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# Three-Way Complementarities: Performance Pay, Human Resource Analytics, and Information Technology

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We test for three-way complementarities among information technology (IT), performance pay, and human resource (HR) analytics practices. We develop a principal-agent model examining how these practices work together as an incentive system that produces a larger productivity premium when the practices are implemented in concert rather than separately. We assess our model by combining fine-grained data on human capital management (HCM) software adoption over 11 years with detailed survey data on incentive systems and HR analytics practices for 189 firms. We find that the adoption of HCM software is greatest in firms that have also adopted performance pay and HR analytics practices. Furthermore, HCM adoption is associated with a large productivity premium when it is implemented as a system of organizational incentives, but has less benefit when adopted in isolation. The system of three-way complements produces disproportionately greater benefits than pairwise interactions, highlighting the importance of including all three complements. Productivity increases significantly when the HCM systems “go live” but not when they are purchased, which can be years earlier. This helps rule out reverse causality as an explanation for our findings.

*Key words:* incentive systems; information technology; performance pay; human resource analytics; complementarity; enterprise systems; ERP; productivity; production function; principal-agent model

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## 1. Introduction

As information technology (IT) investments grew in the 1980s and 1990s, substantial variation emerged in both the returns to IT investments (Brynjolfsson and Hitt 1995, Devaraj and Kohli 2003, Melville et al. 2004, Aral and Weill 2007) and the effectiveness of incentive compensation plans across firms (Ichniowski and Shaw 2003). We propose that these two phenomena are related and that the performance benefits of IT and incentive schemes depend on one another.

Successful incentive systems rely on the ability to monitor and manage employee performance accurately to appropriately reward those who excel. Some information technologies are specifically designed to help firms observe, measure, document, track, and manage performance accurately and transparently, and therefore complement such incentive practices. We develop an analytical model that illustrates this complementarity and demonstrate how the copresence of IT and incentive practices can explain variation in both the returns to IT and the effectiveness of performance pay contracts and human resource (HR)

analytics practices that monitor and provide feedback on performance.

We argue that effective incentive practices are made up of a tightly knit incentive “system” that combines performance pay with both HR analytics practices and suitable IT software. We hypothesize that adopting performance pay and HR analytics practices without the information technologies that enable them lessens the incentives offered by performance pay and the insights gained from analysis, and that performance monitoring and management technologies implemented without performance pay and HR analytics are also less effective. Our goal is to examine the complementarities among IT, HR analytics, and performance pay to determine whether these practices can be effectively implemented piecemeal or rather must be introduced as a three-way “system of practices” (Milgrom and Roberts 1990).

To explore these propositions, we narrow our investigation to the adoption of a specific technology—human capital management (HCM) solutions found in typical enterprise resource planning (ERP) systems. These “process-enabling technologies” represent

firmwide suites of business software and hardware designed to generate productivity and performance by supporting specific business processes (Hitt et al. 2002, McAfee 2004, Aral et al. 2006).

Simply identifying a correlation between adoption and performance is not sufficient to test the hypothesis that adoption *causes* performance, because causality could run in the opposition direction, for instance, if improved cash flows increased investments. Unobserved factors may also cause both adoption and higher performance. An important feature of our data enables us to assess the direction of causality in relationships between adoption of HCM systems and higher performance. We collected detailed data on both the purchase and the go-live decisions of 189 enterprise systems adopters from the sales database of a large enterprise systems vendor from 1995 to 2006. Thus, we can separate the purchase of IT from the actual use of IT, which for HCM systems may occur years later because of the time-consuming installation process. By doing so, we address the potential endogeneity of the relationship between IT and productivity. Specifically, if causality ran from productivity to adoption, we would expect the strongest correlations between performance and the *purchase* of HCM, whereas if causality ran from adoption to productivity, we would expect the strongest correlations between the *adoption* (or *use*) of HCM and performance (Aral et al. 2006).

To test three-way complementarities between performance pay, HR analytics, and IT, we gathered a data set surveying the detailed human resource practices of these 189 firms in 2005, of which about half (90) adopted the HCM system. By focusing on a narrow set of technologies, we explore how HCM systems complement the specific set of business processes they are designed to support. Combining data on technology adoption, financial performance, and human resource practices, we estimate how HR analytics and performance pay complement HCM to generate a productivity premium. Our tests for three-way complementarities can easily be extended to test for  $n$ -way complementarities.

## 2. Theory and Literature

### 2.1. Information Technology and Organizational Complementarities

Since the early 1990s, firm-level evidence has documented productivity and performance gains for IT-intensive firms (Brynjolfsson and Hitt 2003). However, substantial variation exists in the returns to IT across firms (Brynjolfsson and Hitt 1995). A leading explanation for this variation is that firms with higher returns also adopt complementary organizational practices that produce productivity and performance premiums (Bresnahan et al. 2002, Caroli

and Van Reenen 2001, Aral and Weill 2007, Bloom et al. 2012). For instance, financial markets disproportionately reward firms that invest in IT when they have also made appropriate organizational investments (Brynjolfsson et al. 2002). With a highly skilled workforce that can efficiently use information technology, firms can achieve higher productivity through increased efficiency and customization because line workers are empowered with more decision rights (Bresnahan et al. 2002, Caroli and Van Reenen 2001). Furthermore, IT and organizational investments such as those in innovative people management practices can help explain why the United States has experienced sustained increases in productivity growth in the last decade, whereas Europe has not (Bloom et al. 2012).

Most of the literature on IT and organizational coinvestment has focused on general-purpose information technologies (Bresnahan and Trajtenberg 1995). Given the general-purpose flexibility of IT, the predominant approach to measuring IT investment has simply been to count the number of IT employees or to estimate the total dollars spent on hardware purchases. However, prior research has shown that investments in different types of IT can have orthogonal and at times competing performance implications (Aral and Weill 2007). Although aggregate measures of information processing capabilities inside firms are a good first step for understanding how IT-intensive firms experience greater productivity, a more precise view of IT and organizational complementarity is possible with explorations of complementarities between particular technologies and the specific systems of practices they are intended to support (Aral and Weill 2007, Bartel et al. 2007). We therefore examine complementarities between a specific technology, HCM software, and the practices it is designed to support.

### 2.2. Human Capital Management Software

HCM software is part of the ERP suite of systems. The main purpose of HCM is to equip executives, HR professionals, and line managers with information needed for workforce support and HR analytics, including accurate planning on performance pay, employee performance feedback, talent management, and the ability to continuously monitor work performance. By tightly linking human resource data with other operational and financial systems, HCM enables managers to understand the demand on human capital, track workforce costs, align the goals of employees with the organization's business strategy, and measure employee performance.

Of particular relevance for our study, HCM allows the firm to monitor metrics of employee effort and performance. The systems keep detailed records of employees' attendance, such as time worked, overtime, and illnesses and vacation time and can track

detailed work records, including each task completed by employees. HCM also provides feedback to employees to help them understand strategic performance goals and key performance indicators (KPIs) so they can better align their effort with the performance objectives of the firm. In addition, the software analyzes and presents data to managers to help them understand what makes some employees more effective than others. This makes it possible to design more effective rewards systems, including performance pay.

Although enterprise systems, such as HCM, constitute a large share of IT investments, especially for large and medium-sized enterprises, empirical evidence examining the productivity and performance implications of these investments is sparse. In particular, we lack large-scale empirical evidence on complementarities between specific organizational practices and HCM or ERP investment in general. Hitt et al. (2002) provided one of the first large-scale statistical analyses of the productivity and performance impact of ERP adoption. By examining 350 publicly traded firms from 1986 to 1998, they found that ERP implementation is associated with positive productivity and performance gains. Aral et al. (2006) provided an updated study using ERP adoption data on 698 firms from 1998 to 2005. By separately estimating the effects of the purchase of enterprise systems from the effects of installation and use years later, they addressed endogeneity concerns to document a potential causal relationship between ERP use and firm productivity. However, neither of these studies explicitly tested the complementarity between enterprise systems and organizational coinvestments.

### 2.3. Organizational Practices

Our interviews with HCM practitioners and survey results indicate that HCM solutions are used to provide performance-monitoring capabilities, allowing managers to better understand work performance and employee contributions as well as workforce support functions that help employees understand key performance indicators that align with firm goals. To fully leverage the HR analytics capabilities provided by the HCM solution, we hypothesize that firms should also have in place or adopt an appropriate performance pay scheme and policies to monitor and manage employee performance. Our theory is consistent with existing frameworks demonstrating the importance of analyzing a firm's work policies not in isolation but as a part of coherent systems (Holmstrom and Milgrom 1994; Milgrom and Roberts 1990, 1995; Kandel and Lazear 1992). Ichniowski et al. (1997) completed one of the first large-scale econometric studies on complementarities and found that factories with a cluster of complementary human resource

practices are significantly more productive than those that implement the same practices separately. These practices include performance pay, teamwork, flexible job assignment, employment security, and training. Bartel (2004) documented similar findings in the banking sector. Black and Lynch (2001) and Bresnahan et al. (2002) also found that new technologies, human capital investments, and changes in work practices often combine to drive productivity.

Perhaps the paper most closely related to our work is the Bartel et al. (2007) analysis of several plant-level mechanisms through which IT promotes productivity growth. By studying a specific technology that is used to improve valve-making processes, they find plants that adopt new IT-enhanced equipment improve productivity by lowering setup times for new product runs. They subsequently document that IT also shifts firms' business strategies to produce more customized goods. IT and the demands for customization prompt changes in skill requirements and work practices needed to implement the new business strategies. Although their work focuses on a specific technology and its associated impact on work practices, the authors do not directly test the complementarities between the two. Our work not only focuses on a specific technology and a set of organizational practices that the technology is designed to support, it also formally tests whether HR analytics practices, HCM adoption, and performance pay together act as a complementary system.

### 2.4. A Model of Three-Way Complementarities: Performance Pay, HR Analytics, and IT

We use a principal-agent model with moral hazard to illustrate the complementarity of HCM software and compensation systems that include HR analytics practices and performance pay (e.g., Banker and Kemerer 1992). Our model builds on the work of Baker (1992) and Prendergast (1999), who examined incentive systems in which both the principal and the agent are risk neutral, and the agent makes a single effort decision. We differ from these models by incorporating the utility of monitoring and workforce support (Baker and Hubbard 2004). This makes it possible to model reductions in these costs made possible by HCM solutions. We show that firms profit more from the use of an appropriate performance pay scheme if they also simultaneously improve their ability to monitor and manage work performance, preventing employees from gaming the compensation system and improving workers' ability to understand and meet performance targets. In addition, we analyze the profitability impact of the compensation system and information technology when HR analytics, performance pay and HCM systems are simultaneously adopted.

We allow for a divergence between the level of effort that is optimal for the agent and the level that would be optimal for the principal, in the spirit of Baker (1992). If, for example, the agent is rewarded on the total number of patents he produces, he may file patents that take little effort but have minimal value to the principal. We model this scenario by assuming that the principal cannot contract with the agent on actual output  $q$ . Instead, the principal observes a performance measure  $p$ , which she uses to reward the agent. In turn, we assume output is a function of the agent's effort,  $a$ , as follows:

$$q = a + \varepsilon_q, \quad (1)$$

where  $\varepsilon_q$  is normally distributed with mean 0 and variance  $\sigma_q^2$ . The performance signal  $p$  is also a function of effort except that indicators of performance are noisy, such that the marginal effect of effort on the performance indicator depends on a scaling factor  $\alpha$ , whereas the true marginal productivity of effort is independent of  $\alpha$ . We assume  $\alpha$  is normally distributed with mean 1 and variance  $\sigma_\alpha^2$ , where  $\sigma_\alpha^2$  can be viewed as a direct measure of the degree to which the agent's action deviates from what is expected to maximize profit. The deviation can happen in two ways. First, the agent can game the compensation system at the expense of the principal. Second, even when agent does not choose to game the system, a misalignment can occur when the principal fails to ensure that the agent understands and meets the performance goals set by the firm. These deviations directly model the potential for monitoring and workforce support practices to reduce variation in worker performance. The error term  $\varepsilon_p$  is also normally distributed with mean 0 and variance  $\sigma_p^2$ :

$$p = \alpha a + \varepsilon_p \quad (2)$$

The risk neutral principal maximizes profit, which is a function of output  $q$ , the agent's wage  $w$ , and the cost of monitoring and managing performance  $\Gamma(s)$ :

$$\Pi = E\{q - w - \Gamma(s)\}, \quad (3)$$

where

$$\Gamma(s) = ks, \quad \sigma_\alpha^2 = e^{-sm}. \quad (4)$$

The cost of using the technology to monitor and manage performance is a linear function of a constant  $k$  and a binary variable,  $s$ , indicating whether the firm has adopted the appropriate technology to monitor and manage workforce performance. To discourage the agent from gaming the compensation system or to ensure the agent's effort results in performance along the principal's desired dimension  $q$  (to reduce  $\sigma_\alpha^2$ ), the principal should have both the *policy to conduct HR analytics* ( $m$ ) and the *technical ability* ( $s$ ) to monitor and

manage employees' performance. In this case,  $m$  measures the extent to which the principal adopts HR analytics practices such as monitoring, performance management, and workforce support. When the principal adopts human capital management technology ( $s = 1$ ) without explicit policies to perform HR analytics ( $m = 0$ ), information produced by the technologies will be less useful. Similarly, having HR analytics policies without an appropriate technology to monitor employees' performance or give them feedback on how to improve would be similarly ineffective. Thus, the principal can reduce  $\sigma_\alpha^2$  most effectively when she possess *both* the technology and HR analytics practices.

The agent is also risk neutral with linear utility as a function of wage and a quadratic cost of effort. The reservation utility is  $\bar{V}$

$$w - \frac{1}{2}ca^2 \geq \bar{V}, \quad (5)$$

$$w = t + bp = t + b\alpha a + b\varepsilon_p. \quad (6)$$

Wage  $w$  is a linear function of the performance measure, with a fixed component  $t$  and a pay-for-performance component at a rate,  $b$ . An agent receives higher compensation by signaling higher performance,  $p$ , to the principal. Given a contract  $(t, b)$ , the agent chooses an optimal effort level  $a$  to maximize his utility. From the first-order condition, we can solve for the optimal effort:

$$a^* = \frac{\alpha b}{c}. \quad (7)$$

Solving the principal's maximization problem subject to the agent's participation constraint and incentive compatibility constraint yields the following result:

$$\pi^* = \frac{b}{c} - \frac{b^2}{2c}(1 + \sigma_\alpha^2) - ks. \quad (8)$$

If adopting HCM technology allows the principal to better monitor the agent's work performance, or if the technology allows the worker to more accurately deliver on KPIs, we expect the firm to improve its profitability. Our interviews and surveys indicate that HCM can act as an instrument for reducing the magnitude of  $\sigma_\alpha^2$ , the variance of the worker's measured performance through both monitoring and workforce support. We assume the value of  $k$  to be small such that the cost of HR analytics is minimal once the HCM system is in place. Typically, HCM systems have large fixed costs with relatively low marginal costs because it takes multiple years of planning and implementation before the system can "go live." However, the incremental cost of using the system is small after it is fully implemented. By reducing the error in performance signals through improved technological monitoring and workforce support capabilities ( $s$ ) and by

having policies in place to collect HR analytics to assist workers in meeting KPIs, firms should experience higher profits. Thus, the marginal benefit of having policies to collect HR analytics should be higher when HCM is used than that when HCM is not used. Equation (9) shows that having a higher level of monitoring policies in place increases profitability only when the technology to monitor and support workforce performance ( $s$ ) is also present:

$$\frac{\partial \pi}{\partial m} \Big|_s = \frac{b^2}{2c} s e^{-sm}, \quad \frac{\partial \pi}{\partial m} \Big|_{s=1} > \frac{\partial \pi}{\partial m} \Big|_{s=0}. \quad (9)$$

However, firms can obtain even greater profits if both the power of the incentive,  $b$ , and their HR analytics practices (technology and policy) are high at the same time. As the principal reduces the ability of the agent to game the compensation system through effective use of monitoring technologies and helps the agent understand and meet key performance goals through feedback, the introduction of performance pay can direct employees to exert even more effort to produce. Acting as a complementary system, performance pay, HR analytics policies, and HCM technologies work together as a cluster of organizational practices that improve firm performance. Adopting each separately is less beneficial than adopting them all in concert (Milgrom and Roberts 1990, Brynjolfsson and Milgrom 2012). As shown in Equation (10), HR analytics and performance pay are complementary only when HCM technology is used:

$$\frac{\partial^2 \pi}{\partial b \partial m} \Big|_s = \frac{1}{c} s b e^{sm}, \quad \frac{\partial^2 \pi}{\partial b \partial m} \Big|_{s=1} = \frac{1}{c} b e^{-m} > 0, \\ \frac{\partial^2 \pi}{\partial b \partial m} \Big|_{s=0} = 0. \quad (10)$$

The results of our analytical model illustrate that there should be complementarities between HR analytics practices (having both the technology and policies to monitor and manage performance) and performance pay. Because employees are compensated for stronger observed performance, the ability to reduce the error in the performance indicators should reduce the ability of employees to game the system, improve the firm’s ability to distinguish top performers from weak performers, and increase the effectiveness of the incentive. Thus, we hypothesize the following:

**HYPOTHESIS 1.** *There are positive interaction effects of performance pay, HR analytics practices, and adoption of the HCM software in concert, and adoption of any two components of this system without the third forgoes the full benefits of this complementarity.*

**Table 1** Descriptive Statistics

Variable	Obs.	Mean	Std. dev.	Min	Max
Sales (MM\$)	858	6,272.71	12,138.77	0	110,789
Employees (M)	797	27.25	61.85	0.007	484
Capital (MM\$)	825	4,928.56	8,524.2	0.304	44,381
Capital/labor ratio	783	276.11	562.3	1.000	5,724.38
HRAnalytics	577	2.559	0.763	1.222	4.222
PerformancePay	769	3.445	0.859	1	5

### 3. Empirical Methods

#### 3.1. Data and Survey Methods

We collected detailed data on the enterprise system purchase and go-live decisions of 189 firms that adopted HCM systems from 1995 to 2006. The data include the U.S. sales of a major vendor’s HCM software and were collected directly from the vendor’s sales database. Because these data record separate dates for purchase and go-live events, we can separately measure technology investment and technology use, as well as the correlation of each with firm performance. We matched these firms with data on their financial performance. Of the 189 firms in our survey, 90 firms are publicly traded with performance data in the COMPUSTAT database. Table 1 provides descriptive statistics for these firms from 1995 to 2006.

Our human resource practice data were collected from a survey administered to the 189 firms between 2005 and 2006. We obtained the survey from a non-profit organization whose purpose is to share experiences of firms that adopt ERP to educate them about best practices. The organization is composed of 1,750 member corporations and 50,000 individual members. The survey was sent to all the customers of this major ERP vendor that provided HCM adoption data. Because the majority of these customers are also members of this independent user organization, the response rate for the survey was very high: 80%.<sup>1</sup> All surveyed firms adopted some form of ERP from the vendor that provided the adoption data, but only half specifically adopted the HCM software module. We use survey responses to understand how the HCM software is used to monitor and manage work performance and how the compensation system is implemented. Participants ranked the degree to which their firm has adopted a given practice on a scale from 1 to 5, with a value of 1 indicating that there is no

<sup>1</sup> The survey is a multiyear effort and is conducted on the Web. The survey is conducted by a large ERP user group that provides a report comparing the practice of each firm to its peers as well as reports of best practices and lessons learned. The survey is often completed by a team from the responding firm whose members range from senior management to the rank and file of the organization, depending on who has the expertise to answer a particular question. A senior executive from the human resources department typically coordinates this effort.

**Table 2** Human Resource Practices Survey Variables

	Survey question	Obs.	Avg.	Std. dev.	Min	Max
HR analytics						
M1	Compensation planning system integrates information with other relevant non HR systems, such as financial systems, OSHA, manufacturing, sales	61	2.13	1.16	1	5
M2	HR system allows for a balanced scorecard framework, which is integrated into department and individual performance appraisal documents and supports benchmarking and continuous improvement	73	2.66	1.27	1	5
M3	HR system provides data analysis and reporting tools to support HR policy development and decision making	76	3.00	1.14	1	5
M4	HR system allows to analyze workforce data; design, implement and monitor corporate strategies to optimize the workforce; and continuously evaluate how various courses of action might affect business outcomes	72	2.38	1.01	1	4
M5	HR system enables HR professionals to develop cost-effective resource strategies, by supporting accurate the planning process, allowing to monitor actual performance relative to plan and allowing to simulate multiple planning scenarios or analyze the financial impact of head count changes	73	2.30	1.04	1	5
M6	Time worked routed automatically to project accounting/resource-planning systems: coverage	71	2.97	1.43	1	5
M7	Time and attendance system has automated analysis and reporting capabilities to analyze KPIs such as lost time, productivity, cost of absence, overtime, or illness	76	2.37	1.32	1	5
M8	Time and attendance system accounts for corrections, calculates the impact of the adjustment, and brings it forward to the current period	66	3.11	1.55	1	5
M9	Standardized job descriptions and evaluations are available online	75	2.43	1.38	1	5
	$HRAnalytics = Norm(Norm(M1) + \dots + Norm(M9))$	47	0	1	-1.89	2.21
Performance pay						
I1	Compensation plans are designed to support overall corporate business strategy as well as strategies of individual divisions/departments	85	3.77	0.943	1	5
I2	Compensation plans are designed to align pay with performance and are linked to easily understood KPIs (e.g., corporate, divisional, organizational profitability)	84	3.53	1.13	1	5
I3	Compensation plans are aligned with resource plans to attract and retain the desired skill set	74	3.18	1.09	1	5
I4	Employee performance expectations clearly communicated during recruiting process	68	3.42	1.14	1	5
	$PerformancePay = Norm(Norm(I1) + \dots + Norm(I4))$	65	0	1	-2.85	1.81

Note. OSHA, Occupational Health and Safety Administration.

adoption of the practice and a value of 5 indicating that the practice is fully adopted by the organization. To test our hypotheses, we use the survey to construct variables on the level of performance pay and HR analytics practices currently implemented by firms in our sample. Definitions and descriptive statistics for survey questions are listed in Table 2.

We focus our analysis at the firm level rather than the department or business-unit level. The decision to adopt enterprise systems such as HCM is generally made at the firm headquarters, and the scope of enterprise system implementation is usually firmwide. Furthermore, because intrafirm transfer pricing need not face a market test (if it even exists at all) the key performance metrics will be more meaningful and credible when assessed at the firm level. Finally, firm-level analysis has more direct implications for firm strategy and bottom-line business performance than analysis conducted at the department or business-unit level.

### 3.2. HR Analytics Practices

The HR analytics variable is constructed by combining nine survey questions that gauge how firms monitor workers, provide performance feedback, integrate workforce support data, and manage talent. The goal

is to measure practices that provide information for HR analytics. The questions are divided into three categories. The first category measures how firms monitor performance, to what degree the monitoring systems are integrated with other relevant systems such as financial reporting and sales systems, and whether these business processes support overall firm strategy (M1–M5). The second category measures the extent to which firms can directly monitor employees' effort using detailed attendance and overtime records, and the ability of the firm to verify the productivity impact of these signals (M6–M8). The third category measures transparency (M9). When management clearly communicates evaluation criteria to employees, it does not leave room for employees to misinterpret where they should exert effort. Adopting these practices is beneficial because they deter employees from gaming the compensation system and help employees meet KPIs designated by the firm (reducing  $\sigma_\alpha^2$ ). To construct the *HRAnalytics* variable, we combine all these factors into a single measure where each factor is first normalized (*Norm*) by subtracting the mean of the responses and dividing by the

standard deviation, yielding a measure of HR analytics with mean zero and a standard deviation of one:

$$HRAalytics = Norm(Norm(M1) + Norm(M2) + \dots + Norm(M9)).$$

Correlations among individual constructs are all positive but not necessarily high, and the Cronbach's alpha is 0.30.<sup>2</sup> The relatively low value reflects the multidimensionality of HR analytics practices—firms adopting any one practice do not necessarily adopt all of the others. Firm and industry characteristics can also lead to divergent practices. For example, attendance may be more important for a manufacturing firm than a software engineering firm, because the former requires workers to show up on time to operate machinery, whereas software engineers can work from anywhere. Therefore, we may expect manufacturing firms to implement monitoring policies that log detailed records of workers' attendance, such as practices in M6–M8, whereas software engineering firms focus more on other types of HR analytics practices, such as benchmarking and continuous improvement. Our goal in this paper is not to identify which practices are most beneficial, but to evaluate the overall extent to which a firm manages its workers' performance. As long as firms manage work performance in some way, they may reap economic rewards from HR analytics regardless of the specific practices they choose. To test the validity of including all nine measures into a single component, we separately introduced the measures into our main regression and found that we cannot reject the hypothesis that all nine practices have the same coefficients. Consequently, for simplicity of analysis and interpretation, we combined them into a single HR analytics measure.

### 3.3. Performance Pay

Our measures of performance pay practices assess the degree to which firms reward employees for their work performance. Four questions pertaining to performance pay are used to construct the variable. These questions are classified into two groups: monetary incentives that motivate employees and self-selection mechanisms designed to attract and retain high quality employees. Incentives using monetary rewards can have the direct benefit of motivating workers to exert more effort and produce optimally. Selection is another potential benefit of performance pay, helping firms to attract and retain productive workers. Performance pay is likely to help firms retain high performers because they derive

higher income as a function of their performance. At the same time, incentive compensation systems can induce poor performers to leave the firm as their relative income is reduced. As incentive compensation takes on a greater share of the overall wage, these effects should be magnified.

To calculate the extent to which direct monetary rewards are used to motivate employees, we asked firms to report the importance of performance pay in their current compensation systems and the degree to which incentives are aligned with business goals (I1, I2). The incentive compensation motivation variable is calculated by normalizing and summing the survey responses, yielding a measure with mean zero and a standard deviation of 1. Cronbach's alpha for the set of motivation measures is 0.64.

$$Motivation = Norm(Norm(I1) + Norm(I2)).$$

Finding the right people and putting their talent to good use is one of the most important goals in any human resources department. The appropriate compensation plan enables firms to hire and retain the talent they need. To assess this capability, we asked respondents to report the degree to which their firms use compensation plans to attract and retain talent (I3, I4). Cronbach's alpha for these measures is 0.59.

$$Selection = Norm(Norm(I3) + Norm(I4)).$$

We construct the performance pay variable as the sum of motivation and selection. The correlations among responses to the survey questions used to construct these variables are strongly positive (see Tables A.1–A.3 in the appendix).

$$PerformancePay = Norm(Motivation + Selection).$$

### 3.4. Model Specification

Because we have a set of longitudinal IT adoption and financial performance data as well as a cross-sectional survey on organizational practices, we can test for complementarities between IT adoption and a system of human resource practices. Two types of statistical tests have been developed to assess the existence of such complementarities: correlations (adoption or demand equations) and performance differences (productivity equations) (Arora and Gambardella 1990, Arora 1996, Athey and Stern 1998, Aral and Weill 2007, Novak and Stern 2009, Brynjolfsson and Milgrom 2012). The first test determines if a cluster of practices is more likely to be adopted jointly rather than separately. The second test examines whether the hypothesized complements are more productive when adopted together or separately (Milgrom and Roberts 1990, Ichniowski et al. 1997, Bresnahan et al. 2002).

<sup>2</sup> Correlations are omitted to save space but are available from the authors.



We first examine the correlations among performance pay, HR analytics, and HCM adoption. According to the model, we expect these three practices to form a system of complements in which any pairwise correlation between two components of the system is positive when the third component is also present, but not necessarily otherwise. In assessing these correlations, we control for transitory shocks to adoption or performance using dummy variables for each year and industry controls for 15 industries.

Next, we use performance differences to test the complementarities between HCM and an incentive system that includes performance pay and HR analytics. If HR analytics, performance pay and use of HCM are complements, we would expect firms that use these practices and technologies in concert to be the most productive. We test this hypothesis using a production function framework. Following the literature on IT productivity (Brynjolfsson and Hitt 1996, 2003; Hitt et al. 2002; Aral et al. 2006), we adopt a Cobb–Douglas specification. In addition to Labor and Capital inputs, we incorporate HCM adoption and HR practices into the model to show how firms convert these inputs to outputs.

We first test whether HR analytics, HCM adoption, and performance pay separately impact productivity using the specifications below, where  $K$  represents capital,  $L$  is the number of employees, and  $HCM$  represents a dummy variable that is equal to 1 each year after HCM is “live” in the firm. As shown in our theoretical model, we expect better HR analytics capabilities to improve firm performance. We then test whether HR analytics, performance pay, and HCM adoption form a system of complements that provides additional performance improvements when used together. From our theoretical model, if these practices form a system of complements, we expect the three-way interaction  $HCMLive \times HRAnalytics \times PerformancePay$  to be positive ( $\beta_9 > 0$ ).

$$\begin{aligned} \ln(\text{Sales}) &= \alpha + \beta_1 \ln(K) + \beta_2 \ln(L) + \beta_3 HCMLive + \beta_4 HRAnalytics \\ &+ \beta_5 PerformancePay + \beta_6 (HCMLive \times HRAnalytics) \\ &+ \beta_7 (HCMLive \times PerformancePay) \\ &+ \beta_8 (HRAnalytics \times PerformancePay) \\ &+ \beta_9 (HCMLive \times HRAnalytics \times PerformancePay) \\ &+ \sum_j \beta_j IndustryControls_j + \sum_k \beta_k Year_k + \varepsilon. \end{aligned}$$

### 3.5. Identification

Endogeneity may hamper causal interpretations of this model. Of particular concern, HCM adoption

**Figure 1** Timeline of HCM Adoption of a Firm in the Manufacturing Industry



may be endogenous. Although we hypothesize that HCM adoption drives firm performance, the reverse is also possible—firms may choose to adopt HCM when they perform well or experience exogenous shocks to productivity. To distinguish these explanations, we separately measure the *decision to invest* and the *actual investment* itself.

When adopting an enterprise system such as HCM, firms typically experience a lag of up to several years between the time they decide to invest in the system and the time when the system finally goes live. This reflects the complex implementation process requiring redesign of business processes, software customization, and extensive training. Figure 1 shows a typical timeline of HCM adoption as represented by one of the manufacturing firms in our sample. In this firm, the purchase of HCM software in 1997 initiated a five-year implementation sequence, which made it possible to actually use the system in 2002. On average, it takes a firm 2.71 years to complete an implementation of an HCM system from the initial purchase to use of the system.

Using similar methodology to Aral et al. (2006), we estimate separately the HCM *purchase* event and the *go-live* event in the regressions to distinguish firms’ decisions to purchase new technology from the impact of actually using the technology. If firm performance is correlated with the actual use of the technology but uncorrelated with the purchase decision, we can reasonably infer that technology drives performance instead of performance driving technology adoption.

Including the  $HCMPurchase$  variable in the model generates the following regression. The model predicts  $HCMLive$  to be part of the complementary system but not necessarily  $HCMPurchase$ :

$$\begin{aligned} \ln(\text{Sales}) &= \alpha + \beta_1 \ln(K) + \beta_2 \ln(L) + \beta_3 HCMPurchase \\ &+ \beta_4 HCMLive + \beta_5 HRAnalytics \\ &+ \beta_6 PerformancePay \\ &+ \beta_7 (HCMPurchase \times HRAnalytics) \\ &+ \beta_8 (HCMPurchase \times PerformancePay) \\ &+ \beta_9 (HRAnalytics \times PerformancePay) \\ &+ \beta_{10} (HCMPurchase \times HRAnalytics \times PerformancePay) \end{aligned}$$

$$\begin{aligned}
 &+ \beta_{11}(\text{HCMLive} \times \text{HRAnalytics}) \\
 &+ \beta_{12}(\text{HCMLive} \times \text{PerformancePay}) \\
 &+ \beta_{13}(\text{HRAnalytics} \times \text{PerformancePay}) \\
 &+ \beta_{14}(\text{HCMLive} \times \text{HRAnalytics} \times \text{PerformancePay}) \\
 &+ \sum_j \beta_j \text{IndustryControls}_j + \sum_k \beta_k \text{Year}_k + \varepsilon.
 \end{aligned}$$

A second potential source of endogeneity is that human resource practices such as performance pay and HR analytics may be endogenous. Because our human resource practice data are cross-sectional, we cannot directly assess the level of HR practices before and after the HCM adoption. However, we take advantage of the fact that organizational practices are often quasi fixed (Brynjolfsson and Hitt 1996, Milgrom and Roberts 1990, Bresnahan et al. 2002). Thus, our regressions can be interpreted as assessing whether preexisting firm differences in human resource practices influence the productivity return from using HCM.

Under the quasi-fixed assumption, firms that have already implemented performance pay and HR analytics practices are more likely to invest in HCM because it can enhance the effectiveness of these organizational practices. HCM enables firms to improve the monitoring of employees and make their performance pay more salient. Firms that have implemented performance pay and HR analytics practices are in a better position to reap the rewards of using HCM. In fact, the earlier these firms adopt HCM, the faster they will reap rewards from using HCM. Conversely, adoption costs are expected to be higher and benefits delayed for firms that do not have these hypothesized complements in place.

Consequently, we expect the demand for HCM to be higher for firms that have already implemented performance pay and HR analytics practices. To test this hypothesis, we specify a logistic regression, estimating the adoption of HCM as a function of existing organizational practices and other firm characteristics:

$$\begin{aligned}
 &\ln\left(\frac{P(Y_i = 1)}{1 - P(Y_i = 1)}\right) \\
 &= \alpha + \beta_1 \text{HCMLive} + \beta_2 \text{PerformancePay} + \beta_3 \text{HRAnalytics} \\
 &\quad + \sum_j \beta_j \text{IndustryControls}_j + \sum_k \beta_k \text{Year}_k + \varepsilon.
 \end{aligned}$$

A third source of endogeneity may arise from omitted variables that drive HCM adoption, HR analytics adoption, and performance. To mitigate possible omitted variables bias, we include industry and time dummies to capture any industry or exogenous temporal shocks to performance or organizational change. We also employ fixed-effects specifications to control for time-invariant characteristics

of each firm. For example, if “good management” is an omitted variable that confounds our results, fixed-effects specifications are likely to eliminate the cross-sectional variance from this variable. Although our organizational factors are cross-sectional, the HCM adoption variables are longitudinal, allowing us to use a fixed-effects specification to estimate coefficients on all time-varying variables including those that interact with the HCM variables. The fixed-effect specifications give us more confidence in our results because they eliminate the influence of any unobservable time-invariant characteristics of firms. However, there is also the risk that fixed effects will overcontrol for firm-specific factors that are legitimately part of the complementarity system we are examining. Thus, the coefficient estimates from those specifications may underestimate the true effects of the complements.

## 4. Results

As discussed above, both correlations and productivity differences can be used to test for complementarities (Athey and Stern 1998, Aral and Weill 2007, Brynjolfsson and Milgrom 2012). In fact, each test tends to be strongest when the other is weakest. If a particular set of complementary practices is well understood, we would expect all firms to adopt this system of complementarities, and the correlations for the copresence of these practices should be nearly perfect. However, precisely because every firm adopted the complements, there would not be any performance differentiation, and the productivity test would have no power to identify any benefit from adopting the system.<sup>3</sup> On the other hand, when firms are still experimenting with various practices, the covariation of complementarity practices would not be perfect, but there should be detectable differences in productivity between firms that adopt the system of complements and those that do not. In the extreme case, where managers have no knowledge of the complementarities, the practices will be uncorrelated, but the statistical power of the productivity test will be maximized.

### 4.1. The Correlation Test

We first examined the evidence for correlations between HCM adoption and the cluster of human resources practices. Tables 3, 4, and 5 show the pairwise correlations among HR analytics policies, performance pay, and HCM adoption, controlling for

<sup>3</sup> In this case, if firms are homogeneous, the “off-diagonal” cells where practices are mismatched would be empty, providing no source of variation for the regression. If firms are heterogeneous, a subtler problem would arise. There might be observations in the off-diagonal cells, but these would be precisely the situations in which, for some reason, the benefits of being mismatched were greater than having matched practices. Again, the performance regression would have no power to identify complementarities.

**Table 3 Three-Way Correlations—Logistic Regression: HCM and Performance Pay**

Dep. var.	(1)	(2)	(3)
	All obs.	<i>HRAnalytics</i> > 0	<i>HRAnalytics</i> ≤ 0
	<i>HCM</i>	<i>HCM</i>	<i>HCM</i>
<i>PerformancePay</i>	−.057 <sup>†</sup> (0.032)	0.058 <sup>†</sup> (0.030)	−0.221 (0.212)
Control variables	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>
Observations	461	333	45
log-likelihood	−221.50	77.30	−21.06
χ <sup>2</sup> (df)	109.40	−166.39	21.20
Pseudo- <i>R</i> <sup>2</sup>	0.244	0.225	0.30

Notes. Parameter estimates of logistic regression analysis are shown. Huber-White robust standard errors are shown in parentheses. All analyses employ two-tailed tests of statistical significance.

<sup>†</sup>*p* < 0.1.

the number of employees, industries, and years. The results show broad support for the simultaneous adoption of a system of incentives and human capital management technologies.

Table 3 shows pairwise correlations between HCM adoption and performance pay practices using logistic regressions (because HCM adoption is binary). The negative coefficient on the pairwise correlation between performance pay and HCM adoption using the full sample seems to indicate that performance pay and HCM are not part of the complementary system ( $\beta = -0.057$ ,  $p < 0.1$ ; Model 1). However, after separately examining the subsample of firms that have adopted HR analytics practices, we see that the correlation between *HCMLive* and performance pay is positive and significant ( $\beta = 0.058$ ,  $p < 0.1$ ; Model 2), suggesting that performance pay and HCM are part of a complementary system only when firms simultaneously adopt HR analytics practices. On the other hand, for firms that do not institute HR analytics practices, performance pay is negatively correlated with HCM adoption (albeit not significantly). Together, these results suggest the importance of examining the complete system of putative complements together. In contrast, pairwise correlations between elements of the system can be misleading.

Table 4 shows pairwise correlations between HCM adoption and HR analytics using logistic regressions. Again, we see a similar pattern in which the correlation between HCM adoption and HR analytics practices is statistically significant only when firms also adopt performance pay policies. When firms use performance pay in compensation schemes, the correlation between HR analytics and HCM adoption is positive and statistically significant at the 5% level ( $\beta = 0.033$ ,  $p < 0.05$ ; Model 2), suggesting that HCM and

**Table 4 Three-Way Correlations—Logistic Regression: HCM and HR Analytics**

Dep. var.	(1)	(2)	(3)
	All obs.	<i>PerformancePay</i> > 0	<i>PerformancePay</i> ≤ 0
	<i>HCM</i>	<i>HCM</i>	<i>HCM</i>
<i>HRAnalytics</i>	0.102* (0.053)	0.033* (0.015)	0.124 (0.178)
Control variables	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>
Observations	263	169	45
log-likelihood	−125.80	−75.88	−28.95
χ <sup>2</sup> (df)	56.5	44.25	5.22
Pseudo- <i>R</i> <sup>2</sup>	0.404	0.626	0.806

Notes. Parameter estimates of logistic regression analysis are shown. Huber-White robust standard errors are shown in parentheses. All analyses employ two-tailed tests of statistical significance.

\**p* < 0.05.

HR analytics practices are complements in the presence of performance pay. On the other hand, when performance pay is not used, the correlation between HR analytics and HCM is not different from zero, suggesting that these practices and HCM are not complements in the absence of performance pay schemes.

The logistic regressions in Tables 3 and 4 can also be used to estimate the probability of adopting HCM as a function of HR analytics and performance pay practices. Assuming a firm's organizational practices are quasi fixed, these tables support the hypothesis that a firm is more likely to adopt HCM when it already has policies in place to monitor and manage work performance and simultaneously uses performance pay to motivate employees (Model 2, Table 3; Model 2, Table 4). When a firm does not use performance pay, implementing HR analytics practices alone does not increase the likelihood of adopting HCM (Model 3, Table 4). Furthermore, when a firm does not monitor and manage employees' performance, it is less

**Table 5 Three-Way Correlations—Linear Regression: HR Analytics and Performance Pay**

Dep. var.	(1)	(2)	(3)
	All obs.	<i>HCMLive</i> = 1	<i>HCMLive</i> = 0
	<i>HRAnalytics</i>	<i>HRAnalytics</i>	<i>HRAnalytics</i>
<i>PerformancePay</i>	0.433*** (0.080)	0.127 <sup>†</sup> (0.076)	0.528*** (0.120)
Control variables	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>	<i>Industry</i> <i>Year</i> <i>Firm size</i>
Observations	396	222	174
<i>R</i> <sup>2</sup>	0.404	0.626	0.806

Notes. Parameter estimates of pooled OLS regression analysis are shown. Huber-White robust standard errors are shown in parentheses. All analyses employ two-tailed tests of statistical significance.

<sup>†</sup>*p* < 0.1; \*\*\**p* < 0.001.

likely to adopt HCM despite having performance pay policies in place (Model 3, Table 3). Again, this is consistent with the existence of ‘three-way complementarities’ among IT, incentives, and HR analytics practices.

Last, Table 5 shows the pairwise correlations between HR analytics and performance pay practices. The correlation between the two sets of practices is positive and significant ( $\beta = 0.433$ ,  $p < 0.001$ ; Model 1) when the full sample of firms is used. In the split sample, HR analytics and performance pay practices remain positively correlated whether or not the firm has invested in HCM, suggesting that they may be complements regardless of IT adoption. Though the correlation between HR analytics and performance pay is positive and significant for all firms, the magnitude of the correlation is larger for firms that have not adopted HCM. This could be because some less technologically intensive firms are slow to adopt HCM and are satisfied to implement performance pay and HR analytics on their own, seeking to achieve benefits from their complementarity without investing in IT. It could also be that certain industries, such as information or professional services industries, use performance pay and HR analytics to provide incentives without investing in HCM because output and effort in those industries is less easily measured, making technology less relevant to the “system.” Whether this strategy works in practice for individual firms (for example, whether adopting performance pay and HR analytics without HCM is good for performance) is an empirical question. It could be that firms that attempt to implement two parts of the system without the third forgo benefits of the entire system. For this reason, it is important to also examine productivity tests to determine whether a lack of adjustment by these firms creates detectable differences in productivity.

When we examine these correlations after removing firms in the information, professional scientific, technical services, and finance industries, where output and effort may be harder to measure, the relationship between performance pay and HR analytics is stronger when HCM is adopted ( $\beta = 0.218$ ,  $p < 0.05$  compared to  $\beta = 0.127$ ,  $p < 0.10$  in the full sample) and weaker when HCM is not adopted ( $\beta = -0.622$ ,  $p < 0.01$  compared to  $\beta = 0.528$ ,  $p < 0.001$  in the full sample). This suggests some differences in the relationships between HCM, performance pay, and HR analytics practices across industries, which we explore in more depth in the robustness section of this paper below.

Collectively, the pattern of correlations is consistent with three-way complementarities among HCM, HR analytics and performance pay practices, and supports predictions from the economic model. However,

we cannot rule out the existence of unobservable factors which, given the right set of unobserved correlations, could mimic the correlation patterns resulting from true complements.

#### 4.2. The Productivity Test

Table 6 shows the productivity regressions examining our main hypothesis that the combination of performance pay, HR analytics practices, and HCM technology drives productivity. We also performed several outlier tests and detected a single firm that has an unusually large influence on all the regressions.<sup>4</sup> We show the results in Table 6 after eliminating this outlier. The results do not change qualitatively due to outliers, although the statistical significance falls in some specifications. Models are reported using ordinary least squares (OLS) with robust clustered standard errors or fixed-effects or random-effects specifications. Model 1 uses the standard Cobb–Douglas production function framework, correlating the log of annual sales with the logs of capital and labor inputs in a fixed-effects specification. Coefficients for labor and capital are statistically significant and are within the range of theoretical predictions (Brynjolfsson and Hitt 1995).

We estimate the impact of HCM adoption (defined as the “go-live” date) on performance in Model 2. To better isolate the impact of HCM, we use a fixed-effect specification to eliminate influence from all time-invariant unobservables and add seasonality controls for time-specific changes. To address the simultaneity bias in estimating the return from HCM adoption, we separately estimate the purchase of HCM from the go-live event. If firm performance is correlated with the actual use of HCM rather than with the mere purchase of the technology, we can infer that the HCM technology drives firm performance instead of performance driving the purchase of HCM software.

The estimated parameter of the go-live variable is positive and significant, whereas the purchase variable is not significantly different from zero. This implies that the decision to purchase HCM is uncorrelated with productivity, whereas the actual use of the system is correlated with productivity ( $\beta = 0.069$ ,  $p < 0.01$ ; Model 2). The magnitude of the HCM go-live parameter has an intuitive economic interpretation—firms that adopt the HCM software produce approximately 6.9% greater output holding other inputs constant. However, it could be that HCM adoption is correlated with adoption of a broader suite of ERP

<sup>4</sup>The residual is more than three times the standard deviation; Cook’s  $D > 4/n$ , where  $n$  is the number of observations; and  $D_{fit}$  is three times the value of the cutoff.

**Table 6** Productivity Effects of HCM, HR Analytics, and Performance Pay

	1	2	3	4	5	6	7	8	9	10
Dep. var.: <i>Output</i>	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)	ln(Y)
Specification	FE	FE	Cluster	Cluster	Cluster	Cluster	Cluster	Cluster	RE	FE
<i>ln(Capital)</i>	0.257*** (0.0266)	0.265*** (0.0256)	0.248** (0.0985)	0.277*** (0.0677)	0.247** (0.0984)	0.280*** (0.0678)	0.254** (0.0931)	0.256** (0.0923)	0.414*** (0.034)	0.428*** (0.036)
<i>ln(Labor)</i>	0.517*** (0.0369)	0.579*** (0.0340)	0.712*** (0.0845)	0.638*** (0.0804)	0.713*** (0.0843)	0.643*** (0.0823)	0.683*** (0.0780)	0.689*** (0.0754)	0.432*** (0.049)	0.400*** (0.051)
<i>HCMPurchase</i>		0.0430 (0.0406)	0.0480 (0.155)	0.136 (0.130)	0.0501 (0.156)	0.148 (0.134)	0.0172 (0.147)	0.017 (0.148)	−0.009 (0.046)	−0.011 (0.046)
<i>HCMLive</i>		0.0689** (0.0341)	0.117 (0.158)	0.179 (0.129)	0.110 (0.157)	0.199 (0.127)	0.143 (0.154)	0.125 (0.155)	0.057 (0.039)	0.057 (0.0393)
<i>HRAnalytics</i>			0.150 (0.0942)		0.145 (0.0993)		0.114 (0.0983)	0.103 (0.0984)	−0.017 (0.134)	
<i>PerformancePay</i>				0.010 (0.0764)		−0.0224 (0.0877)	0.0868 (0.149)	0.102 (0.118)	0.225 (0.176)	
<i>HRAnalytics</i> × <i>HCMLive</i>					0.0305 (0.105)			0.019 (0.109)	0.106** (0.032)	0.108*** (0.032)
<i>PerformancePay</i> × <i>HCMLive</i>						0.124 (0.133)		−0.235 (0.326)	−0.126* (0.050)	−0.129* (0.051)
<i>HRAnalytics</i> × <i>PerformancePay</i>							0.0859 (0.104)	0.062 (0.105)	0.060 (0.159)	
<i>HRAnalytics</i> × <i>PerformancePay</i> × <i>HCMLive</i>								0.445† (0.242)	0.170* (0.068)	0.165* (0.069)
Control variables	Year Firm	Year Firm	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year
<i>R</i> <sup>2</sup>	0.817	0.821	0.932	0.916	0.932	0.917	0.934	0.936	0.876	0.871
Observations	772	772	384	552	384	552	384	384	384	384

Notes. Parameter estimates of pooled OLS with clustered standard errors, fixed-effects and random-effects regression analyses are shown. Huber–White robust standard errors are shown in parentheses. All analyses employ two-tailed tests of statistical significance.

†  $p < 0.1$ ; \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ .

software and process changes, and that we are picking up some of the productivity effects of the other components of ERP adoption as well in this estimate.

The estimates for HCM purchase imply that simultaneity bias is not affecting our results and lend credibility to the argument that HCM adoption drives performance, rather than higher performance leading firms to adopt HCM.<sup>5</sup> Although this result gives us some confidence that the relationship between HCM adoption and productivity is causal, there could still be alternative explanations for this pattern of results including lagged performance effects of enterprise systems adoption. When we add lagged HCM adoption into the model, the results do not fundamentally change.

Models 5, 6, and 7 assess the pairwise interactions among HCM, HR analytics, and performance pay. Model 5 estimates the pairwise interaction between

HR analytics and HCM (for the *go-live* event). We find that the interaction between HR analytics and HCM is not statistically different from zero. This suggests that in the absence of performance pay practices, HR analytics and HCM are not complements. Similarly, we do not find evidence that performance pay and HR analytics practices are complements in the absence of HCM, because the coefficient of their interaction term is not statistically different from zero (Model 7). This result suggests that HR analytics policies and performance pay are not as strongly complementary when firms lack the appropriate technologies to monitor and manage work performance. There is also no definitive evidence of a pairwise complementarity between performance pay and HCM (Model 6).<sup>6</sup>

Overall, these results largely support the complementarities interpretation of the earlier results from

<sup>5</sup> To conserve journal space and simplify the exposition, we have removed models that estimate interaction terms with both *HCMLive* and *HCMPurchase* simultaneously. Results of these models show interactions with *HCMLive* to be significant as reported and interactions with *HCMPurchase* to be indistinguishable from zero. These results are available from the authors.

<sup>6</sup> The coefficient of their interaction is positive and approaching significance, however, suggesting they might be complements. This could be due to the fact that firms that have adopted both performance pay and HCM may also tend to adopt HR analytics practices as well. Thus, this two-way interaction term may pick up the effect of the missing three-way interaction variable among HR analytics, performance pay, and HCM, as shown in Model 8.

the correlation tests. Both sets of tests illustrate the importance of examining the “system of complements” as a whole because any subset of the system—two of three practices without the third—does not necessarily create complementarities without simultaneous adoption of all the system’s components.

Model 8 applies a test of the three-way complementarities between HCM, HR analytics practices, and performance pay. Similar to what we found in Models 3, 4, and 5, there is no evidence of an interaction effect for a partial system where only two of the three components are used. For example, the coefficient of the interaction term between HR analytics and performance pay is not significantly different from zero. It could be that without appropriate IT systems that make HR analytics effective, performance pay alone does not enhance productivity. As the *HCMLive* variable is a dummy variable indicating whether a firm is actually using the technology, the three-way interaction variable estimates the difference in the coefficients of the incentive system variable in firms with and without HCM, including variation across firms as well as variation within firms over time as they go from being nonadopters to adopters.

As shown in Model 8, the interaction of any individual organizational practice (HR analytics or performance pay) and *HCMLive* is not significantly different from zero. Interestingly, the interaction of *HCMLive* and an incentive system that includes both HR analytics and performance pay practices ( $HCMLive \times HRAnalytics \times PerformancePay$ ) is positive and statistically significant, providing some evidence that they are perhaps complements. However, the positive coefficient by itself is a necessary but not sufficient condition for proving the existence of complementarities. We provide the functional conditions for demonstrating when HCM Go-Live, HR analytics, and performance pay are complements in the appendix. There we show that three components of a system are complements if the output elasticity with respect to one variable increases when the values of the other two variables are high. For example, in our data, the output elasticity with respect to *HCMLive* is increasing when the values of *HRAnalytics* and *PerformancePay* are more than 0.06 standard deviations above the average. We derive the analogous complementarity conditions for when the elasticity with respect to performance pay and HR analytics are increasing in Table A.1 in the appendix. We estimate that the output elasticity with respect to HR analytics is increasing when *PerformancePay* and *HCMLive* are more than  $-0.39$  standard deviations above the mean. When *HCMLive* is 1, it easily exceeds the requirement for complementarities. For performance pay, we find the output elasticity is increasing when *HRAnalytics* and *HCMLive* are more than 0.35

standard deviations above the mean. Thus, when the other inputs are high, the output elasticity for performance pay is increasing.

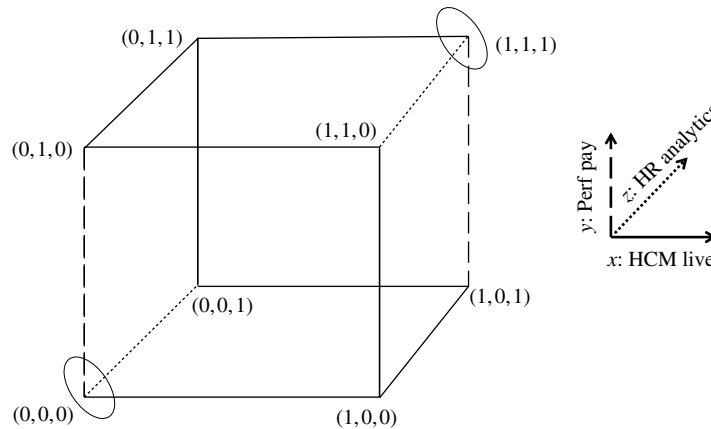
Together, these estimates provide evidence for complementarities between the complete incentive system and the HCM technology that supports it. These results indicate that the productivity of firms that have adopted the full set of incentive system practices are substantially higher in firms that have also adopted HCM compared to firms that have not adopted HCM. The OLS estimation of the three-way interaction is quite large, leading us to believe there are still other unobserved organizational practices that are correlated with HR analytics and performance pay but missing in our data. True organizational complementarities may be far more than two-way or three-way complementarities, and instead include larger sets of interlocking firm practices that complement each other.

Fixed- and random-effects estimates, which seek to control for observable and unobservable heterogeneity among firms, corroborate the three-way complementarity. The results again demonstrate that the three way interaction between HCM, performance pay and HR analytics practices is positive and significant. These findings provide additional evidence of complementarity between all three elements of the system. In these estimates, there is also evidence that HR analytics and HCM are pairwise complements, whereas adopting HCM with performance pay is negatively correlated with productivity. We are reluctant to over interpret the results of these models, which ask more of the data. However, one explanation for the last result is that performance pay can sometimes create perverse incentives that may be exacerbated when the agent has more information (Holmstrom and Milgrom 1987, 1991; Baker 1992). For example, sales teams may game the system to meet quarterly sales targets. This earns them bonuses at the expense of firm value. Such contortions may be made easier when more information is provided to employees without sufficient guidance and controls on how they should most appropriately allocate their effort. One of the goals of HR analytics, which provide structured performance feedback to appropriately direct employee effort, is to mitigate this sort of misalignment of incentives. This may be why we observe a significant productivity premium when HR analytics is added to an existing system of performance pay and HCM technology.

#### 4.3. The Cube View of Three-Way Complementarities

A graphical framework—the “cube view”—is useful for understanding the complementarities among three-way systems of technology and organizational

Figure 2 Cube View of Complementarities



Four tests of complementarities

HCM live	$F(1, 1, 1) - F(0, 1, 1) > F(1, 0, 0) - F(0, 0, 0)$	✓	$p = 0.014^*$
Perf pay	$F(1, 1, 1) - F(1, 0, 1) > F(0, 1, 0) - F(0, 0, 0)$	Not rejected	$p = 0.300$
HR analytics	$F(1, 1, 1) - F(1, 1, 0) > F(0, 0, 1) - F(0, 0, 0)$	✓	$p = 0.033^*$
The system	$[F(1, 1, 1) - F(0, 1, 1)] + [F(1, 1, 1) - F(1, 0, 1)] + [F(1, 1, 1) - F(1, 1, 0)] - [F(1, 0, 0) - F(0, 0, 0)] + [F(0, 1, 0) - F(0, 0, 0)] + F(0, 0, 1) - F(0, 0, 0) > 0$	✓	$p = 0.025^*$

\* $p < 0.05$ .

practices. In Figure 2, we present a  $1 \times 1 \times 1$  cube with the  $x$ -axis representing HCM, the  $y$ -axis representing use of performance pay, and the  $z$ -axis representing HR analytics. The binary version of the variable is used to label the coordinates in the cube, with 0 indicating a low level of implementation and 1 indicating a high level of implementation. For example, the coordinate (1, 1, 1) indicates that a firm has an HCM system installed, fully implements performance pay, and fully implements HR analytics practices.

Based on the theory of complementarities, we expect firms located at coordinate (1, 1, 1), where they adopt HCM and simultaneously implement high levels of HR analytics and performance pay policies, to be disproportionately more productive than firms that have implemented partial systems like coordinate (1, 0, 0) where firms have implemented HCM but adopt neither performance pay nor HR analytics policies. Similarly, coordinate (1, 1, 0), represents firms that have adopted HCM and implemented performance pay but choose not to actively monitor and manage employee performance.

Using the production function framework, we first determine whether firms that engage in HR analytics and implement performance pay compensation schemes reap greater productivity gains from HCM than firms that do neither. We find this to be true by comparing the magnitude of parameter estimates for firms at the edge from (0, 1, 1) to (1, 1, 1) with those at the edge from (0, 0, 0) to (1, 0, 0). The difference between the edges is statistically significant ( $p = 0.014$ ;

HCM test), suggesting that firms reap greater benefits from HCM when they have a complementary system of incentives that includes HR analytics and performance pay.<sup>7</sup>

Similarly, we determined whether firms that already have HCM and use performance pay reap greater productivity benefits from adopting HR analytics policies than firms that have neither the technology to monitor employees nor the performance pay contracts to hire, retain and motivate talent. Our analyses find evidence that firms reap a greater reward from adopting HR analytics when they simultaneously use performance pay and adopt HCM ( $p = 0.033$ ; HR analytics test). In the third test (Perf pay test), we determine whether firms experience greater returns from using performance pay when they choose to use the technology and manage performance. In contrast to the previous tests of complementarities, we do not find evidence supporting this claim ( $p = 0.300$ ).

Last, we develop and estimate a full test of three-way complementarities. The system test has greater statistical power than any of the previous tests and assesses whether firms that complete the system

<sup>7</sup>Results are obtained from random effects specifications dividing samples at the median, using  $\chi^2$  tests of differences between edges of the cube. Results obtained from pooled OLS specifications and those dividing samples at the mean are qualitatively similar, though less precisely estimated. These results are available from the authors.

of complements (1, 1, 1) by adopting just one of the three practices—HCM, HR analytics, and performance pay—experience a greater productivity gain than firms that choose to adopt the same practice but in isolation (i.e., starting from (0, 0, 0) and adding one practice). We find evidence supporting this claim through a *t*-test that demonstrates the difference to be highly significant at  $p = 0.025$  (*system test*). A straightforward explanation of this result is the existence of three-way complementarities between incentive compensation, HR analytics, and IT.

Thus, the *system test* offers a powerful way to assess the presence of a complementary system that may not be obvious from the regression results alone. In Table 6, the three-way interaction among HR analytics, performance pay, and HCM adoption is positive and statistically significant compared to the null in which no components of the system are adopted. However, strictly speaking, complementarities imply that the benefits of implementing the full system are greater than the sum of the benefits of the individual parts, not just greater than zero. This is precisely what the *system test* estimates.<sup>8</sup> When applied to our sample, we find that the productivity gains from completing a full system of complements using all three practices is greater than the sum of gains from adopting any one of the three practices in isolation. These results together provide evidence that technology adoption is complementary to a system of organizational practices that includes HR analytics and performance pay.

#### 4.4. Robustness and Limitations

Results of three different sets of empirical tests (correlation, productivity, and system tests) provide consistent evidence of three-way complementarities between IT, performance pay, and HR analytics practices in our data. However, there may be alternative explanations for our results, which we consider here in more depth. To save space, we have not reported the detailed results of robustness analyses in this paper, but all results reported here are available from the authors.

First, industry differences may explain some of the correlations we see. It could be, for example, that firms with employees whose work can be easily monitored and measured will naturally choose to implement HCM systems along with performance pay and HR analytics practices. Conversely, firms that primarily engage in “knowledge work” may not be able to monitor, manage, and support workers in the same

explicit ways, and thus may not adopt the complements together. Knowledge work firms may choose to adopt incentives, but rely less on monitoring because their employees’ work is more difficult to monitor. Although we see minor differences in the adoption of HR analytics and performance pay between knowledge work and non-knowledge work firms, these differences are not statistically significant. Any differences between firms on these dimensions are therefore not likely to be big enough to explain away the three-way complementarity. Given that our correlation and productivity tests include industry controls and that our productivity tests are also robust to the inclusion of firm fixed effects, it is unlikely these differences can account for our results.

To further explore how industry differences may affect our results, we first tested whether firms that primarily do knowledge work were less likely to adopt HCM, both in general and in the presence of the organizational complements. Results of logistic regression analysis predicting the likelihood of adopting HCM as a function of being in a knowledge work industry, as well as HR analytics adoption and performance pay adoption, and the interaction of knowledge work and these practices, show that knowledge work firms are less likely to adopt HCM and that the interaction of performance pay and knowledge work significantly predicts a lower likelihood of adopting HCM. This may mean that in industries in which work is difficult to measure, performance incentives may not complement measurement based technologies such as HCM. Because knowledge work firms that adopt performance pay incentives are less likely to adopt HCM, these results also seem to suggest that three-way complementarities between performance pay, HR analytics, and HCM technology are more pronounced when work is measurable.

To test whether differences between knowledge work and non-knowledge work firms bias our productivity analyses, we removed knowledge work firms from the sample and estimated the productivity regressions again. The results show that our finding of three-way complementarities is robust to removing these firms. Although we could not reject the null hypothesis of no complementarities among knowledge work firms, the power of this test is very low given the small number of knowledge work firms in this subsample. It may be that the three-way complementarities we test are more pronounced in non-knowledge work industries, where employees’ performance can be measured precisely and thus managed explicitly. But, these differences do not explain the existence of three-way complementarities in our sample. Future work should examine differences in these relationships across knowledge work and non-knowledge work firms in more depth.

<sup>8</sup> In the analysis of the HCM system, we assess a three-way system. In principle, systems with four, five, or more dimensions could be estimated using a generalized version of the *system test* we estimate here.



Second, there are at least two mechanisms through which incentive pay may drive productivity gains—employee motivation and self-selection. The first effect, employee motivation, is the direct effect of monetary rewards that motivate workers to exert more effort and produce more output. The second effect, self-selection, is the effect of performance pay on the likelihood that more talented and productive workers are likely to take and keep jobs in which they are disproportionately rewarded, whereas less productive workers are likely to turn over. When compensation is tied to performance, poor performers whose cost of effort is relatively high are likely to leave as performance pay decreases their total compensation and makes the job difficult to justify from the perspective of their participation constraint. On the other hand, high performers are more likely to stay because they can earn more under performance pay compensation systems (Lazear 2000a, b). To test whether our results were sensitive to the inclusion or removal of the proxies for either of these two mechanisms in our tests of complementarity, we removed the self-selection questions and assessed the productivity regressions with only the motivation questions included in the measure of performance pay. We then removed motivation and ran the regressions with only self-selection. The results remain essentially unchanged, and the three way complementarity is robust to these alternative specifications.

Third, it could be that HCM adopters are somehow different than nonadopters. When we examine the descriptive statistics, we see that they are statistically significantly larger whether measured by sales, employees, or capital. However, they are not significantly better or worse on performance dimensions such as return on assets or profits. More importantly, the design of our analyses makes it unlikely that such selection effects bias our results for several reasons.

First, our productivity tests are essentially immune to any simple types of selection bias. Although HCM adopters are different than nonadopters in some observable ways, such as firm size, performance premiums accrue only to firms with all three complements in place. If HCM adopters were generally more productive, selection bias should exist both for those firms that adopt the complements as well as those that do not. We would therefore expect to see no evidence of complementarities in our tests. Evidence of complementarities with performance pay and HR analytics practices suggests that differences between adopters and nonadopters of HCM are not sufficient to explain observable differences in performance between those with the system of complements in place and those that are missing a portion of the system.

In addition, our design allows us to test and rule out endogeneity of the purchase of HCM. As we

observe purchase and go-live decisions and find that only going live is correlated with performance, we can be reasonably sure that higher-performing firms are not simply selecting to purchase HCM. When we add HCM purchase and its two-way and three-way interactions with HR analytics and performance pay to the estimation, none of the estimates for these variables are statistically significant. Because all firms that purchase HCM in our data eventually go live with the software, there can also be no selection effect caused by some firms dropping out between the purchase and go-live dates.

Finally, fixed-effects specifications assess variation within observations over time, meaning productivity regressions compare firms' performance before and after their adoption. Any time-invariant differences in performance between adopters and nonadopters are held constant in this specification. Given this evidence, it is unlikely that differences between HCM adopters and nonadopters, besides the hypothesized difference caused by in the decision to adopt complementary organizational practices, are driving the results.

Given the nature of our sample and the pattern of results that we have found, a few important caveats are worth noting. First, our sample is not representative of the entire U.S. economy and is comprised disproportionately of manufacturing firms. Though removing knowledge work firms does not change our results in any significant way, it may be that the complementarities between performance pay, HR analytics, and IT behave differently in larger samples of services firms. Although most of our key results are significant at the 5% level, our sample is relatively small, and some estimates are less precise than they may be in larger samples. Estimates of higher-order complementarities may be noisy and thus more precisely estimated in future work with larger samples.

Second, our results by no means rule out the existence of pairwise complementarities between any two of the three complements we test. However, statistical evidence does confirm that the existence of all three complements on average creates greater than additive performance benefits for the firms in our sample. Pairwise complementarities may still exist, especially for certain subgroups of firms or industries.

Third, we have adopted a common assumption in the IT complementarity literature and taken advantage of the fact that organizational complements are often quasi fixed. However, because we do not have time-varying data on organizational complements, we cannot attribute causal interpretations to the impact of HR policies.

Finally, although we have found evidence of significant complementarities among information technology, HR analytics, and performance pay, we

interpret the exact coefficient estimates of the three-way interaction terms with caution. These coefficients are often larger than expected, leading us to believe there are still other unobserved organizational practices that are correlated with HR analytics and performance pay but missing in our data. This is likely because true organizational complementarities may be far more than two-way or three-way complementarities, encompassing larger sets of interlocking firm practices that complement each other. Econometricians and even managers themselves may not understand the full set of complements involved.

## 5. Conclusion

Previous research has found evidence of complementarities between general investments in information technology and broad metrics of organizational capital. We move this stream of inquiry from an expansive perspective of IT as a general-purpose technology toward examination of specific process-enabling technologies designed to support human resource management and specifically incentive management. By studying a specific type of enterprise system, the human capital management solution within the ERP suite, we are able to examine very specific, theory-driven predictions about *how* information technology complements a narrow set of business practices focused on designing and implementing effective incentive contracts.

We use a principal–agent model to illustrate how incentives affect observable performance. In particular, we examine HR analytics and performance pay as a set of organizational practices that complements HCM. Using a detailed survey of human resource practices and comprehensive objective enterprise IT adoption data, we provide some of the first firm-level evidence on how clusters of human resource practices complement a specific type of information technology.

Our analysis uncovers two key results. First, we find that HCM, performance pay, and HR analytics practices are mutually correlated. In particular, the demand for HCM is significantly higher in firms that have adopted the other two practices. Second, these practices generate a disproportionate productivity premium when they are implemented simultaneously as a tightly knit system of organizational incentives. We develop and assess a cube view of complementarities, which illustrates the increased productivity from completing the triad of complements compared to introducing one of its elements in isolation.

An important feature of our data is that we can rule out reverse causality between high productivity and HCM adoption. We do this by exploiting separate measures for purchase and go-live events,

allowing us to infer a causal explanation for the complementarities we find. These results support the theoretical prediction of a three-way complementary system of organizational practices and suggest a path to greater productivity from technology innovations such as enterprise IT. At the same time, these three-way complementarities may be only part of an even larger complementary system, highlighting the complexity of successful technology-enabled organizational change.

Milgrom and Roberts (1990) formally analyzed how nonconvexities can exist in a firm’s decision to adopt any or all of a set of organizational characteristics that together complement new technology. The marginal benefit of adopting any one of a complementary set of activities increases with the adoption of the others. Thus, adoption of systems of practices (what Milgrom and Roberts 1990 call “groups of activities”) “may not be marginal decision[s].” They argue “exploiting such an extensive system of complementarities requires coordinated action between traditionally separate functions” (Milgrom and Roberts 1990, p. 515). Because such discovery and coordination is difficult, it is not surprising that we find a nonempty set of firms at each of the eight vertices of the three-way complements cube, even though theory predicts that this is not optimal. As expected, a disproportionate, but not universal, subset of them is in the higher-performing clusters. Over time, we expect that a combination of focused analysis by researchers, and trial and error by managers, will reveal more and more of the nature and scope of organizational complementarities.

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## Appendix. Functional Derivations for When Performance Pay, HR Analytics, and HCM are Complements

Here, we provide derivations for when performance pay, HR analytics, and HCM are complements (based on the work of Tambe et al. 2012). We assume a Cobb–Douglas production function and take the natural log on both sides:

$$\begin{aligned}
 Y &= \beta_X X + \beta_Y Y + \beta_Z Z + \beta_{XY} XY + \beta_{XZ} XZ \\
 &\quad + \beta_{YZ} YZ + \beta_{XYZ} XYZ, \\
 \eta_x &= \frac{\partial Y}{\partial X} = \beta_x + \beta_{xy} Y + \beta_{xz} Z + \beta_{xyz} YZ.
 \end{aligned}$$

**Table A.1** Conditions for Complementarities

X = HR analytics	$\beta_{xz} = 0.106$	$\eta_x$ is increasing with increases
Y = Performance pay	$\beta_{xy} = 0.060$	in Y and Z when $G > -0.39$
Z = HCM live	$\beta_{xyz} = 0.170$	
X = Performance pay	$\beta_{xz} = -0.126$	$\eta_x$ is increasing with increases
Y = HR analytics	$\beta_{xy} = 0.060$	in Y and Z when $G > 0.35$
Z = HCM live	$\beta_{xyz} = 0.170$	
X = HCM live	$\beta_{xz} = 0.060$	$\eta_x$ is increasing with increases
Y = Performance pay	$\beta_{xy} = -0.126$	in Y and Z when $G > 0.06$
Z = HR analytics	$\beta_{xyz} = 0.170$	

**Table A.2** Correlations for Survey Questions Used to Construct the Monitoring Practice Variable

	M1	M2	M3	M4	M5	M6	M7	M8	M9
M1	1								
M2	0.2417	1							
M3	0.3253	0.3491	1						
M4	0.3642	0.0114	0.5428	1					
M5	0.1879	0.1765	0.5713	0.6517	1				
M6	0.5236	0.1914	0.1984	0.1384	0.0411	1			
M7	0.3098	0.371	0.2686	0.1047	0.0687	0.4604	1		
M8	0.4322	0.0501	0.2596	0.1878	0.013	0.6655	0.5205	1	
M9	0.4298	0.1064	0.1458	0.2336	0.1418	0.5066	0.3645	0.6857	1

**Table A.3** Correlations for Survey Questions Used to Construct Performance Pay Variable

	I1	I2	I3	I4
I1	1			
I2	0.6312	1		
I3	0.6886	0.5973	1	
I4	0.4200	0.2603	0.3754	1

If we move Y and Z simultaneously in the same direction with the same distance G, the elasticity of Y with respect to X is as follows:

$$\eta_x(G) = \frac{\partial Y}{\partial X} \Big|_{X=G, Y=G} = \beta_x + (\beta_{xy} + \beta_{xz})G + G^2\beta_{xyz}.$$

The change of elasticity with respect to G is

$$\frac{\partial \eta_x}{\partial G} = \beta_{xy} + \beta_{xz} + 2G\beta_{xyz}.$$

Because X, Y, and Z are all standardized in the sample, we focus on observations in the sample that are within two standard deviations from the mean  $G \in [-2, 2]$ . So the elasticity of X with respect to Y is increasing in G when

$$\beta_{xy} + \beta_{xz} + 2G\beta_{xyz} > 0.$$

This is also the condition for which an increase in Y and Z increases the output elasticity with respect to X. We find the range of G for this to be true using the estimates in Table A.1 and the coefficient estimates in Model 9 of Table 6.

## References

Aral, S., P. Weill. 2007. IT assets, organizational capabilities, and firm performance: How resource allocations and organizational differences explain performance variation. *Organ. Sci.* 18(5) 763–780.

- Aral, S., E. Brynjolfsson, D. J. Wu. 2006. Which came first, IT or productivity? The virtuous cycle of investment and use in enterprise systems. *Proc. 27th Annual Internat. Conf. Inform. Systems, Milwaukee*, 1819–1839.
- Arora, A. 1996. Testing for complementarities in reduced-form regressions: A note. *Econom. Lett.* 50(1) 51–55.
- Arora, A., A. Gambardella. 1990. Complementarity and external linkages: The strategies of large firms in biotechnology. *J. Indust. Econom.* 38(4) 361–379.
- Athey, S., S. Stern. 1998. An empirical framework for testing theories about complementarities in organizational design. NBER Working Paper 66, National Bureau of Economic Research, Cambridge, MA.
- Baker, G. P. 1992. Incentive contracts and performance measurement. *J. Political Econom.* 100(3) 598–614.
- Baker, G. P., T. N. Hubbard. 2004. Contractibility and asset ownership: On-board computers and governance in U.S. trucking. *Quart. J. Econom.* 119(4) 1443–1479.
- Banker, R. D., C. F. Kemerer. 1992. Performance evaluation metrics for information systems development: A principal-agent model. *Inform. Systems Res.* 3(4) 379–400.
- Bartel, A. 2004. Human resource management and organizational performance: Evidence from retail banking. *Indust. Labor Relations Rev.* 57(2) 181–203.
- Bartel, A., C. Ichniowski, K. Shaw. 2007. How does information technology affect productivity? Plant-level comparisons of product innovation, process improvement, and worker skills. *Quart. J. Econom.* 122(4) 1721–1758.
- Black, S. E., L. M. Lynch. 2001. How to compete: The impact of workplace practices and information technology on productivity. *Rev. Econom. Statist.* 83(3) 434–445.
- Bloom, N., R. Sadun, J. Van Reenen. 2012. Americans do IT better: US multinationals and the productivity miracle. *Amer. Econom. Rev.* 102(1) 167–201.
- Bresnahan, T., M. Trajtenberg. 1995. General purpose technologies: Engines of growth? *J. Econometrics* 65(1) 83–108.
- Bresnahan, T., E. Brynjolfsson, L. M. Hitt. 2002. Information technology, workplace organization and the demand for skilled labor: Firm-level evidence. *Quart. J. Econom.* 117(1) 339–376.
- Brynjolfsson, E., L. M. Hitt. 1995. Information technology as a factor of production: The role of differences among firms. *Econom. Innovation New Tech.* 3(3) 183–200.
- Brynjolfsson, E., L. M. Hitt. 1996. Paradox lost? Firm-level evidence on the returns to information systems. *Management Sci.* 42(4) 541–558.
- Brynjolfsson, E., L. M. Hitt. 2003. Computing productivity: Firm-level evidence. *Rev. Econom. Statist.* 85(4) 793–808.
- Brynjolfsson, E., P. Milgrom. 2012. Complementarities in organizations. R. Gibbons, J. Roberts, eds. *Handbook of Organizational Economics*. Princeton University Press, Princeton, NJ. Forthcoming.
- Brynjolfsson, E., L. M. Hitt, S. Yang. 2002. Intangible assets: Computers and organizational capital. *Brookings Papers Econom. Activity* 2002(1) 137–199.
- Caroli, E., J. Van Reenen. 2001. Skill-biased organizational change: Evidence from a panel of British and French establishments. *Quart. J. Econom.* 116(4) 1449–1492.
- Devaraj, S., R. Kohli. 2003. Performance impacts of information technology: Is actual usage the missing link? *Management Sci.* 49(3) 273–289.
- Hitt, L. M., D. J. Wu, X. Zhou. 2002. Investment in enterprise resource planning: Business impact and productivity measures. *J. Management Inform. Systems* 19(1) 71–98.
- Holmstrom, B., P. Milgrom. 1987. Aggregation and linearity in the provision of intertemporal incentives. *Econometrica* 55(2) 303–328.

- Holmstrom, B., P. Milgrom. 1991. Multitask principal-agent analyses: Incentive contracts, asset ownership, and job design. *J. Law, Econom., Organ.* 7 24–52.
- Holmstrom, B., P. Milgrom. 1994. The firm as an incentive system. *Amer. Econom. Rev.* 84(4) 972–91.
- Ichniowski, C., K. Shaw. 2003. Beyond incentive pay: Insiders' estimates of the value of complementary human resource management practices. *J. Econom. Perspect.* 17(1) 155–180.
- Ichniowski, C., K. Shaw, G. Prennushi. 1997. The effects of human resource management practices on productivity: A study of steel finishing lines. *Amer. Econom. Rev.* 87(3) 291–313.
- Kandel, E., E. P. Lazear. 1992. Peer pressure and partnerships. *J. Political Econom.* 100(4) 801–817.
- Lazear, E. 2000a. Performance pay and productivity. *Amer. Econom. Rev.* 90(5) 1346–1361.
- Lazear, E. 2000b. The power of incentives. *Amer. Econom. Rev.* 90(2) 410–414.
- McAfee, A. 2004. Do you have too much IT? *MIT Sloan Management Rev.* 45(3) 18–22.
- Melville, N., K. Kraemer, V. Gurbaxani. 2004. Review: Information technology and organizational performance: An integrative model of IT business value. *MIS Quart.* 28(2) 283–322
- Milgrom, P., J. Roberts. 1990. The economics of modern manufacturing: Technology, strategy and organization. *Amer. Econom. Rev.* 80(3) 511–528.
- Milgrom, P., J. Roberts. 1995. Complementarities and fit strategy, structure, and organizational change in manufacturing. *J. Accounting Econom.* 19(2–3) 179–208.
- Novak, S., S. Stern. 2009. Complementarity among vertical integration decisions: Evidence from automobile product development. *Management Sci.* 55(2) 311–332.
- Prendergast, C. 1999. The provision of incentives in firms. *J. Econom. Literature* 37(1) 7–63.
- Tambe, P., L. M. Hitt, E. Brynjolfsson. 2012. The extroverted firm: How external information practices affect innovation and productivity. *Management Sci.* 58(5) 843–859.