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Dynamic Knowledge Transfer and Knowledge Development for Product and Process Design Teams

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We consider a manager who invests in knowledge development of a product and a process design team as well as knowledge transfer between teams throughout a new product development (NPD) project. Knowledge development at a particular time (e.g., prototyping and experimentation) increases a team's level of knowledge at that time. In contrast, the recipient's benefits from knowledge transfer may be lagged because of the difficulties in articulating and documenting knowledge as well as the challenges regarding its interpretation and application. Over time, as each team embeds knowledge in the NPD project, the levels of product and process performance increase, thereby increasing the net revenue earned at the product launch time. In a key contribution to the literature, analytic conditions are given that characterize the dynamic rates at which knowledge development and knowledge transfer occur throughout the project. We show that the investment in knowledge development for each team and knowledge transfer between teams may be constant, front-loaded, back-loaded, U-shaped, or the peak rate may be delayed over time. As such, we show how concurrent engineering is optimally pursued throughout the NPD project.

Keywords: product and process development and design; operations management–organizational behavior interface; technology management and process design
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1. Introduction

New product development (NPD) is a dynamic organizational process that systematically expands a firm's scope of knowledge (Macher 2006). Product and process design teams pursue activities to increase the levels of product and process design knowledge over time and thereby impact product and process functionality, manufacturing costs, and the product launch time (Pisano 1997, Mihm et al. 2003). Unfortunately, despite the critical role of NPD on a firm's long-term performance, empirical evidence indicates that many firms do not undertake knowledge management strategies that drive successful NPD outcomes (Nonaka et al. 2008, Cusumano 2010).

Consider the NPD project pursued by Advanced Micro Devices (AMD) to develop the K6 microprocessor, which leveraged a considerable amount of product design knowledge based on the K5 microprocessor (Slater 1996). As a result of new product features, the manufacturing processes for the K6 were substantially different from those of the K5 (Morrison and DeTar 1998). Unfortunately, the limited process design knowledge was not recognized at the outset of the development project. In addition, given the complexity of the K6 microchip architecture, whereas product and process design integration was important, it was not well executed (Wilson 1996). As a result, manufacturing processes had to be redesigned leading to a late market entry and slow ramp-up, which afforded Intel the opportunity to first introduce the Pentium MMX (Takahashi 1997, Willcox 1999).

The AMD example supports the importance of coordinating the dynamic activities of product and process design teams during the NPD project. In this paper, we address this fundamental problem in NPD from the perspective of knowledge management. We consider a project manager who dynamically invests in *knowledge development* (KD) of both a product and a process design team as well as *knowledge transfer* (KT) between teams throughout an NPD project. KD includes problem solving activities such as testing, simulation, prototyping and experimentation as well as training from equipment vendors. KT between the product and process design teams increases the recipient's level of knowledge because its content inspires the recipient to conduct additional experimentation and problem solving. KT from the product to the process design team conveys information such as consumer preferences and desirable product specifications. KT from the process to the product design team describes process capabilities and constraints to ensure the manufacturability of the product.

To capture how KD and KT impact the *levels of product and process design knowledge* over time, we leverage key results from the empirical literature on knowledge management. First, it has been shown that, whereas KD pursued at a particular time increases the level knowledge at that time, the benefits from KT may be lagged. The lag reflects the difficulties of the source team to clearly articulate and document its knowledge, as well as the difficulties of the recipient team to deploy that knowledge. Additionally, a source team may provide incomplete information, and the recipient team may not have sufficient depth of skills to absorb the KT. For example, teams may use different terminology or technical support systems and may respond to incentives that impede the timely effectiveness of KT.

Second, the empirical literature on knowledge management shows that KD and KT increase each team's level of knowledge in a manner that is both interrelated and dynamic. Specifically, the effectiveness of KT at a particular time depends on the levels of knowledge of both teams at that time, since a higher skilled source has more knowledge to offer and a higher skilled recipient is better able to absorb and exploit new knowledge. Similarly, the increase in the levels of knowledge from KD at a particular time depends on the respective team's level of knowledge at that time since a higher skilled team is better able to develop and deploy new knowledge.

Over time, as each team embeds knowledge in the NPD project, the *levels of product and process performance* increase (e.g., new product features and functionality are created that increase product performance; yield and process efficiency improve thereby increasing process performance). As such, *net revenue* at the product launch time is a function of the levels of product and process knowledge. Lastly, the NPD manager's dynamic investment in KD and KT considers the corresponding costs incurred.

Our research contributes to the NPD literature by demonstrating forces that drive the dynamic interplay between KD and KT for a product and a process design team throughout an NPD project. We show that the existence and direction of KT drive markedly different optimal solutions over time, which we refer to as constant, front-loaded, U-shaped, delayed (inverse U-shaped), or back-loaded. An optimal solution is *front-loaded* (*back-loaded*) if its peak rate occurs at the initial (terminal) time of the NPD project. An optimal solution is *U-shaped* (*delayed*) if the minimum (maximum) rate occurs at an intermediate time in the NPD project. We find that if KT is not permitted in either direction, then the rates of KD of both the product and process design teams are constant over time. Also, if KT only occurs to the process design team (a common assumption in the literature), then KT to the process design team is either front-loaded or the peak rate of KT is delayed; KD for the product design team is front-loaded; and KD of the process design team is U-shaped. In addition, if KT is bidirectional, then KT is either front-loaded or delayed, whereas KD for each design team is U-shaped. Furthermore, we demonstrate the key role of the lag associated with the recipient realizing the benefits from KT. Finally, we contribute to the literature by analytically demonstrating how attributes of the firm as well as characteristics of the marketplace drive the dynamic KD and KT solutions.

2. Literature Review

2.1. Knowledge Management Literature

The knowledge management literature provides three anchors in support of our modeling assumptions. First, the literature has extensively measured knowledge in terms of inputs and outputs (Hedlund 1994, Haas and Hansen 2007). For our model, the two inputs are KD and KT, which are measured in terms of the engineering hours devoted to each activity (Carrillo and Franza 2006). Similarly, the two outputs for our model are the levels of product and process knowledge. The level of product knowledge is measured in terms of product performance features and functionality such as the battery life or weight of a PC (Loch and Terwiesch 2005). Similarly, the level of process knowledge is measured in terms of process performance such as cost efficiency and yield (Grant 1996).

Second, the knowledge management literature provides insights on how to model the process of KT, whereby one team's knowledge is affected by the experience of another (Argote and Ingram 2000). According to Carlile (2002), the specialized knowledge held by product and process design teams, while essential for knowledge creation, poses a challenge for effective KT. Van de Ven (2007) finds that the effectiveness of KT may be limited by different interpretations of knowledge among teams. Overall, the empirical literature indicates that there is a lag between the time KT is initiated by the source and the time that the recipient's benefits occur (Szulanski 2000). Consistent with this literature, we assume that the recipient's benefits from KT are lagged.

Third, Cohen and Levinthal (1990) introduce the concept of absorptive capacity, which they define as the capability to recognize the value of new information, absorb it, and apply it. Consistent with the notion of absorptive capacity, we assume that the levels of knowledge of both the source and recipient teams impact the benefits derived by the recipient of KT. Moreover, we assume that a team's level of knowledge impacts the benefits obtained from KD since a team with a higher level of knowledge is better able to formulate designs, conduct simulations, and develop prototypes (Nonaka 1994, Carrillo and Gaimon 2004). However, diminishing returns are associated with the increase in the levels of product and process design knowledge obtained from KD and KT (Bhuiyan et al. 2004).

2.2. NPD Literature

For successful NPD, KD is required to identify and solve problems early to reduce the lead time and costs of product development (Thomke and Fujimoto 2000, Terwiesch and Xu 2004). Also, NPD research discusses the importance of managing communication from the product to the process design team through KT. Clark and Fujimoto (1991) describe the importance of KT from the product to the process design team in the automotive industry.

A considerable body of NPD research concerns strategies for KT from the product to the process design team. Krishnan et al. (1997) show that the timing of KT from the product to the process design team depends on the rate that the product design team converges to the final product attributes and features, and the difficulties of pursuing process development activities while upstream information evolves. Terwiesch and Loch (1999) show that the impact of changes triggered by KT to the process design team is a function of the magnitude of the change and its timing. Roemer and Ahmadi (2004) determine the optimal rate and duration of KT from the product to the process design team to reduce development time. Loch and Terwiesch (2005) consider KT from the product to the process design team to minimize time-to-market. For large and complex engineering projects, Mihm et al. (2003) show how misaligned objectives of different sub-teams drive coordination problems in KT, which delay project completion.

There are several fundamental differences between our approach and those in the NPD literature. First, most prior research assumes that either KT occurs only from the product to process design team, or communication between teams occurs without specifying the direction (Ha and Porteus 1995, Krishnan et al. 1997, Terwiesch et al. 2002, Mihm et al. 2003). In contrast, the timing and direction of KT between the product and process design teams are explicit decisions in our model. Lin et al. (2008) and Yang et al. (2014) explicitly consider KT in both directions. However, neither obtains conditions that drive the rates and timing of KT, and neither considers KD. We provide analytic results that demonstrate the manager optimally invests in KD at significantly different rates over time when KT is not permitted, when KT is only permitted from the product to process design team, and when KT is permitted in both directions.

Second, we show that a holistic view is crucial to manage the dynamic interplay between KD and KT for product and process design teams. Thomke and Fujimoto (2000) and Carrillo and Franza (2006) describe situations where KD is front-loaded, while Thomke and Fujimoto (2000) and Fixson and Marion (2012) observe and critique situations where KD is back-loaded. However, none of these papers explicitly considers KT. While Adler (1995), Loch and Terwiesch (1998), and Roemer and Ahmadi (2004) refer to situations where a high level of KT from the product to the process design team is pursued later in the NPD project (back-loaded), none of these papers explicitly considers KD. In contrast, we demonstrate that by simultaneously considering KD and KT (if it exists), the dynamic solutions may be constant over time, front-loaded, back-loaded, U-shaped, or the peak rate may be delayed. Xiao (2012) considers a three-stage NPD derivative versus platform project and obtains analytic conditions where KD is front-loaded, back-loaded, U-shaped, or inverse U-shaped. In contrast to this paper, Xiao assumes that the rates of KT are not endogenous. We advance the results of these papers by providing explicit analytic conditions depicting how the manager should invest in KD of each team and KT in both directions between teams throughout the NPD project.

Third, unlike the above-mentioned literature, we recognize that, whereas KD increases a team's level of knowledge instantaneously, the benefits to the recipient of KT are lagged because of the time and effort necessary to document and deploy that knowledge. We show that the dynamic KD and KT solutions are significantly impacted by the nature of the lags associated with KT. Furthermore, we analytically show that the rates of KD and KT over time (i.e., the shapes of the solutions) are dramatically different when the benefits of KT are lagged versus instantaneous.

3. The Model Formulation

We introduce our model mathematically (notation appears in §1 of the online supplement, available at http://dx.doi.org/10.1287/msom.2014.0507). The subscript "t" denotes the time derivative; Z_w and Z_{ww} denote the first and second order partial derivatives of Z with respect to w, respectively.

3.1. Knowledge

We consider the time horizon $t \in [0, T]$, where 0 is the initial time of the NPD project and T is product launch time. Let $D(t)$ denote the level of *knowledge of the product design team* at time t. Similarly, let $M(t)$ denote the level of *knowledge of the process design team* at time t. The levels of knowledge reflect each team's competence about the scientific and engineering information related to the NPD project. The initial levels of knowledge are known, $D_0 = D(0) > 0$ and $M_0 = M(0) > 0$, and may be inferred from the educational background of team members, performance appraisals, and past experience (Epple et al. 1996, Carrillo and Gaimon 2004).

The knowledge levels of the product and process design teams increase as the manager allocates resources (engineering hours) for KD. Let $\gamma(t)$ and $g(t)$ denote the rates of *KD of the product and process design teams*, respectively, with $0 \le \gamma(t) \le \bar{\gamma}$ and $0 \le g(t) \le \bar{g}$. The upper bounds $\bar{\gamma}$ and $\bar{g}$ reflect budget or labor constraints that limit KD (Carrillo and Gaimon 2000, Carrillo and Franza 2006). Inspired by the concept of absorptive capacity (Cohen and Levinthal 1990), the increase in the level of product (process) design knowledge from KD is determined by the rate of KD of the product (process) design team, the team's current level of product (process) design knowledge, and the effect of diminishing returns (Nonaka 1994, Lapre and Van Wassenhove 2001). Mathematically, the increase in the level of knowledge of the product design team from KD at time t is $\gamma(t)[D(t)]^{\rho_1}$ where $\rho_1 \in (0, 1)$ indicates the rate of diminishing returns. Similarly, for the process design team this expression is given by $g(t)[M(t)]^{r_1}$ with $r_1 \in (0, 1)$.

The manager also invests in KT in both directions to increase the levels of product and process design knowledge. The recipient's level of knowledge increases because additional experimentation and problem solving occur in response to the KT (Szulanski 2000, Haas and Hansen 2007). Consistent with the concept of absorptive capacity (Cohen and Levinthal 1990), whereas a source team with a larger level of knowledge is capable of transferring more knowledge to the recipient, the benefits to the recipient exhibit diminishing returns. Also, the recipient team with a larger level of knowledge is better able to comprehend and respond to the KT, subject to diminishing returns. The return parameters may reflect the capability of the technical system to support KT.

Let $\beta(t)$ denote the rate of *KT from the process to the product design team* at time t, with $0 \le \beta(t) \le \bar{\beta}$. Similarly, let $b(t)$ denote the rate of *KT from the product to the process design team* at time t, with $0 \le b(t) \le \bar{b}$. The upper bounds $\bar{\beta}$ and $\bar{b}$ reflect budget or labor constraints that limit the investment in KT. Let ρ_2 and ρ_3 (ρ_2, $\rho_3 \in (0, 1)$) indicate the rates of diminishing returns associated with the ability of process and product design knowledge at time t, respectively, to increase the level of product design knowledge at that time. Similarly, let r_2 and r_3 ($r_2, r_3 \in (0, 1)$) indicate the rates of diminishing returns associated with the ability of product and process design knowledge at time t, respectively, to increase the level of process design knowledge at that time. The returns parameters reflect the capabilities of the technical systems that aid in the documentation of information and the managerial incentives for knowledge sharing (Adler 1995, Mihm 2010).

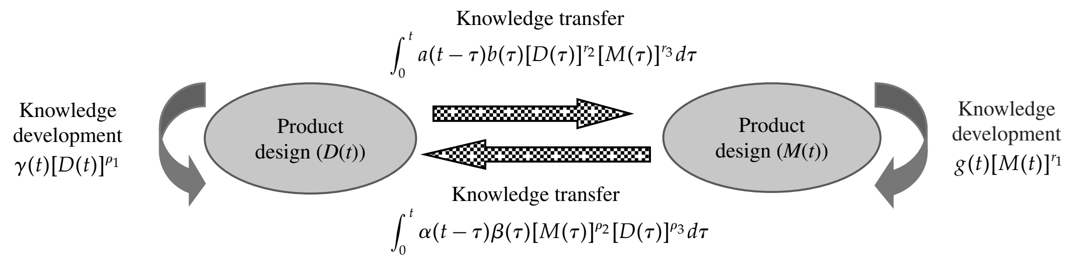
Whereas KD increases the level of knowledge at the instant of time it is pursued, the increase in the recipient's level of knowledge obtained from KT may be lagged and occur over a nonzero interval of time. Therefore, KT from the process (product) design team undertaken at time τ may increase the level of product (process) design knowledge at time t, where $t \ge \tau$ holds. Let the function $\alpha(t-\tau)(a(t-\tau))$ represent a continuously distributed time lag indicating the portion of KT undertaken at time τ that increases the level of product (process) design knowledge at time t with a lag of $t-\tau$, for $t \ge \tau$ (Gaimon 1997, Carrillo and Gaimon 2000). Also, we have $\alpha(t-\tau) \in [0, 1](a(t-\tau) \in [0, 1])$ and $\int_\tau^T \alpha(t-\tau)\, dt \le 1$ ($\int_\tau^T a(t-\tau)\, dt \le 1$). As such, the portion of KT to the product design team at time τ that is immediately effective at increasing the level of product knowledge is $\alpha(0)$ (zero lag). Similarly, the portion of KT from the process design team at time τ that is absorbed and increases the level of product design knowledge $t-\tau$ periods later is $\alpha(t-\tau)$, for $t \ge \tau$. The integral of the lag equals one only if all of the KT to the recipient team at time τ is fully effective by time T. We make no assumptions regarding the specific form of the function $\alpha(t-\tau)(a(t-\tau))$.

From the above, the increase in the level of knowledge of the product design team at time t because of KT is driven by the accumulation of the portions of all past KTs from the process design team (occurring at time τ) that are effective at time t with a lag of $t-\tau$, for $\tau \in [0, t]$. The increase in the level of product design knowledge at time t because of KT from the process design team is $\int_0^t \alpha(t-\tau) \cdot \beta(\tau)[M(\tau)]^{\rho_2}[D(\tau)]^{\rho_3}\, d\tau$. Similarly, the increase in the level of process design knowledge at time t because of KT from the product design team is given by $\int_0^t a(t-\tau)b(\tau)[D(\tau)]^{r_2}[M(\tau)]^{r_3}\, d\tau$. Figure 1 illustrates how the levels of product and process design knowledge change over time through KD and KT. Clearly, $D(t)$ and $M(t)$ are positive and nondecreasing for $t \in [0, T]$.

3.2. The Objective

The manager's objective is to maximize *profit*. Let the *net revenue* earned by a product launched in the marketplace at time T be denoted by $V[D(T), M(T)]$. We reasonably assume that as the level of product design knowledge increases, the team's capability to

Figure 1 The Dynamic Levels of Product and Process Design Knowledge



develop enhanced product features increases so that the level of product performance increases but at a nonincreasing rate (Christensen and Raynor 2003). Also, we assume that as process design knowledge increases, the level of process performance increases at a nonincreasing rate (Macher 2006). Naturally, net revenue increases as either product or process performance increases. Therefore, net revenue increases at nonincreasing rates in relation to the levels of product and process design knowledge giving us $V_{D(T)} \geq 0$, $V_{D(T)D(T)} \leq 0$, $V_{M(T)} \geq 0$, and $V_{M(T)M(T)} \leq 0$ (Krishnan et al. 1997, Cohen et al. 2000, Bhuiyan et al. 2004). Since the increase in net revenue that occurs from an increase in the level of product (process) design knowledge is not reduced by a unit increase in the level of process (product) design knowledge, we have $V_{D(T)M(T)} \geq 0$.

Beyond the net revenue earned at the product launch time, costs are incurred during the NPD project (Clark and Fujimoto 1991). The cost for KD of the product (process) design team at time t is given by $C_1[\gamma(t)]$ ($C_2[g(t)]$) and increases at an increasing rate in relation to amount of KD pursued at that instant of time. The second order effect occurs since, as the manager allocates more and more engineering hours to KD at a particular time, the costs for integration, coordination, and supervision increase at an increasing rate. This gives us $C_{1\gamma}$, C_{2g}, $C_{1\gamma\gamma}$, $C_{2gg} > 0$ (Gaimon et al. 2011, Terwiesch and Xu 2004). The cost of KT from the process (product) design team at time t is given by $C_3[\beta(t)]$ ($C_4[b(t)]$) and increases at an increasing rate as the extent of resources (engineering hours) allocated to KT increases at that time. This characterization reflects the overall disruption to ongoing activities and the difficulty of integrating and coordinating larger amounts of KT initiated at a single instant of time (Loch and Terwiesch 1998, Carrillo and Gaimon 2000). This gives $C_{3\beta}$, C_{4b}, $C_{3\beta\beta}$, $C_{4bb} > 0$.

In summary, the NPD manager maximizes profit in Equation (1) subject to the dynamics in Equations (2) and (3).

$$V[D(T), M(T)] - \int_0^T \{C_1[\gamma(t)] - C_2[g(t)] - C_3[\beta(t)] - C_4[b(t)]\}\,dt, \quad (1)$$

$$D_t(t) = \gamma(t)[D(t)]^{\rho_1} + \int_0^t \alpha(t-\tau)\beta(\tau)[M(\tau)]^{\rho_2}[D(\tau)]^{\rho_3}\,d\tau, \quad (2)$$

$$M_t(t) = g(t)[M(t)]^{r_1} + \int_0^t a(t-\tau)b(\tau)[D(\tau)]^{r_2}[M(\tau)]^{r_3}\,d\tau. \quad (3)$$

4. The Optimal Solutions

The Hamiltonian (H) to be maximized is in Equation (4), where the variables $\lambda_1(t)$ and $\lambda_2(t)$ correspond to $D(t)$ and $M(t)$, respectively (Sethi and Thompson 2000). Since an additional unit of product (process) design knowledge at time t is sustained throughout the remainder of the development project, $\lambda_1(t)$ ($\lambda_2(t)$) is interpreted as the marginal value of an additional unit of product (process) design knowledge from time t through T. The necessary conditions for optimality of $\lambda_1(t)$ and $\lambda_2(t)$ are in Equations (5) and (6), respectively. The necessary conditions for optimality of γ, g, β, and b are in Equations (7) and (8). Optimal solutions are obtained by solving Equations (2), (3), (5), (6), (7), and (8) simultaneously. The notation depicting time is suppressed whenever possible. The symbol "*" indicates an optimal solution. The proofs appear in §2 of the online supplement.

$$H = -C_1[\gamma] - C_2[g] - C_3[\beta] - C_4[b] + \lambda_1\gamma D^{\rho_1} + \lambda_2 g M^{r_1} + \beta M^{\rho_2} D^{\rho_3}\phi_1(t) + bD^{r_2}M^{r_3}\phi_2(t), \quad (4)$$

$$\lambda_{1t} = -\lambda_1\gamma\rho_1 D^{\rho_1-1} - \beta\rho_3 M^{\rho_2} D^{\rho_3-1}\phi_1(t) - br_2 D^{r_2-1}M^{r_3}\phi_2(t), \quad \lambda_1(T) = V_{D(T)}, \quad (5)$$

$$\lambda_{2t} = -\lambda_2 g r_1 M^{r_1-1} - br_3 D^{r_2} M^{r_3-1}\phi_2(t) - \beta\rho_2 M^{\rho_2-1} D^{\rho_3}\phi_1(t), \quad \lambda_2(T) = V_{M(T)}, \quad (6)$$

where $\phi_1(t) = \int_t^T \lambda_1(\tau)\alpha(\tau-t)\,d\tau$ and $\phi_2(t) = \int_t^T \lambda_2(\tau)a(\tau-t)\,d\tau$.

Theorem 1 states that the marginal values of the levels of product and process design knowledge are nonnegative and nonincreasing functions of time. Further interpretations of $\lambda_1(t)$ and $\lambda_2(t)$ are postponed until later when we explore the dynamic solutions for KD and KT. Theorem 1 follows directly from Equations (5) and (6).

Theorem 1. *The marginal value functions satisfy* $\lambda_1^*(t)$, $\lambda_2^*(t) \geq 0$, $\lambda_{1t}(t)$, $\lambda_{2t}(t) \leq 0$, *for* $t \in [0, T]$.

To interpret $\phi_1(t)$ in Equation (6), recall that $\alpha(\tau - t)$ denotes the portion of a unit of KT from the process design team at time t that increases the level of product design knowledge at time $\tau \geq t$ with a lag of $\tau - t$. With the interpretation of $\lambda_1(\tau)$ and since $\lambda_1(\tau) \geq 0$, we know $\lambda_1(\tau)\alpha(\tau - t)$ denotes the marginal value of the increase in the level of product design knowledge at time τ derived from a unit of KT at time t. As such, $\phi_1(t)$ represents the cumulative value, from time t to T, because of a unit of KT to the product design team initiated at time t. The interpretation of $\phi_2(t)$ is analogous. Note that $\phi_1(t)$ and $\phi_2(t)$ are nonnegative and nonincreasing functions of time so that the cumulative marginal value of a unit of KT that occurs earlier (rather than later) in the project is larger.

Along with the nonnegativity and upper bound constraints, the optimal solutions for KD and KT are given in Equations (7) and (8). Therefore, the optimal KD solution for the product (process) design team equates the additional marginal cost at time t with the marginal value of the increase in the level of product (process) design knowledge at that time. Similarly, the optimal KT solution from the process (product) to the product (process) design team equates the marginal cost at time t with the lagged benefits realized from time t through T. From Theorem 1 and Equations (7) and (8), γ^*, g^*, β^*, and b^* are nonnegative for $t \in [0, T]$.

$$\begin{aligned}
&\gamma^* \text{ such that } -C_{1\gamma} + \lambda_1 D^{\rho_1} = 0 \text{ and } \gamma^* \in [0, \bar{\gamma}];\\
&\quad\beta^* \text{ such that } -C_{3\beta} + M^{\rho_2} D^{\rho_3}\phi_1(t) = 0 \qquad (7)\\
&\qquad\qquad \text{and } \beta^* \in [0, \bar{\beta}];
\end{aligned}$$

$$\begin{aligned}
&g^* \text{ such that } -C_{2g} + \lambda_2 M^{r_1} = 0 \text{ and } g^* \in [0, \bar{g}];\\
&\quad b^* \text{ such that } -C_{4b} + D^{r_2} M^{r_3}\phi_2(t) = 0 \qquad (8)\\
&\qquad\qquad \text{and } b^* \in [0, \bar{b}].
\end{aligned}$$

Equations (7) and (8) demonstrate that the dynamic solutions for KD and KT are interrelated. Specifically, KD for the product design team at time t is large if the cost *of any other* knowledge-creating activity is small; the effectiveness of any other knowledge creating activity is large; the marginal net revenue from process design knowledge is large; the level of process design knowledge is large; or the return to process design knowledge is large. Analogous interpretations hold for KD of the process design team and KT between design teams. Therefore, *there exists a complementary relationship among all KD and KT strategies*. In other words, *any* investment that increases either the level of product or process design knowledge makes *all* future investments more beneficial.

While many of the above interpretations are intuitively appealing, it is not obvious what drives the marginal value functions and thereby impacts Equations (7) and (8). Section 5 is devoted to such analysis. For ease of exposition, in the remainder of the paper we assume the upper bounds on γ^*, g^*, β^*, and b^* are implicitly satisfied.

5. The Dynamics of KD and KT

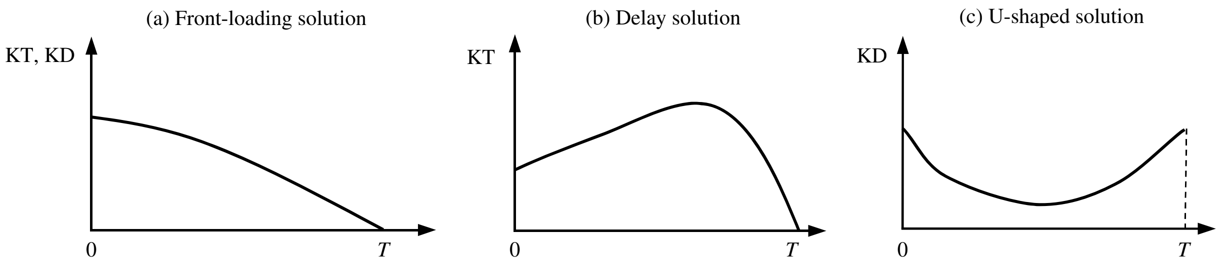
It is critical that the manager understands how the rates of KD and KT should evolve throughout the NPD project and how the rates are interrelated. The change in the rate of KD for the product (process) design team at time t, γ_t^* (g_t^*), satisfies Equation (9) (Equation (10)). Moreover, the change in the rate of KT from the process (product) to the product (process) design team at time t, β_t^* (b_t^*), satisfies Equation (11) (Equation (12)).

$$\begin{aligned}
\gamma_t^* &= (D^{\rho_1 - 1}/C_{1\gamma\gamma})\\
&\quad \cdot [\lambda_1\rho_1\phi_3(t) - \beta M^{\rho_2}\rho_3 D^{\rho_3}\phi_1 - br_2 D^{r_2} M^{r_3}\phi_2], \quad (9)\\
g_t^* &= (M^{r_1 - 1}/C_{2gg})\\
&\quad \cdot [\lambda_2 r_1\phi_4(t) - bD^{r_2} r_3 M^{r_3}\phi_2 - \beta\rho_2 M^{\rho_2} D^{\rho_3}\phi_1], \quad (10)\\
\beta_t^* &= (M^{\rho_2} D^{\rho_3}/C_{3\beta\beta})\Big\{\phi_{1t} + \phi_1\frac{\rho_2}{M}[gM^{r_1} + \phi_4(t)]\\
&\qquad + \phi_1\frac{\rho_3}{D}[\gamma D^{\rho_1} + \phi_3(t)]\Big\}, \quad (11)\\
b_t^* &= (D^{r_2} M^{r_3}/C_{4bb})\Big\{\phi_{2t} + \phi_2\frac{r_2}{D}[\gamma D^{\rho_1} + \phi_3(t)]\\
&\qquad + \phi_2\frac{r_3}{M}[gM^{r_1} + \phi_4(t)]\Big\}, \quad (12)
\end{aligned}$$

where $\phi_3(t) = \int_0^t \alpha(t - \tau)\beta(\tau)(M(\tau))^{\rho_2}(D(\tau))^{\rho_3}\, d\tau$ and $\phi_4(t) = \int_0^t a(t - \tau)b(\tau)(D(\tau))^{r_2}(M(\tau))^{r_3}\, d\tau$.

There are four possible dynamic solutions for KD and KT throughout the NPD project: the optimal solution may be constant over time, the peak rate may be front-loaded (Figure 2(a)), the peak rate may be delayed until an intermediate time in the project (Figure 2(b)), or the optimal solution may be U-shaped over time (Figure 2(c)). Naturally, an optimal solution is a positive constant when its time derivative is zero. An optimal solution is front-loaded when it is a positive nonincreasing function of time and its peak rate occurs at the initial time (i.e., when its derivatives at times zero and T are both negative). Alternatively, the nonnegative optimal solution may initially increase, reach a maximum value, and then be a nonincreasing function over the remainder of the project. In this case, we say the peak rate of the optimal solution is delayed (i.e., the derivative at time zero is positive and the derivative at time T is negative, so that the

Figure 2 Possible Dynamic Solutions for KD and KT



peak solution occurs at an intermediate time during the project). Fourth, the optimal solution may initially decrease, reach a minimum (but positive) value, and then increase over the remainder of the project. This U-shaped solution is obtained when the derivative at time zero is negative and the derivative at time T is positive.

As stated in Theorem 2, depending on the existence and direction of KT, we obtain significantly different dynamic solutions for KD of the product and process design teams and KT between teams. The interpretation of Theorem 2 follows.

Theorem 2. (i) *If KT is not permitted, KD for both the product and process design teams are pursued at constant rates over time.*

(ii) *If KT is permitted only from the product to the process design team, then KT to the process design team may be front-loaded or its peak rate may be delayed, KD of the product design team is front-loaded, and KD of the process design team is U-shaped.*

(iii) *If KT occurs in both directions, then KT in either direction may be front-loaded or the peak rate may be delayed, whereas KD for each design team is U-shaped.*

From Theorem 2(i), if KT is not permitted in either direction, then the rates of KD of both the product and process design teams are constant over time so that $\gamma_t^* = g_t^* = 0$ hold throughout the NPD project. Therefore, by excluding the possibility of KT, the manager's breadth of decision making is so limited that the dynamic KD solutions are only driven by the desire to reduce the convex costs incurred for KD at each instant of time.

If KT occurs only to the process design team, we analytically show that KT to the process design team is either front-loaded or the peak rate of KT is delayed; KD for the product design team is front-loaded; and KD of the process design team is U-shaped. These results are given in Theorem 2(ii). Intuitively, if the initial level of product design knowledge is sufficiently large, then KT to the process design team is front-loaded. In contrast, if the initial level of product design knowledge is sufficiently small, then the peak rate of KT to the process design team is delayed until later in the project when the level of product design knowledge is larger. The rates of KD of both teams decrease early in the project because of diminishing returns, which makes it increasingly difficult to obtain further additions to the levels of product and process design knowledge, and because over time less of the NPD project remains to accrue the benefits from generating more product and process design knowledge. However, whereas KD of the product design team continues to decrease over time (front-loaded), KD of the process design team increases later in the project (U-shaped) to leverage the lagged benefits of KT from the product design team.

Finally, from Theorem 2(iii), if KT is permitted in both directions, then KT in either direction is front-loaded or the peak rate is delayed, whereas KD for both the product and process design teams are U-shaped. The rates of KD of the product and process design teams decrease early in the project due to diminishing returns, and because less time remains in the project to realize the benefits from more knowledge. Later, however, KD of the product (process) design team increases to leverage the lagged benefits of KT from the process (product) design team and since the knowledge levels at the product launch time drive net revenue. Essentially, both teams "ramp-up" KD at the end of the NPD project.

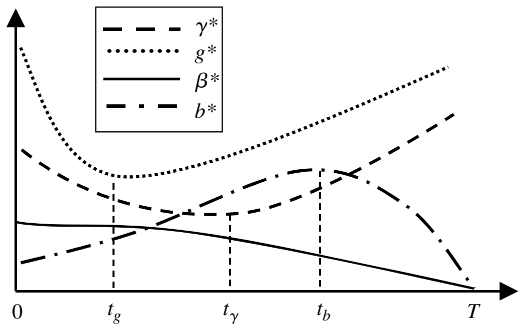
The dynamic KD and KT solutions (Equations (9)–(12)) are driven by many complex relationships, including those involving a firm's internal capabilities, external market forces, and the nature of the lag for KT, as described in §§5.1–5.3.

5.1. Impact of the Initial Levels of Knowledge

We analyze the situation where KT occurs in both directions and the optimal solutions are driven by the initial levels of product and process design knowledge along with the return parameters. Whereas we know from Theorem 2(iii) that KD for both design teams are U-shaped, we do not know whether KT to either of these teams is front-loaded or if the peak rate is delayed. Next, we provide analytic insights for three special cases. We refer to a return parameter as small (large) if it is less (greater) than 0.5; moderate if it equals 0.5.

First, suppose D_0 is small, M_0 is large, and ρ_1, ρ_2, ρ_3, r_1, r_2, $r_3 > 0.5$. The optimal analytic solutions for

Figure 3 **Leveraging Process Design Knowledge**



KD and KT, illustrated in Figure 3, are interpreted below. (Figure 3 is given for illustrative purposes only, since we do not know the convexity or concavity of KD or KT over time, whether $\beta^*(0) > b^*(0)$, or that $t_b > t_\gamma, t_g$.)

From Theorem 2, we know that KD for both the product and process design teams are U-shaped. Furthermore, we analytically find that as compared to KD of the product design team, KD of the process design team is larger at the initial time, decreases faster early in time, and reaches its positive minimum value earlier before increasing over the remainder of the NPD project. Intuitively, with the large initial level of process design knowledge, KD of the process design team is highly effective at increasing the level of process design knowledge at the outset of the NPD project. In contrast, because of its small initial level of knowledge, the effectiveness of KD of the product design team is relatively small at the outset of the project. As such, we can say that KD of the process design team is skewed early in the NPD project, whereas KD of the product design team is skewed late. In Figure 3, we observe that the initial time rate of KD for the process design team exceeds that of the product design team ($g^*(0) < \gamma^*(0)$) and decreases faster; KD for process design team reaches its minimum value earlier than KD for product design team ($t_g < t_\gamma$).

Also, we analytically find that KT to the product design team is front-loaded in order to leverage the large initial level of process design knowledge and thereby increase the initially small level of product design knowledge. In addition, front-loading KT allows the product design team to realize more of the lagged benefits by the end of the project. This solution is consistent with the notion of design for manufacturability. In contrast, because of the small initial level of product design knowledge, the effectiveness of KT from the product design team is limited early in the project so that its peak rate is delayed until later in the project when that team has sufficiently addressed the manufacturing process constraints. In Figure 3, while KT to the product design team decreases throughout the project (β^*), KT to the process design team initially increases and later decreases, reaching its maximum value at (t_b). Naturally, KT to both teams reach zero at the product launch time, T.

Second, suppose D_0 and M_0 are sufficiently small and ρ_1, ρ_2, ρ_3, r_1, r_2, $r_3 \leq 0.5$. We analytically find that the peak rates of KT to both the product and process design teams are delayed. Therefore, the NPD manager increases the levels of product and process design knowledge through KD early in the NPD project to make KT more effective later. As such, the benefits of delaying the peak rates of KT until the levels of product and process design knowledge are larger exceed the benefits of pursuing KT early in order to fully realize the lagged benefits.

Third, if D_0 and M_0 are both sufficiently large and the returns to KD and KT are less than or equal to 0.5, then we analytically find that KT is front-loaded in both directions. Clearly, given the large initial levels of product and process design knowledge, KT is highly effective at the outset of the project so there is no incentive to delay the peak rates. The three scenarios discussed above show the importance of properly characterizing the initial levels of product and process design knowledge as well as the values of the return parameters. Moreover, the above discussion demonstrates the interplay between the manager's KD and KT strategies. Beyond the three special cases described above, all optimal solutions are given in Table A.1 of the appendix.

5.2. Impact of the Distributed Lags and Marginal Net Revenue

In Table A.2 of the appendix, we present the analytical solutions obtained for KD and KT when (1) KT occurs in both directions and (2) the optimal rates of KT are driven by either the distributed lags or marginal net revenue at the launch time. In §5.2.1, we assume the distributed lags drive the dynamic KT solutions, whereas in §5.2.2, we assume marginal net revenue drives those solutions.

5.2.1. Distributed Lags Drive Solutions. Suppose the distributed lags are the key drivers of the optimal solutions; most of the benefits from KT to the product design team are realized shortly after KT is initiated ($\alpha(\tau - t)$ is larger for smaller $\tau - t$ with $\tau \geq t$); and most of the benefits from KT to the process design team are realized long after KT is initiated ($a(\tau - t)$ is larger for larger $\tau - t$ with $\tau \geq t$). Whereas KD of both the product and process design teams are U-shaped, we analytically find that KD of the process design team is larger at the initial time and skewed early in the project relative to KD of the product design team. The buildup of process design knowledge is accelerated early in the project to limit the detrimental impact of the long lags associated with obtaining the benefits from KT. Similarly, KT to the process design team is front-loaded so that sufficient time remains in the development project to realize the associated benefits. Lastly, the peak rate of KT from the process design team is delayed until later in the project when more process design knowledge has been accumulated since the lag associated with obtaining the benefits from KT to the product design team is small.

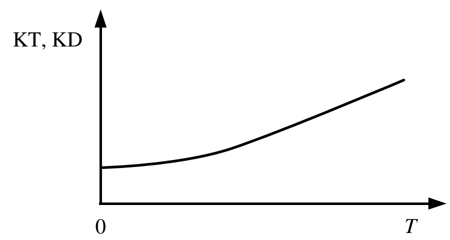
5.2.2. Values of Marginal Net Revenue Drive Solutions. Suppose marginal net revenue at the launch time is the key driver of the optimal solutions; marginal net revenue from product design knowledge ($V_{D(T)}$) is small; and marginal revenue from process design knowledge ($V_{M(T)}$) is large. We already know that KD of both the product and process design teams are U-shaped. Furthermore, we analytically find that because of the higher marginal net revenue obtained from process design knowledge, KD is larger and skewed early for the process design team relative to KD of the product design team. Also, we analytically find KT to the process design team is front-loaded to accelerate the accumulation of process design knowledge early in the project. As such, we observe a positive synergy between the rapid pursuits of both KD of the process design team and KT to the process design team early in the project. Lastly, the peak rate of KT to the product design team is delayed. It occurs at an increasing rate early in the project to accelerate the level of product design knowledge transferred to the process design team. Later, once most of the KT to the process design team has occurred, and given the limited benefits obtained from product design knowledge at the launch time, KT to the product design team optimally decreases.

5.3. Impact of the Instantaneous Transfer of Knowledge

To fully appreciate the key role of the lagged benefits from KT, we now consider the situation where the benefits from KT to both recipient teams are instantaneous (no lags). In §5.3.1, we consider a no-lag scenario where marginal net revenue drives the solutions. In §5.3.2, we consider a no-lag scenario where the initial levels of product and process design knowledge drive the solutions. Beyond the two cases presented here, Table A.3 in the appendix describes all analytic solutions obtained when the benefits from KT are instantaneous in both directions.

5.3.1. Values of Marginal Net Revenue Drive Solutions. We assume the benefits from KT are instantaneous and the marginal net revenue drives the optimal solutions. In particular, suppose $V_{D(T)}$ is small, $V_{M(T)}$ is large, and $\rho_3 > \rho_1$, $r_3 > r_1$. First, we analytically find that the peak rate of KT to the product design team is delayed and KT to the process design team is back-loaded (the peak rate occurs at the launch time) (Figure 4). These results contrast those in §5.2.2, where the benefits of KT are lagged so that KT to the process design team is front-loaded. Intuitively, since the benefits from KT are instantaneous, KT to the process design team is more desirable later in the project in order to leverage the larger levels of product and process design knowledge attained from KD. However, while KT to the product design team increases early in the project, it later declines since the marginal net revenue from product design knowledge is lower than that of process design knowledge and since most of the instantaneous benefits from KT to the process design team have already been realized. Second, in contrast to the results in §5.2.2, we find that KD for both the product and process design teams are front-loaded and not U-shaped. Front-loading occurs because the desirability of KD does not increase later in the project, since there is no need to wait for the realization of the benefits from KT.

Figure 4 **Back-Loading Solution**



5.3.2. Initial Levels of Product and Process Design Knowledge Drive Solutions. We assume the benefits from KT are instantaneous, D_0 and M_0 are both sufficiently large; and the returns to KD and KT equal 0.5. We analytically find that, with the large initial levels of knowledge, KD is highly effective at the outset of the project so that both teams front-load KD. This result is in contrast to the U-shaped KD solutions obtained for both teams when the benefits from KT are lagged. Intuitively, when KT is instantaneous there is no need to wait for its benefits to be realized so that KD is large early in the project and does not increase later. Also, we analytically find that KT is back-loaded to both the product and process design teams since the benefits are instantaneous, enabling the manager to leverage the larger levels of product and process design knowledge that occur later.

6. Discussion and Conclusions

We consider an NPD manager responsible for improving product and process performance by investing in KD of the product and process design teams and KT between teams. While KD increases the level of product or process design knowledge instantaneously, the benefits to the recipient of KT may be lagged. Also, we assume the benefits from KT depend on the levels of knowledge of both the source and recipient teams. The manager's objective is to maximize net revenue earned at the product launch time (which is driven by the levels of product and process performance at that time) and the costs incurred for KD and KT throughout the project.

In a key contribution to the NPD literature, we show that the dynamic solutions for KD and KT are not always straightforward and are driven by the complex dynamic relationships among many parameters, including those that reflect a firm's internal capabilities and external market forces. Moreover, we provide explicit analytic conditions that characterize when a KD or a KT solution is optimally constant, front-loaded, back-loaded, U-shaped, or the peak rate is delayed until an intermediate time in the project. In this context, we show the importance of understanding whether KT occurs, if it does occur then in what direction, and whether the benefits of KT are lagged or instantaneous.

First, we consider the extreme situation where KT is not permitted in either direction. Given the limited breadth of decision making, we show that the manager focuses on minimizing the convex costs so that KD of both design teams are constant over time.

Second, we consider the situation where the benefits from KT are lagged and KT occurs only from the product to the process design team. Therefore, we ignore any possible knowledge that may be leveraged in relation to the design for manufacturability. We analytically find that the product design team front-loads KD; KD of the process design team is U-shaped; and KT to the process design team is front-loaded or the peak rate is delayed until some intermediate time in the project. The product design team front-loads KD to accelerate the increase in product design knowledge so that more knowledge is transferred to the process design team earlier. KD of the process design team is U-shaped because (1) early in the project the manager quickly builds up process design knowledge to improve its ability to absorb and deploy KT from the product design team; and (2) later in the project the manager builds up process design knowledge faster, because the prior transfer of product design knowledge makes KD of the process design team highly effective. KT to the process design team is front-loaded if sufficient process design knowledge exists at the outset of the project, which ensures KT is effective early in the project. Alternatively, if the initial level of process design knowledge is small, then the peak rate of KT is delayed until later when more process design knowledge is available. Therefore, we extend the results of Ha and Porteus (1995), Krishnan et al. (1997), Loch and Terwiesch (1998), Terwiesch et al. (2002), which also consider KT from the product to the process design team in an important way: we provide explicit analytic conditions depicting how a manager should dynamically invest in KD of each team and KT to the process design team throughout the NPD project.

Third, if the benefits from KT are lagged and KT is permitted in both directions, we find that both teams pursue KD that is U-shaped and KT to either team may be front-loaded or the peak rate may be delayed until an intermediate time in the project. Each team pursues high rates of KD early in the project to rapidly accumulate knowledge that is transferred to the other team, and each team pursues high rates of KD later in the project after more of the benefits from KT are realized. Whereas several parameters may drive the optimal KT solutions, for ease of exposition consider the situation where the initial levels of product and process design knowledge and the return parameters are the key drivers of the optimal solutions. (A more complete discussion of conditions that drive the optimal KT solutions appears in §5; all cases are given in Tables A.2 and A.3 in the appendix.) Suppose the initial level of process design knowledge is small and the initial level of product design knowledge is large. We find that (1) KD is larger for the product design team than for the process design team early in the project because the product design team can leverage its higher initial level of knowledge so that KD is more effective; (2) KT from the product design team is front-loaded to accelerate the increase in process design knowledge; and (3) the peak rate of KT to the product design team is delayed until later, when more process design knowledge is available. As such, we extend the results of Lin et al. (2008) and Yang et al. (2014) by providing explicit analytic conditions depicting how the manager should dynamically invest in KD of each team and KT in both directions between teams throughout the NPD project.

The above analytic results are particularly meaningful since the manager can influence the initial levels of knowledge and the return parameters. To ensure the availability of a highly skilled workforce at the outset of an NPD project, a manager should provide formal education programs and fund attendance at conferences and workshops (Van de Ven 2007). Also, a manager can encourage its design teams to participate in alliances with university research labs to increase their initial levels of knowledge (Argote and Ingram 2000). To improve the returns to KD and KT, a manager can employ boundary spanning structures (Bardhan et al. 2013). For example, technical systems such as collaboration software are associated with high returns because they aid in the documentation of information and define procedures to codify knowledge (Staats et al. 2011). Lastly, the manager should ensure team members are fully able to operate the technical systems, which may require formal training from vendors (Gaimon et al. 2011).

The importance of identifying the initial levels of product and process design knowledge are explored in the context of two industry examples. First, our analytic results provide one possible explanation for AMD's performance during the development of the K6 microprocessor that was described in the introduction. Initially, management assumed that the process design team would design the manufacturing system for the K6 chip by employing the same die size that had been used for the K5 (Morrison and DeTar 1998). Therefore, the initial level of process design knowledge was estimated to be large relative to the initial level of product design knowledge. However, in reality this was not the case. In fact, serious problems arose while designing the high yield process technology to manufacture the K6 given its high density of transistors, which demonstrated an insufficient level of process design knowledge relative to product design knowledge at the outset of the project (DeTar 1997). Thus, we may infer that by overestimating the initial level of process design knowledge, the peak rate of KT from the product design team was delayed when it should have been front-loaded to build process knowledge. Moreover, we may infer that the high initial rate of KD for the process design team was premature and undertaken without sufficient understanding of the product attributes. Finally, it is possible that as a result of overestimating the initial level of process design knowledge, AMD front-loaded KT to the product design team, which was unproductive. Overall, AMD's problems may be explained by its pursuit of a strategy that did not properly leverage its relatively large amount of product design knowledge to compensate for its relatively small amount of process design knowledge at the outset of the NPD project.

As a second practical example of our results, consider the development of the first commercially mass-produced hybrid automobile, the Toyota Prius, which uses both a gasoline engine and an electric motor for propulsion (Nonaka and Peltokorpi 2006). The product design of the Prius entailed a complex electrical architecture for the power train, including the designs of electric motors, electric inverters and converters, high-voltage batteries, electronic control units, as well as semiconductors and sensors (Tilin 2005). As such, we can reasonably assume that the initial level of product design knowledge was limited. Despite substantial innovations in product attributes, Toyota manufactured and assembled the Prius in the same factories as conventional (gasoline powered) vehicles (Weber 2006) thereby suggesting that the initial level of process design knowledge was relatively large. In fact, the development of Toyota's Prius demonstrates how process design expertise may shape product design objectives. Toyota created the Unit Production Technology Department (UPTD) to facilitate the early and substantial rate of KT from the process design team (including the drive system and chassis) on the manufacturability of the hybrid vehicle. Once the manufacturing process constraints were reliably addressed in the product design, product development intensified until the final product features were established (e.g., fuel infrastructure, battery-powered design, engine system) (Nonaka and Peltokorpi 2006). From the above, we can infer that while KT to the product design team was front-loaded, the peak rate of KT to the process design team was delayed. Also, whereas both KD solutions may have been U-shaped, the rate of KD for the product design team early in the project was less than that of the process design team. Thus, our analytic results offer one possible explanation for Toyota's success in developing the Prius: its ability to properly leverage a considerable level of process design knowledge at the outset of the development project.

In contrast to the above industry examples that focus on the initial levels of product and process design knowledge, we also contribute to the literature by demonstrating how other forces may drive the optimal solutions. Suppose KT occurs in both directions and the lags associated with KT drive the optimal solutions. We find that if there is a large lag between the time the source initiates KT and the time the recipient exploits KT, then the manager is driven to front-load KT to ensure that the recipient has sufficient time to obtain the benefits during the project. Alternatively, if the recipient team realizes more of the benefits shortly after KT is initiated, then the peak rate of KT is delayed to leverage the larger levels of knowledge attained by both teams later in the project as a result of accumulating KD.

These results demonstrate the advantage realized by the manager capable of reducing the distributed lags associated with realizing the benefits from KT. The literature suggests several means by which the manager can reduce the lags. At the outset of the project, the manager can select team members with cross-functional training or shared work experience to enhance communication (Carlile 2002, Mihm and Cui 2010); build systems that translate and clarify industry-specific knowledge (Staats et al. 2011); provide information-technology–based communication resources to codify and document tacit knowledge into explicit knowledge (Huckman and Staats

2011); establish incentives and rewards for effective KT (Szulanski 2000); and reduce project complexity (Gaimon et al. 2011).

Analytic results are also obtained, which demonstrate that the dynamic KD and KT solutions are dramatically different when the benefits of KT are lagged versus instantaneous. When the benefits of KT are lagged and KT occurs in both directions, we find that KD of both the product and process design teams are U-shaped. In contrast, we find that KD may be front-loaded or back-loaded, or the peak rate may be delayed if the benefits of KT are instantaneous. These results demonstrate the importance to the NPD manager of identifying whether or not the benefits of KT are lagged or instantaneous.

Lastly, there are several opportunities to extend this research. First, to focus our analysis on the dynamic KD and KT solutions and to retain tractability, we do not consider multiple stakeholders (as in the principle-agent problem). Instead, our approach is consistent with the notion of a "heavyweight" project manager who has complete authority over KD and KT decisions (Cusumano 2010). Nevertheless, consideration of the various incentives among different stakeholders in an NPD project represents an opportunity for future research (Chao et al. 2009, Mihm 2010). Second, while we include upper bounds on KD and KT reflecting budget restrictions, we do not introduce an explicit budget constraint to evaluate the resource allocation decision. However, based on the results obtained by Chao et al. (2009), we expect that including a binding budget constraint would reduce the instantaneous rates of KD and KT by amounts reflecting their respective relative costs and benefits. Third, the opportunity exists for future research to explore the impact of uncertainty in the marketplace or uncertainty in the benefits from KD and KT.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.2014.0507.

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Appendix

Table A.1 KT Solutions When KT Is Lagged and Driven by the Initial Levels of Knowledge

KT to the product design team (β) is front-loaded if	KT to the process design team (b) is front-loaded if
Both M_0 and D_0 are sufficiently small and (1) if all ρ's and r's > 0.5, or (2) if ρ_1, ρ_3, and $r_2 > 0.5$, and r_1, r_3, and $\rho_2 \leq 0.5$;	Both M_0 and D_0 are sufficiently small and (1) if all ρ's and r's > 0.5, or (2) if ρ_1, ρ_3, and $r_2 \leq 0.5$, and r_1, r_3, and $\rho_2 > 0.5$;
Both M_0 and D_0 are sufficiently large and (1) if all ρ's and r's ≤ 0.5, or (2) if ρ_1, ρ_3, and $r_2 \leq 0.5$, and r_1, r_3, and $\rho_2 > 0.5$;	Both M_0 and D_0 are sufficiently large and (1) if all ρ's and r's ≤ 0.5, or (2) if ρ_1, ρ_3 and $r_2 > 0.5$, and r_1, r_3, and $\rho_2 \leq 0.5$;
M_0 is sufficiently small; D_0 is sufficiently large and (1) if all ρ's and r's ≤ 0.5, or (2) if ρ_1, ρ_3, and $r_2 \leq 0.5$, and r_1, r_3, and $\rho_2 > 0.5$;	M_0 is sufficiently small; D_0 is sufficiently large and (1) if all ρ's and r's > 0.5, or (2) if ρ_1, ρ_3, and $r_2 \leq 0.5$, and r_1, r_3, and $\rho_2 > 0.5$;
M_0 is sufficiently large; D_0 is sufficiently small and (1) if all ρ's and r's > 0.5, or (2) if ρ_1, ρ_3, and $r_2 > 0.5$, and r_1, r_3, and $\rho_2 \leq 0.5$.	M_0 is sufficiently large; D_0 is sufficiently small and (1) if all ρ's and r's ≤ 0.5, or (2) if ρ_1, ρ_3, and $r_2 > 0.5$, and r_1, r_3, and $\rho_2 \leq 0.5$.
If the reverse of any of the above conditions holds, the peak rate of KT to the product design team (β) is delayed.	If the reverse of any of the above conditions holds, the peak rate of KT to the process design team (b) is delayed.

Table A.2 KT Solutions When KT Is Lagged and Driven by the Distributed Lags or Marginal Net Revenue

KT to the product design team (β) is front-loaded if	KT to the process design team (b) is front-loaded if
$\alpha(\tau - t)$ is larger for larger $\tau - t$; $\alpha(T)$ is large; or $V_{D(T)}$ is large.	$a(\tau - t)$ is larger for larger $\tau - t$; $a(T)$ is large; or $V_{M(T)}$ is large.
If the reverse of any of the above conditions holds, the peak rate of KT to the product design team (β) is delayed.	If the reverse of any of the above conditions holds, the peak rate of KT to the process design team (b) is delayed.

Table A.3 KD and KT Solutions When KT Occurs Instantaneously

$V_{D(T)}$ (large) and $V_{M(T)}$ (small) drive the solutions; or D_0 (large) and M_0 (small) drive the solutions.
γ is front-loaded if (1) $\rho_1 \le \rho_3$, or (2) ρ's and r's $= 0.5$; γ is back-loaded if $\rho_1 > \rho_3$.
g is front-loaded if (1) $r_1 \le r_3$, (2) $r_1 > r_3$ and $\rho_2 \ge r_2$, or (3) ρ's and r's $= 0.5$; g is back-loaded if $r_1 > r_3$ and $\rho_2 < r_2$.
β is front-loaded if (1) $\rho_1 \ge \rho_3$, or (2) ρ's and r's $= 0.5$; β is back-loaded if $\rho_1 < \rho_3$.
b is front-loaded if $r_1 \ge r_3$ and $\rho_2 > r_2$; b is back-loaded if (1) $r_1 \ge r_3$ and $\rho_2 \le r_2$, or (2) ρ's and r's $= 0.5$. The peak rate of b is delayed if $r_1 < r_3$.

$V_{D(T)}$ (small) and $V_{M(T)}$ (large) drive the solutions; or D_0 (small) and M_0 (large) drive the solutions.
γ is front-loaded if (1) $\rho_1 \le \rho_3$, (2) $\rho_1 > \rho_3$ and $\rho_2 \le r_2$, or (3) ρ's and r's $= 0.5$; γ is back-loaded if $\rho_1 > \rho_3$ and $\rho_2 > r_2$.
g is front-loaded if (1) $r_1 \le r_3$, or (2) ρ's and r's $= 0.5$; g is back-loaded if $r_1 > r_3$.
β is front-loaded if $\rho_1 > \rho_3$ and $\rho_2 < r_2$; β is back-loaded if (1) $\rho_1 \ge \rho_3$ and $\rho_2 \ge r_2$, or (2) ρ's and r's $= 0.5$. The peak rate of β is delayed if $\rho_1 < \rho_3$.
b is front-loaded if (1) $r_1 \ge r_3$, or (2) ρ's and r's $= 0.5$; b is back-loaded if $r_1 < r_3$.

$V_{D(T)}$ and $V_{M(T)}$ (moderate or large) drive the solutions; or D_0 and M_0 (moderate or large) drive the solutions.
γ is front-loaded if (1) $\rho_1 \le \rho_3$, or (2) ρ's and r's $= 0.5$; γ is back-loaded if $\rho_1 > \rho_3$ and $\rho_2 \le r_2$. The peak rate of γ is delayed if $\rho_1 > \rho_3$ and $\rho_2 > r_2$.
g is front-loaded if (1) $r_1 \le r_3$, or (2) ρ's and r's $= 0.5$; g is back-loaded if $r_1 > r_3$ and $\rho_2 \ge r_2$. The peak rate of g is delayed if $r_1 > r_3$ and $\rho_2 < r_2$.
β is front-loaded if (1) $\rho_1 > \rho_3$ and $\rho_2 \le r_2$, or (2) $\rho_1 > \rho_3$, $\rho_2 > r_2$ and $\rho_2 - r_2 \le \theta$, where $0 \le \theta < 1$; β is back-loaded if (1) $\rho_1 \le \rho_3$ and $\rho_2 \ge r_2$, (2) ρ's and r's $= 0.5$, or (3) $\rho_1 > \rho_3$, $\rho_2 > r_2$ and $\rho_2 - r_2 > \theta$, where $0 \le \theta < 1$. The peak rate of β is delayed if $\rho_1 < \rho_3$ and $\rho_2 < r_2$.
b is front-loaded if (1) $r_1 > r_3$ and $\rho_2 \ge r_2$, or (2) $r_1 > r_3$, $r_2 > \rho_2$ and $r_2 - \rho_2 \le \delta$, where $0 \le \delta < 1$; b is back-loaded if (1) $r_1 \le r_3$ and $\rho_2 \le r_2$, (2) ρ's and r's $= 0.5$, or (3) $r_1 > r_3$, $r_2 > \rho_2$ and $r_2 - \rho_2 > \delta$, where $0 \le \delta < 1$. The peak rate of b is delayed if $r_1 < r_3$ and $\rho_2 > r_2$.

References

Adler PS (1995) Interdepartmental interdependence and coordination: The case of the design/manufacturing interface. *Organ. Sci.* 6(2):147–167.
Argote L, Ingram P (2000) Knowledge transfer in organizations: A basis for competitive advantage in firms. *Organ. Behav. Human Dec. Proc.* 82:150–169.
Bardhan I, Krishnan VV, Lin S (2013) Team dispersion, information technology, and project performance. *Production Oper. Management* 22:1478–1493.
Bhuiyan M, Gerwin D, Thomson V (2004) Simulation of the new product development process for performance improvement. *Management Sci.* 50(12):1690–1703.
Carlile PR (2002) A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organ. Sci.* 13(4):442–455.
Carrillo JE, Gaimon C (2000) Improving manufacturing performance through process change and knowledge creation. *Management Sci.* 46(2):265–288.
Carrillo JE, Gaimon C (2004) Managing knowledge-based resource capabilities under uncertainty. *Management Sci.* 50(11):1504–1518.
Carrillo JE, Franza RM (2006) Investing in product development and production capabilities: The crucial linkage between time-to-market and ramp-up time. *Eur. J. Oper. Res.* 171(2):536–556.
Chao R, Kavadias S, Gaimon C (2009) Revenue driven resource allocation: Funding authority, incentives, and new product development portfolio management. *Management Sci.* 55(9):1556–1569.
Christensen C, Raynor ME (2003) Creating a killer product. *Forbes* 172:82–84.
Clark KB, Fujimoto T (1991) *Product Development Performance: Strategy, Organization and Management in the World Auto Industry* (Harvard Business School Press, Boston).
Cohen MA, Eliashberg J, Ho T-H (2000) An analysis of several new product performance metrics. *Manufacturing Service Oper. Management* 2(4):337–349.
Cohen WM, Levinthal DA (1990) Absorptive capacity: A new perspective on learning and innovation. *Admin. Sci. Quart.* 35(1):128–152.
Cusumano MA (2010) *Staying Power: Six Enduring Principles for Managing Strategy and Innovation in an Uncertain World* (Oxford University Press, New York).
DeTar J (1997) K6 chief Vinod Dham leaving AMD. *Electronic News* 43(2195):20.
Epple D, Argote L, Murphy K (1996) An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing. *Oper. Res.* 44(1):77–86.
Fixson SK, Marion TJ (2012) Back-loading: A potential side effect of employing digital design tools in new product development. *J. Prod. Innov. Management* 29(S1):140–156.
Gaimon C (1997) Planning information technology—Knowledge worker systems. *Management Sci.* 43(9):1308–1328.
Gaimon C, Ozkan GF, Napoleon K (2011) Dynamic resource capabilities: Managing workforce knowledge with a technology upgrade. *Organ. Sci.* 22(6):1560–1578.
Grant RM (1996) Prospering in dynamically-competitive environments: Organizational capability as knowledge integration. *Organ. Sci.* 7(4):375–387.
Ha AY, Porteus EL (1995) Optimal timing for reviews in concurrent design for manufacturability. *Management Sci.* 41(9):1431–1447.
Haas MR, Hansen MT (2007) Different knowledge, different benefits: Toward a productivity perspective on knowledge sharing in organizations. *Strategic Management J.* 28(11):1133–1153.
Hedlund G (1994) A model of knowledge management and the *N*-form corporation. *Strategic Management J.* 15(S2):73–90.
Huckman RS, Staats BR (2011) Fluid tasks and fluid teams: The impact of diversity in experience and team familiarity on team performance. *Manufacturing Service Oper. Management* 13(3):310–328.
Krishnan V, Eppinger SD, Whitney DE (1997) A model-based framework to overlap product development activities. *Management Sci.* 43(4):437–451.
Lapre MA, van Wassenhove LN (2001) Creating and transferring knowledge for productivity improvement in factories. *Management Sci.* 47(10):1311–1325.
Lin J, Chai KH, Wong YS, Brombacher AC (2008) A dynamic model for managing overlapped iterative product development. *Eur. J. Oper.* 185(1):378–392.
Loch CH, Terwiesch C (1998) Communication and uncertainty in concurrent engineering. *Management Sci.* 44(8):1032–1048.
Loch CH, Terwiesch C (2005) Rush and be wrong or wait and be late? A model of information in collaborative processes. *Production Oper. Management* 14(3):331–343.
Macher JT (2006) Technological development and the boundaries of the firm: A knowledge-based examination in semiconductor manufacturing. *Management Sci.* 52(6):826–843.
Mihm J (2010) Incentives in new product development projects and the role of target costing. *Management Sci.* 56(8):1324–1344.
Mihm J, Cui Z (2010) Decision making in multifunctional teams: The strategic impact of a forgotten dimension. Working paper, INSEAD, Fontainebleau, France.
Mihm J, Loch CH, Huchzermeier A (2003) Problem-solving oscillations in complex engineering projects. *Management Sci.* 49(6):733–750.
Morrison G, DeTar J (1998) Multimedia will drive the 1998 market. *Electronic News* 44(2200):16–22.

Nonaka I (1994) A dynamic theory of organizational knowledge creation. *Organ. Sci.* 5(1):14–37.

Nonaka I, Peltokorpi V (2006) Knowledge-based view of radical innovation: Toyota Prius case. Hage JT, Meenus M, eds. *Innovation and Knowledge Growth* (Oxford University Press, Oxford, UK), 88–104.

Nonaka I, Toyama R, Hirata T (2008) *Managing Flow: A Process Theory of the Knowledge-Based Firm* (Palgrave Macmillan, New York).

Pisano GP (1997) *The Development Factory: Unlocking the Potential of Process Innovation* (Harvard Business School Press, Boston).

Roemer TA, Ahmadi RH (2004) Concurrent crashing and overlapping in product development. *Oper. Res.* 52(4):606–622.

Sethi SP, Thompson GL (2000) *Optimal Control Theory Applications to Management Science and Economics*, 2nd ed. (Kluwer Academic Publishers, Boston).

Slater M (1996) The microprocessor today. *Micro IEEE* 16(6):32–44.

Staats BR, Brunner DJ, Upton DM (2011) Lean principles, learning, and knowledge work: Evidence from a software services provider. *J. Oper. Management* 29(5):376–390.

Szulanski G (2000) The process of knowledge transfer: A diachronic analysis of stickiness. *Organ. Behav. Human Decision Processes* 82(1):9–27.

Takahashi D (1997) Intel plans deeper price cuts on chips in an effort to ward off competitors. *Wall Street Journal* (April 11) B2.

Terwiesch C, Loch CH (1999) Measuring the effectiveness of overlapping development activities. *Management Sci.* 45(4): 455–465.

Terwiesch C, Xu Y (2004) The copy-exactly ramp-up strategy: Trading-off learning with process change. *IEEE Trans. Engrg. Management* 51(1):70–84.

Terwiesch C, Loch CH, De Meyer A (2002) Exchanging preliminary information in concurrent engineering: Alternative coordination strategies. *Organ. Sci.* 13(4):402–419.

Thomke SH, Fujimoto T (2000) The effect of "front-loading" problem-solving on product development performance. *J. Production Innovation Management* 17:128–142.

Tilin A (2005) The smartest company of the year: And the winner is . . . Toyota hot cars. *Business* 2.0 6:65–66.

Van de Ven AH (2007) *Engaged Scholarship: A Guide to Organizational and Social Research* (Oxford University Press, New York).

Weber A (2006) The hybrid challenge. *Assembly Magazine* (June 1), http://www.assemblymag.com/articles/84379-the-hybrid-challenge.

Willcox JK (1999) Chip makers geared up for year-end battle. *TWICE* 14(21):36.

Wilson R (1996) AMD renews Intel battle with K6 CPU. *Electronic Engrg. Times* 11:4.

Xiao W (2012) Essays on knowledge management, Ph.D. dissertation, Scheller College of Management, Georgia Institute of Technology, Atlanta.

Yang Q, Yao T, Lu T, Zhang B (2014) An overlapping-based design structure matrix for measuring interaction strength and clustering analysis in product development project. *IEEE Trans. Engrg. Management* 61(1):159–170.