# Adapting Real Options to New Product Development by Modeling the Second Toyota Paradox

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***Abstract*—Uncertainty in product development projects creates significant challenges for managers who are under intense competitive pressures to increase product quality, while reducing development time and costs. Traditional wisdom dictates the early selection of a single design in order to freeze interfaces between product subsystems so that team members can work effectively in parallel, resulting in more productive product development efforts. Prior research, however, uncovered a paradoxical case. Toyota Motor Corporation achieves the fastest development times in its industry by intentionally delaying alternative selection, a strategy termed set-based development. The current work adapts real options concepts to product development management to partially explain this paradox. A formal simulation model is used to show that converging too quickly or too slowly degrades project value. Furthermore, the model demonstrates that the wisdom of set-based strategies can be explained by the application of a real options approach to product development management. Implications for managers and directions for future work are discussed.**

***Index Terms*—Product development, project management, real options, set-based concurrent engineering, system dynamics.**

## I. Introduction

PRODUCT development organizations must recognize and capture as much value as possible to be competitive in today's global market. Some value is easy to recognize and relatively predictable, such as increased productivity from training or potentially lower costs from shorter cycle times. Such value can be recognized and realized using traditional management methods and tools. However, significant value may remain hidden and, therefore, unexploited in the uncertain portions of projects, so-called *latent* project values [1]. Effective development strategies for recognizing and exploiting these latent sources of value can increase overall project value. For example, delaying the selection of a final design can add value if the delay allows developers to select a better alternative. Without effective strategies, product development managers may not recognize latent project value and, therefore, miss opportunities to increase the value of their projects to the firm.

However, exploiting the latent project value due to uncertainty in product development (PD) is difficult for at least two reasons. First, complex development processes and managerial decisions interact to affect PD behavior, project performance, and value in delayed and nonlinear ways which obfuscate the impacts of uncertainty on PD project performance. Second, PD programs are subject to multiple sources of uncertainty whose effects are not typically cumulative, so strategies designed to manage uncertainty based on one or two conditions alone can be seriously flawed. Numerous process models have been proposed in the new PD literature [2], but how specific strategies designed to manage uncertainty affect development behavior, performance, and value is not well understood.

Real options represent one approach to managing assets in the face of uncertainty. A real option is a right without an obligation to take specific future actions in managing a real asset depending on how uncertain conditions evolve [3], [4]. The central premise of real options is that, if future conditions are uncertain and changing the strategy later incurs substantial costs, then investing in flexible strategies can increase overall project value. In short, retaining flexibility in the form of options to change course can have value in the face of uncertainty.

This paper describes key challenges in applying traditional real options models to the management of new PD projects, and introduces a methodological approach for applying real options concepts to new PD management. The primary purpose is to provide managers with tangible insight into the impacts and value of different flexible development plans. We propose to do this by adapting options decision rules to PD, then incorporating these decision rules into a system dynamics simulation model of a PD process and using the model to understand project performance as a key decision parameter varies. We focus on a single but important PD practice, set-based development, a unique approach to managing PD uncertainty that has been associated with sustained competitive advantage and industry-leading profits [5]. By using a model based on real options concepts to show how set-based development can add value, we demonstrate that real options concepts can at least partially explain the Second Toyota Paradox [5].

This work contributes to PD by expanding set-based development from a binary (set-based or not) to a continuous (how set-based) description, formalizing a model of alternative selection in set-based development, and testing real options concepts as an explanatory framework of Toyota's paradoxical approach to PD. The work contributes to the real options body of knowledge by proposing and initially testing a methodological approach to adapting real options concepts to PD management.

The following section introduces real options and reviews traditional models for their application to PD management. The set-based development model is then described, followed by a case example of set-based decision-making at Toyota Motor

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Corporation. Next, Sections IV and V present the formal modeling approach used, first by describing the adaptation of real options concepts to PD, then presenting a simulation model based on the Toyota case. The results of a series of simulation runs provide insights about how set-based approaches impact development project behavior, performance, and value. A discussion of the implications of the results for PD managers is followed by conclusions and recommendations for future research.

## II. REAL OPTIONS

Real options can be described along several dimensions, including ownership, the source of value, complexity, and degree to which the option is available. A common topology separates real options according to the type of managerial action applied [6]–[8]. Categories include options that postpone (hold and phasing options), change the amount of investment (growth, scaling, or abandonment options), or alter the form of involvement (switching options). The current work focuses on an option to postpone the elimination of design alternatives.

Real options have been used to value strategies in many domains, including specific aspects of PD [3], [7], [9]–[12]. Examples include valuation of options to hedge technology investment risk [8], and application to design modularity [13], research and development resource allocation [14], and maximum price contracts for construction project options [15]. Real options have also been promoted as an effective tool for improving the insight of strategic planners and managers [3], [4], [16]–[18]. Potential benefits of real options applied to PD stem from several sources, including: a broader range of strategies considered, a focus on objectives instead of solutions, sensitivity to multiple project futures, more frequent testing of plans, and increased awareness of the value of flexibility [19].

Thus, it seems a real options approach can improve planning in PD by helping managers recognize, design, and use flexible alternatives to manage dynamic uncertainty. However, there has been little research on how real options can be operationalized to improve PD effectiveness. PD managers may underutilize real options to capture the value of flexibility because they lack tools and means to build insight about the impacts of those strategies. By modeling different decision strategies for coping with uncertainty, real options can potentially reveal and quantify latent project value. Further, specifying the managerial signals, decision rules, exercise criteria, and action plans operationalizes flexible strategies for implementation because it gives managers specific levers to use rather than general admonitions. These improved models of PD project valuation can add a precision and rigor to decision-making that engineers commonly apply to design but rarely to project planning.

Conventionally, researchers have estimated the value of real options based on approaches used to value financial options [20]–[22]. Much of the formal modeling of real options has focused on valuing (in economic terms) options for specific asset characteristics (value, uncertainty, discount rate) and option designs (timing, exercise conditions, and exercise costs), but researchers have identified common modeling assumptions that do not apply to typical PD projects [23]. Specifically, most real options models assume that: 1) future asset behavior and value conform to well-defined processes; 2) markets are complete and arbitrage opportunities are available; 3) sources of uncertainty are few and independent; 4) payouts or other costs of delaying decisions are small; and 5) planners have one or few options. None of these assumptions hold well for PD environments: asset value behaviors are not well-defined or market-based, many sources of uncertainty exist and interact, delaying decisions can be very costly, and planners usually have, practically speaking, unlimited options.

In addition, Garvin and Cheah [24] describe problems in assuming risk-neutrality and using overly simple models of uncertainty as it affects performance and value, as oversimplification can lead to erroneous conclusions. Further, Alessandri *et al.* [25] describe problems posed by assuming that asset performance and option holder activity are independent, when in fact PD option holders (i.e., project managers) purposefully and significantly manipulate the linkages between uncertainties and project values. Finally, the relative costs of PD versus other real options applications also call for models that closely reflect PD practice. The development costs incurred to maintain progress are large compared to the analogous costs in stock options (dividends) that are often assumed small or zero; while the exercise cost of an option in PD (such as abandoning a design alternative) may be small compared with the exercise costs of other options.

The current work directly addresses these issues through a model of PD processes that behaves similarly to actual PD projects. The model explicitly allows for uncertain asset behaviors, includes multiple interdependent options, and enables the option holder to affect option value. In addition, the current work assumes relatively large development costs and small exercise costs. The model is motivated by a provocative case from the literature, described in Section III.

## III. SECOND TOYOTA PARADOX

A key decision that PD managers face is how to converge from an initial set of conceptual ideas to one idea that will become the final design. Prior research has identified two contrasting PD convergence strategies. The first is an early convergence strategy termed "point-based concurrent engineering" and typified by the popular early-design-freeze policy [26]. In a point-based approach, design teams initially consider a range of alternatives from members' individual perspectives (e.g., styling, body engineering, stamping, etc.), but quickly select the best alternative to reduce project complexity and constrain development costs. In the spirit of concurrent engineering, the design thought to be the best alternative is critiqued from multiple perspectives, changes made accordingly, and the iteration process continues until all constraints are satisfied. But, in large PD projects with hundreds of contributors, a point-based strategy does not necessarily resolve into a satisfactory design fast enough. This is because any change propagates changes elsewhere, which in turn create more changes, and so on, resulting in what some have called design churning [27]. Engineers have confided to us that frequently the process never does resolve completely; it just stops because the project has reached a deadline.

In contrast, Toyota applies a slow convergence strategy, a key component of what Ward *et al.* [5] term “set-based concurrent engineering.” Upon evaluating the initial range of alternatives, rather than selecting the apparently best alternative, PD teams develop the *set* of viable alternatives from multiple perspectives. Alternatives are gradually eliminated as weaknesses in areas of performance, reliability, cost, manufacturability, and systems integration become apparent. Eventually, the process converges to a single, final alternative. This can occur as late as the vehicle prototype stages for some vehicle components. In addition, Toyota often uses a set-based approach as it develops engineering requirements, first defining a range that is gradually refined to a final requirement as alternatives are explored [28]. On the surface, a slow convergence strategy would seem to result in slow and expensive development projects, but the astounding fact is, Toyota has been the industry benchmark in automobile development speed for many years, and does so with a leaner engineering workforce than most competitors! Ward *et al.* [5] called this apparent contradiction the Second Toyota Paradox.

Design theory and the PD literature strongly support generating multiple alternative solutions to design problems as an essential component of an effective PD process [29], [30]. Toward this goal, tools and strategies have been developed to aid design teams in selecting the best alternative, such as decision trees and alternative comparison matrices. If uncertainty is small enough, these approaches allow useful analysis and effective alternative selection, but often the performance, costs, and impacts on project duration of undeveloped alternatives cannot be predicted accurately enough in early stages to identify the best alternative.

Take, for example, the challenge of selecting a body style for a new automobile from among several alternatives. On one hand, management would like to decide on a body style early in the process so that all development resources can focus on the chosen style with the aim of successfully bringing the product to market on time and under budget. On the other hand, body design involves a complex set of tradeoffs between aesthetics and creative design, aerodynamics, vehicle packaging, and manufacturability. Developing alternatives in parallel not only enhances the creative process by considering a broad range of competing designs, but also enables the design team to gather information on the tradeoffs associated with the set of alternatives. This information is invaluable in making the best alternative selection and/or in creatively resolving conflicts among the competing criteria. In addition, stamping technology itself is fairly complex and subtle, and it is not always obvious what is easily manufacturable. So developing multiple design alternatives in parallel and delaying design decisions can be advantageous.

### *A. Case Study of Set-Based Development at Toyota*

To illustrate the set-based approach in practice and to provide a basic framework on which to base the model described later, this section presents a case study of a typical development process for a major automobile subsystem at Toyota. This case is based on Sobek’s [31] study of Toyota’s vehicle development system from dozens of hours of interviews with 23 Toyota engineers and engineering managers across the major vehicle development units in Japan, engineers at numerous Toyota suppliers, and several American engineers working in Toyota’s U.S. operations. Interviews were semi-structured and data were captured from field notes taken during the interviews combined with notes transcribed from memory immediately following the interview. Interview data were systematically analyzed using a grounded theory methodology [32].

*1) Concept Design:* The vehicle development program begins with the chief engineer developing a vehicle concept—a written document describing his vision for the product and the overall vehicle specifications. The functional engineering units (body engineering, chassis engineering, etc.) develop comparable concept documents in parallel. Vehicle stylists simultaneously develop dozens of two-dimensional renderings of numerous artistic conceptions for the chief engineer so he can see the impact of decisions regarding vehicle specifications. Examples of questions concerning body development include “What is the aesthetic impact of a shorter wheel-base?” or “How does a taller passenger compartment impact driver comfort?” This process ends with the approval of the chief engineer’s concept.

*2) System-Level Design:* After concept approval stylists continue to explore ideas based on the chief engineer’s concept document, and eventually 6–10 ideas are selected for 1/5 scale clay models. Body engineering conducts engineering design studies on these ideas, called *kentouzu* drawings. These studies include all the planning required to realize the vehicle: typical cross sections of structural parts, joint definition, preliminary part layout, wire harness routing, crash analysis, and so on. Taking input from engineering, manufacturing, and aesthetic evaluation, 2–3 ideas are chosen for full-scale clay modeling. The *kentouzu* studies continue on the remaining alternatives and feedback is given to the chief engineer and styling team. By the time styling approval occurs, body engineering has laid out a fairly well-defined body design plan for each alternative under consideration. Styling approval is a high-publicity event within the corporation at which one style is chosen. That style’s surface geometry is then converted to digital CAD data and sent to body engineering. Body engineering compiles the relevant *kentouzu* drawings, updating or adding to them as necessary, and creates a document called the body structures design plan, or *kozokeikaku* (K4) in Japanese. The K4 is distributed for approval and feedback from all relevant vehicle development units.

*3) Detail Design:* From the K4, detailed design begins on all the body panels and structural components. As they are completed, body engineering drawings are sent to die engineering without tolerances, delaying the determination of final dimensions until after die tryout. Die engineers design die sets to create parts that are as close to nominal dimensions as possible, then have soft-tool dies produced that can stamp out prototype parts. The prototype parts are assembled in a “slow build” of the vehicle. Fit and function are adjusted through modifications to the part or die design, whichever is most appropriate. Full vehicle prototypes are built and tested. Starting with prototype testing and continuing past completion, hard-tool dies are ordered and tried out with a first set of parts. These parts are assembled into a “screw body” and the final adjustments are made to the body or die design, whichever is most economical and achieves engineering standards. From there, the vehicle enters a trial production stage before ramping up to full production.

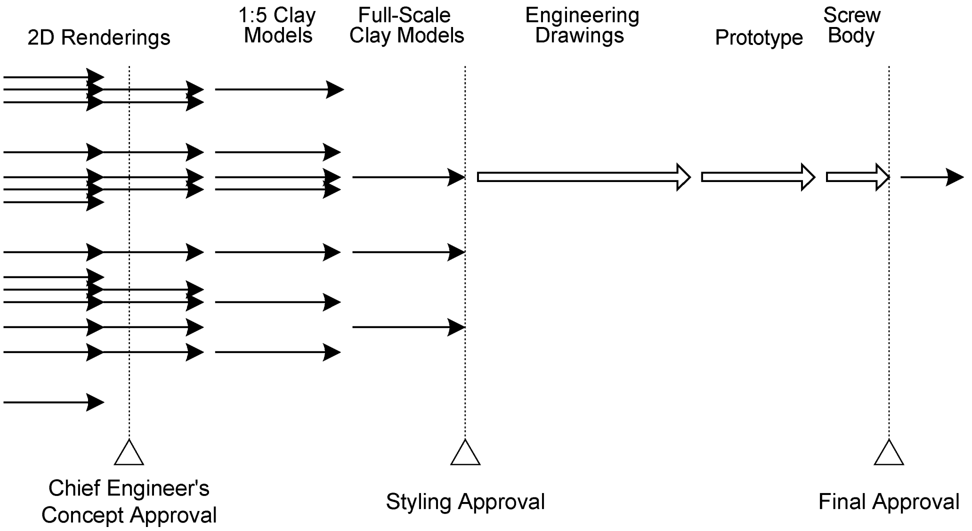

Fig. 1. Body design and development at Toyota.

Fig. 1 depicts this process graphically. The diagram shows the gradual narrowing of alternatives over time. The process can be divided into three phases as shown. The double-line arrows represent drawings without tolerances, which imply that a range (albeit small) of final designs may be acceptable.

Although prior work has demonstrated that Toyota achieves competitive advantage using set-based development, parallel development also requires resources for alternatives that will not be realized, potentially increasing overall development costs. In fact, these development costs can be so large that they dominate the creation of value by the project. Without understanding the underlying mechanisms at work, applying set-based development is fraught with risk. A better understanding of the underlying causal relationships within this approach is needed for PD organizations to take maximum advantage of the approach while minimizing risk. Because Toyota's purposeful delaying of design alternative selection decisions resembles the use of real options in other contexts, the current work uses a real options approach as a first step to explain the utility of set-based approaches to PD.

## IV. Adapting Real Options to Product Development

To adapt and operationalize real options concepts into PD applications, using the Second Toyota Paradox as a test case, we must first formalize the convergence decisions from an options perspective. In addition, to evaluate the effectiveness of alternative strategies, we must develop a method for valuing the flexibility afforded by the strategy. This section presents the formalization of convergence decisions and our flexibility valuation approach.

### *A. Formalization of PD Convergence Decisions*

In real options terms, a project that converges early (point-based) does not retain options to abandon alternatives in the event that the chosen alternative does not work out or encounters significant difficulties. In other words, delaying the start of convergence retains an option to choose any design alternative while additional information becomes available. This is consistent with the classic real options message, that delaying decisions while uncertainty resolves can add value.

One way to structure this form of alternative selection is with a decision rule. An option holder decides whether to exercise the option based on the asset's performance when compared to specified criteria. For an option to buy a common stock, the stock's value at the decision time $(V_{\text{stock}})$ is the signal, and the stock's minimum value to justify purchasing the stock (the strike price, $V_{\text{strike}}$) is the decision criterion. The decision rule is

$$\text{IF } (V_{\text{stock}} \geq V_{\text{strike}}) \text{ THEN (Purchase Stock)} \qquad \text{ELSE (Do not Purchase Stock)}. \quad (1)$$

Adapting this basic decision rule for use in PD may require multiple signals from the development project (S) and several criteria (C) to decide whether or not to exercise an option. Therefore the signal(s) about the asset's performance and decision criteria can be represented as vectors of parameter values. Increasing net project value to the option-holder is the traditional justification for exercising an option, but the literature on the strategic advantages of real options [3], [4], [16], [19] suggests noneconomic benefits that may also be the basis for deciding whether to exercise an option. Generalizing (1) for an option to change a PD strategy, the decision rule becomes

$$\text{IF } (S \geq C) \text{ THEN (Change to New Strategy)} \qquad \text{ELSE (Retain Current Strategy)} \quad (2)$$

where

$S$ vector of signaling parameter values used to describe performance;

$C$ vector of parameter values describing conditions that must be met to justify a change in PD strategy.

To illustrate (2), a project manager could decide to change from only loading the workforce in regular workweeks (the current strategy) to one using overtime (the new strategy) if the forecasted completion date $(S)$ exceeds the project deadline $(C)$. The conditional portion of the decision rule can be expanded to include multiple, and potentially linked, criteria; for example, that the cost of other contingencies must also be less than the forecasted budget surplus. The comparison operator in (2) is dependent on how signaling and criteria parameters are chosen and specified.

Toyota holds an option to select from among all design alternatives and then narrows to a single design through a gradual elimination process. We model this elimination process as a set of options to abandon individual design alternatives. Therefore, we specify (2) by defining two option exercise condition parameters: the convergence initiation time $(T_c)$ and the probation period $(T_p)$. The convergence initiation time is the time from the start of the project, when no alternatives have been eliminated, to the time when the project team begins eliminating alternatives. During this time (when $t < T_c$), development proceeds on all alternatives. Once $t$ reaches $T_c$, elimination of inferior alternatives can begin. However, managers are aware that temporarily quality problems can be misleading and, therefore, they do not eliminate an alternative as soon as it appears to be the worst. Instead, they require that an alternative be the apparent worst for a minimum period of time before eliminating it—this is the probation period. Therefore, the decision rule for eliminating an alternative is

$$\text{IF } (t \geq T_c \text{ AND } T_i \geq T_p) \text{ THEN } (\text{Eliminate Alt}_i) \quad \text{ELSE } (\text{Retain Alt}_i) \quad (3)$$

where

$T_i$ time that alternative $i$ has been the apparent worst alternative;

$T_p$ probation period required to abandon an alternative;

$t$ project time;

$T_c$ convergence initiation time.

Components of the convergence timing decision rule (3) are similar to some in traditional real options models.[1] However, the convergence initiation time and probation period reflect important managerial policy decisions. Describing alternative selection decisions made in practice with these parameters in a form similar to an option can help managers capture the strategic thinking benefits of real options described above.

Generally, point-based development is described with early and fast convergence to a single alternative (small $T_c$ and $T_p$) and set-based development with later and slower convergence (larger $T_c$ and $T_p$). Posed this way, development convergence speed is characterized on a continuum of more or less set-based, rather than as a binary decision. It also suggests that, under some circumstances, one can be "too set-based," taking the idea to the extreme and possibly decreasing expected project value.

Assuming unique alternatives, only one alternative can be the apparent worst at any time and, therefore, only that alternative is a candidate for elimination. The decision rule in (3) does not guarantee that only one alternative will remain at the end of the project because uncertainty can create repeated changes in the apparently worst alternative in periods less than the probation period, preventing the elimination of alternatives. Project managers feel pressure to end the project with only one alternative and reduce the probation period as the project approaches its deadline. Doing so accelerates the elimination of apparently suboptimal alternatives until only one alternative remains at the end of the project. This simple dynamic feature of decision-making in PD management is a specific example of the complexity that makes traditional approaches to modeling PD management with real options difficult to apply.

### *B. Flexibility Valuation*

To address some of the challenges in applying traditional option valuation models to PD management described above, we use a simple, direct approach to valuing the flexibility in set-based development. The expected value of the flexibility is assumed to be the difference between expected project value using (flexible) set-based development and expected project value using a more point-based (and, therefore, more rigid) development

$$V_{\text{flex}} = V_{\text{set}} - V_{\text{pt}} \quad (4)$$

where

$V_{\text{flex}}$ expected value of flexibility provided by set-based development;

$V_{\text{set}}$ expected value of a project using set-based development $(T_c > 0)$;

$V_{\text{pt}}$ expected value of project using more point-based development $(T_c = 0)$.

Positive values of flexibility suggest an advantage of set-based development over more point-based development, while negative values suggest the opposite and recommend not adopting set-based development.[2]

We specify this approach to the Second Toyota Paradox as follows. At Toyota, missing launch dates is simply not permitted. Toyota developers may work in excess of 80 h/week as phase deadlines approach in order to finish projects by the launch date. Since a project must finish within a specified time frame regardless of which alternative is selected, values of PD projects ($V_{\text{set}}$ or $V_{\text{pt}}$) can be quantified based on quality and cost alone. Quality is quantified as the percent of the final alternative's scope without quality problems (e.g., defects or unsatisfied requirements) and monetized with an average marginal profit value for a percent of quality above a minimum level $(v_q)$. Development costs are the product of the amount of work performed during the project on all alternatives $(W)$ and an average unit cost of performing a development activity $(c)$.[3] Expanding the project values in (4) to reflect the value added by quality and lost due to development costs, the net value of the

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[1] The convergence initiation time $(T_c)$ is a condition for exercise and is analogous to the lifespan of the option to select from among all alternatives, the time to exercise. The time that an alternative has been the worst $(T_i)$ is a signal of asset performance and is analogous to a current stock price. The probation period $(T_p)$ is a condition for abandonment and analogous to a strike price.

[2] Such a recommendation for point-based development when the value of flexibility is negative is consistent with assigning an option no value and the implied recommendation to not use options with negative values for flexibility that is incorporated into the Max (0, value of flexibility) form of some traditional real-option valuation models (e.g., binomial models).

[3] In comparing our structuring of flexibility in set-based development to traditional option valuation models the value of quality is analogous to the value of an income stream and development costs are analogous to stock dividends.

flexibility in set-based development compared with point-based development is, therefore

$$V_{\text{flex}} = ((Q_{\text{set}} * v_q) - (W_{\text{set}} * c)) - ((Q_{\text{pt}} * v_q) - (W_{\text{pt}} * c)) \quad (5)$$

where

$Q$ final alternative quality at project completion with set-based ($Q_{\text{set}}$) or point-based ($Q_{\text{pt}}$) strategy;

$v_q$ average marginal value of a percent of quality;

$W$ development work effort with set-based ($W_{\text{set}}$) or point-based ($W_{\text{pt}}$) strategy;

$c$ unit development cost.

Rearranging and consolidating to more directly reflect differences between performance in quality and development effort with the two development approaches

$$V_{\text{flex}} = ((Q_{\text{set}} - Q_{\text{pt}}) * v_q) - ((W_{\text{set}} - W_{\text{pt}}) * c) \quad (6)$$

The quality ($Q$) and development effort ($W$) of PD projects managed with different design alternative selection approaches are estimated as the mean values of many projects with differing evolutionary paths for the uncertain parameters as simulated with a dynamic computer model, described next. Although the model and (6) provide a means of estimating the economic value of flexibility, the conceptual and formal model potentially are as, or more, valuable for their ability to describe project behavior and performance as well as economic value.

## V. PRODUCT DEVELOPMENT SIMULATION MODEL

From the case study of vehicle development at Toyota and the formalized decision rule for convergence just described, a system dynamics model [33], [34] was built that reflects Toyota's development processes. System dynamics is a methodology for studying and managing complex systems. This approach focuses on how performance evolves in response to the interactions of management decision-making and development processes. System dynamics has been successfully used to explain failures in fast track implementation [35], [36], impacts of changes [37], and other project management issues, and is considered appropriate for modeling PD processes.

### A. Model Structure

The model has four sectors. In the work flows sector PD work packages move through a rework cycle based on work by Ford and Sterman [38], but the model was adapted for the current work to reflect multiple alternatives, the interactions among phases within alternatives, and the path dependent uncertainties that impact progress. The current work also developed a resource sector that adjusts the quantity of development labor based on remaining work and the impacts of schedule pressure, and allocates resources among alternatives and development activities within alternatives. The alternative selection sector describes Toyota's managerial decision-making based on (3) and is unique to this model. A performance sector models project duration, quality, and development costs.

In the work flows sector, work packages move through four parallel development efforts, each representing a different design alternative. If not eliminated, each alternative passes through three sequential phases as depicted in Fig. 2. The model simulates the flows and accumulations of development work within and among phases, as impacted by the uncertainty in predicting alternative quality and managerial behaviors.

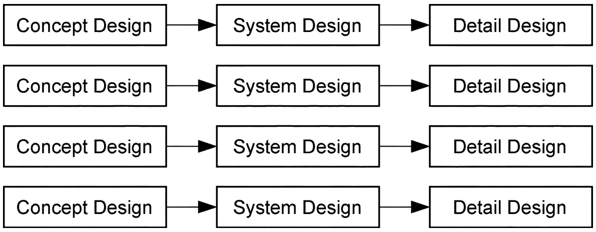

Fig. 2. Model structure of alternatives in Toyota's development process.

Within each phase a rework cycle begins with a stock of development work to be completed. As work is completed, there is a probability that a change is needed in the work. Changes could be defects or errors that must be corrected to meet minimum requirements or could be improvement opportunities to increase customer satisfaction or improve manufacturability. Completed work is checked by quality assurance and either passes inspection and moves to the next phase, or does not pass and enters a rework loop. In the rework loop, work is corrected or improved with a probability of creating or exposing the need for another change, and then returned to quality assurance. Rework not discovered by the originating phase is released, reducing the overall quality of the alternative.

The four development activities in each phase (initial completion, quality assurance, change, and coordination) require resources. Consistent with Toyota's management practices, resources (primarily labor) are dedicated to phases and allocated to alternatives and development activities within phases in direct proportion to labor demand (Fig. 3).

The willingness of Toyota developers to work in excess of 80 hours per week to meet deadlines is modeled with a set of strong control loops in the resources sector that adjust labor quantity in response to schedule pressure and force the project to finish by the prescribed deadline. Product quality, measured with the fraction of work that do not require changes, is controlled in the model through feedback loops that shift resources toward quality assurance and change activities when those backlogs are relatively large. Therefore, when quality drops and testing and rework backlogs grow, more developers are assigned to those activities to improve quality.

### B. Modeling Design Alternatives

The four alternatives are distinguished by their complexity and tractability in each phase (24 descriptive variables, see Table I). Complexity reflects the novelty and difficulty of development and is modeled with the likelihood that initially completing a work package generates a need for a change [*P*(*generate change initially*)]. Tractability reflects the difficulty of discovering and subsequently changing work and is modeled with the likelihood of discovering a change [*P*(*discover change need*)]. In this way, alternatives with different characteristics can be modeled. For example, an alternative with many "hidden" defects can be modeled by assigning a high change generating probability and a low change discovery probability. Likewise, an alternative with many easily resolved problems

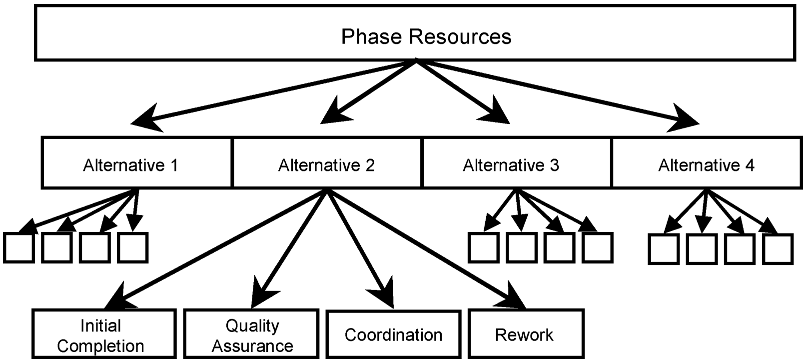

Fig. 3. Resource allocation in model of Toyota development.

TABLE I
INITIAL AND MEAN VALUES OF UNCERTAINTY PARAMETERS

| | *P(generate change initially)* | | | *P(discover change need)* | | |
|---|---|---|---|---|---|---|
| *Phase* | **Concept** | **System** | **Detail** | **Concept** | **System** | **Detail** |
| **Alternative 1** | 0.60 | 0.40 | 0.20 | 0.50 | 0.70 | 0.90 |
| **Alternative 2** | 0.70 | 0.50 | 0.30 | 0.40 | 0.60 | 0.80 |
| **Alternative 3** | 0.80 | 0.60 | 0.40 | 0.30 | 0.50 | 0.70 |
| **Alternative 4** | 0.90 | 0.70 | 0.50 | 0.20 | 0.40 | 0.60 |

can be modeled by assigning a high change generation probability and a high change discovery probability. We chose parameter values so that more complex alternatives are less tractable and less complex alternatives are more tractable. The descriptive parameters for the four alternatives are specified according to Table I. Otherwise, all alternatives are identical.

Notice that Alternative 1 generates the fewest changes and discovers the largest fraction of those change needs, whereas Alternative 4 generates the most changes and discovers the lowest fraction. The alternatives were described such that they increase in complexity and decrease in tractability from Alternative 1 to Alternative 4. This was done so that the alternatives would unambiguously and monotonically progress from best (Alternative 1) to worst (Alternative 4), thereby providing a means of assessing the quality of alternative selection. Better selection is reflected in lower average final alternative numbers.

## C. Modeling Uncertainty

Uncertainty is modeled by varying the likelihood of generating a change [*P*(*generate change initially*)] and the likelihood of discovering a need for a change [*P*(*discover change need*)] within each phase and alternative (24 uncertain variables). Their behaviors are path dependent to reflect the evolutionary nature of alternative development. In each time period, uncertain values move a portion of the distance to their mean value (Table I) and a random draw from a normal distribution, constrained to keep probabilities within the range $\{0, 1\}$. Similar random mean-reverting behavior has been used to value other real options (e.g., [39] and [40]). Uncertainty levels relative to mean values are kept constant (10%) for all uncertain variables by specifying the coefficient of variation (= standard deviation/mean). Changing the initial seeds of the random number generators allows the simulation of different scenarios of the evolution of the uncertain variables.

Alternative elimination in the model implements (3). To reflect the PD manager's perspective, only discovered imperfections are used in convergence decision-making. Therefore, the model captures the impacts of change discovery timing, an important PD management challenge. The performance sector implements (6).

## D. Model Calibration, Behavior, and Testing

Detailed model calibration data was not available. Therefore, the model was calibrated to reflect a generic single system of an automobile development, such as body development, based on information about Toyota practice. From its annual report [41], Toyota spends approximately $6.7 billion on research and development per year, supporting 10–12 models per year. This corresponds to approximately $610 million in R&D expenses per model on average. If body engineering accounts for about 1/5 of the development costs (based on engineering head count), body development would account for $121 million of a vehicle's development cost. The average simulated development cost for a project with a convergence initiation time of 450 days (a reasonable estimate of Toyota practice) was $123 million.

New model introductions are generally on a four-year cycle. However, development projects at Toyota, at the time the Paradox was documented, started about 30–33 months before product launch. Styling approval in recent programs has occurred as late as just 15 months before launch. Thus, the model uses convergence initiation times varying from zero (to simulate very point-based convergence) to 900 days, well past the 15 months, to capture the full range of convergence timing possibilities.

Product quality is paramount in the automobile industry, and quality is a cornerstone of Toyota's success. The model measures quality as a percent of work packages with imperfections. Imperfections could be anything from a minor manufacturability opportunity (worth tens of thousands of dollars over the vehicle's production life) to a major warranty or recall issue that costs the company hundreds of millions of dollars. Given the high importance of quality, we chose a fairly high marginal value of quality ($10 million per percent quality).

According to Toyota's annual report [41], Toyota's net income per vehicle sold in 2003 was $1000 on average, worldwide. Ford Motor Corporation (not a set-based developer), had net earnings of about $460 per vehicle sold in North America [42]. Assuming 100 000 vehicles sold per year and four-year production life, a typical Toyota model nets $216 million more than a typical Ford model. Again assuming that the body subsystem accounts for roughly 1/5 of this, we would expect the model to produce value differences in the neighborhood of $43 million. This value will be used later to validate the model calibration.

The model was also tested for usefulness using established system dynamics validation methods [34], [43]. The structural consistency of the model with the target system is strengthened by the use of previously developed and tested system dynamics model structures that reflect the in-depth knowledge of Toyota development processes. Qualitatively, model behavior appears consistent with development project behavior and Toyota's experience. In addition, model behavior is reasonable under a wide range of parameter values. For example, increasing available resources significantly decreases project durations, and increasing the differences among alternatives make alternative selection more consistent across many uncertainty scenario simulations. The results of model calibration and testing support the use of the model to test the operationalization of real options concepts to the Second Toyota Paradox.

## VI. SIMULATION RESULTS

Expected project performance is the average of 100 simulations for a specific condition. Point-based development $(T_c = 0)$ was simulated as the basis for performance differences in (6). Toyota typically does not delay the initiation of convergence until very near the end of their projects. However, they do consider when to initiate convergence across some time span. Therefore, we investigated performance and value with convergence initiation times over essentially the entire project length (0–900 days).

### A. Average Project Quality

As $T_c$ increases from 0 to 900, expected quality improves from a minimum of 73% to a maximum of 92%, as shown in Fig. 4. We surmise that quality improvements are a result of better alternative selection because the average number of the final alternative decreases with the convergence initiation time in a pattern similar to Fig. 4. This is consistent with the description of decision-making in set-based development and our conceptual design of it as an option—as teams wait longer to start eliminating design alternatives, they gain access to more and more accurate quality information and, therefore, make wiser choices, on average.

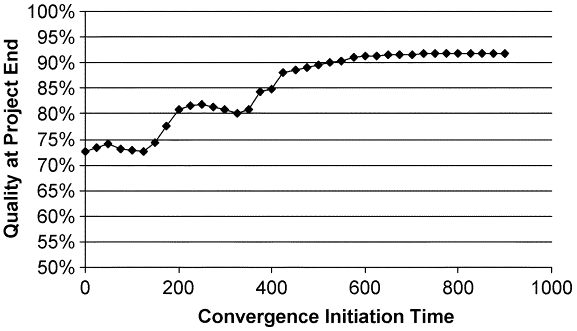

Fig. 4. Expected quality of point-based and set-based development projects.

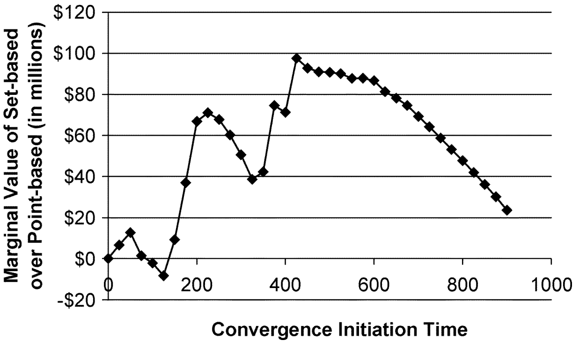

Fig. 5. Expected values of flexibility in set-based development relative to point-based development.

But quality levels off after a certain point—decisions do not improve after a certain amount of delay. In our model and in practice, waiting longer, developing multiple alternatives, and gathering more information after a certain point may increase managerial confidence, but it does not necessarily improve decision-making. Interestingly, quality does not increase continuously, indicating transitory periods of development work that do not yield additional useful information, followed by periods of improvement. We speculate later on potential causes of these transitions.

### B. Average Development Cost

The expected point-based development cost [$W_{\text{pt}} * c$ in (6)] is $73 million. As the convergence initiation time increases the development costs [$W_{\text{set}} * c$ in (6)] increase roughly linearly to $239 million when convergence begins on day 900. More alternatives kept alive longer translate into higher development costs.

### C. Value of Flexibility in Set-Based Development

Fig. 5 displays the marginal values of flexibility in set-based development over point-based development for increasing convergence initiation times.[4] Note that the increase in value as $T_c$ increases from 180 to 360 days is \$50 million, which is close to the calibration estimate of \$43 million described earlier. Similarly, value increases by a similar magnitude again as $T_c$ increases from 360 to 450 days. This provides some validation that the model results are reasonable.

Fig. 5 illustrates how the value of flexibility initially increases as convergence initiation time increases due to better alternative selection that outweighs increases in development costs. After convergence delays have improved alternative selection nearly as much as possible (450 days of delay under this set of conditions), further delaying alternative elimination incurs additional cost without increased quality, and the net value of set-based flexibility decreases.

Fig. 5 also displays an oscillatory effect, where the marginal value of increasing convergence time can actually decrease for a period, then increase again. These periods are associated with the latter portions of development phases. Inspection of model behavior indicates that during these times development work occurs in parallel, thus increasing cost, but most of the quality issues that can be found in the phase have been discovered and, therefore, the additional information is insufficient to improve alternative selection enough to add more value than the cost of parallel development. New information becomes available relatively suddenly when a new development phase begins, thereby significantly increasing the probability of selecting a better alternative. This characteristic seems consistent with PD practice.

In summary, the simulation results demonstrate how a real options approach can be adapted and operationalized to model design alternative selection. Set-based development decision-making rules can be modeled like exercise decisions used in traditional options, but in forms that allow for multiple dimensions of performance and variety in strategies [(1)–(3)]. Modeling that reflects many of the complexities of PD practice can provide a means of developing insight about how options impact performance (e.g., Fig. 4) and can capture the value of flexibility [(4)–(6) and Fig. 5].

## VII. MANAGERIAL IMPLICATIONS

The current work has several potential implications for PD managers, despite the preliminary nature of the investigation. First, structuring set-based flexibility with real options concepts suggests that managers can use options to improve their recognition, descriptions, and modeling of managerial flexibility, a potentially useful PD approach that to date has been tacit and difficult to improve and exploit [11]. To the extent that adaptations of real options improve managers' mental and formal models of flexibility, their understanding and insight about the effectiveness of development plans can also improve. In addition, practicing managers at Toyota and elsewhere [11] seem to implicitly recognize the value of hedging their bets to acquire more and better information on alternatives, but many companies do not have a culture that values broad searches of alternative solutions. Real options adaptations that closely reflect practice may help managers recognize that developing alternatives in parallel (and options in general) has utility, with potential for significant improvements in PD management. Still, these results are preliminary and more work is needed to incorporate the options perspective into actionable tools to fully test these potential impacts.

Second, real options may provide a partial explanation for how delayed convergence adds value and contributes to Toyota's sustained competitive advantage. Explaining the Paradox with an adaptation of established tools and methods that are more general than Toyota (real options) provides a foundation for customizing Toyota's process to other PD contexts. For example, under the conditions modeled, increasing convergence initiation time beyond a certain point does not add value. Under other conditions, this point of negative returns for holding the option longer may be much earlier (e.g., low end consumer goods) or much later (e.g., high cost of failure, as in space programs). Although further investigation is needed, the current work suggests that adapting and operationalizing real options may be helpful in effectively transferring set-based practices to other PD contexts.

Finally, the shape of the curves in Figs. 4 and 5 suggests both a promise and a warning for PD managers. One possible insight for managers is the existence of an optimal convergence initiation time for maximizing the value added by the flexibility in set-based development. For the conditions modeled here, the optimal lifespan is nearer the middle of the project life than the beginning or end of the project. The results can help managers recognize the importance of estimating the size of the optimal lifespan.

But, transitory periods may exist early in a project when the quality of decision-making and value-adding may stall or even decline, and that delaying convergence a little longer (e.g., into a new development phase) may restart improvements because enough new knowledge is being gained to improve decisions. More generally, this warns managers that using real options to manage PD is not necessarily straightforward. Managers are warned to consider carefully and thoroughly if and how real options can be effectively designed and used before attempting to exploit their potential to improve insight and add value.

## VIII. CONCLUSION

We have proposed an adaptation of the real options approach to managing PD for the purpose of developing insight into how strategies to manage uncertainty through flexibility impacts project behavior, performance, and value. We operationalized the adaptation to model design alternative selection in set-based development. Managerial decisions about changing development strategies were structured as decision rules based on one used in traditional options and specified for the elimination of inferior alternatives. A formal PD model simulated projects that retain flexibility for different periods of time to investigate how project performance and value changes with different flexible strategies. Results described how, and to some extent why, delaying the initiation of design convergence impacts decision quality and project value.

The current work makes at least two valuable contributions. First, we have demonstrated that real options concepts can be

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[4] From a more traditional options perspective, Fig. 5 is analogous to a graph of different times to the exercise date (convergence initiation time) versus the value of a European option (set-based flexibility) on an asset that pays very large dividends (development costs).

adapted to reflect the process and managerial complexity of PD practice, and that these adaptations can be operationalized to develop insight into how and why flexible development plans impact project behavior, performance, and value. In doing so, we explore an options modeling method that relaxes common assumptions used in some traditional real options valuation models and that can more closely reflect PD practice. However, considering the complexity and specificity of the set-based decision-making modeled here, we also conclude that effectively designing and implementing real options to increase PD project value requires a deep understanding of development processes, managerial and developer behavior, option designs, and how their interactions impact project value. This work also suggests methods that may be used to expand real options models to a broader range of assets, such as those with uncertainties that are proactively managed by those who hold options on those assets.

The current work also contributes to the existing body of work on new PD and technology management. We propose and initially test the applicability of real options as a framework for improving the understanding and management of PD projects. We provide a preliminary test of the ability of real options concepts to explain the Second Toyota Paradox. We also expand the set-based theory from a binary description (point-based or set-based) into a continuum of set-based development plans based on the timing of design convergence.

Much work, however, remains to be done, both from PD and real options perspectives. Validation would be improved by calibrating the model more tightly to actual development statistics, particularly across multiple projects, and validating the results empirically. Although data collection and analysis would be challenging, the results would significantly improve confidence in the conclusions. Future work will investigate the design of set-based development with other parameters as managerial levers to control PD projects (e.g., probation period, or selecting the best alternative versus eliminating the worst), effects of the characteristics of uncertainty, and how PD management might differ with respect to specific characteristics in the set of alternatives (e.g., Do optimal decision points change if the set includes a "fall-back" alternative?). Impacts of factors that are important in traditional real options models but less important in set-based decision-making (such as discount rates and exercise costs) or that are important in set-based decision-making but less so in traditional real options models (such as development costs) will also be investigated to improve the understanding of what project components to utilize in real options application, and how. Finally, we hope this work will culminate in the development of tools and methods that apply real options to PD management and help development teams perform more effectively.

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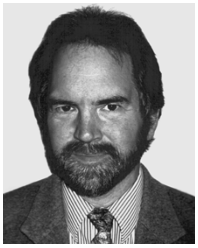

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