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Managing Knowledge in a Three-Stage New Product Development Project

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***Abstract*--We consider managerial decision-making regarding the evolution of knowledge in a three-stage new product development project. The manager invests in knowledge development activities (such as prototyping, pilot line testing, ramp-up experiments) at each stage throughout the project. The links between development activities at different stages are captured by recognizing that, as a result of knowledge transfer, the ability of the recipient team to generate new knowledge is enhanced. Over time as the levels of knowledge increase, product features and process characteristics improve. The performance of the new product in the marketplace, which drives net revenue, reflects the levels of knowledge attained at each stage of the project at the product launch time. The objective is to maximize the net revenue earned when the product is released to the marketplace less development costs. We show that the rate of each development activity follows an entirely different dynamic strategy during the project. In the first stage, development activities follow a front-loading strategy; in the second stage, development activities follow a moderate delay strategy, and in the third stage development activities follow an extreme delay strategy.**

I. INTRODUCTION

Due to time-based competition as well as short product life cycles, a firm must rapidly launch new products with the features and functionality desired in the marketplace ([11], [14], [19], [29]). Managing new product development (NPD) projects entails managing highly skilled employees responsible for designing components of the product and process. Over time, as more and more knowledge is embedded into the development project, product and process performance improve. This leads us to the fundamental problem: how to manage the evolution of knowledge in all stages of an NPD project.

Our research is motivated by our work with several firms, including a major U.S. consumer products firm in the U.S. and a major electronic products manufacturer in Asia. NPD managers sought a deeper understanding of how knowledge is both created and transferred in order to improve the performance of development activities and thereby improve the performance of the new products when they ultimately reached the marketplace.

In this paper, we address NPD through the lens of knowledge management. We introduce a model to analyze how to manage the creation and the flow of knowledge for employees in a three-stage NPD project. Progress in the NPD project is inferred by the growing levels of knowledge at three stages starting with prototyping, continuing to pilot line testing, and concluding with production ramp-up ([21], [29], [32]). The manager of the NPD project determines the rates and timing of development activities to be pursued during the project to increase the levels of knowledge. Naturally, costs are incurred as development activities are undertaken over time. Ultimately, the levels of knowledge accumulated by the product launch time determine the net revenue earned when the new product is released to the marketplace ([9], [13], [25]).

We conceptualize the creation and the flow of knowledge at each stage of the NPD project as follows. At the initial prototyping stage, the level of knowledge increases as the team pursues prototyping activities over time. At the second stage, the level of pilot line knowledge increases as the team pursues pilot line testing activities as well as through knowledge transfer (KT) from the prototyping stage. Prototyping knowledge improves the ability of engineers involved in pilot line testing to identify design features to be tested and to undertake pilot line testing ([33]). Similarly, the level of ramp-up knowledge increases over time as the team pursues more production ramp-up activities and through KT from the pilot line stage. Knowledge from pilot line testing improves the ability of the production ramp-up team to identify which experiments or engineering trials to perform as well as how to perform them ([28]). In practice, we observed that current telecommunications technologies facilitate the real-time KT between development employees in different stages that are either co-located or reside at diverse locations (also see [27]). Consistent with these observations, we examine highly interactive stages of an NPD project such that the knowledge developed at the prototyping stage is continuously transferred to the pilot line stage, and the knowledge developed at the pilot line stage is continuously transferred to the ramp-up stage.

We contribute to the literature by developing a deep understanding of how the creation and transfer of knowledge should be managed in a 3-stage NPD project. Important analytic results are described to characterize how the manager should pursue prototyping, pilot line testing and ramp-up activities over time throughout the NPD project. In particular, we find that the optimal rates of knowledge development activities at each stage are dramatically different over time during the NPD project. We explore how the accumulation of knowledge at one stage, which is continuously transferred to the next stage, impacts the optimal flows of knowledge in all stages of the project. We find that the effectiveness of knowledge generating activities at *one* stage impacts the creation of knowledge in *all* other stages of the NPD project. This is important as the manager has some control over the effectiveness of development activities, which may be enhanced with higher skilled team members or through superior technical support. Also, we show how the return to KT from one stage to the next impacts the pursuit of prototyping, pilot line testing, and production ramp-up activities throughout the NPD project. Again, these insights are important to the extent that the manager has some control over the return to KT since she can formalize methods to document knowledge and can invest in advanced technical systems to facilitate the transfer of knowledge.

This paper is organized as follows: In Section 2, a review of the literature is provided. In Section 3, the model is introduced. The optimal solutions and interpretations are provided in Section 4. The concluding remarks are given in Section 5.

II. LITERATURE REVIEW

This research is related to the literature on KT and the literature on concurrent engineering in NPD projects, as described below.

A. The Knowledge Transfer Literature

Learning activities have been categorized as either autonomous or induced in the knowledge management (KM) literature ([12]). Induced learning requires managerial action for the learning activities to occur ([6], [7], [28]). Knowledge transfer is a form of induced learning that requires one party to pass knowledge to the other either orally or through documentation ([1], [14], [23]). [3] (p. 151) define KT as "the process through which one unit (e.g., group, department, or division) is affected by the experience of another".

The importance of KT to a firm's performance has been shown empirically. Based on data from the construction of Liberty ships, [2] find that a shipyard that begins operation late is more efficient than those starting early because of KT. In a study of the global semiconductor industry, [24] find that KT shortens the time a firm needs to ramp-up to full production at a new manufacturing facility.

To understand the factors that impact the effectiveness of KT, [18] examine factories in a steel manufacturing firm. They find that learning within the factory results in significant improvements in productivity. However, the knowledge transferred from one factory to another does not generate significant productivity improvements because of the lack of management buy-in and interdepartmental problem solving skills. Based on an eight-year field investigation of Xerox-Europe, [16] examine whether the use of templates improves the effectiveness of KT. A template refers to an existing business model that is observable, and is continuously used as a replication example ([38]). [16] find that using templates increases the likelihood of adopting a transferred routine, thereby enhancing the effectiveness of KT.

In this paper, we consider how activities (including prototyping, pilot line testing, and ramp-up production) should be pursued over time during and NPD project, where knowledge accumulated at one stage is transferred to the next stage in real time. We recognize that the knowledge transferred from a source team can improve the effectiveness of development activities of the recipient team, which is consistent with the literature mentioned above. Furthermore, we specifically examine how the return of KT from one stage to the next impacts the rates of development activities throughout the NPD project.

B. The Concurrent Engineering Literature

We consider three distinct stages of engineering activities in an NPD project: prototyping ([29], [33]), pilot line testing ([21], [33]), and production ramp-up ([28], [32]). The transfer of prototyping knowledge improves the effectiveness of pilot line testing activities ([33]), and the transfer of knowledge based on pilot line testing improves the effectiveness of production ramp-up activities ([31]).

In NPD projects, the time-to-market is a key source of competitive advantage ([19], [35]). To shorten product development time, concurrent engineering is widely used ([30], [37]). [14] (p. 1431-1432) define concurrent engineering as a process "in which engineering activities are conducted concurrently rather than sequentially." [17] provide a model-based framework to manage the concurrency of product development activities. They introduce the notion of the evolution of upstream information and the downstream sensitivity to the upstream information whereby development activities are overlapped.

In our paper, activities at each stage (prototyping, pilot line, and ramp-up) can occur concurrently or sequentially. In addition, we explicitly identify the rates that development activities should be pursued by the NPD manager in a three-stage project. We obtain analytic results demonstrating that the optimal rate of prototyping activities is front-loaded (peak rate occurs at the initial time) ([4], [23], [34]); the optimal rate of pilot line testing follows a moderate delay strategy (peak rate occurs later in the development project) ([23]); and the optimal rate of ramp-up activities follows an extreme delay strategy (peak rate occurs at the end of the development project). Therefore, we demonstrate that unique timing strategies exist whereby knowledge development optimally occurs during a three-stage NPD project. [23] focus on knowledge development of product and process design teams and KT between the product and the process design teams during an NPD project. Therefore, they do not consider the optimal creation and flow of knowledge in a three-stage project and thus obtain substantially different results.

Most of the NPD literature focuses on minimizing the product's time-to-market ([17], [19], [20]). In contrast, we recognize that for many products, the time-to-market is determined by seasonality conditions or external market forces. Firms in the automotive industry release products annually at the start of the year, whereas many computer electronics firms release new models in time for the annual holiday season. Therefore, in contrast to the literature, we focus on maximizing the net revenue earned from NPD activities (i.e., the extent of functionality and features embedded in the project) that is released to the market at a predetermined launch time. The features and functionality that drive net revenue are determined by the levels of knowledge from prototyping, pilot line, and ramp-up activities generated throughout the NPD project. We provide insights on how the marginal contributions to net revenue from each level of knowledge impact the optimal solutions over time in all stages of the NPD project.

III. THE MODEL

The NPD manager determines the optimal rates of prototyping, pilot line testing, and production ramp-up activities throughout the NPD project to maximize the payoff at the given product launch time. Additionally, KT occurs continuously as it develops over time from the prototyping to the pilot line stage and from the pilot line stage to the ramp-up stage. Product development begins at time t=0 and concludes at time t=T, where T is the given product launch time. The payoff at the product launch time reflects the knowledge accumulated in each of the three stages. (In the remainder of the paper let $X_Z(Z)$ and $X_{ZZ}(Z)$ denote the first and second order derivatives of X(Z) with respect to Z; let $dX(t)/dZ$ denote the total derivative of X with respect to Z).

A. The Levels of Knowledge

There are three flows of knowledge (one at each stage) to consider. First, the manager determines the optimal rate of prototyping activities to pursue over time, denoted by $y(t)\geq 0$ for $t\in[0,T]$ (control variable). The rate of prototyping at time t can be measured in terms of hours of workforce effort. As prototyping activities occur, prototyping knowledge accumulates. Let Y(t) denote the level of prototyping knowledge at time t for $t\in[0,T]$ (state variable). The level of prototyping knowledge at time t is comprised of the initial level ($Y(0)>0$ is given) and learning benefits derived from the rate of prototyping activities undertaken through time t. The initial level of prototyping knowledge reflects the overall skill of the prototyping team at time 0. The extent that prototyping activities at time t increase the level of prototyping knowledge, at that time, is driven by the actual rate of prototyping, the skill of the team, and the quality of the technical support available. With higher skill or superior technical support, the effectiveness of any rate of prototyping activities is larger as indicated by the parameter $\alpha_0>0$. This gives us (1).

$$dY(t)/dt = \alpha_0 y(t) \quad (1)$$

Second, the manager determines the optimal rate of pilot line activities to pursue over time, denoted by $p(t)\geq 0$ for $t\in[0,T]$ (control variable). Again, the rate of pilot line activities can be measured in terms of hours of workforce effort. Let P(t) (state variable) denote the level of pilot line knowledge at time t. The level of pilot line knowledge at time t is comprised of the initial level ($P(0)>0$ is given) and learning benefits from the rate of pilot line testing activities pursued through that time. The initial level of pilot line knowledge reflects the skill of the pilot line team. The increase in the level of pilot line knowledge at a particular time is driven by the rate of pilot line testing activities at that time as well as the skill of the team and the quality of the technical support available. Moreover, the effectiveness of pilot line testing activities on increasing the level of pilot line knowledge is enhanced by the knowledge transferred from prototyping ([22]). Workforce skill and the quality of technical support available for pilot line testing are inferred by the parameter $\beta_0>0$. The parameter $\beta_1\in(0,1)$ denotes the return to KT from the prototyping stage. If the ability of the prototyping team to document and communicate results is large and the ability of the pilot line team to understand the results received is large then β_1 is close to 1 ([36]). This gives us (2).

$$dP(t)/dt = \beta_0 p(t) Y(t)^{\beta_1} \quad (2)$$

Third, the manager determines the optimal rate of production ramp-up activities to pursue over time, denoted by $n(t)\geq 0$ for $t\in[0,T]$ (control variable), which can be measured in terms of hours of workforce effort. Let N(t) denote the level of ramp-up knowledge at time t, with $N(0)>0$ given (state variable). The level of ramp-up knowledge at time t reflects the initial level N(0) as well as the learning benefits from the rate of production ramp-up activities and the transfer of pilot line knowledge through time t. The transfer of pilot line knowledge enhances the effectiveness of production ramp-up activities to increase the level of ramp-up knowledge by providing direction regarding the nature of the experiments or engineering trials needed ([28]). In (3), the parameter $\gamma_0>0$ indicates the amount of workforce skill and the quality of technical support provided for production ramp-up activities, and the parameter $\gamma_1\in(0,1)$ indicates the return to KT from the pilot line stage.

$$dN(t)/dt = \gamma_0 n(t) P(t)^{\gamma_1} \quad (3)$$

B. The Objective

The profit-maximizing objective appears in (4). The first terms outside the integral represent the net revenue earned when the product is released to the market at time T. The terms inside the integral represent the costs incurred for development activities during the NPD project. Since KT is fluid and occurs continuously over time along with development activities, its costs are simply subsumed in those associated with the rates of prototyping, pilot line testing and production ramp-up activities. Below, we elaborate on each term.

Maximize $r_1Y(T) + r_2P(T) + r_3N(T) - \int_0^T [c_1y(t)^{\sigma_1} + c_2p(t)^{\sigma_2} + c_3n(t)^{\sigma_3}]dt$ (4)

The ability of the firm to earn net revenue is a function of the cumulative knowledge generated by NPD activities at the product launch time ([9], [11], [13]). As such, we assume the levels of knowledge at the launch time T characterize the final product features, functionality and process efficiency for the new product. In addition, the levels of prototyping, pilot line and ramp-up knowledge may have value and thereby contribute to net revenue for future NPD projects. Let net revenue generated by the NPD project at the launch time be denoted by $r_1Y(T) + r_2P(T) + r_3N(T)$ with r_1, r_2, and $r_3 \geq 0$. (See [5], [9], and [23].)

Costs are incurred for prototyping activities, pilot line testing and production ramp-up throughout the NPD project. Let $c_1y(t)^{\sigma 1}$ denote the cost incurred for prototyping activities undertaken at time t, with $c_1>0$ and $\sigma_1>1$. The cost includes salaries for team members who conduct prototyping and the cost of the technical support systems, such as computer aided design workstations. We assume the cost is convex with respect to the rate of prototyping activities pursued at any instant of time, giving us $C_{1y} \geq 0$ and $C_{1yy} \geq 0$ ([7], [8], [31]). The cost increases at an increasing rate to reflect coordination costs and overtime or the use of less efficient methods as the finite development resources are increasingly strained. Similarly, we define $c_2p(t)^{\sigma 2}$ and $c_3n(t)^{\sigma 3}$, with c_2 and $c_3>0$, σ_2 and $\sigma_3>1$, as the costs for pilot line testing and production ramp-up activities at time t, respectively, giving us $C_{2p} \geq 0$, $C_{3n} \geq 0$, $C_{2pp} \geq 0$, $C_{3nn} \geq 0$.

IV. THE SOLUTION

We solve the model using optimal control methods ([26]). In particular, we maximize the Hamiltonian given in (5). The adjoint variable $\lambda_1(t)$ represents the marginal value of the level of prototyping knowledge at time t. Similarly, the adjoint variables $\lambda_2(t)$ and $\lambda_3(t)$ represent the marginal values of the level of pilot line and ramp-up knowledge at time t, respectively. Note that the level of prototyping knowledge at time t is sustained from that time through the remainder of the development project. Therefore, $\lambda_1(t)$ is interpreted as the marginal value of an additional unit of prototyping knowledge from time t to the product launch time, T. Similar interpretations hold for $\lambda_2(t)$ and $\lambda_3(t)$. The optimality conditions for $\lambda_1(t)$, $\lambda_2(t)$ and $\lambda_3(t)$ are given in Lemma 1. (In the remainder of the paper, the notation depicting time is suppressed whenever possible, all proofs appear in the Appendix, and "*" indicates an optimal solution.)

$$H = -c_1y(t)^{\sigma_1} - c_2p(t)^{\sigma_2} - c_3n(t)^{\sigma_3} + \lambda_1(t)\alpha_0y(t) + \lambda_2(t)\beta_0p(t)Y(t)^{\beta_1} + \lambda_3(t)\gamma_0n(t)P(t)^{\gamma_1}$$

***LEMMA 1*:** For all $t \in [0,T]$, the optimality conditions for $\lambda_1(t)$, $\lambda_2(t)$ and $\lambda_3(t)$ satisfy the following:

(i) $d\lambda_1/dt = -\lambda_2(t)\beta_0p(t)\beta_1Y(t)^{\beta_1-1}$, $\lambda_1(T) = r_1$;
(ii) $d\lambda_2/dt = -\lambda_3(t)\gamma_0n(t)\gamma_1P(t)^{\gamma_1-1}$, $\lambda_2(T) = r_2$;
(iii) $\lambda_3(t) = r_3$ for $t \in [0,T]$.

Lemma 1 provides important insights on how the levels of knowledge at each stage during the NPD project drive net revenue. Specifically, we see that the marginal value of prototyping knowledge is positive and decreasing over time. Similarly, we find the marginal value of pilot line knowledge is positive and decreasing over time. In contrast, however, the marginal value of production ramp-up knowledge is constant over time. The marginal value of prototyping knowledge at time t is comprised of the sum of the marginal contribution to net revenue from prototyping knowledge at T and the marginal benefit to pilot line testing from the transfer of prototyping knowledge at time t. The timing of the knowledge transfer is critical. If an additional unit of prototyping knowledge is transferred early, the rate that pilot-line testing activities increase the level of pilot line knowledge is larger early and throughout the remainder of the development project. Thus, the marginal value of the level of prototyping knowledge decreases over time. Similarly, the marginal value of the level of pilot-line testing activities decreases over time. In contrast, the level of ramp-up knowledge is valuable only at the product launch time as a driver of net revenue so that the marginal value of ramp-up knowledge is constant.

A. Optimal Rates of NPD Activities

The optimal rates of development activities, as given in Theorem 1, reflect the optimality conditions in (1)-(3) and Lemma 1. Intuitively, we see that the optimal rate of prototyping activities at time t is a function of its marginal value and the marginal cost at that time. Similarly, the optimal rates of pilot line testing and production ramp-up activities are functions of the corresponding marginal values and costs at that time. Furthermore, it is important to observe that the marginal value of pilot line testing activities at time t is a function of the level of prototyping knowledge transferred at that time. Similarly, the marginal value of ramp-up activities at time t is a function of the level of pilot line testing knowledge transferred at that time. In Corollary 1, we describe how the optimal rates of development activities change throughout the NPD project; the interpretations follow.

***THEOREM 1*:** The optimal rates the NPD manager pursues development activities are:

(i) $y^*(t) = \left(\frac{\lambda_1(t)\alpha_0}{\sigma_1c_1}\right)^{\frac{1}{\sigma_1-1}}$; (ii) $p^*(t) = \left(\frac{\lambda_2(t)\beta_0Y(t)^{\beta_1}}{\sigma_2c_2}\right)^{\frac{1}{\sigma_2-1}}$; and (iii) $n^*(t) = \left(\frac{\lambda_3(t)\gamma_0P(t)^{\gamma_1}}{\sigma_3c_3}\right)^{\frac{1}{\sigma_3-1}}$. (5)

***COROLLARY 1*:** (a) $dy/dt < 0$ for $t \in [0,T]$; (b) $dn/dt > 0$ for $t \in [0,T]$; (c) (Case i) $dp/dt > 0$ for $t \in [0,t_s)$, $dp/dt = 0$ at t_s, and $dp/dt < 0$ for $t \in (t_s,T]$, where $t_s \in [0,T]$;

(Case ii) $dp/dt < 0$ for $t \in [0,T]$; (Case iii) $dp/dt > 0$ for $t \in [0,T]$.

From Theorem 1 and Corollary 1 (a), we observe that the optimal rate of prototyping is positive and decreasing over time until reaching $\left(\frac{r_1 \alpha_0}{\sigma_1 c_1}\right)^{\frac{1}{\sigma_1 - 1}}$ at the product launch time. Therefore, the maximum rate of prototyping occurs at the outset of the NPD project. (See Fig. 1; for illustrative purposes only the solution is shown as convex in time.) Consistent with the literature, we refer to this development strategy as *front-loading* ([4], [23], [34]). There are two intuitive explanations for front-loading. First, front-loading occurs since an additional unit of prototyping activity early in the project increases the level of prototyping knowledge at that time and enhances the effectiveness of pilot line testing from that time through the remainder of the project. Second, front-loading the rate of prototyping activities occurs since, as the NPD project progresses over time, there is less opportunity to benefit from KT to the pilot line testing stage.

From Theorem 1 and Corollary 1 (b), we find that the optimal rate of production ramp-up activities is positive and increasing throughout the NPD project. Therefore, the maximum rate of production ramp-up occurs at the product launch time. (See Fig. 1; for illustrative purposes only the solution is shown as convex in time.) This result is obtained since production ramp-up activities are more and more effective over time due to the transfer of more and more pilot-line knowledge. We refer to this solution as the *extreme delay* strategy since the maximum pursuit of production ramp-up is delayed until the product launch time is reached.

Lastly, for reasonable parameter values, the optimal rate of pilot line testing given in Theorem 1 and Corollary 1 (c) (Case i). Therefore, the optimal rate of pilot line testing first increases, peaks, and then decreases over time. Since the peak rate of pilot line testing is delayed until later in the planning horizon but occurs before the launch time, we refer to this as the *moderate delay* strategy. (See Fig. 1; for illustrative purposes only the solution is shown as concave in time.) Two forces drive this result. First, as the level of prototyping knowledge increases over time, KT makes pilot line testing activities more effective. As a result, early in the development project the desirability of pilot line testing increases over time. In contrast, later in the project less time remains to reap the benefits from the transfer of knowledge from the pilot line to the ramp-up stage. As a result, later in the project, the rate of pilot line testing activities decreases over time. Putting these two forces together, we find that the maximum rate of pilot line testing is moderately delayed until later in the development project in order to take advantage of the transfer of more prototyping knowledge, while also providing sufficient pilot line knowledge to be utilized at the ramp-up stage.

From Corollary 1 (c), two other solutions are possible, though highly unlikely, for the optimal rate of pilot line testing activities. First, if Y(0) is extremely large or r_2 is extremely small, we may obtain the solution in Corollary 1 (c) (Case ii). Starting at the initial time, the pilot line stage leverages the extremely large level of prototyping knowledge so that the maximum rate of pilot line testing activities occurs at time t=0. Similarly, with extremely small r_2, if prototyping does not, in itself, contribute to net revenue then its only value is through the KT to the ramp-up stage. Since the marginal value of KT decreases over time, we see that the rate of pilot line testing activities has its maximum at the initial time and decreases thereafter. Alternatively, if Y(0) is extremely small or r_2 is extremely large, then the peak rate of pilot line testing occurs at t=T, as in Corollary 1 (c) (Case iii). The interpretation of case (c) (Case iii) is the reverse of case (c) (Case ii).

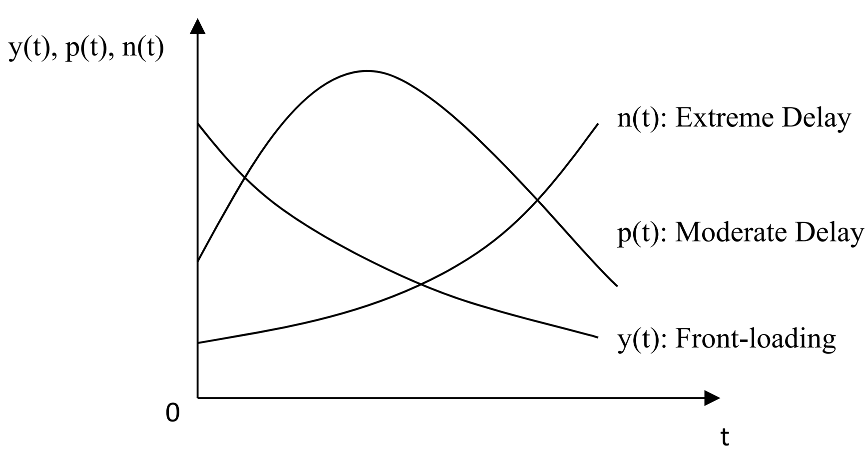

Fig. 1: Rates of NPD Activities over Time

B. Analytic Sensitivity Analysis

From the results in Section 4.1, we observe a synergistic relationship among the rates of prototyping, pilot line testing and production ramp-up activities. In particular, we find that if the effectiveness of the rate of *any* development activity (α_0, β_0, γ_0) or the return to any KT activity (β_1, γ_1) is larger, then the optimal rates of *all* development activities are larger. Naturally, this leads to larger levels of knowledge in all stages and over all time. Similarly, if the cost of *any* development activity is larger, then the optimal rates of *all* development activities are smaller. Again, this gives us smaller levels of knowledge at all stages and for all time. Note that the source of the synergy is the mathematical structure that links each stage to the next through KT. We explore this result more deeply through the parameter β_0, below.

Recall that β_0 denotes the effectiveness of pilot line testing activities on increasing the level of pilot line knowledge. Suppose β_0 is larger. It follows that the pilot line team is better able to increase pilot line knowledge so that the rate of pilot line testing activities is larger throughout the project. Moreover, the rate of production ramp-up activities is larger over all time since the transfer of more pilot line knowledge makes it more effective at increasing the level of production ramp-up knowledge. In addition, if β_0 is larger then the marginal value of the level of prototyping knowledge is larger throughout the project since the transfer of prototyping knowledge provides more benefits to the pilot line stage. In conclusion, larger β_0 is associated with larger levels of prototyping, pilot line and ramp-up knowledge throughout the NPD project. The above discussion is summarized in Corollary 2.

COROLLARY 2: If workforce skill or technical support associated with pilot line testing (β_0) is larger, then the optimal rates of prototyping, pilot line testing, and production ramp-up activities are larger and the levels of knowledge in all stages of development are larger for $t \in (0,T]$. Analogous results are obtained for α_0, γ_0, β_1, and γ_1. The reverse results hold for c_1, c_2 and c_3.

C. Numerical Sensitivity Analysis

While considerable insights are obtained analytically, numerical sensitivity analysis was performed to understand how the predetermined product launch time, T, impacts the development activities in each stage. Holding all other input parameters fixed, we find that if the product is launched later (T larger), then the rates of prototyping, pilot line testing and ramp-up activities are all larger for $t \in [0,T]$. It follows that the knowledge levels of each stage of the NPD project are larger at the product launch time, as well. Intuitively, this result is obtained for two reasons. First, since there is more time to leverage the KT from the prototyping stage to the pilot line stage, the marginal value of prototyping knowledge is larger over all time. Second, since there is more time to leverage KT from the pilot line stage to the ramp-up stage, the marginal value of pilot line knowledge is larger over all time. It is important to recognize, however, that a later product launch may also be associated with smaller values of r_1, r_2, and r_3 due to time-based competition. In that situation, the effect of a delayed product launch on the optimal rates of development activities throughout the NPD project is unclear.

V. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we introduce a model that characterizes the evolution of knowledge in an NPD project with three stages of engineering activities conducted concurrently: prototyping activities, pilot line testing, and production ramp-up. The manager determines the optimal rates that activities in each stage should be pursued over the NPD project which drive the levels of prototyping knowledge, pilot line knowledge, and ramp-up knowledge, respectively. An important feature of our research is that we capture the link between successive stages of engineering activities. Specifically, we recognize that by transferring knowledge on prototyping to the pilot line testing stage, the manager enhances the ability of pilot-line testing to increase the level of pilot line knowledge. Similarly, transferring pilot line knowledge enhances the ability of the production ramp-up activities to increase the level of ramp-up knowledge. Reflecting the widespread use of telecommunications technologies while undertaking product development projects ([27]), knowledge transfer occurs from one stage to the next continuously over time as it is developed. Ultimately, the manager seeks to maximize the net revenue earned when the product is released to the marketplace less the costs incurred during development for prototyping activities, pilot line testing, and production ramp-up. The net revenue earned at the product launch time is a function of the levels of prototyping, pilot line, and ramp-up knowledge embedded in the product.

Analytic results are obtained demonstrating that the optimal rate of prototyping activities follows a front-loading strategy; the optimal rate of pilot line testing follows a moderate delay strategy; and the optimal rate of production ramp-up activities obeys an extreme delay strategy. In addition, we find that an increase in the effectiveness of any knowledge development activity results in larger rates of all development activities for all three stages over time. As such, we show a complementary relationship exists among all means of knowledge creation.

In this research, we assume that the effectiveness of development activities is constant throughout the NPD project. However, in reality due to technological advances in underlying the KT systems, the effectiveness of knowledge development may improve over time. Future research can examine the impact on the optimal solutions if technological advances increase the return obtained from KT over time. Additionally, we assume the product launch time is given and, consistent with that assumption, the payoff at the product launch is independent of time. Future research may explore the situation where the product launch time is optimally determined to reflect the following tradeoff: a superior product may be developed by delaying the product launch (e.g., allowing more time to invest in product development activities) versus the loss in net revenue due to time-based competition when a launch time is delayed. Lastly, we consider knowledge transfer in the forward direction only. While this assumption is reasonable in many situations, particularly for incremental NPD projects, an interesting extension of this paper could include the effect of knowledge transfer in the backward direction as feedback ([39]).

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APPENDIX

Proof of Lemma 1: Follows from the following optimality conditions (see [26]).

$d\lambda_1/dt = -H_Y = -\lambda_2(t)\beta_0 p(t)\beta_1 Y(t)^{\beta_1 - 1},\ \lambda_1(T) = r_1$ (A-1)

$d\lambda_2/dt = -H_P = -\lambda_3(t)\gamma_0 n(t)\gamma_1 P(t)^{\gamma_1 - 1}, \lambda_2(T) = r_2$ (A-2)

$d\lambda_3/dt = -H_N = 0,\ \lambda_3(T) = r_3 \Rightarrow \lambda_3(t) = r_3$ for $t \in [0, T]$ # Q. e. d.

Proof of Theorem 1: Follows from the following optimality conditions (see [26]).

$H_y = -\sigma_1 c_1 y(t)^{\sigma_1 - 1} + \lambda_1(t)\alpha_0 = 0$ (A-3)

$H_p = -\sigma_2 c_2 p(t)^{\sigma_2 - 1} + \lambda_2(t)\beta_0 Y(t)^{\beta_1} = 0$ (A-4)

$H_n = -\sigma_3 c_3 n(t)^{\sigma_3 - 1} + \lambda_3(t)\gamma_0 P(t)^{\gamma_1} = 0$ (A-5)

Q. e. d.

Proof of Corollary 1: Taking the first order derivatives of y(t), p(t), and n(t) with respect to t, we obtain:

$$\frac{dy}{dt} = \left(\frac{\alpha_0}{\sigma_1 c_1}\right)^{\frac{1}{\sigma_1 - 1}} \frac{\lambda_1^{\frac{2-\sigma_1}{\sigma_1 - 1}}}{\sigma_1 - 1} \frac{d\lambda_1}{dt} \quad \text{(A-6)}$$

$$\frac{dp}{dt} = \left(\frac{\beta_0}{\sigma_2 c_2}\right)^{\frac{1}{\sigma_2 - 1}} \frac{(\lambda_2 Y(t)^{\beta_1})^{\frac{2-\sigma_2}{\sigma_2 - 1}} Y(t)^{\beta_1 - 1}}{\sigma_2 - 1} \left(\frac{d\lambda_2}{dt} Y(t) + \lambda_2 \beta_1 \frac{dY(t)}{dt}\right) \quad \text{(A-7)}$$

$$\frac{dn}{dt} = \left(\frac{r_3 \gamma_0}{\sigma_3 c_3}\right)^{\frac{1}{\sigma_3 - 1}} \frac{\gamma_1}{\sigma_3 - 1} P(t)^{\frac{1+\gamma_1 - \sigma_3}{\sigma_3 - 1}} \frac{dP(t)}{dt} \quad \text{(A-8)}$$

In (A-6), since $\frac{d\lambda_1}{dt} < 0$, we have $\frac{dy}{dt} < 0$. In (A-8), since $\frac{dP(t)}{dt} > 0$, we have $\frac{dn}{dt} > 0$. The sign of $\frac{dp}{dt}$ depends on the sign of the expression $\frac{d\lambda_2}{dt} Y(t) + \lambda_2 \beta_1 \frac{dY(t)}{dt}$, given in (A-7). We know $\frac{d\lambda_2}{dt} < 0$ whereas Y(t), $\frac{dY(t)}{dt}$ and $\lambda_2 > 0$ so that the first term is negative while the second term is positive. Case i: First, early in the planning horizon, since both λ_2 and $\frac{dY(t)}{dt}$ are decreasing in time, $\lambda_2\beta_1 \frac{dY(t)}{dt}$ has its maximum value at the initial time 0. Second, $\lambda_2\beta_1 \frac{dY(t)}{dt}$ has its minimum value at time T. Thus, for reasonable parameter values, $\frac{d\lambda_2}{dt} Y(t) + \lambda_2 \beta_1 \frac{dY(t)}{dt}$ is positive at the initial time, and negative at the terminal time. Therefore, $p^*(t)$ first increases and then decreases over time. Let t_s denote the time the expression equals zero: $\frac{d\lambda_2}{dt}|_{t=t_s} Y(t_s) + \lambda_2(t_s)\beta_1 \frac{dY(t_s)}{dt}|_{t=t_s} = 0$ where $t_s \in [0,T]$. Theoretically, two other cases are possible though they require highly unrealistic input parameter values. For completeness, we provide these two cases. Case ii: If Y(0) is very large or r_2 is very small, we have $\frac{d\lambda_2}{dt} Y(t) + \lambda_2 \beta_1 \frac{dY(t)}{dt} < 0$ so that $\frac{dp}{dt} < 0$ for $t \in [0,T]$. Case iii: If Y(0) is very small or r_2 is very large, we have $\frac{d\lambda_2}{dt} Y(t) + \lambda_2 \beta_1 \frac{dY(t)}{dt} > 0$ so that $\frac{dp}{dt} > 0$ for $t \in [0,T]$. # Q. e. d.

Proof of Corollary 2:

a) Taking derivative of $y(t)$ with respect to β_0, we obtain:

$$\frac{dy}{d\beta_0} = \frac{\partial y}{\partial \lambda_1} \frac{d\lambda_1}{d\beta_0} = \frac{\partial y}{\partial \lambda_1} \left[\frac{\partial \lambda_1}{\partial \beta_0} + \frac{\partial \lambda_1}{\partial \lambda_2} \frac{d\lambda_2}{d\beta_0} + \frac{\partial \lambda_1}{\partial p} \frac{dp}{d\beta_0} + \frac{\partial \lambda_1}{\partial Y} \frac{dY}{d\beta_0}\right]$$
$$= \frac{\partial y}{\partial \lambda_1} \left[\frac{\partial \lambda_1}{\partial \beta_0} + \frac{\partial \lambda_1}{\partial Y} \frac{\partial Y}{\partial y} \frac{dy}{d\beta_0} + \frac{\partial \lambda_1}{\partial p} \left(\frac{\partial p}{\partial \beta_0} + \frac{\partial p}{\partial \lambda_2} \frac{d\lambda_2}{d\beta_0} + \frac{\partial p}{\partial Y} \frac{dY}{d\beta_0}\right) + \frac{\partial \lambda_1}{\partial \lambda_2} \left(\frac{\partial \lambda_2}{\partial n} \frac{dn}{d\beta_0} + \frac{\partial \lambda_2}{\partial P} \frac{dP}{d\beta_0}\right)\right]$$

From the above, we see that $\frac{dy}{d\beta_0}$ includes second, third, and fourth order effects. We reasonably assume that the fourth order effects are negligible compared to the second and third order effects. (Similar assumptions are made in [5], [7], [15], [13], [23]. Also see [10].) As such, we obtain:

$$\frac{dy}{d\beta_0} \approx \frac{\partial y}{\partial \lambda_1} \left(\frac{\partial \lambda_1}{\partial \beta_0} + \frac{\partial \lambda_1}{\partial p} \frac{\partial p}{\partial \beta_0}\right)$$
$$= \frac{y}{\lambda_1(\sigma_1 - 1)} \left[\beta_1 \int_t^T \lambda_2 p Y^{\beta_1 - 1} d\tau + \frac{p\beta_1}{\beta_0(\sigma_2 - 1)} \int_t^T \lambda_2 p Y^{\beta_1 - 1} d\tau\right]$$

Since $\sigma_1 \geq 1$ and $\sigma_2 \geq 1$, we have $\frac{dy}{d\beta_0} > 0$. Taking derivative of $Y(t)$ with respect to β_0, we obtain $\frac{dY}{d\beta_0} = \frac{\partial Y}{\partial y} \frac{dy}{d\beta_0} = \frac{dy}{d\beta_0} \int_0^t \alpha_0 d\tau > 0$.

b) Taking derivative of $p(t)$ with respect to β_0, we obtain:

$$\frac{dp}{d\beta_0} = \frac{\partial p}{\partial \beta_0} + \frac{\partial p}{\partial \lambda_2}\frac{d\lambda_2}{d\beta_0} + \frac{\partial p}{\partial Y}\frac{dY}{d\beta_0}$$
$$= \frac{\partial p}{\partial \beta_0} + \frac{\partial p}{\partial \lambda_2}\left(\frac{\partial \lambda_2}{\partial n}\frac{\partial n}{\partial P} + \frac{\partial \lambda_2}{\partial P}\right) + \frac{\partial p}{\partial Y}\frac{\partial Y}{\partial y}\frac{\partial y}{\partial \lambda_1}\left(\frac{\partial \lambda_1}{\partial \beta_0} + \frac{\partial \lambda_1}{\partial p}\frac{dp}{d\beta_0} + \frac{\partial \lambda_1}{\partial \lambda_2}\frac{d\lambda_2}{d\beta_0} + \frac{\partial \lambda_1}{\partial Y}\frac{dY}{d\beta_0}\right)$$

We reasonably assume that the first order effect dominates and the third, fourth and fifth order effects (which are negligible). Therefore, we obtain: $\frac{dp}{d\beta_0} \approx \frac{\partial p}{\partial \beta_0} = \frac{p}{\beta_0(\sigma_2 - 1)} > 0$. Taking derivative of $P(t)$ with respect to β_0, we obtain $\frac{dP}{d\beta_0} = \frac{\partial P}{\partial \beta_0} + \frac{\partial P}{\partial p}\frac{dp}{d\beta_0} + \frac{\partial P}{\partial Y}\frac{dY}{d\beta_0} = \int_0^t pY^{\beta_1} d\tau + \frac{dp}{d\beta_0}\int_0^t \beta_0 Y^{\beta_1} d\tau + \frac{dY}{d\beta_0}\int_0^t \beta_0\beta_1 pY^{\beta_1 - 1} d\tau > 0$.

c) Taking derivative of $n(t)$ with respect to β_0, we obtain:

$$\frac{dn}{d\beta_0} = \frac{\partial n}{\partial P}\frac{dP}{d\beta_0} = \frac{P^{-1}\gamma_1 n}{(\sigma_3 - 1)}\frac{dP}{d\beta_0} > 0$$

Taking derivative of $N(t)$ with respect to β_0, we obtain:

$$\frac{dN}{d\beta_0} = \frac{\partial N}{\partial n}\frac{dn}{d\beta_0} + \frac{\partial N}{\partial P}\frac{dP}{d\beta_0} = \frac{dn}{d\beta_0}\int_0^t \gamma_0 P^{\gamma_1}\, d\tau + \frac{dP}{d\beta_0}\int_0^t \gamma_0\gamma_1 n P^{\gamma_1 - 1}\, d\tau > 0$$

The proofs for α_0, γ_0, β_1, γ_1, c_1, c_2 and c_3 are analogous and are omitted. # Q.e.d.