 V_i(a_i, \theta_i)/\partial^2 a_i < 0)$; and is convex in production activity $(\partial^2 V_i(a_i, \theta_i)/\partial a_i \partial \theta_i > 0)$.$^{12}$ Disutility costs $V_i(\cdot)$ are not observable to HQ since they depend on managers’ private information $\theta_i$; HQ’s prior beliefs about $\theta_i$ are characterized by a cumulative probability distribution $F_{\theta_i}(\cdot; \Theta_i)$ where $\Theta_i \equiv [\theta_1, \theta_u]$.

2.3. Coordination decisions

In general the objectives of the HQ and the managers objectives are not compatible and both have asymmetric access to information; these two conditions create incentives for adverse-selection and/or moral hazard in the behavior of the division managers.$^{13}$

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$^8$ $(a - b)^+ = \max(a - b, 0)$.

$^9$ Reported private information $\tilde{\theta} = (\tilde{\theta}_1, \tilde{\theta}_2)$ is a decision variable, whereas true private information $\theta = (\theta_1, \theta_2)$ is a parameter. The arguments of $z_1$ and $z_2$ are omitted for ease of exposition.

$^{10}$ In our case the Manager who has private objectives that are not aligned with those of the principal (in our case HQ) and is better informed than HQ [5].
HQ coordinates and decides on the operational and the enforcement rules for the one-shot project of releasing to the market a new technology, consistent with its objectives and beliefs [6]. The operational rules determine managers’ responsibilities and regulate the interactions between the divisions involved in the project. The enforcement rules make managers accountable for executing the operational rules by determining divisions’ performance measures and managers’ compensations $\Phi_i$.

Managers actions and decisions obey a utility maximization rationale with participation and incentive compatibility conditions. Managers participate in HQ’s contract if and only if their utility is greater than their reservation utility $U_i$ (without loss of generality, we set $U_i = 0$). Managers’ incentive compatibility condition requires them to act and decide so as to maximize their individual utilities. Incentive compatibility implies that when managers report their private information parameter $\bar{\theta}_i$, they report a parameter value that maximizes their utility:

$$\bar{\theta}_i^\pi \in \arg\max_{\theta_i} \{ E_{d, t, 0} [U_i(\Phi_i, \bar{\theta}_i, \bar{\theta}_j^\pi(\theta_j); \theta_i)] \}$$

$$= E_{d, t, 0} [\Phi_i - V_i(a^\pi(\bar{\theta}_i, \bar{\theta}_j^\pi(\theta_j)), \theta_i)]. \quad (2)$$

### 3. Centralized command and control (CCC) policy

This coordination policy is commonly observed in the industry and results from formulations proposed in the Operations Management literature [7–9]. HQ implements the operational and enforcement rules for this policy assuming that managers are altruistic, i.e., $\bar{\theta}_i^\pi = \theta_i$.15

14 HTMOs allocate many resources to these critical projects, often hiring experts that join these companies with the mentality of make-it or break-it.

15 HQ ignores that if managers report $\bar{\theta}_i^\pi \neq \theta_i$, HQ cannot detect the distortions: productivity $z_1$ is ex-post observable but depends on unobservable and random production noise $e_i$ and productivity $z_2$ cannot be accurately inferred from a single realization of random demand.

3.1. Coordination rules

HQ implements the following operational rules. At time $t = 0$, HQ determines managers’ compensation $\Phi_i$ and ranking measures; at time $t = 0^+$, HQ asks managers to report their private information, $\bar{\theta}_i$, which is equivalent to reporting their productivity; at time $t = 0^+$, HQ determines production activities $k_p, I$; at time $t = 1$, demand $d$ and profits $\Pi$ are realized, and the managers are compensated. Fig. 1 shows the flow of information, in dotted lines, and the flow of product, in solid lines, as implemented by the above operational rules.

HQ’s enforcement rule, consistent with its assumption about managers’ altruism, sets managers’ compensations as flat wages with profit sharing incentives, $W_i + \mu_i \Pi$; and it sets subjective managers’ performance evaluation measures such as initiative, quality commitment, productivity contributions, and dependability.

3.2. HQ’s decisions

HQ makes production and marketing decisions with a profit maximizing rationale; in contrast, HQ decides on the manager’s wages $W_i$ and profit sharing fraction $\mu_i \Pi(\cdot)$ using a labor market rationale:

$$\text{Find } k_p^*, k_s^*, I^* \in \arg\max E_{d, t} [\Pi(k_s, k_p, I, \bar{\theta}; \bar{\theta})]$$

$$\text{s.t. } (i) \ k_p + k_p \leq K.$$  \hspace{1cm} (3)

Since profits from $k_p$ are higher than the ones from $k_s$, HQ sets $k_s^* = K - k_p^*$ and solves an unconstrained problem using first-order necessary
conditions for optimality. HQ selects the $k^*_p$ at which Division-1’s expected marginal costs of overstock equate Division-2’s expected marginal costs of understock:

$$p - h_1 \frac{\partial E_i}{\partial k_p} \left[ \int_{0}^{\infty} g(k, x, \theta, \phi) F_d(x; I, z_2) \partial x \right] \bigg|_{k_p = k^*_p} = s_2 \frac{\partial E_i}{\partial k_p} \left[ \int_{0}^{\infty} g(k, x, \theta, \phi) F_d(x; I, z_2) \partial x \right] \bigg|_{k_p = k^*_p}.$$ (4)

HQ selects the $I^*$ at which expected marginal revenue equals the expected marginal cost from marketing projects:

$$\left( p_2 - \sum_i c_i - s_2 \right) \frac{\partial E_i}{\partial I} \bigg|_{I = I^*} = 0$$

3.2.1. Managers’ decisions

Managers follow their utility maximizing objective and accept HQ’s contract if their compensations are competitive, i.e.,

$$E_{d, \theta, \phi}[\Phi_i - V_i(a^*_i, \theta_i)] \geq 0.$$  

Managers that choose to participate then report the private information $\tilde{\theta}^*_i$ that maximizes their utility. Managers’ utilities are the sum of three concave functions, $E[U_i] = W_i + \mu_i E[\Pi] + \left(-E[V_i]\right)$; therefore, their utilities would be maximized when their expected marginal benefits equals their expected marginal cost corresponding to the reported private information:

$$\mu_i \times \frac{\partial E_{d, \theta, \phi}[\Pi(a^*_i(\tilde{\theta}^*_i, \theta_i), \theta_i, \tilde{\theta}^*_j(\theta_j), \theta_j)]}{\partial \tilde{\theta}^*_i} \bigg|_{\tilde{\theta}^*_i = \tilde{\theta}^*} = \frac{\partial E_0[V_i(a^*_i(\tilde{\theta}^*_i, \tilde{\theta}^*_j(\theta_j), \theta_j)]}{\partial \tilde{\theta}^*_i} \bigg|_{\tilde{\theta}^*_i = \tilde{\theta}^*}.$$  

3.2.2. Efficiency losses

Efficiency losses in this policy occur because HQ’s decisions use distorted productivity information, and because managers have no incentive to report their true private information. HQ ignores the fact that managers are utility maximizers with valuable private information, and that they incur disutility costs. Consequently, managers distort their private information because their expected marginal benefits from reporting truthfully is zero:

$$\mu_i \times \frac{\partial E_{d, \theta, \phi}[\Pi(a^*_i(\tilde{\theta}^*_i, \theta_i), \theta_i, \theta_j)]}{\partial \tilde{\theta}^*_i} \bigg|_{\tilde{\theta}^*_i = \tilde{\theta}^*} = \sum_{k \in i, j} \left( a^*_k(\tilde{\theta}^*_i, \tilde{\theta}^*_j, \theta_i, \theta_j) \right) \frac{\partial a^*_k}{\partial \tilde{\theta}^*_i} \bigg|_{\tilde{\theta}^*_i = \tilde{\theta}^*} = 0 \forall k \in i, j.$$  

To reduce their disutility costs, managers underreport their private information, i.e., $\tilde{\theta}^*_i(\theta_i) < \theta_i$. Consequently, HQ’s production activity levels $a^*_k$ are based on distorted private information, i.e., lower estimates of productivity.

$$a^*_k(\tilde{\theta}^*_i, \tilde{\theta}^*_j, \theta_i, \theta_j) \neq \arg \max E_{d, \phi}[\Pi(a^*_i(\tilde{\theta}^*_i, \theta_i), \theta_i, \theta_j)]$$  

Comparing the efficiency of this policy to the benchmark efficiency of the ‘first best’ solution provides a measure of the efficiency losses of this policy, given by Eq. (9). The first best solution would be achieved if private information would not exist and HQ would not need to align managers and firms objectives.

$$E[L_{ccc}] = E_{d, \phi}[\Pi(a^*_i(\theta_i, \theta_i), \theta_i, \theta_i; \theta_i)]$$

$$- E_{d, \phi}[\Pi(a^*_i(\tilde{\theta}^*_i, \tilde{\theta}^*_i, \theta_i, \theta_i; \theta_i)] > 0.$$  

4. A centralized revelation (CR) policy

In this coordination policy, HQ maintains centralized control but does not assume that managers are altruistic. In order to access private information
HQ must align the manager’s objective with the objective of the firm, which is accomplished by a direct revelation mechanism [2,3].

4.1. Coordination rules

HQ sets forth the following operational rules: at time \( t = 0 \), it determines managers’ compensations \( \hat{\Phi}_t^* \); at time \( t = 0^+ \), it asks managers to report their private information parameters \( \hat{\theta}_t^* \); at time \( t = 0^{++} \), it makes production activity decisions; at time \( t = 1 \), demand \( d \) and profits \( \Pi \) are realized, and managers are compensated. Fig. 2 shows the flow of information, in dotted lines, and the flow of product, in solid lines, for the above set of rules.

HQ designs the enforcement rules, determining managers’ compensations and performance evaluation measures, that maximize the utility of managers who subscribe to the above operational rules and report their true private information.

4.2. HQ’s decisions

HQ offers managers the minimum compensation \( \hat{\Phi}_t^* \) that maximizes their utility when they are not distorting their private information:

\[
\max_{\Phi_t} E_{d, e, \theta, r} \left[ \Pi \left( a^g(\theta), \tilde{\theta}; \hat{\theta}_t^* \right) - \sum_{i=1}^{2} E_{d, e, \theta, r} \left[ \hat{\Phi}_t(\tilde{\theta}_i; \theta_i) \right] \right]
\]

subject to

(i) \( \theta_i = \hat{\theta}_i^* \in \arg \max_{\theta_i \in \Theta_i} E_{d, e, \theta, r} \left[ \hat{\Phi}_t(\tilde{\theta}_i; \theta_i) \right] \)

\( - V_i(\hat{\theta}_i^*(\tilde{\theta}_i, \theta_i), \theta_i) \) \( \forall (i, j) \),

(ii) \( E_{d, e, \theta, r} \left[ \hat{\Phi}_t(\tilde{\theta}_i; \theta_i) \right] 

\( - V_i(\hat{\theta}_i^*(\tilde{\theta}_i, \theta_i), \theta_i) \geq U_i \) \( \forall (i, j) \).

The optimal managers’ compensations \( \hat{\Phi}_t^* \) must cover managers’ disutility costs and pay them informational rents [2]. This results from assuming that \( E_{d, e, \theta, r} \left[ \hat{\Phi}_t(\tilde{\theta}_i; \theta_i) \right] = E_{d, e, \theta, r} \left[ V_i(\hat{\theta}_i^*(\tilde{\theta}_i, \theta_i), \theta_i) \right] + T(\tilde{\theta}_i) \), where \( T(\tilde{\theta}_i) \) are managers’ informational rents. To achieve managers’ participation \( T(\tilde{\theta}_i) \geq 0 \), and to achieve incentive compatibility \( T(\tilde{\theta}_i) \) must be equal to the second term of Eq. (10).

\[
\hat{\Phi}_t^*(\tilde{\theta}_i; \theta_i) = E_{\theta_i} \left[ V_i(\hat{\theta}_i^*(\tilde{\theta}_i, \theta_i), \tilde{\theta}_i) \right] - \int_{\theta_i}^{\hat{\theta}_i^*} \frac{\partial V_i(\hat{\theta}_i^*(t, \theta_j), t)}{\partial \theta_i} dt \right] \quad (10)
\]

HQ decides on the divisions’ production activity levels by solving an unconstraint optimization problem that takes into account the expected optimal managers’ compensation \( E_{\theta_i} \left[ \hat{\Phi}_t^*(\tilde{\theta}_i, \theta_i) \right] \) also known as the virtual costs of the managers \( \tilde{H}_1(\hat{a}_i^*, \tilde{\theta}_i) \).

\[
\max_{i, \theta_c} E_{d, e, \theta_c, r} \left[ \Pi(\hat{k}_c, \tilde{\theta}; \tilde{\theta}) - \tilde{H}_1(\hat{k}_c, \tilde{\theta}_1) - \tilde{H}_2(\hat{\theta}_1, \tilde{\theta}_2) \right]. \quad (11)
\]

At the optimal capacity \( \hat{k}_c^* \), marginal expected cost of understock and overstock are equal, but now Manager-1’s marginal virtual cost increases the

\[ ^{18} \text{Revelation mechanisms are based on the revelation principle for communication games with imperfect information} [10]. \]
\[ ^{19} \text{Profits before payment to the managers } E[\Pi] \text{ are defined in Eq. (1).} \]
\[ ^{20} \text{The virtual cost of the managers } \tilde{H}_1(\hat{a}_i^*, \tilde{\theta}_i) \text{ is convex in } a_i \text{ as a result of the conditions imposed on } V_i \text{ and } F(a). \]
marginal cost of understock.

\[
p + \frac{\partial \hat{H}(k_p, \bar{Z})}{\partial k_p} \Bigg|_{k_p = k^*_p} - h_1 \frac{\partial E_a[\hat{\theta}(\hat{\theta}, \bar{Z})] F_{a}(x; I, \bar{z}) \partial x}{\partial k_p} \Bigg|_{k_p = k^*_p} = \frac{\partial E_a[\hat{\theta}(\hat{\theta}, \bar{Z})] F_{a}(x; I, \bar{z}) \partial x}{\partial Z} \Bigg|_{Z = \bar{Z}}.
\]

At the optimal expenditures \( k^* \) the marginal expected costs are equal to the marginal expected revenues from marketing expenditures, but now Manager-2’s revelation cost decreases expected marginal revenue.

\[
\left( p_2 - \sum_i c_i - s_2 \right) \frac{\partial E_a[d(I, \bar{z})]}{\partial I} \Bigg|_{I = \bar{I}^*} - (s_2 - h_1) \frac{\partial E_a[\hat{\theta}(\hat{\theta}, \bar{Z})] F_{a}(x; I, \bar{z}) \partial x}{\partial I} \Bigg|_{I = \bar{I}^*} - \frac{\partial \hat{H}_2(I, \bar{Z})}{\partial I} \Bigg|_{I = \bar{I}^*} = 1.
\]

### 4.4. Efficiency losses

The losses corresponding to this policy result from having to pay managers informational rents to access truthful information. The relative efficiency measure of this policy, as compared to the first-best solution, is given by

\[
\hat{L} = \left[ E_{d, \alpha}[\Pi(a^*(\theta), \theta) - \sum_i V_i(a^i, \theta_i)] \right] - \left[ E_{d, \alpha}[\Pi(\hat{a}^*(\theta), \theta) - \sum_i \hat{H}_i(\hat{a}^i, \theta_i)] \right] = E_{d, \alpha} \left[ \frac{\partial V_i(\hat{a}^i, \hat{\theta}_i)}{\partial \hat{\theta}_i} F_{\theta}(\hat{\theta}_i) \right] f_{\theta}(\hat{\theta}_i). \tag{15}
\]

If the production resources being allocated are very expensive, paying for access to true private information is more efficient than underallocating these resources. This is typically the case in HTMOs which tend to use very expensive resources with a high rate of obsolescence that must be utilized efficiently. For instance, a modern production facility for integrated circuits costs around one billion dollars; A single photolithography machine costs around five million dollars [11].

### 5. A decentralized revelation (DR) policy

Under this coordination policy the HQ delegates all the local decisions to the divisional managers and assumes that managers are selfish (rather than altruistic).\(^{21}\) HQ in HTMOs may want to delegate local decision for the following reasons: faster reaction to the urgency needs of many internal supply chain decisions [12]; empowerment of well-informed managers to make the best decisions[13]; and regulation of the monopolistic behavior of divisions controlling captive technologies [14,15].\(^{22}\)

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\(^{21}\) Arrow [1] proposed the decentralization of large organizations as a way to reduce the inefficiencies due to asymmetric information.

\(^{22}\) Decisions in HTMOs require increasingly more accurate real-time technical and economic information to remain competitive.
the transfer price among the divisions. Fig. 3 shows the product and information flow among the divisions. Fig. 3 shows the product and information flow implemented by the above rules.

5.1. Coordination rules

The operational rules for this policy are: at $t = 0$, HQ sets managers’ responsibilities and compensation $\hat{\Phi}_i$; at $t = 0^+$, it asks the managers to report their private information; at $t = 0^{++}$, it determines the transfer price $T(s, \theta_1)$ that Division-2 must pay to Division-1 for its services $S$; at $t = 0^{+++}$, Division-2 decides on $I$ and $S$ and Division-1 on $k_s$ and $k_p$; at $t = 1$, demand and profits are realized. To enforce the above operational rules, HQ specifies managers’ responsibilities and compensations, and the transfer price among the divisions. Fig. 3 shows the product and information flow implemented by the above rules.

5.2. HQ’s decisions

HQ decides on managers’ responsibilities by separating the firm profit maximization function into several divisional profit maximization functions, and by giving each manager the authority and decision domain needed to maximize its local profits [6]. In our model, decentralization can be implemented in two ways depending on the services $S$ that Division-2 orders from Division-1: $S$ can be capacity hours $k_p$ (case i) or it can be inputs $Q$ (case ii). In case (i) $S = k_p$, Division-2 decides on $\bar{N}^{(i)}$, and Division-1 decides on $\bar{N}^{(o)}$. Profits for each division are:

\[
\bar{\pi}_1(k_p^{(i)}, \bar{\theta}_1; \theta_1) = T(k_p^{(i)}, \bar{\theta}_1) + p\bar{k}^{(o)} - c_1g(k_p^{(i)}, \bar{z}_1),
\]

\[
\bar{\pi}_2(I^{(o)}, k_p^{(o)}, \bar{\theta}_2; \theta_2) = p_2d(I^{(o)}; \theta_2) - (s_2 + c_1)(d - g(k_p^{(o)}, \bar{z}_1) + h_1(g(k_p^{(o)}, \bar{z}_1) - d^+) + T(k_p^{(o)}, \bar{\theta}_1; \theta_2).
\]

In case (ii) $S = Q$, Division-2 decides on $\bar{I}^{(o)}$, $Q$; and Division-1 decides on $k_p^{(o)}$, $p$. Profits for each division are:

\[
\bar{\pi}_1(k_p^{(ii)}, \bar{\theta}_1; \theta_1) = T(\bar{\theta}, \bar{\theta}_1) + p\bar{k}_s - c_1Q + h_1(g(k_p^{(ii)}, \bar{Q}) - Q^+) + s_2(Q - g(k_p^{(ii)}, \bar{Q})^+) + h_1(Q - d^+) + T(\bar{\theta}_1; \bar{\theta}_1) - \bar{I}^{(o)} - c_2d.
\]

HQ also decides on the transfer price that Division-2 pays Division-1 in exchange for $S$. Vaysman [3] showed that an efficient transfer price must transfer the production as well as the virtual costs associated with $S$:24

\[
T^{(i)}(k_p^{(i)}, \bar{\theta}_1^{(i)}) = \left( p + \frac{c_1}{E_s[\bar{z}_1]} \right) \times \bar{k}_p^{(i)} + \bar{H}_1(k_p^{(i)}, \bar{\theta}_1),
\]

\[
T^{(ii)}(Q, \bar{\theta}_1) = c_1Q + p\bar{F}(Q) + \bar{H}_1(F(Q), \bar{\theta}_1).
\]

HQ must design the compensation $\hat{\Phi}_t$ that satisfies managers’ participation and incentive compatibility conditions in this policy. The simplest form of a decentralized incentive compatible compensation scheme is linear in divisional profits [16]:

\[
\hat{\Phi}_t = \alpha_t(\bar{\theta}_t)\pi_t + \beta_t(\bar{\theta}_t).
\]

The slope $\alpha_t$ must induce managers to replicate HQ’s decisions by making managers’ optimization conditions the same as HQ’s conditions.25 The

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23 Hereafter, superscripts (i) and (ii) refer respectively to case (i) and case (ii).

24 $\bar{F}(Q) = k_p^{(o)}$ represents Manager-1’s capacity allocation decision as a function of $Q$.

25 $\bar{E}_x[\sum \bar{z}_i, (\bar{\theta}_i; \theta_i)] = \sum \bar{H}(\bar{x}_i, \bar{\theta}_i) = 0 = \bar{E}_x[\sum \bar{z}_i, \bar{\theta}_i] + \beta_t(\bar{\theta}_t) - V_t(\bar{\theta}_t, \bar{\theta}_t)$.}

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required \( x_i \) distributes divisional profits proportionally to the ratio of manager’s marginal disutility costs to HQs marginal virtual costs:

\[
\begin{align*}
\gamma_i(\bar{\theta}_i) &= \frac{dV_i(\bar{a}_i, \bar{\theta}_i)/d\bar{a}_i}{dH_i(\bar{a}_i, \bar{\theta}_i)/d\bar{a}_i}. \tag{20}
\end{align*}
\]

The intercept \( \beta_i \) must induce incentive compatibility. Intuitively, the compensation under this policy must be equal to or greater than the compensation under the centralized revelation policy,\(^{26}\) but decentralization increases managers’ expected marginal disutility cost because they have to make all the local decisions. The decentralized informational rents must cover the increase in managers’ disutility costs, i.e., \( \beta_i(\bar{\theta}_i) \) must be increased by\(^{27}\)

\[
\int_{\bar{\theta}_i}^{\theta_i} \gamma_i(\bar{\theta}_i) \frac{\partial E_{a_i}[\pi_i(\bar{\theta}_i), t, \theta_i]}{\partial \bar{\theta}_i} \, dt.
\]

The decentralized revelation compensation \( \Phi^*_{d}(\bar{\theta}_i, \bar{\theta}_i) \) pays managers for their net contribution to divisional profits \( x_i(\pi_i - E[\pi_i]) \), for their disutility costs, and for the value of their private information:

\[
\Phi^*_{d}(\bar{\theta}_i, \bar{\theta}_i) = x_i(\bar{\theta}_i)\bar{\pi}_i(\bar{a}_i, \bar{\theta}_i; \theta_i) - E_{a_i}[\bar{\pi}_i(\bar{a}_i, \bar{\theta}_i; \theta_i)]
\]

\[
+ E_{d_a}[V_i(\bar{a}_i, \bar{\theta}_i), \bar{\theta}_i] - \int_{\bar{\theta}_i}^{\theta_i} \gamma_i(\bar{\theta}_i) \frac{\partial E_{a_i}[\pi_i(\bar{\theta}_i), t]}{\partial \bar{\theta}_i} \, dt
\]

\[
+ \int_{\bar{\theta}_i}^{\theta_i} \gamma_i(\bar{\theta}_i) \frac{\partial E_{a_i}[\pi_i(\bar{\theta}_i), t]}{\partial \bar{\theta}_i} \, dt. \tag{21}
\]

The increase in informational rents due to decentralization causes an increase in the decentralized managers’ virtual costs:

\[
E_{a_i}[\Phi^*_{d}] = \tilde{H}(\bar{a}_i, \bar{\theta}_i)
\]

\[
= V_i(\bar{a}_i, \bar{\theta}_i) - \left( \frac{\partial V_i(\bar{a}_i, \bar{\theta}_i)}{\partial \bar{\theta}_i} - \gamma_i(\bar{\theta}_i) \frac{\partial \pi_i(\bar{a}_i, \bar{\theta}_i)}{\partial \bar{\theta}_i} \right) F_{a_i}(\bar{\theta}_i).
\tag{22}
\]

### 5.3. Managers’ decisions

Managers make participation, reporting, and production activity decisions. The decentralized revelation payment \( \Phi^* \) induces managers to participate and align their objectives with the objectives of the firm; the previous section shows how this payment induces managers to participate and to report their true private information. To make production activity decisions, managers solve:

\[
\max \left[ x_i(\bar{\theta}_i) E_{d_a}[\bar{\pi}_i(\bar{a}_i, \bar{\theta}_i; \theta_i)] - E_{d_a}[V_i(\bar{a}_i, \theta_i)] + \beta_i(\bar{\theta}_i) \right]
\]

\[
\bar{a}_i,
\]

\[
= x_i(\bar{\theta}_i) E_{d_a}[\bar{\pi}_i(\bar{a}_i, \bar{\theta}_i; \theta_i)] - \tilde{H}(\bar{a}_i, \bar{\theta}_i) + \beta_i(\bar{\theta}_i)]. \tag{23}
\]

Whereas HQ would have solved:

\[
\max \left[ E_{d_a}[\bar{\pi}_i(\bar{a}_1, \bar{\theta}_i; \theta_1)] + \bar{\pi}_2(\bar{a}_2, \bar{\theta}_2) \right]
\]

\[
\bar{a}_1, \bar{a}_2,
\]

\[
- \tilde{H}_1(\bar{a}_1, \bar{\theta}_1) - \tilde{H}_2(\bar{a}_2, \bar{\theta}_2). \tag{24}
\]

\( x_i \) has been chosen to make the above two maximization problems equivalent.

In Case (i), Manager-1 selects \( \tilde{a}_1^{(o)} = K - \tilde{a}_1^{(0)} \); this decision does not increase Manager-1’s virtual costs because the decision does not increase his/her disutility costs.\(^{28}\) Manager-2 selects \( \tilde{a}_2^{(0)} = \tilde{a}_2^{(0)} \); these decisions increase Manager-2’s disutility costs and consequently his/her virtual costs.\(^{29}\) The increase in Manager-2’s virtual costs is separable and independent.

\( x_1 = 0, \tilde{H}_1 = \tilde{H}_1, \Phi_1^{(o)} = \Phi_1 \).

\( x_2 \neq 0, \tilde{H}_2 > \tilde{H}_2, \Phi_2^{(o)} > \Phi_2 \).
of production activity decisions; as a result, Manager-2 selects the same production activity levels as in the centralized revelation policy \( k_p^{(i)} = k_p^* \) and \( \tilde{f}^{(i)} = \tilde{f} \).

In case (iii), Manager-1 selects \( k_p^{(i)}(Q) \) so that Division-1’s marginal cost of understock and overstock are equal; this decision does not consider Division-2’s demand uncertainty.\(^{30}\)

\[
P + \frac{\partial \tilde{H}_1^{(i)}(k_p^{(i)}, \tilde{\theta}_1)}{\partial k_p} - h_1 \frac{\partial \tilde{f}_e^{(i)}(g(k_p^{(i)}, z_1(\tilde{\theta}_1, x)) - Q) f_e(x) dx}{\partial k_p} = \frac{\partial \tilde{e}_e^{(i)}(Q - g(k_p^{(i)}), z_1(\tilde{\theta}_1, x)) f_e(x) dx}{\partial k_p}.
\]

The above decision increases Manager-1’s marginal disutility costs and hence his/her informational rents.\(^{31}\) Manager-2 selects \( I^{(i)} \) and \( Q \) not taking into account the production uncertainty at Division-1 and ignoring the effect of his/her decisions on Division-1’s understock and overstock costs. Manager-2 selects \( Q* \) so that Division-2’s expected marginal costs of overstock and understock are equal:

\[
p \frac{\partial \tilde{H}_1^{(i)}(k_p^{(i)}, \tilde{\theta}_1)}{\partial Q} + \frac{\partial \tilde{H}_1^{(i)}(\tilde{f}(Q), \tilde{\theta}_1)}{\partial Q} - h_1 F_d(Q^*, \tilde{I}^{(i)}(Q^*, z_2)) = s_2 F_d(Q^*, \tilde{I}^{(i)}(Q^*, z_2)).
\]

It selects \( \tilde{I}^{(i)}(Q) \) so that Division-2’s expected marginal revenues and costs from investment are equal:

\[
(p_2 - \sum_{i} c_i - s_2) \frac{\partial E_d[d(\tilde{I}^{(i)}(Q^*, z_2))]}{\partial I} - (s_2 - h_1) \frac{\partial [F_d(x; \tilde{I}^{(i)}(Q^*, z_2))] dx}{\partial I} - \frac{\partial \tilde{H}_2^{(i)}(\tilde{I}^{(i)}, \tilde{\theta}_2)}{\partial I} = 1.
\]

The exclusion of Division-1’s uncertainty in Division-2’s decisions, due to decentralization, decreases Division-2’s perceived marginal costs of overstock and understock leading to inefficient allocations \( (\tilde{f}^{(i)} > \tilde{f}) \) and \( (k_p^{(i)}(Q^*) > k_p^*) \).

5.4. Efficiency losses

In Case (i), the losses \( L^{(i)} \) are higher than in the Centralized Revelation Policy due to the increase in Manager-2’s informational rents.\(^{32}\) In Case (ii), the losses \( L^{(i)} \) are higher than in the Centralized Revelation Policy due to an increase in managers’ informational rents and due to overallocation of production resources. The decoupling of divisional uncertainties in Case (ii) leads to a distortion of expected marginal stockout, overstock, and investment calculations: Manager-1 does not account for understock costs when \( d > Q \), and Manager-2 does not account for costs when \( Q > d < g^{(i)}[Q] \). Consequently, Manager-2 expects unrealistic higher marginal revenues from investment and over allocates resources.

5.4.1. Rectifying efficiency losses in Case (ii)

To rectify efficiency losses in Case (ii), Division-2’s price structure can be modified, \((p_2, h_1, s_2) \Rightarrow (p_2', h_1', s_2')\) so as to induce Manager-2 to internalize the effect of his/her decision on Division-1. Manager-2 needs to take into consideration that when \( d < Q \) and \( g(k_p^*, z_1) < Q \) and expected salvage revenues are lower; and when \( Q < d \), \( Q < g(k_p^*, z_1) \) expected stock-out costs are also lower.\(^{33}\)

\[
p_2' = p_2 P[d \leq g(k_p^*, z_1)] + \left( p_2 - s_2 - \sum_{i} c_i - \frac{p}{E_d(z_1)} \right) \times P[d > g(k_p^*, z_1)]
\]

\(^{30}\) Here \( g(k_p^{(i)}, z(\tilde{\theta}_1, \epsilon_2)) = Q \) and \([\epsilon_1, \epsilon_2]\) is the support for the distribution \( f_e(.) \). The solution to this equation determines \( \tilde{H}_1^{(i)}(k_p^{(i)}, \tilde{\theta}_1) \) which is needed to determine the transfer price, \( T(Q; \tilde{\theta}_1) \).

\(^{31}\) \( z^{(i)} > 0, \tilde{I}^{(i)} > \tilde{I}^{(i)}(Q) \), and \( \Phi^{(i)} > \Phi^i \).

\(^{32}\) This case is just like the Centralized Revelation Policy, except that Manager-2 makes all the decisions instead of HQ.

\(^{33}\) To compute these prices, one can use the probability structure characterized in the Centralized Revelation Policy. For example,

\[
P[d > g(k_p^*, z_1)] = \frac{F_d(g_k^{(i), (i)}; I^*, \tilde{\theta}_2) - F_d(Q; I^*, \tilde{\theta}_2)}{F_d(Q; I^*, \tilde{\theta}_2)}
\]
$$h_1 = h_1 P[d \leq g(k_p^*, z_1)|d < Q]$$
$$+ 0P[d > g(k_p^*, z_1)|d < Q]$$
$$s_2' = s_2 P[d > g(k_p^*, z_1)|d < Q]$$
$$+ \left( \sum_i c_i + \frac{p}{E[z_1]} \right) P[d \leq g(k_p^*, z_1)|d > Q].$$

(28)

The above price rectification prevents Division-2 from overexpending and from operating at a high probability of stock-out because it decreases Division-2’s decentralized marginal expected revenues.

6. Numerical example

The following examples is primarily intended to illustrate the comparative efficiency of the three policies studied in this paper. However, the functional forms used in the example are sufficiently rich to be considered as a first-order approximate model of a manufacturing/marketing organization, which with proper parameterization can be used to set compensation and transfer prices.

- Division-1’s production of inputs for Division-2 is $g(k_p^*, z_1) = k_p \times (z_1(\bar{\theta}_1, 0) - \epsilon); (z_1(\bar{\theta}_1, 0) = \bar{z}_1 + \gamma_1 \bar{\theta}_1)$ is the theoretical productivity, $\bar{z}_1 = 0.6$ is the productivity upper bound without private information is, $\gamma_1 = 0.25$ is a constant of proportionally, and $\epsilon \in [0, z_1(\bar{\theta}_1, 0)]$ is the uniformly distributed uncontrollable production noise.

- Division-2’s demand $d(I, z_2)$ is exponentially distributed with mean $E[d(I, z_2)(\bar{\theta}_2)] = (r1(\bar{\theta}_2) \times r_2(I)); r_2(I) = 500,000 \ln (I/500,000)$, and $r_{1(\theta_i)} = 0.125\theta_2 + 0.0625$.

- Managers’ disutility costs are $V_1(a_i, \theta_i) = \eta_1 a_i (1.5 - \theta_i)$, where $\eta_1 = 1$ and $\eta_2 = 0.1$ are proportionality constants. Managers’ private information parameter $\theta_i \in [\theta_l, \theta_u] = [0.2, 1.2]$ is uniformly distributed.

- The revenue parameters for the firm are: price per unit of Division-2’s final product $p_2 = 275$,
  price per unit of Division-1’s capacity sold in the external market $p = 29$, and net profits after sal-
use very expensive resources with a high rate of obsolescence, which have to be utilized very efficiently.  

6.3. Using DR policy

In Case (i), DR and CR allocations are the same; whereas in Case (ii), DR allocations are greater as shown in Fig. 10.

Fig. 11 illustrate the efficiency losses in a DR policy. Losses in case (ii) are greater than in case (i), because in case (ii) activity
allocations and compensations are higher and more inefficient.

Fig. 12 shows a reduction in the efficiency losses in Case (ii) after rectifying prices \( L_u = \). now the losses in both cases are similar. This figure also shows that even after the price rectification, the efficiency losses of the DR policy are lower than in the CCC policy but higher than in the CR policy.

7. Conclusion

Our results have theoretical and practical implications.

7.1. Theoretical results

We have found desirable conditions for each policy.

- When private information does not exist centralized command and control policies are superior.
- When private information exists but it does not affect operational decisions there are two situations. If the production resources are inexpensive, the centralized command and control policy is superior, because it does not have to pay informational rents in exchange for true private information. If the production resources are expensive, the centralized revelation policy is superior, because it relies on true private information.
- When private information exists and it affects operational decisions across the divisions in the chain, the decentralized revelation policy is superior but it requires carefully designated internal markets; it requires compensations based on
Our work added operational uncertainties to the models of MMR [2] and Vaysman [3]. We show that even under unlimited communication, decentralization is less efficient than centralization if private information affects interim operational decisions, thus increasing managers’ personal costs and rents. The efficiency losses due to decentralization can be rectified: Bushnell and Oren [17] and Gilbert and Riordan [18] have shown that competition can reduce the capacity to extract informational rents, and we have shown that internal prices can induce divisions to account for the global impact of their decisions, i.e., decentralization costs.

7.2. Practical results

In practice, the level of abstraction used in this research is not needed because private information and disutility costs are not measurable, but they should not be ignored. The following are rules of thumb based on the insights derived from our model and analysis that can be used to minimize the losses due to asymmetric information:

- In organizations with complex operations, delegate the decisions to the better informed workers; delegation must be accompanied by incentives, performance evaluation measures,
and mechanisms geared to achieve incentive compatibility.\textsuperscript{37}

- Use economic instead of technical measures of performance; they induce a direct focus on value-added contributions and uncover the hidden inefficiencies characteristic of internal supply chains with captive technologies.\textsuperscript{38}

\textsuperscript{37}Delegation is like decentralization; it gives its best results when there is private information that affects operational decisions.

\textsuperscript{38}We have show that the rewards in the CCC policies are based on qualitative performance evaluations and that they fail to achieve incentive compatibility.
Fig. 12. DR efficiency losses $L^{\text{ii}}$ for the rectified Case (ii).

- Discourage “free riding” by rewarding global productivity using global performance measures and local productivity using local performance measures.\(^ {39} \)
- Base rewards on a combination of estimated and observed performance to improve the efficiency outcomes of planning decisions.\(^ {40} \)

7.3. Future research

Large organizations, public and private, are viewing themselves as supply chains connecting suppliers and customers; they are modeling their operations as a chain of functions, events, transactions, and decisions that occur in the flow of their product or services from suppliers to customers. A natural addition to this research would be to expand the model to analyze the coordination of production for several periods where learning of private information is possible in each period. The model will also consider the design of market mechanisms to coordinate supply chain operations that are outside the organization’s control, i.e., suppliers and customers. The mechanisms will be designed to increase quality, improve delivery performance, and reduce demand fluctuations.

8. Uncited References

The following works are also of interest to the reader: [19–80].

References


\(^ {39} \) The CCC policy in our example paid high rewards based on global profits but it failed to induce the right behavior.

\(^ {40} \) The revelation compensation in the DR policy is based on expected and realized profits to fully induce incentive compatibility.


[25] D.E. Bailey, Focus study on work groups and improvement teams in the semiconductor industry, Working Paper, Department of Industrial Engineering and Operations Research, University of California, Berkeley, CA.


