Strategic Automation and Decision-making Authority

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This paper investigates how automation alters decision-making responsibilities of top-level executives and mid-level managers within organizations. We develop a theoretical model of a firm with a principal and two divisional managers. In each division, production tasks can be performed by workers or be automated. There are two frictions within the firm. First, there is information asymmetry: a manager holds private information that is specific to his division and critical for the firm’s decision-making. Second, there are conflicts of interest: while the principal aims to maximize the firm's total profit, the manager cares about his division more than the other division. In this setting, the principal chooses between a centralized structure and a decentralized structure, and, in addition, determines the firm’s automation strategy in the two divisions.

We formalize the communication and decision-making dynamics between the principal and the manager through an extensive-form game with embedded cheap talk. We show that the principal automates tasks strategically to manage intra-firm frictions and protect divisions from negative productivity shocks. With higher levels of automation, the principal becomes more likely to choose a centralized structure as opposed to a decentralized structure—by retaining decision-making rights rather than delegating them to a manager. In other words, automation can trickle up in organizational hierarchies and alter the decision-making structure in a firm. As a consequence, as firms automate tasks, mid-level managers become more focused on day-to-day operations and less involved in strategic decision-making on behalf of the firm.

Key words: Artificial Intelligence, Automation, Decision Making, Organizational Hierarchy

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1. Introduction

A long-standing challenge for top-level executives is to assign decision-making rights across their organizations, when mid-level managers have different priorities, incentives, and beliefs. Consider an executive who needs to sign off on the design of a next-generation product. She knows customer demand and manufacturing requirements associated with the existing design. However, to assess new designs, she needs inputs from the heads of various divisions in her firm. For instance, the head of marketing is better informed about the demand for new product designs, while the head of engineering knows more about the changes in the production processes required to manufacture the new designs. At the same time, the heads of the divisions may potentially have conflicting objectives. For instance, the head of marketing may prefer significant design changes that bring easy-to-market features, while the head of engineering may prefer minimal design modifications to avoid significant changes in the manufacturing process. The executive knows that division heads are experts in their fields but their priorities lie with their divisions—and may therefore not be fully aligned with the firm’s objectives. Should the executive make the design decision herself or leave the decision to the division heads? More generally, when should a top-level executive centralize or decentralize decision-making in her organization?

The core trade-off faced by the top-level executive in this example is ultimately a trade-off between “unbiased” and “informed” decision-making. Under centralization, the executive retains decision-making authority. Her decision treats all divisions of the firm equally and is thus unbiased—that is, aligned with the firm’s overall objective. At the same time, her decision is possibly less informed as she may not have access to all the information available to the division heads.

Under decentralization, the executive delegates decision-making authority to the division heads, thus resulting in more informed decision-making. But, on the other hand, this may introduce a bias because division managers are more concerned about their divisions’ success than that of other divisions—especially if the top-level executive’s and mid-managers’ incentives are not well-aligned.

In this paper, we revisit the centralization vs. decentralization dichotomy from a novel perspective. We study how technology can be used as an instrument to manage information asymmetries and conflicts of interest within an organization, and how it may ultimately impact the allocation of decision-making rights. Specifically, we focus here on the automation of tasks by considering a production technology that can substitute human labor (e.g., robotics, artificial intelligence). While automation has many features, we focus here on two of its critical properties. First, automation can impact operational efficiency by altering the costs of production and productivity. Second, automation can reduce the variability of operations (McKinsey & Co. 2017a) by alleviating outcome uncertainty. For instance, the International Society of Automation (2010) argues that automation reduces reliance on skill, experience, and availability of human operators, and thus improves Just
In Time (JIT) manufacturing, Total Quality Management (TQM), and Six Sigma manufacturing—the three main levers to reduce variability in operations. Similar effects are observed in health care, where automation reduces treatment variability (Kamphuis et al. 2018), and in transportation where automation ensures stricter adherence to planned trajectories (Hansen et al. 2009). While the effect of automation on operational efficiency has been well-documented, its impact on production variability has received little attention in the literature. As we shall see in this paper, however, it can play a critical role by making the divisions’ output less sensitive to the firm’s decisions—with important strategic and organizational implications.

It is timely and relevant to investigate how automation influences managerial decision-making. Technological innovation is changing organizations at a striking pace, with up to 40–50% of tasks currently performed by humans projected to be automated within the next 20 years (World Bank 2016, McKinsey & Co. 2017b). The Boston Consulting Group (2015) forecasts that robotic installations will accelerate from 2–3% today to 10% within the next decade. It is natural that many marketing tasks relevant to design, manufacturing, distribution, and after-sales support of products will in part be automated (Bhardwaj 2001). The impact of automation on labor markets has become a topic of fierce public policy debates and economic research (David and Dorn 2013, Acemoglu and Restrepo 2017, World Economic Forum 2018), but there is surprisingly little work in the marketing literature to study the impact of automation on firms’ management and organization.

To jointly study managerial decision-making and automation, we develop a theoretical model of a firm with a top-level executive (“principal”) and two division heads (“managers”). To isolate the interactions between the principal and a manager, we assume that Division 0 faces business-as-usual conditions known to the principal, while Division 1 faces uncertain conditions—the manager of Division 1 is therefore the only manager who may play a strategic role, and we refer to him as “the manager”. This environment features an internal conflict of interest, because the principal is interested in maximizing the firm’s overall profit, whereas the manager is more concerned about Division 1’s profit. It also features information asymmetry, because the manager has access to private information regarding the conditions faced by Division 1. The principal needs to make a firm-level decision, which requires weighing the considerations of both divisions and to account for the uncertainty associated with the operating conditions of Division 1.

We formalize the problem as an extensive-form game with embedded cheap talk communication (Crawford and Sobel 1982). In this setting, the principal makes two critical choices. First, she allocates decision-making rights by choosing an organizational structure between (i) centralization, in which the principal receives information from the manager but retains decision-making rights, or (ii) decentralization, in which the principal delegates decision-making rights to the manager. Second, the principal determines the firm’s automation strategy in the two divisions. We first focus on
automation deployment, assuming that the firm is endowed with an exogenous automation capacity; we then extend the analysis by endogenizing the overall level of automation capacity within the firm. The subsequent stages of the game define the resulting communication and decision-making between the principal and the manager. We solve for the Perfect Bayesian Equilibrium under the centralized and decentralized organizational structures.

In contrast to existing studies, this paper does not focus solely on the adoption of automation but also on its strategic utilization—that is, how it should strategically be allocated between the divisions in a firm to manage internal conflicts. Our paper’s key contribution is to show that, when deployed strategically, automation can alter the decision-making structure in a firm. So automation of low-level production tasks does not only affect the lower-level workers in an organization, but it also alters the decision-making authority of higher-level managers. Put differently, the impact of automation trickles up in organizational hierarchy. As we shall see, this effect of automation is not a direct outcome of increased efficiency, but stems from the reduction of production variability.

The key qualitative findings are threefold. First, automation deployment can be used as a strategic device to manage uncertainty and information asymmetry in an organization by shielding the divisions from the adverse consequences of biased or uninformed decision-making. We find that the optimal deployment of automation varies with the firm’s organizational structure. Under a decentralized structure, the principal automates the more stable division (Division 0) to mitigate the impact of biased decision-making by Division 1’s manager. Under a centralized structure, the principal does the opposite and automates the less-stable, more uncertainty-facing division (Division 1). By doing so, she reduces the importance of the manager’s private information, and mitigates the ill-effects of her poorly-informed decision. In this sense, automation deployment provides an additional degree of freedom to the principal, besides the allocation of decision-making rights within the firm—therefore reducing her reliance on the manager.

Second, automation can be used to manage intra-firm conflict. We show that, when automation capacity is endogenously determined by the principal, the capacity adopted increases in the level of intra-firm conflict. This implies that firms’ adoption of automation technologies is not a mere outcome of their cost and technological benefits, but also depends on intra-firm conflict and the firm’s organizational structure.

Third, and most importantly, with higher levels of automation, managerial decision-making in a firm becomes more centralized. We find that, all else equal, higher automation capacity (or less expensive automation adoption) makes centralization more attractive than decentralization. Automation thereby reduces the strategic role of mid-level managers and reinforces the decision-making authority at the top. This finding is counterintuitive since technology has traditionally
been considered a driving force for less hierarchical and more decentralized organizations (Acemoglu et al. 2007). We find the opposite. Note that our findings do not imply that verticals in organizational hierarchies will disappear. But, all else equal, the role of mid-level managers are likely to change and focus more on day-to-day operations of their divisions rather than strategic decision-making on behalf of the firm. This change is not due to the automation of managers’ tasks or due to reduced need for the manager (e.g., a lower need for coordination between a manager and subordinates); instead, it is an outcome of automating lower-level tasks and the resulting change in the strategic interactions between the principal and the managers.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 describes the theoretical model of the firm. It formulates extensive-form games characterizing the centralized and decentralized structures. Section 4 solves for the game’s equilibrium, and outlines the impact of automation on communication and decision-making under each structure. Section 5 highlights the firm’s allocation of automation across the two divisions and the choice of the optimal organizational structure. Section 6 extends the analysis to a setting where automation capacity is endogenously determined by the principal. We summarize our insights in Section 7.

2. Literature Review

The factors that influence firms’ decision-making structures and communication between decision-makers in organizations are of high importance to all managerial fields (Little 1970, Sah and Stiglitz 1991, Felli and Villas-Boas 2000) with studies dating back to Simon (1951) and Cyert et al. (1963).

A fundamental problem identified by this literature is the dichotomy between a centralized and a decentralized organizational structure (e.g., Grossman and Hart 1986, Jensen and Meckling 1995, Aghion and Tirole 1997, Athey and Roberts 2001, Dessein 2002). These studies formalize the trade-off between unbiased (and potentially less informed) decision-making under centralization and informed (and potentially biased) decision-making under decentralization. Rantakari (2008) and Alonso et al. (2008) consider a similar centralization-decentralization trade-off by modeling the strategic interactions between a principal and two divisional managers in a setting with two divisions that face conflicting interests but nonetheless need to coordinate—which is achieved through a communication and decision-making structure that embeds a cheap talk model (Crawford and Sobel 1982). In this paper, we leverage a similar modeling structure to integrate automation decisions and study the strategic impact of automation within the organization.

In marketing, the allocation of decision-making rights within a firm—whether the decision pertains to pricing, product design, or quality of service—has been studied largely in three ways. A first stream of studies focuses on the conflict between marketing and other divisions of the firm. For instance, Balasubramanian and Bhardwaj (2004) study the conflict between manufacturing and
marketing managers and consider a centralization-decentralization choice in the context of quality and pricing decisions. They argue that firm profits can be higher under higher levels of conflict between the two departments. Another stream focuses on the allocation of decision-making rights within sales organizations (Rubel and Prasad 2015). Bhardwaj (2001) analyze the delegation of pricing decisions by the firm to risk-averse sales representatives. They show that firms are more likely to delegate pricing decisions to the agents when competition is more intense. Mishra and Prasad (2005) extend the problem to a setting with asymmetric information between the sales agents and senior management. A third stream studies the allocation of decision-making rights in retail channels, between manufacturers and retailers. Jerath and Zhang (2010) consider a store-within-a-store arrangement in which retailers rent out retail space to manufacturers and give them autonomy over pricing and in-store service decisions. Chang and Harrington (2000) propose a computational model to determine the optimal amount of discretion given to store managers. They find that decentralization can enhance firm performance when stores’ markets are sufficiently different, the horizon is sufficiently long, and markets are sufficiently stable. In contrast to these studies, our paper explicitly considers conflicting interests and information asymmetries, and focuses on the strategic role of automation technologies in the firm’s centralization-decentralization choice.

We also contribute to the literature on the impact of technology on workers and organizations in general, and to the literature on automation in particular (e.g., Bakos and Treacy 1986, Bakos and Brynjolfsson 2000, Seidmann and Sundararajan 1997, Moriarty and Swartz 1989, Venkatraman 1994, Adamopoulos et al. 2018). Keynes (1930) and Leontief (1952) famously predicted significant macroscopic and microscopic effects of technological improvements on the economy and organizations. Rapid developments in computing, robotics, and artificial intelligence (AI) certainly confirm these early predictions. However, conclusions from recent studies do not necessarily converge to a set of unified findings (e.g., Brynjolfsson and McAfee 2011, Graetz and Michaels 2015, Acemoglu and Restrepo 2018, Frey and Osborne 2017, Acemoglu and Restrepo 2017). Greater levels of job automation are expected to increase labor skills (Mobius and Schoenle 2006) and productivity (Graetz and Michaels 2015), but also to reduce the employment of low-skill workers. Acemoglu and Restrepo (2017) estimate that the net effect of robotic installations in manufacturing environments will be negative, reducing both employment and wages. Others argue that the effect of automation is likely heterogenous across workers of different skill levels (Autor et al. 2003, 2008) as well as across firms with different service quality (Lu et al. 2017).

A related but different track investigates the complementarity and substitution between AI and human judgment (Agrawal et al. 2018a). Agrawal et al. (2018b) discuss the implications for allocating decision-making tasks to humans vs. machines and pricing artificial intelligence software. Dogan and Yildirim (2017) argue that, despite reducing production costs and the scope of moral
hazard, automation may still result in sub-optimal outcomes due to the increasing cost of incentive provision. While the research on automation, robotics and AI is growing remarkably, to our knowledge, no earlier study investigated the impact of strategic automation deployment on managerial decision-making and firms’ organizational structures—a gap that this paper aims to fill.

Studies at the intersection of organizational design and technology are rare. Bresnahan et al. (2002) find that information technology leads to more decentralized decision-making by empowering more self-managing teams. Colombo and Delmastro (2004) show that communication technologies lead to more centralization by reducing the costs of coordination between top-level executives and mid-level managers. This differentiated impact of information and communication technologies is identified explicitly by Bloom et al. (2014). Using three datasets of French and British firms, Acemoglu et al. (2007) show that the diffusion of new technologies lead to decentralization. Specifically, they find that more technologically-advanced firms are more likely to choose a decentralized organizational structure. In contrast, our paper explicitly models the decision-making and communication dynamics within a firm—and shows that the strategic use of automation to resolve inner-firm frictions leads to more centralization.

3. Model

This section introduces the structure of the firm (Section 3.1) and of production (Section 3.2). We then characterize the firm’s automation deployment (Section 3.3), and the possible centralized and decentralized organizational structures (Section 3.4).

3.1. Setting and Assumptions

Consider a firm that consists of two divisions. An executive (principal) is the head of the overall firm, and each division is led by a manager. The firm needs to make a decision, which will impact both divisions. One of the divisions (“Division 1”, henceforth) is facing changes to its operating environment. In contrast, the other division (“Division 0”, henceforth) operates in “business as usual” conditions. Given its impact on both two divisions, the firm’s decision needs to balance the stable conditions faced by Division 0 and the changing conditions of Division 1.

This environment features asymmetric information: the realized conditions of Division 1 are privately observed by its manager. The manager of Division 1 has access to early information regarding the anticipated changes in the operating environment. In contrast, the manager of Division 0 does not have access to any local information that is relevant to the firm’s decision—and thus does not play a role in the strategic decisions of the firm. Our model’s setting therefore ignores the manager of Division 0; hereafter, we refer to the manager of Division 1 as “the manager”.¹

¹ We refer to the principal as “she” and to the manager as “he” throughout the paper.
In addition, the environment under consideration features a conflict of interest between the principal and the manager. The principal’s objective is to maximize the firm’s total profit, denoted by $\Pi$. The manager, however, cares more about the economic output of Division 1 than Division 0’s. In other words, the manager’s utility, denoted by $U$, weights the profit of Division 0 by a factor $\alpha \leq 1$: the larger the value of $\alpha$, the weaker the conflict of interest between the principal and the manager. By denoting the expected profit of Division 0 and Division 1 by $\Pi_0$ and $\Pi_1$, respectively, the firm’s profit and the manager’s utility are expressed as follows:

$$\Pi = \Pi_1 + \Pi_0.$$  \hspace{1cm} (1)

$$U = \Pi_1 + \alpha \Pi_0.$$  \hspace{1cm} (2)

The asymmetric information and conflict of interest in our environment are consistent with the organizational design literature (Alonso et al. 2008, Rantakari 2008).

3.2. Production Structure

Each division is in charge of performing a continuum of tasks—normalized to unit mass without loss of generality. Each task generates an output that contributes to the division’s profit.

In each division, each task can be performed by a human worker (“non-automated task,” henceforth) or can be automated—that is, performed by a robot or an artificial intelligence software. Automated and non-automated tasks differ in three aspects. First and foremost, automation reduces production uncertainty—which makes it less contingent on the firm’s decision than human production. Second, the profit contribution of automated and non-automated tasks may be different. Our setting does not make any assumption on the relative productivity of automated machines vs. human workers. Third, workers choose an effort level while executing the task, which impacts the outcome. In contrast, the output of automated tasks depends on technological capabilities alone and not on effort choices.

Non-automated tasks. The output of a non-automated task in Division $i = 0, 1$ depends on two factors: (i) the division’s productivity (denoted by $p_i$), and (ii) the effort exerted by the workers (denoted by $e \geq 0$). We assume that the productivity of Division $i = 0, 1$ can be either high ($p_i = h$) or low ($p_i = l$), with $h > l$. Workers’ effort choice comes at a cost of effort, given by $c(e) = ce^2$ for some $c > 0$. The outcome of each non-automated task is then given by $p_i e$.

Workers’ effort choices are based on the realized productivity in their division. We assume that effort choices are contractible: they can be observed by the principal who can then implement
the efficient effort choice without leaving any rent to the workers. Each worker’s effort choice \( e \) therefore maximizes its profit contribution \( p_i e - ce^2 \). The resulting effort choice satisfies:

\[
e = \begin{cases} \frac{h}{2c} & \text{if } p_i = h, \\ \frac{l}{2c} & \text{if } p_i = l, \end{cases}
\]

Therefore, the profit contribution of each non-automated task in Division \( i = 0, 1 \) is equal to \( \frac{h^2}{4c} \) if \( p_i = h \) and \( \frac{l^2}{4c} \) if \( p_i = l \).

Automated tasks. The output of an automated task is identical across the divisions and does not depend on their productivity. We denote the profit contribution of each automated task by \( \rho \). The qualitative insights derived in this paper would hold if we modeled the effects of automation through reduced production variability—rather than no variability.

Productivity of Divisions As mentioned earlier, the firm needs to make a decision that will affect the productivity of both divisions. Therefore, the firm needs to balance the objectives of complying with the current operating conditions faced by Division 0 and of adapting to the new operating conditions faced by Division 1.

To formalize the operating conditions faced by each division, we introduce a variable referred to as the “state” of Division \( i = 0, 1 \), and denoted by \( \theta_i \). The state of Division 0 is publicly known and normalized to \( \theta_0 = 0 \). The state of Division 1 is subject to uncertainty. We model \( \theta_1 \) as a random variable drawn from the uniform distribution over \([-1, 1]\). This assumption implies that \( \mathbb{E}(\theta_1) = \theta_0 \), hence there is no systematic bias in the changing environment faced by Division 1. The distribution of \( \theta_1 \) is publicly known, but its realized value is privately observed by the manager.

The firm’s decision is denoted by \( d \in \mathbb{R} \). The closer the firm’s decision is to \( \theta_i \), the more likely the productivity in Division \( i \) is to be high. Formally, the firm’s decision impacts the productivity of each division by means of the following quadratic functions:

\[
\mathbb{P}(p_i = h) = 1 - (\theta_i - d)^2 \tag{4}
\]
\[
\mathbb{P}(p_i = l) = (\theta_i - d)^2 \tag{5}
\]

Setting \( d \) close to \( \theta_0 \) (known with certainty) can be interpreted as a continuity strategy. Vice versa, setting the value closer to \( \theta_1 \) (which realizes with uncertainty) can be interpreted as an adaptation strategy. The challenge in setting the variable \( d \) lies in the asymmetry of information between the principal and the manager and the internal conflict of interest (Equations (1) and (2)). The firm’s automation strategy and organizational structure will aim to manage these frictions.

\(^2\) Alternatively, one could assume that the workers’ effort choices are not publicly observed—thus creating a moral hazard problem. This would lead to a more complex exposition but would not affect any of the results or insights.
3.3. Automation Deployment
We first assume that the firm is endowed with an exogenous “automation capacity”—the resources available to the firm for the automation of tasks. We denote this automation capacity by $\zeta$.

The principal decides how to allocate this automation capacity between the divisions. We denote by $\zeta_0$ and $\zeta_1$ the automation capacity allocated to Division 0 and Division 1, respectively, such that $\zeta_0 + \zeta_1 = \zeta$. We assume $\zeta < 1$, i.e., the principal cannot automate all the tasks in any division. The allocation of automation is publicly observed and does not alter operating costs. Without loss of generality, we assume that the cost of operation for each automated task is equal to 0.

In Section 6, we relax the assumption that the automation capacity is exogenously given. Instead, we consider a setting where the principal simultaneously determines the overall automation capacity $\zeta$ and its allocation across the two divisions.

3.4. Possible Organizational Structures of the Firm
We consider two alternative organizational structures: centralization and decentralization. Under centralization, the principal remains in charge of the decision $d \in \mathbb{R}$. In this case, she asks the manager to send an informative message about the realized state variable $\theta_1$. In practice, this communication corresponds to any report or input that informs the top-level management. Under decentralization, the principal delegates the decision-making rights to the manager, who then makes the decision $d \in \mathbb{R}$ on behalf of the entire firm. In this case, there is no communication between the principal and the manager, as the informed party is in charge of decision-making.

As discussed in the introduction, this dichotomy involves a trade-off between unbiased vs. informed decision-making. Under centralization, the principal can align the decision with the firm’s overall objective, but may not base this decision on accurate information in case the conflict of interest between the principal and the manager leads to imperfect information transmission. Under decentralization, the manager has access to perfect information but may make a biased decision toward Division 1, which may thus result in a sub-optimal decision from the firm’s standpoint.

These two organizational structures are shown in Figure 1. We formalize next the strategic interactions between the principal and the manager under each structure. To represent the events, we use the superscripts $C$ and $D$ to refer to the centralized and decentralized structures, respectively.

Centralized Structure The sequence of events under centralization is shown in Figure 2.

In the first stage, the principal determines the allocation of automation capacity between the two divisions (i.e., $\zeta_0^C$ and $\zeta_1^C$). The manager then privately observes the realized value of $\theta_1$. He provides an informative message about the realized value of $\theta_1$ to the principal, denoted by $m(\theta_1)$. Following the seminal paper of Crawford and Sobel (1982), we assume that the communication between the principal and the manager is cheap talk, that is the transmitted information is not
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Figure 1: Representation of centralized and decentralized structures.

(a) Centralized structure

(b) Decentralized structure

Figure 2: Sequence of events and timing under the centralized structure.

1. Principal chooses \( \zeta^C_0 \), and \( \zeta^C_1 \).
2. Manager observes \( \theta_1 \) and sends a message to Principal.
3. Principal makes decision \( d^C \).
4. Productivity realizes for both divisions.
5. Payoffs realize.

Let \( M \) be the set of messages that can be transmitted by the manager to the principal. The manager’s communication strategy is defined via a mapping \( \sigma \) from the state space \( \Theta \) to the space of probability measures over \( M \), which we denote by \( \Delta M \):

\[
\sigma : \Theta \rightarrow \Delta M.
\]

After receiving the message, the principal updates her beliefs about the realized value of \( \theta_1 \) according to Bayes’ Rule. This is written as follows:

\[
P(\theta_1 = \theta | m) = \frac{f(\theta_1)P(\sigma(\theta_1) = m)}{\int_{\theta_1 \in \Theta} f(\tilde{\theta}_1)P(\sigma(\tilde{\theta}_1) = m) d\tilde{\theta}_1}
\]

Following the update, the principal sets \( d^C \) to maximize the total expected profit of the firm \( \Pi \). The decision is a mapping from the message space to the set of real numbers.\(^3\)

\[
d^C : M \rightarrow \mathbb{R}.
\]

\(^3\) Here, \( d^C \) refers to a function that maps each message received by the principal to a decision (rather than the decision itself). This slight abuse of notation makes the exposition clearer, without impacting the developments.
Next, the productivity of each division realizes based on the decision $d^C$ and state variable $\theta_1$, according to Equations (4) and (5). The workers in Division $i = 0, 1$ who are assigned a task make their effort choices based on the realized productivity $p_i \in \{h, l\}$ (Equation (3)).

**Decentralized Structure** The sequence of events under decentralization is shown in Figure 3. The main difference with centralization is that the manager is not asked to report an informative message about $\theta_1$, but is in charge of the decision $d$.

As under centralization, the principal first determines the allocation of automation capacity (i.e., $\zeta^D_1$ and $\zeta^D_0$). Then, the manager privately observes the realized value of $\theta_1$ and makes the decision. The decision is now defined as a direct mapping from the state space to the set of real numbers.

$$d^D : \Theta \rightarrow \mathbb{R}.$$  

Next, the productivity of each division realizes based on the decision $d^D$ and state variable $\theta_1$, according to Equations (4) and (5). As under centralization, the workers in Division $i = 0, 1$ make their effort choices based on the realized productivity $p_i \in \{h, l\}$ (Equation (3)).

### 4. Equilibrium Analysis

In this section, we characterize the equilibrium under both organizational structures. We adopt the Perfect Bayesian Equilibrium solution concept. In other words, we identify the players’ sequentially rational strategies based on their beliefs determined by available information and Bayes’ rule.

We follow the game descriptions in Figures 2 and 3 and proceed by backward induction. We first derive the profits of each division (Steps $C5$ and $D5$ in Figures 2 and 3), contingent on realized productivities, automation allocation, and the firm’s decision. We use the resulting payoff functions to characterize optimal decision-making under each organizational structure (Steps $C3a$, $C3b$ and $D3$). Lastly, we formalize the principal’s strategic problems of automation allocation and organizational structure selection (Steps $C1$ and $D1$). All proofs are reported in Appendix A.
4.1. Payoffs

For any allocation of automation capacity (i.e., $\zeta_1$ and $\zeta_0$), the profit of each division is determined by the realized productivity level (i.e., $h$ or $l$). We denote by $\pi_{ih}(\zeta_i)$ and $\pi_{il}(\zeta_i)$ the profit of Division $i$ under high and low productivity levels, respectively, for any automation capacity $\zeta_i$. These functions incorporate the profit contributions of non-automated tasks and of automated tasks, weighted by the factors $1 - \zeta_i$ and $\zeta_i$ which reflect the fraction of non-automated and automated tasks in Division $i$, respectively.

\[
\pi_{ih}(\zeta_i) = (1 - \zeta_i) \frac{h^2}{4c} + \zeta_i \rho
\]

\[
\pi_{il}(\zeta_i) = (1 - \zeta_i) \frac{l^2}{4c} + \zeta_i \rho
\]

One important expression is the difference between the profit levels for Division $i = 0, 1$ under high and low productivity—which can also be interpreted as the gain from high productivity in Division $i = 0, 1$ for a given allocation of automation capacity. We denote it by $\Delta_i(\zeta_i)$.

\[
\Delta_i(\zeta_i) = (1 - \zeta_i) \frac{h^2 - l^2}{4c}.
\]

4.2. Decision-making

We now turn to the decision-making stage. In contrast to the analysis carried out until now, the decision is made before the productivity levels are realized and observed. Therefore, the decision-maker maximizes the expected profit of the firm (under centralization) or the manager’s expected utility (under decentralization), accounting for productivity uncertainty.

We denote the expected profit of Division $i$ for any allocated automation capacity ($\zeta_i$), firm’s decision ($d$), and state ($\theta_i$) by $\bar{\pi}_i(\zeta_i, d, \theta_i)$. It is written as:

\[
\max_d \bar{\pi}_i(\zeta_i, d, \theta_i) + \alpha \bar{\pi}_0(\zeta_0, d, \theta_0).
\]

4.2.1. Decentralization The manager makes the decision $d^D$ to maximize his expected utility, as a function of the level of automation in each division (i.e., $\zeta_1^D$ and $\zeta_0^D$) and the observed state in Division 1 (i.e., $\theta_1$). It is written as:

\[
\max_{d^D} \bar{\pi}_1(\zeta_1^D, d^D, \theta_1) + \alpha \bar{\pi}_0(\zeta_0^D, d^D, \theta_0).
\]
The optimal decision $d_D$, shown in Lemma 1, is proportional to the observed state $\theta_1$. Moreover, the manager’s decision does not depend on the level of each division’s profit, but only on the difference between the realized profits in high and low-productivity scenarios (Equation (7)).

**Lemma 1.** Under decentralization, the optimal decision of the manager is given by:

$$d_D = \beta_D(\zeta_1^D, \zeta_0^D)\theta_1,$$

where $\beta_D(\zeta_1^D, \zeta_0^D) = \Delta_1(\zeta_1^D) / \Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)$.

An important observation from Lemma 1 is that, as long as $\alpha > 0$, the manager imperfectly adapts to the realized state in Division 1. Indeed, we have $\beta_D(\zeta_1^D, \zeta_0^D) < 1$, so the manager’s decision is such that $|d_D| < |\theta_1|$. In other words, the decision $d_D$ strikes a middle ground between a pure continuity strategy (setting $d = \theta_0 = 0$) and a pure adaptation strategy (setting $d = \theta_1$). This reflects the fact that the manager does account for the profit realized in Division 0 in his decision-making. Moreover, $\beta_D(\zeta_1^D, \zeta_0^D)$ decreases as $\alpha$ gets larger: the manager favors Division 1 to a lesser extent as the conflict between the principal and the manager gets weaker.

From the optimal decision of the manager, we can now derive the expected profit of the firm under decentralization for any allocation of automation capacity. It is denoted by $\Pi^D(\zeta_1^D, \zeta_0^D)$, and given in Equation (10). Specifically, the firm’s expected profit is equal to the sum of profits across two divisions, averaged out over all realizations of $\theta_1$. Note that, even though $\theta_0$ is known deterministically, the profit of Division 0 is also subject to uncertainty given the endogeneity of the manager’s decision with respect to the realization of $\theta_1$, which is only known probabilistically.

$$\Pi^D(\zeta_1^D, \zeta_0^D) = \int_{\Theta} \left[ \bar{\pi}_1(\zeta_1^D, d^D, \theta_1) + \bar{\pi}_0(\zeta_0^D, d^D, \theta_0) \right] \frac{d\theta_1}{2}$$

Following some algebra, we derive a closed-form solution of the expected profit of the firm under decentralization in Proposition 1.

**Proposition 1.** Under decentralization, the expected profit of the firm is equal to:

$$\Pi^D(\zeta_1^D, \zeta_0^D) = \pi_{ih}(\zeta_1^D) + \pi_{0h}(\zeta_0^D) - \frac{\Delta_1(\zeta_1^D) \Delta_0(\zeta_0^D) [\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)]}{3 [\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)]^2}.$$  

The first two terms in Equation (11) correspond to the firm’s total profit when productivity is high in each division. The last term reflects the expected loss resulting from productivity uncertainty. This loss function decreases with $\alpha$: as the manager’s incentives are more aligned with the principal’s, the manager’s decision gets closer to the decision that the principal would make in the absence of information asymmetries, which results in a higher expected profit for the firm. Vice versa, in case of extreme conflict reflected by $\alpha = 0$, the manager completely ignores Division 0 by setting

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$d^D = \theta_1$. This results in high productivity in Division 1 while Division 0’s productivity is subject to uncertainty. The expected profit of the firm is then equal to $\pi_1h(\zeta^D_1) + \frac{2}{3}{\pi_0}(\zeta^D_0) + \frac{1}{3}{\pi_0}(\zeta^D_0)$.\(^4\)

### 4.2.2. Centralization

We now turn to the centralized structure. We first characterize the principal’s decisions after she receives a message from the manager and updates her beliefs regarding the realized value of $\theta_1$ (Step C3b of Figure 2). We then leverage her decision-making behavior to identify the equilibrium communication between her and the manager (Step C3a of Figure 2).

**Principal’s Decision.** For any message $m$ received from the manager, the principal optimizes her decision $d^C$ to maximize the expected profit of the firm as a function of the automation capacity in each division ($\zeta^C_1$ and $\zeta^C_0$). Here, the expectation is taken over the realized productivity level in each division as well as the uncertainty over the realized state of the world in Division 1, conditional on the message received. Note that only the profit of Division 1 is subject to uncertainty on $\theta_1$ here, since $\theta_0$ is known and $d^C$ is controlled by the principal. The problem can be formulated as:

$$\max_{d^C} E [\bar{\pi}_1(\zeta^C_1, d^C, \theta_1) | m] + \bar{\pi}_0(\zeta^C_0, d^C, \theta_0)$$

By proceeding as under decentralization, we derive the optimal decision $d^C$ in Lemma 2. We find that it is proportional to the expected value of $\theta_1$ conditional on the message received.

**Lemma 2.** Under centralization, the optimal decision of the principal, as a function of the message $m$ received from the manager, is given by:

$$d^C(m) = \beta^C(\zeta^C_1, \zeta^C_0)E(\theta_1 | m), \text{ where } \beta^C(\zeta^C_1, \zeta^C_0) = \frac{\Delta_1(\zeta^C_1)}{\Delta_1(\zeta^C_1) + \Delta_0(\zeta^C_0)}. \quad (12)$$

As the value of $\beta^C(\zeta^C_1, \zeta^C_0)$ is lower than 1, the principal only partially adapts to her belief regarding the state of the world in Division 1. This reflects the fact that the principal balances the profit outcomes of the two divisions—similar to the manager’s strategy under decentralization when $\alpha > 0$. However, we have $\beta^C(\zeta^C_1, \zeta^C_0) < \beta^D(\zeta^D_1, \zeta^D_0)$ when $\alpha < 1$. Therefore, if the principal were to observe the realized value of $\theta_1$, she would favor Division 0 to a greater extent than the manager does under decentralization. This results directly from the fact that the principal assigns a higher weight to Division 0’s profit than the manager does.

**Equilibrium Communication.** We now use the principal’s decision-making behavior (Step C3b) to characterize the communication between the principal and the manager (Step C3a). As in any cheap talk model, there exists a babbling equilibrium under which the principal ignores the message.

\(^4\)In this expression, the weights $\frac{2}{3}$ and $\frac{1}{3}$ stem from the expected value of $1 - (\theta_1 - \theta_0)^2$ and of $(\theta_1 - \theta_0)^2$, respectively, when $\theta_1$ is uniformly distributed over $[-1, 1]$ and $\theta_0 = 0$. 

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provided by the manager and the manager fully randomizes his message. This is due to the self-fulfilling nature of the non-verifiable messages. More generally, there may exist multiple equilibria, under which the messages provided by the manager carry various levels of information. In this paper, we consider the most informative communication between the two players, referred to as *equilibrium communication*.

Proposition 2 characterizes the equilibrium communication when $\alpha < 1$. When $\alpha = 1$, the manager simply reports the exact value of $\theta_1$ truthfully to the principal as there is no conflict of interest between the two parties.

**Proposition 2.** When $\alpha < 1$, the equilibrium communication is as follows. The state space $\Theta = [-1, 1]$ is partitioned into infinitely many sub-intervals as follows:

$$
\Theta = \left( \bigcup_{n=1}^{\infty} [\psi_{-n}, \psi_{-(n+1)}] \right) \cup \left( \bigcup_{n=1}^{\infty} (\psi_{n+1}, \psi_n) \right).
$$

The sequences $\{\psi_{-n}\}_{n=1}^{\infty}$, and $\{\psi_n\}_{n=1}^{\infty}$ are defined such that:

$$
-1 = \psi_{-1} < \psi_{-2} < \psi_{-3} < \ldots < \theta_0 = 0 < \ldots < \psi_3 < \psi_0 < \psi_1 = 1,
$$

and

$$
\psi_n = -\psi_n = \left( \frac{\Delta_1(\zeta_1^C) + (2 - \alpha)\Delta_0(\zeta_0^C) - 2\sqrt{(1 - \alpha)\Delta_0(\zeta_0^C)(\Delta_1(\zeta_1^C) + \Delta_0(\zeta_0^C))}}{\Delta_1(\zeta_1^C) + \alpha\Delta_0(\zeta_0^C)} \right)^{n-1}.
$$

There exist message sequences $\{m_{-n}\}_{n=1}^{\infty}$ and $\{m_n\}_{n=1}^{\infty}$ such that the manager’s report satisfies $\sigma(\theta_1) = m_n$, $\forall \theta_1 \in (\psi_{n+1}, \psi_n)$, and $\sigma(\theta_1) = m_{-n}$, $\forall \theta_1 \in [\psi_{-n}, \psi_{-(n+1)})$.

The structure of the equilibrium communication described in Proposition 2 is shown in Figure 4. Specifically, the interval $\Theta = [-1, 1]$ is partitioned into infinitely many sub-intervals, and the manager reports a unique message for all values of $\theta_1$ that fall into the same sub-interval. These intervals are defined by the cutoff values $\{\psi_{-n}\}_{n=1}^{\infty}$, and $\{\psi_n\}_{n=1}^{\infty}$, and the corresponding messages are denoted by $\{m_{-n}\}_{n=1}^{\infty}$, and $\{m_n\}_{n=1}^{\infty}$.

Several observations on the equilibrium communication are noteworthy. First, the sub-intervals governing the equilibrium communication are symmetrically distributed around the value of
\( E(\theta_1) = \theta_0 = 0 \). This is due to the symmetry of the distribution of \( \theta_1 \). Second, the length of the sub-intervals decreases as the value of \( \theta_1 \) approaches \( \theta_0 \); the communication becomes decreasingly informative as Division 1 faces a stronger change in its operating conditions. This stems from the fact that, as \(|\theta_1|\) gets larger, the extent of the conflict between the principal and the manager increases, which increases the strategic behaviors from the manager. Last, the general structure of the equilibrium communication identified in Proposition 2 is similar to the results of Alonso et al. (2008) and Rantakari (2008), obtained with two strategic managers and two sources of uncertainty (unlike our setting, which comprises one strategic manager and one source of uncertainty).

Upon receiving the message \( m_n \), the principal infers that \( \theta_1 \) falls into the sub-interval \((\psi_{n+1}, \psi_n]\). Therefore, the principal updates her beliefs, such that the probability distribution of \( \theta_1 \), conditional on the message, is uniform within the corresponding sub-interval. As a result, we have:

\[
\mathbb{E}(\theta_1|m_n) = \frac{\psi_{n+1} + \psi_n}{2}, \forall n \geq 1.
\]

From Lemma 2, we obtain that:

\[
d^C(m_n) = \beta^C(\zeta^C_1, \zeta^C_0) \frac{\psi_{n+1} + \psi_n}{2}, \forall n \geq 1.
\]

From the equilibrium communication between the principal and the manager and the resulting decision of the principal, we derive the expected profit of the firm under centralization, conditional on the allocation of automation capacity. We denote it by \( \Pi^C(\zeta^C_1, \zeta^C_0) \). As under decentralization, it is equal to the total profit across the two divisions, averaged out over all the possible realizations of \( \theta_1 \), but it now accounts for the information received by the manager. It is given in Equation (15).

\[
\Pi^C(\zeta^C_1, \zeta^C_0) = \sum_{n=-\infty}^{n=-1} \int_{\psi_{n+1}}^{\psi_{n+1}} \left[ \tilde{\pi}_1(\zeta^C_1, d^C(m_{-n}), \theta_1) + \tilde{\pi}_0(\zeta^C_0, d^C(m_{-n}), \theta_0) \right] \frac{d\theta_1}{2} \\
+ \sum_{n=1}^{n=\infty} \int_{\psi_n}^{\psi_{n+1}} \left[ \tilde{\pi}_1(\zeta^C_1, d^C(m_n), \theta_1) + \tilde{\pi}_0(\zeta^C_0, d^C(m_n), \theta_0) \right] \frac{d\theta_1}{2}
\]

The closed-form solution of this profit equation is provided in Proposition 3.

**Proposition 3.** Under centralization, the expected profit of the firm is equal to:

\[
\Pi^C(\zeta^C_1, \zeta^C_0) = \pi_{1h}(\zeta^C_1) + \pi_{0h}(\zeta^C_0) - \frac{(4 - \alpha)\Delta_1(\zeta^C_1)\Delta_0(\zeta^C_0)}{3(3\Delta_1(\zeta^C_1) + (4 - \alpha)\Delta_0(\zeta^C_0))},
\]

An analogous version of this statement holds when the principal receives any message \( m_{-n} \), with \( n \geq 1 \).
The general form of the expected profit of the firm is similar to the one under decentralization (Proposition 1). Indeed, the first two terms correspond to the profit under high productivity, and the last term reflects the cost of productivity uncertainty. Moreover, the firm’s profit increases with the value of $\alpha$ (i.e., as the conflict of interest between the principal and the manager is reduced). This is similar to decentralization but stems from a different mechanism. Under decentralization, higher values of $\alpha$ trigger a decision from the manager that is more aligned with the firm’s profit-maximizing objective. Under centralization, in contrast, higher values of $\alpha$ trigger more informative communication from the manager to the principal.

4.3. Principal’s Strategic Problem

We now move to the final stage of our backward induction, i.e., the allocation of automation capacity across the two divisions (Steps C1 and D1 in Figures 2 and 3). We leverage the expression of the firm’s expected profit for each of the two organizational structures (Propositions 1 and 3). These expressions capture all subsequent equilibrium decisions and uncertainties under each structure.

We refer to the first-stage problem under decentralization as $(P^D)$. It is written as:

$$\max_{\zeta^D_1, \zeta^D_0} \pi_{1h}(\zeta^D_1) + \pi_{oh}(\zeta^D_0) - \frac{\Delta_1(\zeta^D_1)\Delta_0(\zeta^D_0)[\Delta_1(\zeta^D_1) + \alpha^2\Delta_0(\zeta^D_0)]}{3[\Delta_1(\zeta^D_1) + \alpha\Delta_0(\zeta^D_0)]^2},$$

s.t. $\zeta^D_1 + \zeta^D_0 = \zeta, \quad \zeta^D_1, \zeta^D_0 \geq 0$.

We refer to the first-stage problem under centralization as $(P^C)$. It is written as:

$$\max_{\zeta^C_1, \zeta^C_0} \pi_{1h}(\zeta^C_1) + \pi_{oh}(\zeta^C_0) - \frac{(4 - \alpha)\Delta_1(\zeta^C_1)\Delta_0(\zeta^C_0)}{3[3\Delta_1(\zeta^C_1) + (4 - \alpha)\Delta_0(\zeta^C_0)]^2},$$

s.t. $\zeta^C_1 + \zeta^C_0 = \zeta, \quad \zeta^C_1, \zeta^C_0 \geq 0$.

Note that both problems are equivalent when $\alpha = 1$. This stems from the fact that, in the absence of conflict between the principal and the manager, the communication is fully informative under centralization and the equilibrium decisions are identical under the two organizational regimes.

In Section 5, we will use expressions (6) and (7) to solve Problems $(P^D)$ and $(P^C)$, and derive the optimal allocation of automation capacity across the two divisions. By comparing the corresponding optimal expected profits, we can then find the optimal organizational structure from the principal’s perspective. As we will show, this choice depends exclusively on the overall automation capacity and the extent of the conflict between the principal and the manager—that is, it depends on parameters $\zeta$ and $\alpha$ but not on any other parameter.

Before moving to the optimal automation allocation, we summarize the main results of this section and discuss the role of automation on the firm’s decision-making and communication.

Recall that the optimal decision of the manager under decentralization is given by \( d^D(\theta_1) = \beta^D(\zeta_1, \zeta_0)\theta_1 \) (Lemma 1) and that that the optimal decision of the principal under centralization is given by \( d^C(m) = \beta^C(\zeta_1, \zeta_0)E(\theta_1|m) \), where \( m \) is determined by the manager as a function of \( \theta_1 \) (Lemma 2). Figure 5 summarizes these decisions by showing, for each value of \( \theta_1 \): (i) the optimal decision of the manager under decentralization, \( d^D(\theta_1) \), (the blue line); (ii) the optimal decision of the principal under centralization, \( d^C(m(\theta_1)) \) (the red line); and (iii) a benchmark representing the principal’s ideal decision under perfect information, i.e., \( \beta^C\theta_1 \) (the dashed green line).

Notice that, the slopes of both the blue line and the dashed green line are lower than 1, implying that both the principal and the manager balance the profits of both divisions. The slope of the dashed green line, however, is lower than the slope of the blue line, indicating that the principal assigns a higher weight to Division 0’s profit than the manager. Under centralization, due to imperfect communication, there remains uncertainty regarding the true value of \( \theta_1 \) from the principal’s perspective, so her decisions in equilibrium do not necessarily correspond to her ideal decisions. For some values of \( \theta_1 \), the principal’s decision under centralization favors Division 1 even more than the manager’s decision under decentralization.

![Figure 5 Decisions under centralization, the decentralized structure, and perfect information.](https://ssrn.com/abstract=3226222)
Moreover, the manager’s and the principal’s decisions depend on the automation capacity in each division. First, all else equal, larger automation capacity in Division 1 (resp. Division 0) results in more (resp. less) favorable decisions for Division 0, under both organizational structures. Stated differently, the more a division is automated, the less favorable the firm’s decision is toward this division. Recall that, as automation capacity increases in a division, its production becomes less sensitive to the firm’s decision. As a result, the decision-maker (i.e., the principal or the manager, depending on the organizational structure) tends to favor the other division to a greater extent. Mathematically, this result is obtained by showing that $\beta^D(\zeta_1, \zeta_0)$ and $\beta^C(\zeta_1, \zeta_0)$ are both decreasing functions of $\zeta_1$ (keeping $\zeta_0$ constant) and increasing functions of $\zeta_0$ (keeping $\zeta_1$ constant). We summarize this result in Corollary 1.

**Corollary 1.** As $\zeta_1$ increases, the decision of the manager under decentralization (for any value of $\theta_1$) and the decision of the principal under centralization (for any posterior belief regarding $\theta_1$) favor Division 0 to a greater extent. As $\zeta_0$ increases, both decisions favor Division 1 to a greater extent. In other words, $|d^D(\theta_1)|$ and $|d^C(m(\theta_1))|$ are both increasing in $\zeta_1$ and decreasing in $\zeta_0$.

Second, automation impacts the alignment between the principal and the manager. We quantify this alignment as the ratio between the principal’s decision under perfect information (the dashed green line in Figure 5) and the manager’s decision (the blue line). Note that this notion of alignment (defined below via $r(\zeta_1, \zeta_0)$) differs from intra-firm conflict (defined through the parameter $\alpha$) in that intra-firm conflict is an *ex ante* measure of the divergence between the principal’s and the manager’s incentives but alignment is an *ex post* measure of the convergence in their decisions.

**Definition 1.** The degree of alignment between the principal and the manager is given by:

$$r(\zeta_1, \zeta_0) = \frac{\beta^C(\zeta_1, \zeta_0)}{\beta^D(\zeta_1, \zeta_0)} \in [0, 1].$$

The larger the ratio $r(\zeta_1, \zeta_0)$, the more aligned the decisions of the two players. Corollary 2 shows that, all else equal, larger automation capacity in Division 1 (resp. Division 0) results in smaller (resp. greater) alignment between the decisions of the principal and the manager.

**Corollary 2.** The degree of alignment between the principal and the manager is equal to $r(\zeta_1, \zeta_0) = \frac{\Delta_1(\zeta_1) + \alpha \Delta_0(\zeta_0)}{\Delta_1(\zeta_1) + \Delta_0(\zeta_0)}$. It decreases with $\zeta_1$ and increases with $\zeta_0$.

Last, automation impacts the value of the manager’s information to the principal. We quantify the value of information as the difference between the firm’s profit under perfect information vs. no information.

**Definition 2.** The value of information to the principal is given by:

$$VOI(\zeta_1, \zeta_0) = \Pi(\zeta_1, \zeta_0) - \Pi(\zeta_1, \zeta_0),$$

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where \(\Pi(\zeta_1, \zeta_0)\) and \(\Pi'(\zeta_1, \zeta_0)\) denote the expected profit of the firm under no information and perfect information, respectively. Formally, we denote by \(d^C(m)|_{m=\emptyset}\) the decision that the principal would make if she received no message from the manager and by \(d^C(m)|_{m=\theta_1}\) the decision she would make if she received a perfectly informative message. \(\Pi(\zeta_1, \zeta_0)\) and \(\Pi'(\zeta_1, \zeta_0)\) are then given by:

\[
\Pi(\zeta_1, \zeta_0) = \mathbb{E}\left[\bar{\pi}_0(\zeta_0, d^C(m)|_{m=\emptyset}, \theta_0)\right] + \mathbb{E}\left[\bar{\pi}_1(\zeta_1, d^C(m)|_{m=\emptyset}, \theta_1)\right],
\]

(19)

\[
\Pi'(\zeta_1, \zeta_0) = \mathbb{E}\left[\bar{\pi}_0(\zeta_0, d^C(m)|_{m=\theta_1}, \theta_0)\right] + \mathbb{E}\left[\bar{\pi}_1(\zeta_1, d^C(m)|_{m=\theta_1}, \theta_1)\right].
\]

(20)

Corollary 3 shows that, all else equal, larger automation capacity in Division 1 (resp. Division 0) results in smaller (resp. greater) value of information.

**Corollary 3.** The value of information is equal to \(VOI(\zeta_1, \zeta_0) = \frac{\Delta_1(\zeta_1)^2}{3(\Delta_1(\zeta_1)+\Delta_0(\zeta_0))}\). It decreases with \(\zeta_1\) and increases with \(\zeta_0\).

These corollaries highlight the strategic importance of automation on communication and decision-making within the firm. This stems from the fact that automation changes the extent of alignment between the principal and the manager (Corollary 2) and the principal’s reliance on the manager (Corollary 3). Under decentralization, the manager’s decision becomes more favorable to Division 0 as Division 1 is more automated (Corollary 1). Under centralization, as Division 1 is more automated, the principal’s decision also becomes more favorable to Division 0 (Corollary 1), but to a greater extent than the manager would like (Corollary 2). As a result, the manager chooses to shield himself from “excessive” accommodation of Division 0 by the principal, and therefore sends less informative messages.\(^6\) In other words, higher automation capacity in Division 1 makes the manager more accommodating toward Division 0 under decentralization but less informative under centralization. We exploit these results in the next section to determine the optimal allocation of automation capacity across the two divisions.

### 5. Role of Strategic Automation

The main objective of this section is to solve the principal’s problem on automation capacity allocation and to determine the optimal organizational structure. This corresponds to Problems \((P^C)\) and \((P^P)\), and to Steps \(C1\) and \(D1\) in Figures 2 and 3. Before doing so, we establish a benchmark in which the principal treats the two divisions symmetrically when allocating automation capacity. All proofs are reported in Appendix B.

\(^6\) Less informative communication is reflected by wider sub-intervals in Proposition 2. It can be verified numerically that, for any \(n \geq 1\), \(\psi_n\) (resp. \(\psi_{-n}\)) decreases (resp. increases) with \(\zeta_1\) and increases (resp. decreases) with \(\zeta_0\).
5.1. Benchmark: Symmetric Allocation of Automation Capacity

In this benchmark, we assume that the principal allocates automation capacity equally across the two divisions. This is motivated by the fact that both divisions are \textit{ex ante} identical before the realization of $\theta_1$. We derive the resulting profit of the firm for the two organizational structures.

With $\zeta_1 = \zeta_0 = \frac{\zeta}{2}$, we derive the firm’s profits by using Equations (11) and (16) together with Equations (6) and (7). We denote them by $\Pi^D_S$ and $\Pi^C_S$, respectively.

\begin{align}
\Pi^D_S &= (2 - \zeta) \frac{h^2}{4c} + \zeta \rho - \frac{1 + \alpha^2}{3(1 + \alpha)^2} \left(1 - \frac{\zeta}{2}\right) \frac{h^2 - l^2}{4c} \quad (21) \\
\Pi^C_S &= (2 - \zeta) \frac{h^2}{4c} + \zeta \rho - \frac{4 - \alpha}{3(7 - \alpha)} \left(1 - \frac{\zeta}{2}\right) \frac{h^2 - l^2}{4c} \quad (22)
\end{align}

Comparison of these profit functions yields the optimal organizational structure under symmetric automation, as given in Proposition 4.

**PROPOSITION 4.** When automation capacity is symmetrically allocated between the two divisions, the centralized structure is optimal if $\alpha \leq 0.6$ and the decentralized structure is optimal if $\alpha \geq 0.6$.

Intuitively, the choice of organizational structure depends on the level of conflict between the principal and the manager. If conflict is high (when $\alpha$ is small), centralization is optimal for the firm: the principal retains decision-making rights. Conversely, if conflict is low (when $\alpha$ is large), decentralization is optimal: the principal delegates decision-making rights to the manager. Note, importantly, that the optimal organizational structure does not depend on the total automation capacity of the firm under symmetric automation allocation.

5.2. Optimal Allocation of Automation Capacity

We now solve Problems $(\mathcal{P}^C)$ and $(\mathcal{P}^D)$ to determine the optimal allocation of automation capacity and to compute the corresponding profits. Proposition 5 identifies the equilibrium values of $\zeta_1$ and $\zeta_0$ under each organizational structure.

**PROPOSITION 5.** Optimal allocation of automation capacity is as follows:

(i) Under the decentralized structure, $\zeta^D_1 = 0$, and $\zeta^D_0 = \zeta$.

(ii) Under the centralized structure, $\zeta^C_1 = \zeta$, and $\zeta^C_0 = 0$.

Under both organizational structures, the optimal allocation of automation capacity features a “bang-bang” property: the entire capacity is allocated to only one of the two divisions. In other words, one division relies on human labor exclusively, and the other division is automated as much as possible.\(^7\) As a result, symmetric allocation of automation—considered in our benchmark—turns out to be sub-optimal.

\(^7\) This relies on the assumption that $\zeta < 1$. 

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Moreover, the choice of which division to automate differs under the two organizational structures: the principal automates Division 0 under decentralization but Division 1 under centralization. Under decentralization, the principal automates Division 0 to shield it from the productivity shocks resulting from biased decision-making from the manager. Under centralization, the principal automates Division 1 to reduce her reliance on the information privately available to the manager (Corollary 3). Interestingly, this leads to stronger misalignment between the principal and the manager (Corollary 2) and thus to less informative communication from the manager. But this adverse effect is mitigated by the reduced importance of the manager’s information in the principal’s decision—which favors Division 0. To sum up, the principal can adopt two different approaches to balance the profits of the two divisions: (i) she can delegate decision-making rights to Division 1’s manager, and automate Division 0 to shield it from biased decision-making, or (ii) she can automate Division 1 to reduce the importance of the information privately held by the manager, and retain decision-making rights to favor Division 0.

These results highlight the strategic role of automation allocation to manage information asymmetries and intra-firm conflicts. By shielding the divisions from the adverse effects of biased or uninformed decision-making, automation deployment provides an additional degree of freedom to the principal, in addition to choosing the firm’s organizational structure. Next, we show that these two degrees of freedom are not independent from each other; instead, the strategic role of automation impacts the principal’s choice of centralization vs. decentralization.

Proposition 6 characterizes the optimal organizational structure for the firm—shown visually in Figure 6. As it turns out, the choice of centralization vs. decentralization only depends on two parameters: the overall automation capacity $\zeta$ and the intra-firm conflict parameter $\alpha$. In particular, the optimal organizational structure does not depend on the relative profit contribution of automation vs. human labor.

**Proposition 6.** Define $g(\alpha) \equiv \frac{5(\alpha - 0.6)}{\alpha^2}$. The centralized structure is optimal if $\zeta \geq g(\alpha)$ and the decentralized structure is optimal if $\zeta \leq g(\alpha)$.

The first observation is that decentralization is optimal for larger values of $\alpha$; vice versa, centralization becomes optimal for lower values of $\alpha$. This follows from the fact that the condition $\zeta \geq g(\alpha)$ elicited in Proposition 6 is equivalent to $\alpha \leq g^{-1}(\zeta)$.$^8$ This is consistent with the findings under symmetric allocation (Section 5.1): the lower the conflict between the principal and the manager, the more inclined the principal is to delegate decision-making rights to the manager.

---

$^8$ Formally, the function $g$ is bijective over $(0, 1]$. Its inverse is given by: $g^{-1}(\zeta) = \frac{5 - \sqrt{25 - 12\zeta}}{2}$. Thus, centralization is optimal if $\alpha \leq g^{-1}(\zeta)$ and decentralization is optimal if $\alpha \geq g^{-1}(\zeta)$. 

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But in contrast to the symmetric allocation benchmark, the optimal organizational structure now depends on the overall automation capacity. Specifically, the range of $\alpha \in (0,1]$ is divided into three regions. First, when $\alpha \leq 0.6$, centralization is optimal regardless of automation capacity. Second, there exists $\alpha^* = \frac{5-\sqrt{13}}{2} \approx 0.697$ such that, when $\alpha \geq \alpha^*$, decentralization is optimal regardless of automation capacity. Third, when $\alpha \in (0.6, \alpha^*)$, the choice of centralization vs. decentralization depends on automation capacity. In this region—referred to as automation-sensitive region—decentralization is optimal under low automation capacity but centralization is optimal under high automation capacity. This stems from the fact that the function $g$ is increasing with $\alpha$ over $(0,1]$, and so is its inverse $g^{-1}$. All else equal, the greater automation capacity $\zeta$, the more inclined the principal is to keep her decision-making authority.

In the automation-sensitive region, decentralization is optimal if the firm does not have any automation capacity (i.e., $\zeta = 0$) (see Proposition 4)—due the mild conflict between the principal and the manager. As automation capacity increases (i.e., for small values of $\zeta > 0$), decentralization first remains optimal; the principal automates Division 0 to mitigate the impact of biased decision-making by the manager. As a result, the value of the manager’s information increases (Corollary 3) and the manager’s decision favors Division 1 to a greater extent (Corollary 1). Despite reducing the fraction of tasks in Division 0 that are vulnerable to productivity shocks, this strategy also hurts the expected productivity of the remaining non-automated tasks in Division 0. As a result, as
automation capacity increases beyond the frontier (i.e., $\zeta \geq g(\alpha)$), the principal changes both the firm’s organizational structure and automation allocation strategy by switching to centralization and automating Division 1. This alleviates the bias in the firm’s decision toward Division 1. The resulting costs imposed on Division 1 (by taking away decision-making rights) are partly reduced by re-allocating automation capacity to make Division 1 less vulnerable to productivity shocks.

The findings in this section highlight the following managerial insights:

1. **Automation allocation plays a strategic role to manage intra-firm frictions.** The firm’s profit not only depends on overall automation capacity, but also on how this capacity is distributed across divisions. Symmetric allocation of automation capacity across the two divisions is suboptimal. Instead, strategic automation allocation features a “bang-bang” property in that only one division is automated. Most important, the choice of which division to automate is different under the centralized and decentralized structures, underscoring the interplay between decision-making authority and strategic automation.

2. **Automation makes centralization more attractive than decentralization.** Automation reduces the principal’s reliance on the information privately held by the manager—hence, the critical importance of middle management expertise and local knowledge. Thus, automation makes centralized organizational structures comparatively more attractive. As a result, automation lessens the strategic importance of mid-level managers within an organization: managers are focused on “managing” the day-to-day operations of their divisions rather than making strategic decisions on behalf of the firm. Importantly, this shift in decision-making authority happens not because of the automation of the mid-level manager’s tasks or from a reduced need for management (e.g., a lower need for coordination between a manager and subordinates), but rather due to the strategic implications of automating lower-level tasks in an organization.

6. **Extension to Endogenously Set Level of Automation**

Thus far, we have considered an exogenous level of automation $\zeta$, which the principal allocated across the two divisions. In this section, we relax this restriction to endogenize the choice of $\zeta$. All proofs are reported in Appendix C.

**Problem Formulation** In the first stage of the game (Step $C1$ in Figure 2 and Step $D1$ in Figure 3), the principal now determines the overall level of automation within the firm as well as its allocation across the two divisions. Formally, the principal determines $\zeta$, $\zeta_1$ and $\zeta_0$, with $\zeta_1 + \zeta_0 = \zeta$. We assume that the choice of $\zeta \leq 1$ involves a quadratic cost function given by $C(\zeta) = \tau \zeta^2$, with $\tau > 0$. For any value of $\zeta$, the allocation of automation across the two divisions and all subsequent

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9 Our static setting does not incorporate any costs of automation capacity allocation or the “stickiness” of a firm’s organizational structure.
decisions from the manager and the principal follow the results elicited in the previous sections. We now use these results to determine the optimal value of \( \zeta \) under both organizational structures.

We refer to the corresponding problems under the decentralized and centralized structures as \((P^D_\zeta)\) and \((P^C_\zeta)\), respectively. From Proposition 5, we know that only Division 0 will be automated under decentralization and only Division 1 will be automated under centralization. Therefore, by using Propositions 1 and 3, the problems are formulated as follows:

\[
(P^D_\zeta) \quad \max_{\zeta} \quad \pi_{1h}(0) + \pi_{oh}(\zeta) - \frac{\Delta_1(0)\Delta_0(\zeta)[\Delta_1(0) + \alpha^2\Delta_0(\zeta)]}{3[\Delta_1(0) + \alpha\Delta_0(\zeta)]^2} - \tau\zeta^2.
\]

\[
(P^C_\zeta) \quad \max_{\zeta} \quad \pi_{1h}(\zeta) + \pi_{oh}(0) - \frac{(4 - \alpha)\Delta_1(\zeta)\Delta_0(0)}{3[\Delta_1(\zeta) + (4 - \alpha)\Delta_0(0)]} - \tau\zeta^2.
\]

From Equations (6) and (7), we can rewrite Problems \((P^D_\zeta)\) and \((P^C_\zeta)\) as follows, where \(\kappa = \frac{h^2 - l^2}{4c} \).

We denote their optimal solutions by \( \zeta^*_D \) and \( \zeta^*_C \), respectively.

\[
(P^D_\zeta) \quad \max_{\zeta} \quad \frac{h^2}{4c} + (1 - \zeta)\frac{h^2}{4c} + \zeta\rho - \frac{\kappa}{3}\left(\frac{(1 - \zeta)(1 + \alpha^2(1 - \zeta))}{(1 + \alpha(1 - \zeta))^2}\right) - \tau\zeta^2.
\]

\[
(P^C_\zeta) \quad \max_{\zeta} \quad \frac{h^2}{4c} + (1 - \zeta)\frac{h^2}{4c} + \zeta\rho - \frac{\kappa}{3}\left(\frac{(4 - \alpha)(1 - \zeta)}{3(1 - \zeta) + (4 - \alpha)}\right) - \tau\zeta^2.
\]

Proposition 7 states that, when \( \tau \) is sufficiently large, Problems \((P^D_\zeta)\) and \((P^C_\zeta)\) both admit an interior solution if and only if \( \rho \) is sufficiently large.

**PROPOSITION 7.** We define \( \bar{\rho} = \frac{11}{12}\frac{h^2}{4c} + \frac{1}{12}\frac{l^2}{4c} \in \left(\frac{1}{2}\frac{h^2}{4c}, \frac{3}{2}\frac{h^2}{4c}\right) \). There exists \( \bar{\tau} \in \mathbb{R}^+ \) such that, for all \( \tau \geq \bar{\tau} \), Problems \((P^D_\zeta)\) and \((P^C_\zeta)\) are concave in \( \zeta \). If \( \rho > \bar{\rho} \), both problems admit interior solutions \( \zeta^*_D, \zeta^*_C \in (0, 1) \); otherwise, \( \zeta^*_D = \zeta^*_C = 0 \). When \( \rho > \bar{\rho} \), the solutions satisfy the following conditions:

\[
\rho - \frac{h^2}{4c} + \frac{\kappa}{3}\left(\frac{(1 - (\zeta^*_D)(\alpha - 2\alpha^2))}{(1 + \alpha(1 - \zeta^*_D))^3}\right) - 2\tau\zeta^*_D = 0
\]

\[
\rho - \frac{h^2}{4c} + \frac{\kappa}{3}\left(\frac{(4 - \alpha)^2}{(3(1 - \zeta^*_C) + (4 - \alpha))^2}\right) - 2\tau\zeta^*_C = 0
\]

This result shows that the firm adopts automation if automated tasks generate a large enough profit. Specifically, the optimal automation capacity under both organizational structures is positive if the profit contribution of automated tasks is larger than a threshold given by \( \frac{11}{12}\frac{h^2}{4c} + \frac{1}{12}\frac{l^2}{4c} \). This threshold is independent of the organizational structure. It corresponds to a weighted average of the profit contribution of non-automated tasks under high productivity, \( \frac{h^2}{4c} \), and under low productivity, \( \frac{l^2}{4c} \).

This result is intuitive, as higher productivity of automated tasks result in more likely automation adoption—regardless of the organizational structure. However, as we shall see, the optimal level of automation adoption does not only depend on cost and productivity considerations (that is, on the parameters \( \tau \) and \( \rho \)) but also on the intra-firm conflict (that is, on the parameter \( \alpha \)).
Optimal Automation Adoption and Organizational Implications. Proposition 8 shows that the principal adopts higher levels of automation as the conflict within the firm increases (i.e., as $\alpha$ decreases), under both organizational structures—for any given values of the cost parameter $\tau$ and of the profit contribution $\rho$. This result re-affirms the strategic value of automation: automation adoption is not exclusively driven by cost and productivity considerations, but is also a strategic instrument to manage intra-firm conflict between the manager and the principal.

**Proposition 8.** $\zeta_D^*$ and $\zeta_C^*$ are both decreasing functions of $\alpha$.

The optimal level of automation under each organizational structure is shown in Figure 7 as a function of $\alpha$, for a fixed value of $\tau$. The figure uses solid lines when the corresponding organizational structure is optimal and dashed lines otherwise. As identified in Proposition 8, $\zeta_D^*$ and $\zeta_C^*$ both increase as the intra-firm conflict gets stronger, that is, as $\alpha$ becomes smaller. Moreover, $\zeta_D^*$ and $\zeta_C^*$ take different values, indicating that automation adoption depends on the organizational structure.

![Figure 7 Optimal automation adoption.](image)

Last, Figure 8 highlights the implications of automation adoption on the optimal organizational structure. Specifically, the figure partitions the $\alpha$-$\tau$ space into three regions. First, when $\alpha \leq 0.6$, centralization is optimal regardless of the value of $\tau$. Second, when $\alpha \geq \alpha^*$, decentralization is optimal regardless of the value of $\tau$. Third, when $\alpha \in (0.6, \alpha^*)$ (which we refer to as automation-sensitive region), the optimal organizational structure depends on the value of $\tau$. In this region, centralization is optimal for the lower values of $\tau$ (that is, when automation adoption is less expensive) and decentralization is optimal for the higher values of $\tau$ (that is, when automation adoption is more expensive).
These results are consistent with our findings from Section 5 but extend them to the case where the overall level of automation is endogenously chosen by the principal. First, centralization is more attractive when the intra-firm conflict gets weaker. Second, and more importantly, the firm is more likely to adopt a centralized structure under high automation capacity (when automation is exogenous) or under inexpensive automation (when automation is endogenous).

7. Conclusion
Computing technology improved robotics and artificial intelligence dramatically since the 1960s, and these technologies are transforming today’s organizations. Machines and software are integral parts of business operations in a number of industries ranging from manufacturing, retail, law, medicine, geology, to engineering. While the displacement of low-skill workers by automation has a significant effect on employment and wages, we expect that it will also impact the roles of mid-level managers and upper-level executives across organizations.

In this study, we investigated how the automation of low-level tasks may alter the decision-making authority within firms and thereby change their organizational structure. This question is particularly relevant for top marketing executives, who often have to work with multiple divisions in any firm, such as marketing, product design, engineering, and R&D, on questions related to product design, pricing and service quality. We address the following question, broadly: If a top executive can make firm-level decisions on her own, or alternatively, can delegate decisions to a division manager who is better informed than her but is biased towards protecting the profit of his own department, how she the executive choose? Should she centralize or decentralize decision-making authority?
We study this classic managerial problem from a specific angle with the following set of questions: How does technology—specifically, automation of low-level tasks which introduces efficiency and reduces operating variability—tip the decision towards centralization or decentralization? What are the implications of automation deployment for the role of mid-level managers and top-level executives? These questions are essential to the debate on optimal managerial decision making and use of automation; however, to our knowledge no previous study tried to answer them.

We developed a theoretical model of a firm that includes a headquarter, led by a principal, and two divisions, each led by a manager. One division (Division 1) operates in an environment that is uncertain and subject to change. The firm needs to make a decision that will impact both divisions, but faces two sources of friction: (i) information asymmetries—Division 1’s manager has access to local information that is unknown to the principal, and (ii) conflict of interest—the principal aims to maximize the firm’s total profit while Division 1’s manager cares about the profit of his own division more than the profit of the other division. In this environment, the principal chooses between a centralized structure—in which case she makes the decision herself based on information reports from the manager of Division 1—and a decentralized structure—in which case she delegates decision-making rights to the manager. In addition, the principal decides whether to automate production tasks in each division to protect the division from negative productivity shocks.

Our analysis yielded three main findings. First, automation deployment can be used strategically to reduce the principal’s reliance on the manager and to manage intra-firm frictions: in our setting, the choice of the automated division depends on the firm’s organizational structure. Second, the optimal level of automation adoption increases as the intra-firm conflict gets stronger—that is, automation adoption is not exclusively driven by cost and productivity considerations, but is also a strategic instrument to manage intra-firm conflicts. Third, automation makes centralized organizational structures relatively more attractive than decentralized ones. This does not mean that organizational hierarchies will disappear but, all else equal, automating lower-level tasks will reduce the strategic role of mid-level managers in the firm’s decision-making. Ultimately, our study shows that strategic deployment of automation at lower levels of organizations can have ripple effects all the way to higher organizational levels.

This paper makes a contribution to the literature in several areas. For marketing, organizational conflict has been studied in the context of marketing-manufacturing conflict; in contract design within sales force organizations subject to a conflict between sales agents and senior management; and also in retail channel design problems, when there is a conflict or informational asymmetry between the manufacturer and the retailer. We contribute to this literature by introducing technology as a strategic lever which can shift the decision-making authority balance between the upper- and lower-level managers.
Second, we contribute to the body of scholarly work on automation, industrial organization, and organizational strategy—and provide important testable hypotheses for scholars in these areas. We predict that automation will motivate organizations to centralize decision-making at the top of the organization. For empirical researchers, the first important question is whether there is any evidence of such a shift in decision-making authority between middle and top managers as a firm automates jobs. In addition, this study identifies information asymmetries and conflict of interest as drivers of automation deployment. Empirical researchers could test if organizations with greater conflict between managers are more likely to automate jobs—perhaps by adopting automation faster. Third, we argue that automation deployment is motivated by reducing variability and is carried out to shield a division from productivity shocks. These predictions and insights can motivate a number of empirical papers on automation and lay the foundation for future work.

References


Electronic copy available at: https://ssrn.com/abstract=3226222
Dogan, Jacquillat, Yildirim: Strategic Automation and Decision-making Authority


Electronic copy available at: https://ssrn.com/abstract=3226222


Appendix A: Proof of Statements from Section 4

Proof of Lemma 1:
Recall that, for any values of \( \zeta_0^D, \zeta_1^D \), the manager’s problem is given by:

\[
\max_{\theta} \left( 1 - (\theta - d)^2 \right) \pi_{1h}(\zeta_1^D) + (\theta - d)^2 \pi_{1i}(\zeta_1^D) + \alpha \left\{ (1 - (\theta - d)^2) \pi_{0h}(\zeta_0^D) + (\theta - d)^2 \pi_{0i}(\zeta_0^D) \right\} .
\]

Taking the first-order condition, we obtain:

\[
2(\theta - d)^2 \pi_{1h}(\zeta_1^D) - 2(\theta - d)^2 \pi_{1i}(\zeta_1^D) + \alpha \left\{ 2(\theta - d)^2 \pi_{0h}(\zeta_0^D) - 2(\theta - d)^2 \pi_{0i}(\zeta_0^D) \right\} = 0.
\]

Then, with \( \Delta_i(\zeta_i) = \pi_{ih}(\zeta_i) - \pi_{iu}(\zeta_i) \) for each \( i \in \{0, 1\} \), together with \( \theta_0 = 0 \), this yields:

\[
(\theta - d)^2 \Delta_1(\zeta_1^D) - \alpha d^2 \Delta_0(\zeta_0^D) = 0.
\]

Moreover, the second-order derivative of the expected utility is equal to \(-2\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)\), which is negative. Therefore, the manager’s utility-maximizing decision is given by:

\[
d^D = \beta^D(\zeta_1^D, \zeta_0^D) \theta_1, \quad \text{where} \quad \beta^D(\zeta_1^D, \zeta_0^D) = \frac{\Delta_1(\zeta_1^D)}{\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)}.
\]

This completes the proof.

Proof of Proposition 1:
For any value of \( \pi_{ih}(\zeta_1^D) \), and \( \pi_{ih}(\zeta_1^D) \) for each \( i \in \{0, 1\} \), the expected profit of the firm is given by:

\[
\Pi^D(\zeta_1^D, \zeta_0^D) = \pi_{1h}(\zeta_1^D) \int_{-1}^{1} (1 - (\theta - d)^2)^2 \frac{d\theta_1}{2} + \pi_{1i}(\zeta_1^D) \int_{-1}^{1} (\theta - d)^2 (\theta - d)^2 \frac{d\theta_1}{2} + \pi_{0h}(\zeta_0^D) \int_{-1}^{1} (\theta - d)^2 (\theta - d)^2 \frac{d\theta_1}{2}.
\]

Since \( \theta_0 = 0 \), we get after some algebra:

\[
\Pi^D(\zeta_1^D, \zeta_0^D) = \pi_{1h}(\zeta_1^D) + \pi_{0h}(\zeta_0^D) - \frac{1 - \beta^D(\zeta_1^D, \zeta_0^D)^2}{3} \Delta_1(\zeta_1, \theta) - \frac{\beta^D(\zeta_1^D, \zeta_0^D)^2}{3} \Delta_0(\zeta_0, \theta).
\]

Then by using the fact that \( \beta^D(\zeta_1^D, \zeta_0^D) = \frac{\Delta_1(\zeta_1^D)}{\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)} \) (Equation 9), we reach to:

\[
\Pi^D(\zeta_1^D, \zeta_0^D) = \pi_{1h}(\zeta_1^D) + \pi_{0h}(\zeta_0^D) - \frac{\Delta_1(\zeta_1^D) \Delta_0(\zeta_0^D) [\Delta_1(\zeta_1^D) + \alpha^2 \Delta_0(\zeta_0^D)]}{3 [\Delta_1(\zeta_1^D) + \alpha \Delta_0(\zeta_0^D)]^2}.
\]

This completes the proof.

Proof of Lemma 2:
Recall that, for any values of \( \zeta_0^C, \zeta_1^C \), and any message \( m \) received from the manager, the principal’s problem is given by:

\[
\max_{d_c} \mathbb{E} \left[ (1 - (\theta - d)^2)^2 \pi_{1h}(\zeta_1^C) + (\theta - d)^2 \pi_{1i}(\zeta_1^C) + (1 - (\theta - d)^2)^2 \pi_{0h}(\zeta_0^C) + (\theta - d)^2 \pi_{0i}(\zeta_0^C) \mid m \right] .
\]

By proceeding as in the proof of Lemma 1, we obtain directly:

\[
d_c^C(\theta_1) = \beta^C(\zeta_1^C, \zeta_0^C) \mathbb{E}(\theta_1 \mid m), \quad \text{where} \quad \beta^C(\zeta_1^C, \zeta_0^C) = \frac{\Delta_1(\zeta_1^C)}{\Delta_1(\zeta_1^C) + \Delta_0(\zeta_0^C)}.
\]

This completes the proof.
Proof of Proposition 2:

We already know that, for any values of $\zeta_0^C, \zeta_1^C$, and any message $m$, the principal will make a decision $d^C(m)$ given by:

$$d^C(m) = \beta^C(\zeta_1^C, c_0^C)\mathbb{E}(\theta_1|m), \text{ where } \beta^C(\zeta_1^C, c_0^C) = \frac{\Delta_1(\zeta_1^C)}{\Delta_1(\zeta_1^C) + \Delta_0(c_0^C)}.$$  

For the ease of the exposition, we omit the dependency of the $\beta^C$, $\Delta_1$ and $\Delta_0$ functions in this proof.

First, we show that the equilibrium communication must have an interval structure. In order to prove this, suppose that, for two distinct values of $\theta_a < \theta_b \in [-1, 1]$, the manager sends the message $m$, which induces $\mathbb{E}(\theta|m) = e_m$. Then our claim is that, in this communication equilibrium, for any $\theta_c \in (\theta_a, \theta_b)$, the manager sends the same message $m$. We proceed by contradiction. Suppose that the manager finds it strictly better to send another message $m'$, which induce $\mathbb{E}(\theta|m') = e_{m'} \neq e_m$. This means that:

$$(1 - (\theta_c - \beta^C e_m)^2)\pi_{1h}(\zeta_1^C) + (\theta_c - \beta^C e_m)^2\pi_{1l}(\zeta_1^C) + \alpha \left\{ (1 - (\theta_0 - \beta^C e_{m'})^2)\pi_{0h}(\zeta_0^C) + (\theta_0 - \beta^C e_{m'})^2\pi_{0l}(\zeta_0^C) \right\} > (1 - (\theta_c - \beta^C e_m)^2)\pi_{1h}(\zeta_1^C) + (\theta_c - \beta^C e_m)^2\pi_{1l}(\zeta_1^C) + \alpha \left\{ (1 - (\theta_0 - \beta^C e_m)^2)\pi_{0h}(\zeta_0^C) + (\theta_0 - \beta^C e_m)^2\pi_{0l}(\zeta_0^C) \right\}.$$

Given that $\theta_0 = 0$ and $\Delta_i = \pi_{ih}(\zeta_i) - \pi_{il}(\zeta_i)$, for each $i \in \{1, 0\}$, this can be rewritten as:

$$((\theta_c - \beta^C e_m)^2 - (\theta_c - \beta^C e_{m'}))^2 \Delta_1 + \alpha ((\beta^C e_m)^2 - (\beta^C e_{m'}))^2 \Delta_0 > 0,$$

or, equivalently:

$$-2 (\beta^C e_m - \beta^C e_{m'}) \Delta_1 \theta_c + ((\beta^C e_m)^2 - (\beta^C e_{m'}))^2 + \alpha ((\beta^C e_m)^2 - (\beta^C e_{m'}))^2 \Delta_0 > 0.$$

But if this is true, then this expression must also be true for at least one of $\theta_a$ and $\theta_b$. This contradicts with our assumption that the manager sends the message $m$ for both $\theta_a$ and $\theta_b$.

Therefore, the equilibrium communication features a partition of the state space into sub-intervals. Let $(\psi_{k+1}, \psi_k)$, and $(\psi_k, \psi_{k-1})$ be two consecutive intervals that appear in a communication equilibrium satisfying $0 < \psi_{k+1} < \psi_k < \psi_{k-1}$. In this equilibrium, the manager will be indifferent between sending two messages on the boundaries of these intervals. In other words, there exist messages $(m_k, m_{k-1})$ such that the information transmission strategy of the manager is as follows, for all $k$:

$$\sigma(\theta_1) = \begin{cases} m_{k-1} & \text{if } \theta_1 \in (\psi_k, \psi_{k-1}), \\ m_k & \text{if } \theta_1 \in (\psi_{k+1}, \psi_k). \end{cases}$$

Since the state variable $\theta_1$ follows a uniform distribution, the posterior belief of the principal, conditionally on receiving any message $m_k$, is that $\theta_1$ is uniformly distributed between $\psi_{k+1}$ and $\psi_k$. Therefore, the principal’s decision is such that:

$$d^C(m) = \begin{cases} \beta^C \psi_k + \psi_{k-1} \quad & \text{if } m = m_{k-1}, \\ \beta^C \psi_{k+1} + \psi_k \quad & \text{if } m = m_k, \end{cases}$$

where $\beta^C = \frac{\Delta_1}{\Delta_1 + \Delta_0}$ (Lemma 2).

Therefore, when $\theta_1 = \psi_k$, the expected utility of the manager from sending the message $m_k$ is equal to the following expression, for any values of $\zeta_0^C, \zeta_1^C$:

$$(1 - (\psi_k - d^C(m_k))^2)\pi_{1h}(\zeta_1^C) + (\psi_k - d^C(m_k))^2\pi_{1l}(\zeta_1^C) + \alpha \left\{ (1 - (d^C(m_k))^2)\pi_{0h}(\zeta_0^C) + (d^C(m_k))^2\pi_{0l}(\zeta_0^C) \right\}.$$
Similarly, his expected utility from sending message \( m_{k-1} \) is equal to:

\[
(1 - (\psi_k - d^C(m_{k-1}))^2)\pi_{1k}(\zeta_k^C) + (\psi_k - d^C(m_{k-1}))^2\pi_{1l}(\zeta_l^C) + \alpha ((1 - (d^C(m_{k-1}))^2)\pi_{0k}(\zeta_0^C) + (d^C(m_{k-1}))^2\pi_{0l}(\zeta_l^C)).
\]

Then, the fact that the manager is indifferent between \( m_k \) and \( m_{k-1} \) when \( \theta_1 = \psi_k \) translates into:

\[
((\psi_k - d^C(m_k))^2 - (\psi_k - d^C(m_{k-1}))^2) \Delta_1 = (d^C(m_{k-1})^2 - d^C(m_k)^2)\alpha \Delta_0.
\]

By plugging the corresponding values of \( d^C(m_k) \) and \( d^C(m_{k-1}) \), we obtain:

\[
\left( \left( \psi_k - \beta^C \left( \psi_{k+1} + \psi_k \right) / 2 \right)^2 - \left( \psi_k - \beta^C \left( \psi_{k+1} + \psi_{k-1} \right) / 2 \right)^2 \right) \Delta_1 = \left( \beta^C \psi_{k+1} - \psi_{k-1} \right)^2 \alpha \Delta_0.
\]

After some algebra, we obtain:

\[
(\beta^C) (\psi_{k+1} + \psi_{k-1}) - \beta^C (\psi_{k+1} - \psi_{k-1}) \psi_k \left( \psi_{k+1} - \psi_{k-1} \right) \Delta_1 = \alpha (\beta^C) \left( 1/4 \psi_{k-1} - \psi_{k+1} + 1/2 \psi_k \right) \Delta_0.
\]

\[
\left( \frac{\beta^C}{4} (\Delta_1 + \alpha \Delta_0) \psi_{k+1} + \frac{1}{2} \left( \Delta_0 \beta^C \alpha - \Delta_1 (2 - \beta^C) \right) \psi_k + \frac{\beta^C}{4} (\Delta_1 + \alpha \Delta_0) \psi_{k-1} = 0.
\]

Therefore, we reach the following difference equation governing the equilibrium communication:

\[
\psi_{k+1} - \gamma \psi_k + \psi_{k-1} = 0,
\]

where:

\[
\gamma = 2 \frac{\Delta_0 \beta^C \alpha - \Delta_1 (2 - \beta^C)}{\beta^C (\Delta_1 + \alpha \Delta_0)}.
\]

By using the fact that \( \beta^C = \frac{\Delta_1}{\Delta_1 + \Delta_0} \), we obtain:

\[
\gamma = \frac{2 \Delta_0 + (4 - 2\alpha) \Delta_0}{\Delta_1 + \alpha \Delta_0}.
\]

We impose the following initial condition:

\[
\psi_1 = 1.
\]

Since \( \alpha < 1 \), the characteristic polynomial of this difference equation has two real roots \( r_A \) and \( r_B \) satisfying:

\[
\begin{align*}
  r_A &= \left( \frac{\Delta_1 + (2 - \alpha) \Delta_0 - 2 \sqrt{1 - \alpha} \Delta_0 (\Delta_1 + \Delta_0)}{\Delta_1 + \alpha \Delta_0} \right) \in (0, 1), \\
  r_B &= \left( \frac{\Delta_1 + (2 - \alpha) \Delta_0 + 2 \sqrt{1 - \alpha} \Delta_0 (\Delta_1 + \Delta_0)}{\Delta_1 + \alpha \Delta_0} \right) > 1.
\end{align*}
\]

The general solution of the difference equation can be written as:

\[
\psi_k = C_A r_A^{k-1} + C_B r_B^{k-1},
\]

for some constant values \( C_A, C_B \in \mathbb{R} \). Then, by using the facts that \( \psi_1 = 1 \) and that \( |\psi_k| \leq 1 \) for all \( k \), we can see that \( C_A = 1 \), and \( C_B = 0 \). Therefore:

\[
\psi_k = \left( \frac{\Delta_1 + (2 - \alpha) \Delta_0 - 2 \sqrt{1 - \alpha} \Delta_0 (\Delta_1 + \Delta_0)}{\Delta_1 + \alpha \Delta_0} \right)^{k-1}.
\]

This completes the proof.
Proof of Proposition 3:

For the ease of the exposition, we omit the dependency of the \( \beta^C, \pi_{1h}, \pi_{1l}, \pi_{0h}, \pi_{0l}, \Delta_1 \) and \( \Delta_0 \) functions in this proof.

Since the distribution of \( \theta_1 \) is symmetric around \( \theta_0 = 0 \), we can express the principal’s expected payoff as follows:

\[
\frac{\Pi^C(\zeta_1^C, \zeta_0^C)}{2} = \pi_{1h} \sum_{k=1}^{\infty} \psi_k \int_0^\psi_k (1 - (\theta_1 - d^C(m_k))^2) d\theta_1 + \pi_{1l} \sum_{k=1}^{\infty} \psi_k \int_0^\psi_k (\theta_1 - d^C(m_k))^2 d\theta_1
\]

For the ease of the exposition, we omit the dependency of the \( \beta^C, \pi_{1h}, \pi_{1l}, \pi_{0h}, \pi_{0l}, \Delta_1 \) and \( \Delta_0 \) functions in this proof.

Using the fact that \( \theta_0 = 0 \), we get:

\[
\Pi^C(\zeta_1^C, \zeta_0^C) = \pi_{1h} + \pi_{0h} - \Delta_1 \sum_{k=1}^{\infty} \psi_k \int_0^\psi_k (\theta_1 - d^C(m_k))^2 d\theta_1 - \Delta_0 \sum_{k=1}^{\infty} \psi_k \int_0^\psi_k (d^C(m_k))^2 d\theta_1.
\]

We develop this expression by using the values of \( d^C(m_k) = \beta^C \frac{\psi_k + \psi_{k+1}}{2} \), and the fact that \( \psi_k = r_k^{-1} \), where \( r_1 \) is the first root of the second-order equation \( r_1^2 - \gamma r_1 + 1 = 0 \) (see proof of Proposition 2). We obtain:

\[
\int_{\psi_{k+1}}^{\psi_k} (\theta_1 - d^C(m_k))^2 d\theta_1 = \int_{\psi_{k+1}}^{\psi_k} \left( \theta_1 - \beta^C \frac{r_k^{k-1} + r_k}{2} \right)^2 d\theta_1,
\]

\[
= \int_{\psi_{k+1}}^{\psi_k} \left[ \theta_1^2 - \beta^C \left( r_k^{k-1} + r_k \right) \theta_1 + \frac{(\beta^C)^2}{4} \left( r_k^{k-1} + r_k \right)^2 \right] d\theta_1,
\]

\[
= \frac{3}{2} \left( r_1^{3k-3} - r_1^{3k} \right) - \frac{\beta^C}{4} \left( r_k^{k-1} + r_k \right) \left( r_1^{2k-2} - r_1^{2k} \right) + \frac{(\beta^C)^2}{4} \left( r_k^{k-1} + r_k \right)^2 \left( r_k^{k-1} - r_k \right),
\]

\[
= \frac{(r_1^{3k-3} - r_1^{3k})(4 + 3(\beta^C)^2 - 6\beta^C) + (r_1^{3k-2} - r_1^{3k-1})(3(\beta^C)^2 - 6\beta^C)}{12}.
\]

Similarly:

\[
\int_{\psi_{k+1}}^{\psi_k} (d^C(m_k))^2 d\theta_1 = \int_{\psi_{k+1}}^{\psi_k} \frac{(\beta^C)^2}{4} \left( r_k^{k-1} + r_k \right)^2 d\theta_1,
\]

\[
= \frac{(\beta^C)^2}{4} \left( r_k^{k-1} + r_k \right)^2 \left( r_k^{k-1} - r_k \right),
\]

\[
= \frac{(\beta^C)^2}{4} \frac{(r_1^{3k-3} - r_1^{3k} + r_1^{3k-2} - r_1^{3k-1})}{4}.
\]

Therefore, we obtain:

\[
\Pi^C(\zeta_1^C, \zeta_0^C) = \pi_{1h} + \pi_{0h} - \Delta_1 \sum_{k=1}^{\infty} \frac{(r_1^{3k-3} - r_1^{3k})(4 + 3(\beta^C)^2 - 6\beta^C) + (r_1^{3k-2} - r_1^{3k-1})(3(\beta^C)^2 - 6\beta^C)}{12}
\]

\[
- \Delta_0 \sum_{k=1}^{\infty} \frac{(\beta^C)^2(r_1^{3k-3} - r_1^{3k} + r_1^{3k-2} - r_1^{3k-1})}{4}.
\]

This yields, by developing the infinite sums and after some algebra:

\[
\Pi^C(\zeta_1^C, \zeta_0^C) = \pi_{1h} + \pi_{0h} - \Delta_1 \frac{(4 + 3(\beta^C)^2 - 6\beta^C)}{12} - \Delta_1 \frac{3(\beta^C)^2 - 6\beta^C}{12} \frac{r_1}{1 + r_1 + r_1^2} - \Delta_0 \frac{(\beta^C)^2}{4} \left( 1 + \frac{r_1}{1 + r_1 + r_1^2} \right),
\]
We first identify the firm’s profit under no information. The decision of the manager under the decentralized structure is given by:

\[ d^D = \frac{\Delta_1(\zeta^D_1) - 1}{\Delta_1(\zeta^D_1) + \alpha \Delta_0(\zeta^D_0)} \theta_1 = \frac{1 - \zeta^D_1}{1 - \zeta^D_1 + \alpha - \alpha \zeta^D_0} \theta_1. \]

We can verify that this expression is a decreasing function of \( \zeta^D_1 \) (keeping \( \zeta^D_0 \) constant), and an increasing function of \( \zeta^D_0 \) (keeping \( \zeta^D_1 \) constant).

Similarly, for any given posterior belief regarding \( \theta_1 \), and for any values of \( \zeta^C_1, \zeta^C_0 \), the decision of the principal under the centralized structure is given by:

\[ d^C = \frac{\Delta_1(\zeta^C_1) - 1}{\Delta_1(\zeta^C_1) + \zeta^C_0(\zeta^C_0)} E(\theta_1|m) = \frac{1 - \zeta^C_1}{2 - \zeta^C_1 - \zeta^C_0} E(\theta_1|m). \]

We can verify that this expression is a decreasing function of \( \zeta^C_1 \) (keeping \( \zeta^C_0 \) constant), and an increasing function of \( \zeta^C_0 \) (keeping \( \zeta^C_1 \) constant). This completes the proof.

**Proof of Corollary 2:**

For any values of \( \zeta_1, \zeta_0 \), the extent of misalignment is given by:

\[ r(\zeta_1, \zeta_0) = \frac{\beta^C(\zeta_1, \zeta_0, w^*)}{\beta^D(\zeta_1, \zeta_0, w^*)} = \frac{\Delta_1(\zeta_1, w^*) + \alpha \Delta_0(\zeta_0, w^*)}{\Delta_1(\zeta_1, w^*) + \alpha \Delta_0(\zeta_0, w^*)} = \frac{1 - \zeta_1 + \alpha - \alpha \zeta_0}{2 - \zeta_1 - \zeta_0}. \]

We can verify that the function \( r \) is decreasing with \( \zeta_1 \) (keeping \( \zeta_0 \) constant) and increasing with \( \zeta_0 \) (keeping \( \zeta_1 \) constant). This completes the proof.

**Proof of Corollary 3:**

We first identify the firm’s profit under no information. The decision \( d^C(m) \) is equal to 0—which directly results from Equation (12) and from the fact that \( E(\theta_1) = 0 \). Then, the firm’s profit is given by:

\[ \Pi(\zeta_1, \zeta_0) = E [\pi_0_0(\zeta_0, 0, \theta_0)] + E [\pi_1(\zeta_1, 0, \theta_1)] = \pi_{0h}(\zeta_0) + \pi_{1h}(\zeta_1) \int_{-1}^{1} (1 - \theta_1^2) d\theta_1 + \pi_{1l}(\zeta_1) \int_{-1}^{1} \frac{\theta_1^2 d\theta_1}{2} = \pi_{0h}(\zeta_0) + \frac{2}{3} \pi_{1h}(\zeta_1) + \frac{1}{3} \pi_{1l}(\zeta_1). \]
We now turn to the firm’s profit under perfect information. We can directly use Equation (16) with $\alpha = 1$. This yields:

$$\Pi(\xi_1, \zeta_0) = \pi_{1b}(\xi_1^D) + \pi_{0b}(\xi_0^D) - \frac{\Delta_1(\xi_1^D)\Delta_0(\xi_0^D)}{3[\Delta_1(\xi_1^D) + \Delta_0(\xi_0^D)]}$$

We obtain:

$$VOI(\xi_1, \zeta_0) = \Pi(\xi_1, \zeta_0) - \Pi(\xi_1, \zeta_0) = \frac{\Delta_1(\xi_1)^2}{3(\Delta_1(\xi_1) + \Delta_0(\zeta_0))} = \frac{(1 - \xi_1)^2 h^2 - l^2}{3(2 - \xi_1 - \zeta_0) 4c}$$

One can easily check that this expression decreases with $\xi_1$ and increases with $\zeta_0$. This completes the proof.

Appendix B: Proof of Statements from Section 5

Proof of Proposition 4:

From Equations (21) and (22), we know that, conditional on symmetric automation allocation, the centralized structure is optimal if and only if:

$$\frac{1 + \alpha^2}{3(1 + \alpha)^2} \Delta S \geq \frac{4 - \alpha}{3(1 - \alpha)} \Delta S.$$  

After some algebra, we find that it is equivalent to:

$$3 + 5\alpha^2 - 8\alpha \geq 0.$$  

Since $\alpha \in [0, 1]$, this is equivalent to $\alpha \leq 0.6$. This completes the proof.

Proof of Proposition 5:

Problem $(P^D)$ is given by:

$$\max_{\xi_1^D, \xi_0^D} \pi_{1b}(\xi_1^D) + \pi_{0b}(\xi_0^D) - \frac{\Delta_1(\xi_1^D)\Delta_0(\xi_0^D) [\Delta_1(\xi_1^D) + \alpha^2 \Delta_0(\xi_0^D)]}{3[\Delta_1(\xi_1^D) + \alpha \Delta_0(\xi_0^D)]^2},$$

s.t. $\xi_1^D + \xi_0^D = \xi$, $\xi_1^D, \xi_0^D \geq 0$.

First, note from Equation (6) that $\pi_{1b}(\xi_1^D) + \pi_{0b}(\xi_0^D)$ is independent from how the overall automation capacity is allocated between the divisions. Therefore, Problem $(P^D)$ boils down to the following:

$$\min_{\xi_1^D, \xi_0^D \in [0,1]} \frac{\Delta_1(\xi_1^D)\Delta_0(\xi_0^D) [\Delta_1(\xi_1^D) + \alpha \Delta_0(\xi_0^D)]}{3[\Delta_1(\xi_1^D) + \alpha \Delta_0(\xi_0^D)]^2},$$

s.t. $\xi_1^D + \xi_0^D = \xi$.

Moreover, we write in the remainder of this proof (Equation (7)):

$$\Delta_i(\xi_1, w^*) = (1 - \xi_1)\kappa \text{ with } \kappa = \frac{h^2 - l^2}{4c}.$$  

Therefore, Problem $(P^D)$ is equivalent to minimizing $h^D(\xi_1)$, given by:

$$h^D(\xi_1) = \frac{(1 - \xi_1)(1 - \xi + \zeta)(1 - \xi_1 + \alpha(1 - \zeta + \xi_1))}{(1 - \xi_1 + \alpha(1 - \zeta + \xi_1))^2}.$$  

We show that:

$$h^D(0) \leq h^D(\xi_1), \forall \xi_1 \in [0, \xi],$$
i.e.:
\[
\frac{(1 - \zeta)(1 + \alpha^2(1 - \zeta))}{(1 + \alpha(1 - \zeta)^2)} \leq \frac{(1 - \zeta_1)(1 - \zeta + \zeta_1)(1 - \zeta_1 + \alpha^2(1 - \zeta + \zeta_1))}{(1 - \zeta_1 + \alpha(1 - \zeta + \zeta_1))^2}, \forall \zeta_1 \in [0, \zeta].
\]

First, note that, for each \( \zeta_1 \in [0, \zeta] \), we have \((1 - \zeta_1)(1 - \zeta + \zeta_1) \geq 1 - \zeta \). This can easily be verified by noting that \((1 - \zeta_1)(1 - \zeta + \zeta_1)\) is a concave function of \( \zeta_1 \) and takes value \( 1 - \zeta \) when \( \zeta_1 = 0 \) and \( \zeta_1 = \zeta \).

Therefore, a sufficient condition is that:
\[
\frac{1 + \alpha^2(1 - \zeta)}{(1 + \alpha(1 - \zeta)^2)} \leq \frac{1 - \zeta_1 + \alpha^2(1 - \zeta + \zeta_1)}{(1 - \zeta_1 + \alpha(1 - \zeta + \zeta_1))^2}, \forall \zeta_1 \in [0, \zeta].
\]

Let us fix \( \zeta_1 \in [0, \zeta] \) and introduce the following notations:
\[
x = 1 - \zeta_1,
\]
\[
y = 1 - \zeta + \zeta_1,
\]
\[
z = 1 - \zeta.
\]

We want to show that:
\[
\frac{1 + \alpha^2 z}{(1 + \alpha z)^2} \leq \frac{x + \alpha^2 y}{(x + \alpha y)^2}.
\]

After developments, this is equivalent to:
\[
x(1 - x) + \alpha^2 y(1 - y) + 2\alpha x(z - y) + 2\alpha^2 z(1 - x)y + \alpha^2 z(x - z) + \alpha^4 zy(z - y) \geq 0.
\]

This is satisfied because \( x, y, z \in [0, 1], z \geq x \) and \( z \geq y \). This shows that \( \zeta^D = 0 \) and \( \zeta^D_0 = \zeta \) at the optimum.

We now turn to Problem \((P^C)\). It is given by:
\[
\max_{\zeta^C_1, \zeta^C_0} \pi_{1h}(\zeta^C_1) + \pi_{0h}(\zeta^C_0) - \frac{(4 - \alpha)\Delta_1(\zeta^C_1)\Delta_0(\zeta^C_0)}{3[3\Delta_1(\zeta^C_1) + (4 - \alpha)\Delta_0(\zeta^C_0)]}, \text{ s.t. } \zeta^C_1 + \zeta^C_0 = \zeta, \quad \zeta^C_1, \zeta^C_0 \geq 0.
\]

As before, we know from Equation (6) that \( \pi_{1h}(\zeta^C_1) + \pi_{0h}(\zeta^C_0) \) is independent from how the overall automation capacity is allocated between the divisions. Therefore, Problem \((P^C)\) boils down to the following:
\[
\min_{\zeta^D_1, \zeta^D_0 \in [0, 1]} \frac{(4 - \alpha)\Delta_1(\zeta^C_1)\Delta_0(\zeta^C_0)}{3[3\Delta_1(\zeta^C_1) + (4 - \alpha)\Delta_0(\zeta^C_0)]}, \text{ s.t. } \zeta^D_1 + \zeta^D_0 = \zeta.
\]

We define a function \( h^C(\zeta_1) \) as follows:
\[
h^C(\zeta_1) = \frac{(1 - \zeta_1)(1 - \zeta + \zeta_1)}{(1 - \zeta_1 + \alpha(1 - \zeta + \zeta_1)).
\]

We show that \( h^C \) is a concave function of \( \zeta_1 \). Using the same expressions for \( x \) and \( y \) that we defined earlier, we have, for all \( \zeta_1 \in [0, \zeta] \):
\[
(h^C)'(\zeta_1) = \frac{(x - y)(3x + (4 - \alpha)y) - (1 - \alpha)x}{(3x + (4 - \alpha)y)^2},
\]
\[
(h^C)''(\zeta_1) = -\frac{6(4 - \alpha)(2 - \zeta)^2}{(3x + (4 - \alpha)y)^3} < 0.
\]

Therefore, \( h^C \) admits its minimum in \( \zeta_1 = 0 \) or \( \zeta_1 = \zeta \). We have:
\[
h^C(0) = \frac{(4 - \alpha)(1 - \zeta)}{3(3 + (4 - \alpha)(1 - \zeta))} \kappa,
\]
\[
h^C(\zeta) = \frac{(4 - \alpha)(1 - \zeta)}{3(3(1 - \zeta) + (4 - \alpha))} \kappa.
\]

We obtain directly that \( h^C(\zeta) \leq h^C(0) \). This shows that \( \zeta_1^C = \zeta \), and \( \zeta_0^C = 0 \) at the optimum.

This completes the proof.
Proof of Proposition 6:

By using the result of Proposition 5, we can compute the equilibrium profit level under both organizational structures. We denote it by \( \hat{\Pi}^D \) under the decentralized structure and by \( \hat{\Pi}^C \) under the centralized structure.

Under the decentralized structure, we have \( \zeta^D_1 = 0 \), and \( \zeta^D_0 = \zeta \). Therefore:

\[
\hat{\Pi}^D = \pi_{1h}(0, w^*) + \pi_{0h}(\zeta_0, w^*) - \frac{\Delta_1(0, w^*)\Delta_0(\zeta, w^*)}{3[\Delta_1(0, w^*) + \alpha\Delta_0(\zeta, w^*)]^2},
\]
\[
= (2 - \zeta) \frac{h^2}{4c} + \zeta \rho - \frac{h^2 - l^2}{4c} \frac{(1 + \alpha)(1 - \zeta)}{3(1 + \alpha(1 - \zeta))^2}.
\]

Under the centralized structure, we have \( \zeta^C_1 = \zeta \), and \( \zeta^C_0 = 0 \). Therefore:

\[
\hat{\Pi}^C = \pi_{1h}(\zeta, w^*) + \pi_{0h}(0, w^*) - \frac{(4 - \alpha)\Delta_1(\zeta, w^*)\Delta_0(0, w^*)}{3[\Delta_1(\zeta, w^*) + (4 - \alpha)\Delta_0(0, w^*)]^2},
\]
\[
= (2 - \zeta) \frac{h^2}{4c} + \zeta \rho - \frac{h^2 - l^2}{4c} \frac{(4 - \alpha)(1 - \zeta)}{3(1 - \zeta) + 4 - \alpha}.
\]

Therefore, the centralized structure is optimal if and only if:

\[
\frac{4 - \alpha}{3(1 - \zeta) + 4 - \alpha} \leq \frac{1 + \alpha^2(1 - \zeta)}{(1 + \alpha(1 - \zeta))^2}.
\]

After simple algebra, one finds that this is equivalent to the following expression, for any \( \alpha < 1 \):

\[
\zeta \geq \frac{-5\alpha^2 + 8\alpha - 3}{\alpha^2 - \alpha^3}.
\]

This simplifies into:

\[
\zeta \geq \frac{5(\alpha - 0.6)}{\alpha^2}.
\]

When \( \alpha = 1 \), one can easily verify that the inequality \( \frac{4 - \alpha}{3(1 - \zeta) + 4 - \alpha} \leq \frac{1 + \alpha^2(1 - \zeta)}{(1 + \alpha(1 - \zeta))^2} \) is not satisfied, so the inequality \( \zeta \geq \frac{5(\alpha - 0.6)}{\alpha^2} \) also holds. This completes the proof.

Appendix C: Proof of Statements from Section 6

Proof of Proposition 7:

The objective functions of Problems \( P^D_\zeta \) and \( P^C_\zeta \) are continuous, so they both admit a maximum over the compact interval \([0, 1]\). This establishes the existence of \( \zeta^D_0 \) and \( \zeta^C_0 \).

We denote the objective function of Problems \( P^D_\zeta \) and \( P^C_\zeta \) by \( OBJ^D \) and \( OBJ^C \) respectively. We have, with \( \kappa = \frac{h^2 - l^2}{4c} \):

\[
\frac{\partial OBJ^D}{\partial \zeta} = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(1 + 2\alpha^2(1 - \zeta))(1 + \alpha(1 - \zeta))^2 - 2\alpha(1 + \alpha(1 - \zeta))(1 - \zeta)(1 + \alpha^2(1 - \zeta))}{(1 + \alpha(1 - \zeta))^4} \right) - 2\tau \zeta
\]
\[
= \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{-2\alpha(1 - \zeta)(\alpha - 2\alpha^2)}{(1 + \alpha(1 - \zeta))^4} \right) - 2\tau \zeta
\]
\[
\frac{\partial^2 OBJ^D}{\partial \zeta^2} = \frac{\kappa}{3} \left( \frac{(-2\alpha^2)(1 + \alpha(1 - \zeta)) + 3\alpha(1 - (1 - \zeta)(\alpha - 2\alpha^2))}{(1 + \alpha(1 - \zeta))^4} \right) - 2\tau
\]

Notice that for \( \tau \) sufficiently large, the second order derivative of \( OBJ^D \) with respect to \( \zeta \) is negative. This shows that the \( OBJ^D \) is concave with respect to \( \zeta \) when \( \tau \geq \tau^D_1 \) for some \( \tau^D_1 \in \mathbb{R}^+ \).
By defining \( \bar{\rho} = \frac{11}{12} h^2 + \frac{1}{12} l^2 \), we show that the optimal solution \( \zeta_D^* \) is interior if and only if \( \rho > \bar{\rho} \). First, we have:

\[
\frac{\partial OBJ_D}{\partial \zeta} \bigg|_{\zeta=0} = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{1 - (1 - \zeta_D)(1 - 2\alpha^2)}{(1 + \alpha(1 - \zeta_D))^3} \right) \geq \frac{4}{\kappa} \nabla \nabla
\]

\[
\geq \rho - \frac{h^2}{4c} + \frac{1}{12} \frac{h^2 - l^2}{4c}
\]

\[
= \rho - \bar{\rho}
\]

Therefore,

\[
\text{For any } \rho > \bar{\rho}, \quad \frac{\partial OBJ_D}{\partial \zeta} \bigg|_{\zeta=0} > 0.
\]

This proves that \( \zeta_D > 0 \). Second, there exists \( \bar{\tau}_D^* \in \mathbb{R}^+ \) such that, when \( \tau \geq \bar{\tau}_D^* \), \( \frac{\partial OBJ_D}{\partial \zeta} < 0 \) at \( \zeta = 1 \). Therefore, \( \zeta_D^* \in (0, 1) \) and satisfies the following first-order condition.

\[
\rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{1 - (1 - \zeta_D)(1 - 2\alpha^2)}{(1 + \alpha(1 - \zeta_D))^3} \right) - 2\tau \zeta_D = 0
\]

(26)

This proves that \( \zeta_D^* \in (0, 1) \) if \( \rho > \bar{\rho} \), and \( \zeta_D^* = 0 \) otherwise.

We proceed similarly for Problem \((P_C^D)\). We have:

\[
\frac{\partial OBJ_C}{\partial \zeta} = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(4 - \alpha)^2}{(3(1 - \zeta) + (4 - \alpha))^2} \right) - 2\tau \zeta
\]

\[
\frac{\partial^2 OBJ_C}{\partial \zeta^2} = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(4 - \alpha)^2}{(3(1 - \zeta) + (4 - \alpha))^2} \right) - 2\tau \zeta
\]

As earlier, we have:

\[
\frac{\partial OBJ_C}{\partial \zeta} \bigg|_{\zeta=0} = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(4 - \alpha)^2}{(3(1 - \zeta) + (4 - \alpha))^2} \right) \geq \frac{4}{\kappa} \nabla \nabla
\]

\[
\geq \rho - \frac{h^2}{4c} + \frac{1}{12} \frac{h^2 - l^2}{4c}
\]

\[
= \rho - \bar{\rho}
\]

Again, we obtain that:

\[
\text{For any } \rho \geq \bar{\rho}, \quad \frac{\partial OBJ_D}{\partial \zeta} \bigg|_{\zeta=0} > 0.
\]

Moreover, for \( \tau \) sufficiently large, the second order derivative of \( OBJ_C \) with respect to \( \zeta \) is negative. This shows that the \( OBJ_C \) is concave with respect to \( \zeta \) when \( \tau \geq \bar{\tau}_C^* \) for some \( \bar{\tau}_C^* \in \mathbb{R}^+ \).

Moreover, \( \frac{\partial OBJ_C}{\partial \zeta} > 0 \) at \( \zeta = 0 \) and there exists \( \bar{\tau}_C^* \in \mathbb{R}^+ \) such that, when \( \tau \geq \bar{\tau}_C^* \), \( \frac{\partial OBJ_D}{\partial \zeta} < 0 \) at \( \zeta = 1 \). This proves that \( \zeta_C^* \in (0, 1) \) and satisfies the following first-order condition.

\[
\rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(4 - \alpha)^2}{(3(1 - \zeta_C)(1 - 2\alpha^2))} \right) - 2\tau \zeta_C^* = 0
\]

(27)

This again proves that \( \zeta_D^* \in (0, 1) \) if \( \rho > \bar{\rho} \), and \( \zeta_D^* = 0 \) otherwise.

We complete the proof by setting \( \bar{\tau} = \max \{ \bar{\tau}_1^D, \bar{\tau}_2^D, \bar{\tau}_1^C, \bar{\tau}_2^C \} \).
Proof of Proposition 8:

We already showed that the optimal solution $\zeta^*_D$ satisfies the following first-order condition:

$$t^D(\alpha, \zeta^*_D) = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{1 - (1 - \zeta^*_D)(\alpha - 2\alpha^2)}{(1 + \alpha(1 - \zeta^*_D))^4} \right) - 2\tau \zeta^*_D = 0,$$

We already know that:

$$\frac{\partial t^D(\alpha, \zeta^*_D)}{\partial \zeta} = \frac{\kappa}{3} \left( \frac{(\alpha - 2\alpha^2)(1 + \alpha(1 - \zeta^*_D)) + 3\alpha(1 - (1 - \zeta^*_D)(\alpha - 2\alpha^2))}{(1 + \alpha(1 - \zeta^*_D))^4} \right) - 2\tau < 0$$

Moreover, we have:

$$\frac{\partial t^D(\alpha, \zeta^*_D)}{\partial \alpha} = -\frac{\kappa}{3}(1 - \zeta)(1 - \alpha) \left( \frac{4 - 2\alpha(1 - \zeta)}{(1 + \alpha(1 - \zeta))^3} \right) < 0$$

Then by using the implicit function theorem we know that:

$$\frac{\partial \zeta^*_D}{\partial \alpha} = -\frac{\partial t^D(\alpha, \zeta^*_D)}{\partial \alpha} \frac{\partial \zeta^*_D}{\partial \zeta} < 0.$$ 

This shows that $\zeta^*_D$ is a decreasing function of $\alpha$.

Following the same logic, we know that $\zeta^*_C$ satisfies the following first-order condition:

$$t^C(\alpha, \zeta^*_C) = \rho - \frac{h^2}{4c} + \frac{\kappa}{3} \left( \frac{(4 - \alpha)^2}{(3(1 - \zeta^*_C) + (4 - \alpha))\sigma} \right) - 2\tau \zeta^*_C = 0$$

Therefore, we get:

$$\frac{\partial t^C(\alpha, \zeta^*_C)}{\partial \zeta} = \frac{\kappa}{3} \left( \frac{6(4 - \alpha)^2}{(3(1 - \zeta^*_C) + (4 - \alpha))^4} \right) - 2\tau < 0$$

Moreover we have

$$\frac{\partial s(\alpha, \zeta^*_C)}{\partial \alpha} = \frac{\kappa}{3} \left( \frac{-2(4 - \alpha)(3(1 - \zeta^*_C) + (4 - \alpha))^2 + 2(3(1 - \zeta^*_C) + (4 - \alpha))(4 - \alpha)^2}{(3(1 - \zeta^*_C) + (4 - \alpha))^4} \right)$$

$$= \frac{\kappa}{3} \frac{-6(4 - \alpha)(1 - \zeta^*_C)}{(3(1 - \zeta^*_C) + (4 - \alpha))^4} < 0$$

Then by using the implicit function theorem we know that:

$$\frac{\partial \zeta^*_C}{\partial \alpha} = -\frac{\partial t^C(\alpha, \zeta^*_C)}{\partial \alpha} \frac{\partial \zeta^*_C}{\partial \zeta} < 0.$$ 

This shows that $\zeta^*_C$ is a decreasing function of $\alpha$. This completes the proof.