Modeling Real Options to Switch Among Alternatives in Product Development

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Abstract

High uncertainty in the performance of product design alternatives has forced developers to consider multiple alternative designs in parallel. Traditional wisdom dictates the selection of the final alternative as quickly as possible. But delaying decisions on alternatives as designs develop has provided sustainable competitive advantage for Toyota, a leader in automobile development. Real options can potentially explain how Toyota's set-based development approach provides this advantage. The current work builds, initially tests, and uses a system dynamics model of automobile system development at Toyota to: 1) test the hypothesis that Toyota uses real options to switch among alternatives to operationalize set-based development and 2) propose and test a hypothesis of how real options at Toyota add value. Simulation results support these hypotheses and suggest that the effective use of real options requires a deep understanding of both the development process and the structure of real options. Research needs are discussed.

Keywords: product development, strategic planning, real options, project management, flexibility, system dynamics

Introduction

To be competitive product companies must recognize and capture as much value as possible. More value can be captured through increased benefits or reduced costs. Some value is easy to recognize and relatively predictable, such as increased productivity from training and the potential of reduced costs with 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. Many critical aspects of products are uncertain, including future performance, development costs, and market size. Individual product development projects also include project-specific sources of uncertainty that affect value. For example, delaying the selection of a final design can add value if the delay allows developers to select a better alternative. Ford, Lander, and Voyer (2001) describe these project values that are only available due to uncertainty as *latent* project values. Latent project value such as in these examples can remain unrecognized and unexploited by product development planners and managers.

The design theory and product development (PD) literature strongly support generating multiple alternative solutions to design problems as an essential component of an effective PD process. As such, numerous tools and strategies have been developed to aid design teams in selecting the best alternative. These strategies can utilize many project features to manage uncertainty, including contract terms, procurement methods, and technologies. The uncertainty in some strategies is small enough to allow useful analysis and effective decision-making during pre-

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project planning. For example, the uncertainty in the benefits of training developers in an emergent technology when compared to training costs may be small enough to commit to training before development starts. But many conditions evolve over time and the conditions, times, and managerial choices for effective decision-making cannot be completely and accurately determined early in development.

The challenge lies with the larger uncertainties that are inherent in PD projects. From a management viewpoint, one would like to decide on an alternative early in the process so that all development resources can focused on one design. With all resources available to work out the detailed problems that may arise in development and test, it would seem that the design team would have greater possibility to successfully bring the product to market on time. But often little information is available to accurately assess the set of alternatives and make the best choice near the beginning of development. As will be demonstrated, the alternative that at first seems like the best choice may in fact have an unforeseen problem that does not emerge until much later, while another alternative may initially seem problematic, but an innovative breakthrough could resolve the problems easily and effectively resulting in a superior outcome. More testing and analysis can sometimes improve descriptions enough to discern relative performance of fully-developed alternatives. But often uncertainties are, or appear, too vague to effectively design, assess, and select among alternatives before a project must proceed. In these cases, additional development of alternatives in parallel may improve the available information and understanding of alternatives enough to significantly improve decisions. But parallel development also requires that resources be spent on alternatives that won't be realized, potentially increasing overall development costs. *How can PD managers accurately predict which design alternative is best?*

The high uncertainty inherent in product development projects requires that managers develop proactive strategies to reduce risks and capture latent benefits hidden within project uncertainties, while controlling costs. Viewing product development in uncertain project environments and features from an options framework can potentially improve product development project performance by expanding planning processes, structuring managerial flexibility into operational strategies to manage specific uncertainties, and valuing flexible strategy alternatives for comparison and selection (Amram and Kulatilaka 1999, Courtney, Kirkland and Viguerie 1997).

Real Options Theory

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 (Amram and Kulatilaka 1999). The central premise of real options theory is that, if future conditions are uncertain and changing the strategy later incurs substantial costs, then having flexible strategies and delaying decisions can increase project value when compared to making all key strategic decisions early in the project. To estimate project and option values modelers analyze potentially increased and foregone benefits, reduced development costs, costs to obtain and keep flexibility, and strategy change costs. In doing so real options theory attempts to answer the questions: "What are the future alternative actions?", "When should we choose between these actions based on the evolution of conditions to maximize value?", and "How much is an alternative worth at any given time?"

Real options theory is based on the options approach developed to analyze financial investments (Bookstaber 1982). The options approach has been adapted to strategy (Meyers 1984), used to value flexible strategies (Brealey and Meyers 1997, Kensinger 1988, Kemna and Vorst 1990), and applied to capital investment strategy development (Kemna 1993). Methods for valuing options developed specifically for real assets have been developed and analyzed (Dixit and Pindyck 1994), applied to engineering (Park and Herath 2000, Baldwin and Clark 2000), and promoted as a strategic planning aid by both academics (Miller and Lessard 2000, Amram and Kulatilaka 1999, Bierman and Smidt 1992) and practitioners (Leslie and Michaels 1997). Real options have been used to capture latent value in many domains, including natural resources, research and development, real estate, and product development (Brennan and Trigeorgis 2000, Amram and Kulatilaka 1999a, Trigeorgis, 1993, 1995; Dixit & Pindyck, 1994). This work focuses on the application of a real options approach to individual product development projects.

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. A general set of managerial action 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). Many PD strategies can be described as real options. For example, if the future availability of a critical material is uncertain, building a facility to manufacture the material “buys” an option to augment material purchases with internal production. Exit strategies to stop development if markets collapse are options to abandon. Designing and building foundations and columns to support more floors of an office building than are currently constructed purchases an option to expand in the future by adding more floors. Miller and Lessard (2000) provide examples of flexible strategies in large engineering projects that can be described as real options. Baldwin and Clark (2000) describe the use of product modularity as a form of real options.

Challenges in Modeling Product Development Options

Managers often use options to influence project behavior in critical product development issues (Lessard and Miller 2000, Ford and Ceylan 2002, Ward, Liker, Cristiano and Sobek 1995), although they may not see them in terms of real options. In doing so practitioners make judgments and decisions about critical issues, including:

- **Management Focus:** What specific assets and individual uncertainties will be managed with options?
- **Performance**: How is performance measured? What performance measures do the uncertainties impact? How do uncertainties impact specific types of performance?
- **Project Value:** How does performance in different dimensions impact project value?

- **Strategy Development:** What alternatives will be designed, assessed, and considered for use? How will strategy alternatives will be designed, assessed, selected, and implemented? How can the development team hedge against the uncertainty associated with incorporating an innovative, but untried technology? When should the team converge on a particular design alternative?
- **Strategy Value:** How valuable are specific proactively designed flexible strategies to product development projects in economic and non-economic terms?

The current work adopts the focus and measures used by Toyota and develops a structure that can relate strategy to value.

Despite their widespread use of options product development project planners and managers rarely apply the structuring and valuation tools and methods developed by theoretitians. The inability of existing tools and methods to help practitioners answer the questions above partially explain limited application (Lander and Pinches 1998). But the significant differences between existing options models, other available product development models, and the reality of product development practice as experienced by practitioners also contribute to the application problem. In reviewing models for applicability to product development options modelers should ask how well models reflect existing understanding of product development processes, resources, and management and how well they reflect actual development.

Product development project models for options design and evaluation must reflect the dynamic interactions of development processes that are common in current product development research through system dynamics and several other methodologies. They must also reflect the cognitive constraints and responsiveness of practicing managers to project objectives, current conditions, history, etc. Current option models often fail to adequately address these concerns. Improved models of options strategies and their impacts on development are needed to design, assess, select, and implement effective options in product development. *How can models integrate product development processes, uncertainty management strategies, and project valuation to evaluate strategy alternatives? How can product development be modeled to design, value, and select real options?* System dynamics is particularly capable of modelling these critical aspects of options use in product development projects. The current work uses an existing system dynamics model of product development as the basis for options modelling.

To apply system dynamics to product development for option design and valuation, the current work focuses on options to switch among alternative designs. The motivation for this problem is prior research (described next) that has shown that Toyota delays decisions and develops more alternatives in parallel than its competitors, yet achieves higher PD performance. The next section describes Toyota's development process as it relates to the current work. This is followed by a description of the system dynamics model of Toyota's PD process. The model demonstrates and explains the apparent "paradox" of delayed decisions resulting in better performance from an options valuation standpoint. This is followed by discussion and recommendations for future research.

Set-Based Development and the Second Toyota Paradox

Multiple design alternatives are characteristic of "good" design processes. Pugh (1991) said, "…single solutions are usually a disaster." A federal project manager leading a waste processing facility project for the US Department of Energy referred to a development strategy that includes only one possible solution as "a single pathway to failure." (Spears 2003). But managing multiple alternatives is difficult. Effectively managing multiple alternatives requires starting with a fertile set of alternatives, predicting the relative performance of alternatives as those predictions evolve, deciding when the increased costs of maintaining the development of an alternative exceeds the potential benefits, and deciding how many alternatives to retain during development. The management problem is made more difficult as product complexity increases—more product subsystems and their interactions much be managed simultaneously. Ward et al (1995) identified two development paradigms for managing multiple development alternatives: point-based development and set-based development.

Point- based and Set-based Development

The majority of automobile developers use point-based approach to development. This approach selects a single alternative as quickly as possible and iterates on that alternative until development is complete or must be stopped for schedule purposes. Advantages of the point-based approach include that it focuses developers more narrowly, reduces competition and friction among developers, and constrains development costs. This approach operationalizes an early-design-freeze philosophy. Thus many automobile development teams (especially in the U.S. and Europe) push fast convergence in order to reduce project management complexity. The point-based approach, with its fast-convergence to a single alternative, is a traditional, strongly supported, and widely practiced development strategy.

In contrast to a point-based approach, Toyota uses a set-based approach to development. Toyota distinguishes itself from its competitors by imbedding this approach in its development of automobile systems. A set-based strategy purposefully delays the convergence of development to a single alternative to allow information on the expected performance of alternatives to evolve and become more apparent prior to alternative selection. In this way a set-based approach improves the quality of managerial decision-making. In using a set-based approach Toyota's process is primarily different than point-based approaches because it purposefully delays eliminating alternatives instead of converging on a final alternative as early as possible. ***The Second Toyota Paradox***Despite its use of a counter-intuitive strategy, Toyota out-performs its competitors in automobile system development with the fastest development times in the industry and high profitability. This is the Second Toyota Paradox, that Toyota excells by delaying convergence decisions in the face of the traditional wisdom and evidence that early convergence decisions generate improved project values.

Although Ward et al (1995) demonstrate *that* Toyota outperforms its competition using set-based development (the Second Toyota Paradox), no causal explanation has been offered or tested of *how* Toyota does so. Real options provide a *general* theory that can potentially explain the Second Toyota Paradox. However the specific causal mechanisms through which real options can make the Second Toyota Paradox work have not been proposed or tested. **This work uses**

system dynamics to build a causal model of set-based development at Toyota to investigate if and how real options can explain the Second Toyota Paradox.

Modeling Options in Toyota's Set-Based Development

Toyota's set-based development process can be described from an options viewpoint. Toyota's automotive development process occurs in stages, with the set of alternative vehicle designs gradually narrowing with each stage, even as the alternatives are developed in increasingly greater detail (Ward, et al., 1995). Two types of options are created in such a process. Eliminating individual alternatives at the end of project phases creates options to abandon. These options to abandon are alternative-specific in that decisions do not require information about other alternatives. In contrast, switching and improvement options that do depend on sharing information across alternatives are also created. These options allow developers to switch from a less attractive alternative to more attractive alternatives based on comparisons of alternatives. One way to operationalize this switching option is the repeated abandonment of the worst alternative until only one alternative remains. Beginning the abandonment of poor alternatives too early may eliminate the alternative that would eventually be best if fully developed. Delaying the elimination of alternatives provides a potentially more accurate assessment of alternatives but also increases development costs. *When should Toyota start abandoning alternatives? How does delaying alternative selection improve Toyota NPD performance? What is the monetary value of delaying decisions to Toyota?* From a real options perspective Toyota retains options to switch to any alternative during the period before it begins abandoning alternatives. This time is the life of Toyota's "all-alternatives-available" strategy. Real options theory suggests that Toyota's project value can increase as this time increases. The current work models how Toyota's choice of this important development strategy feature can impact performance and thereby project value.

A System Dynamics Model of Options in Set-Based Development

Based on a rich and thorough understanding of Toyota's development processes, a system dynamics model (Forrester 1961, Sterman 2000) was built that reflects Toyota's development processes and management. Ward, Liker, Cristiano and Sobek (1995) describe Toyota's process. Ford and Sterman (1998, 2003) describe fundamental model structures. Ford and Sobek (2002) describe additional model structure. The core of the model is parallel individual development efforts that are impacted differently by characteristic uncertain parameters and behaviors. The model simulates the flows and accumulations of development work for four alternative designs of a single automobile system (e.g. cooling or transmission) through three development phases: Concept Design, Structural Design, and Detailed Design (Figure 1). These three phases are consolidations of the nine phases actually used by Toyota. See Ward, Liker, Cristiano and Sobek (1995) for a detailed description of Toyota's development phases. Consistent with Toyota's process, phases include a rework cycle based on Ford and Sterman (1998) and are sequential.

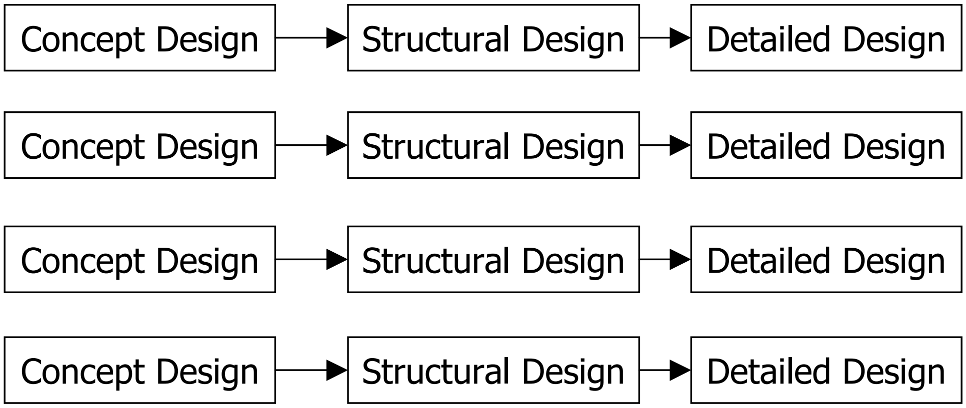

Figure 1: Model Structure of Alternatives in Toyota's Development Process

Coflow structures model imperfections in alternatives, which are broadly defined as any characteristics that do not fully meet stakeholder objectives. Also consistent with Toyota's process, development resources are dedicated to phases and are assumed to be allocated proportional to labor demand for each alternative and development activity (Figure 2).

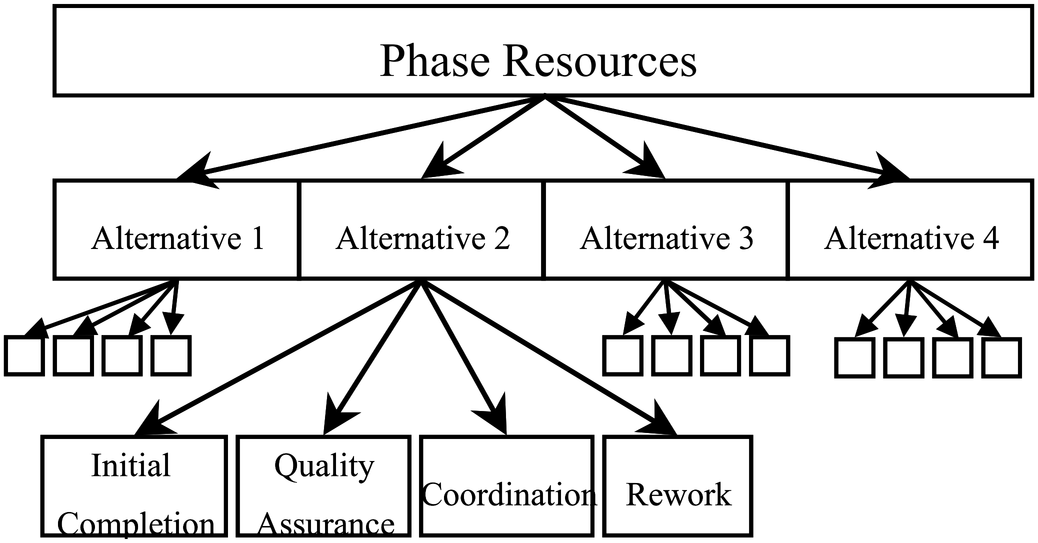

Figure 2: Resource Allocation in Model of Toyota Development

Project performance is described in the three traditional dimensions of time, cost, and quality. Schedule performance is controlled through an adjustment of labor quantity to schedule pressure. At Toyota this primarily represents over time by developers. This is a strong set of control loops in Toyota and the model. Toyota developers frequently work in excess of 80 hours per week as deadlines approach. This causes all projects to finish near the launch date and allows project performance to be measured in quality and development cost. Quality is measured with the fraction of imperfection-free work in each alternative and monetized with a profit value for each percent of quality in the final alternative. Inadequate quality in automobile system development can be very expensive if the imperfection requires a recall of automobiles. Imperfections that require rework are expensive in phased development even if changes are made prior to release to customers. For example Boehm found that software development costs increased by an order of magnitude with each development phase that a required change went undiscovered and addressed. Product quality is controlled in the model through feedback loops that shift resource allocations toward development activities with large backlogs. Therefore, when quality drops and the testing and rework backlogs grow more developers are assigned to those tasks, thereby improving quality. Development costs are measured with a unit cost for each time any of the four development activities are performed. Project value is the value of quality less project development costs.

Modeling Alternatives and Cross-Over

Four stylized alternatives are modeled. In this initial work the alternatives are kept identical except for the complexity of the system as reflected in the number of problems discovered in the system during development and the tractability of imperfections. Complexity is modeled with the probability that an imperfection is generated in initial development work. Tractability is modeled with the probability of resolving an imperfection. These two fundamental descriptors are used to describe four alternatives that range from "best" (simple and tractable) to "worst" (complex and relatively intractable). This allows the modelers to know which alternative is most attractive and "should" be selected by development managers. Development managers are prevented from always selecting the best alternative partially because the generation and discovery of imperfections during development is very uncertain. If the problems were fully understood a priori the selection of the best alternative would be trivial. This uncertainty is modeled the generation of imperfections as an uncertain but path-dependent probabilities that each describe a possible complexity scenario of the development of an automobile system. Complexity and the resolution of problems during product development are evolutionary in nature and therefore path dependent behavior can better describe these factors than uncertain behavior that jumps instantly from potentially very different values. Figure 3 illustrates the complexity scenarios of four alternatives modeled in this way in which alternatives vary from best (#1) to worst (#4).

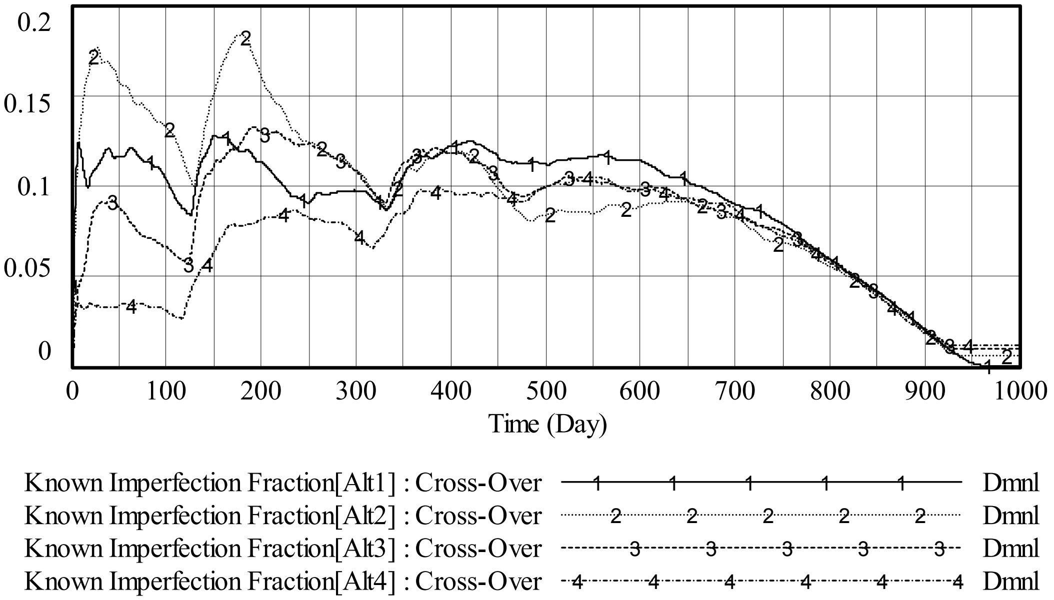

Figure 3: Simulated Uncertain Path-Dependent Imperfection Fractions
in Automobile System Development

Modeling development uncertainty as described is the basis for simulating how development mangers can select sub-optimal alternatives with the best of intentions. The uncertain path dependent behavior allows “worse” alternatives to temporarily appear to have better quality than “better” alternatives in a behavior we refer to as cross-over to describe the behavior. For example, in Figure 3, although alternative 1 is the best choice, its imperfection fraction plot is above those of other alternatives for a significant portion of the project.Cross-over can have serious development implications. A development manager choosing the best alternative from among the four during days 460 to 625 would select alternative 2 and a manager eliminating the (apparently) worst alternative in the same period would eliminate the project’s best alternative!

Options are operationalized with discovered alternative defects as signals, option designs as policies, and the abandonment of poorly developing alternatives as actions. Project value for a given option design is the value of the quality in the selected alternative less development costs.

Model Behavior and Validation

Structural validation is strengthened by the use of previously developed and tested system dynamics model structures as described above and the use of in-depth knowledge of the Toyota development processes by the second author. Model behavior is reasonable under a wide range of parameter values. For example reducing available resources increases project durations and increasing the differences among alternatives make alternative selection more consistent across many scenario simulations. Model behavior also reflects realistic product development project behavior and Toyota’s experience. Realistic behaviour patterns are considered adequate for the current work because the initial application of the model is to test if the described structure can generate behaviour consistent with real options theory and Toyota's superior performance.

Model Use

The model was used to attempt to demonstrate the second Toyota paradox by showing how options can add value to Toyota's development processes. To demonstrate the paradox the two development paradigms described above (point-based and set-based) were simulated and compared. To include the uncertain nature of development processes, projects were simulated for many complexity scenarios and the performances averaged. In a point based approach a single alternative is selected very early in development. We assume that over many projects each of the four alternatives are equally likely to be chosen. Therefore, the value of a point-based approach was the average performance of four stand-alone alternatives.

In Toyota's set-based development approach multiple alternatives are compared and reduced to one by the end of the project. We modeled the elimination of the apparently worst alternative among the four initial alternatives as follows. Managers were assumed to use two basic criteria for eliminating alternatives: 1) development has progressed far enough to elucidate the quality of alternatives, and 2) the alternative is and is likely to remain the worst of the remaining alternatives. The first criteria reflects Toyota's use of options, i.e. the willingness to keep alternatives active longer to improve the ability to identify the best alternative. We operationalize this approach in the lifespan of the All-Alternatives-Available Life, which specifies the time after the beginning of the project when managers begin considering the elimination of alternatives. A small All-Alternatives-Available Life reflects a project in which managers begin alternative elimination early in the project (fast design convergence). A large All-Alternatives-Available Life reflects a project in which managers retain more alternatives longer (slow design convergence). The second criteria for eliminating alternatives reflects managers preference for eliminating apparently poor alternatives. To operationalize this criteria we assume managers use the imperfection fractions of the remaining alternatives as the signal for decision-making. Because managers are aware that temporarily high imperfection fractions can be misleading, they do not abandon an alternative as soon as it has the largest imperfection fraction. Instead, they require that an alternative be the apparent worst for a minimum period of time before abandoning it. We refer to the time when an alternative is apparently the worst as its Probation Period, which we assume to be one month. These two criteria are formalized in the following decision rule:

$$\text{Abandon Alt}_i \text{ IF (Probation Period}_i >= 1 \text{ month AND}$$
$$\text{Time} >= \text{All-Alternatives-Available Life)}$$

Notice that only one alternative can be the apparent worst at any time (assuming unique alternatives) and therefore only that alternative is a candidate for elimination. The decision rule above does not guarantee that only one alternative will remain at the end of the project. Repeated cross-overs at periods less than the Probation Period prevents eliminating alternatives. To simulate the pressure on managers to end the project with only one alternative the Probation Period is reduced as the project approaches the project deadline. This accelerates the elimination of apparently sub-optimal alternatives until only one alternative remains at the end of the project.

To model set-based development projects were simulated with all four alternatives initially available and with different All-Alternatives-Available Life values.

Hypotheses

Two hypotheses are provided by previous research. Based on the definitions and descriptions of point-based and set-based development:

> H1: The average value of a project using a set-based development approach will be greater than the average value of a project using a point-based development approach.

Based on real options theory:

> H2: The average value of a project using a set-based development approach will increase as the All Alternatives-Available Life increases.

Simulation Results

Average Project Quality

The average quality of the point-based projects as described by the compliment of the imperfection fraction is 97.3%. The average quality using a set based approach is shown in Figure 4.

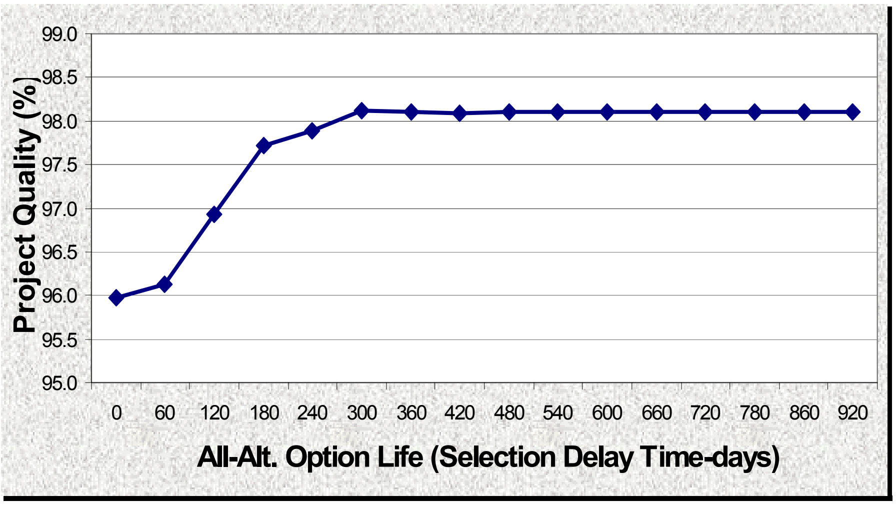

Figure 4: Average Quality of Set-Based Development Projects

Figure 4 demonstrates that the quality of development increases with the length of time that alternative elimination is postponed. If the model is reflecting the same behavior as the Second Toyota Paradox this should occur because managers are selecting better alternatives (i.e. #1 more often than #4). Figure 5 shows the average number of the alternative selected. Remember that alternative #1 is he best and alternative #4 is the worst. As expected, the average number of the alternative selected using a point-based approach is 2.50 (the mean of 1, 2, 3, and 4).

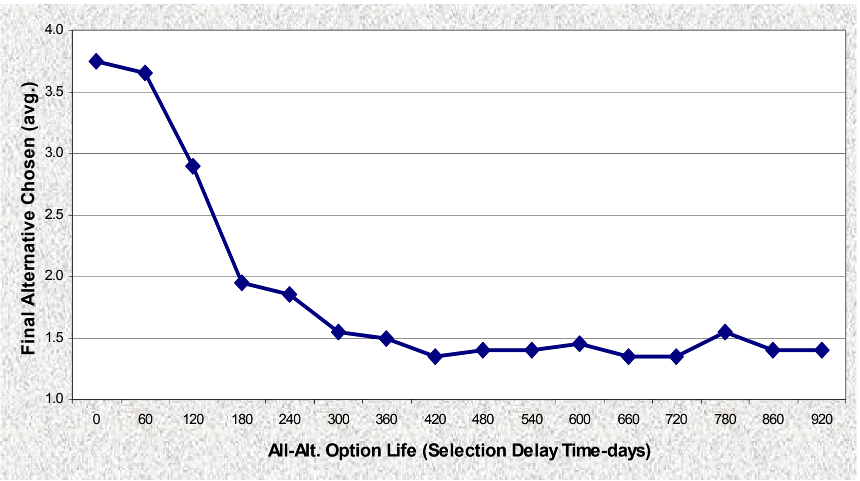

Figure 5: Average Alternative Selected using Set-Based Development

Figure 5 demonstrates that it is the selection of better alternatives that causes the project quality to improve in Figure 4. This shows that the set-based approach uses delaying the selection of alternatives to improve quality by selecting better alternatives than the point-based approach. It also supports our hypothesis that the Second Toyota Paradox operates through real options.

Development Cost and Project Value

The average cost of the project using a point-based approach is $246,000. The average cost using the set-based approach is shown in Figure 6.

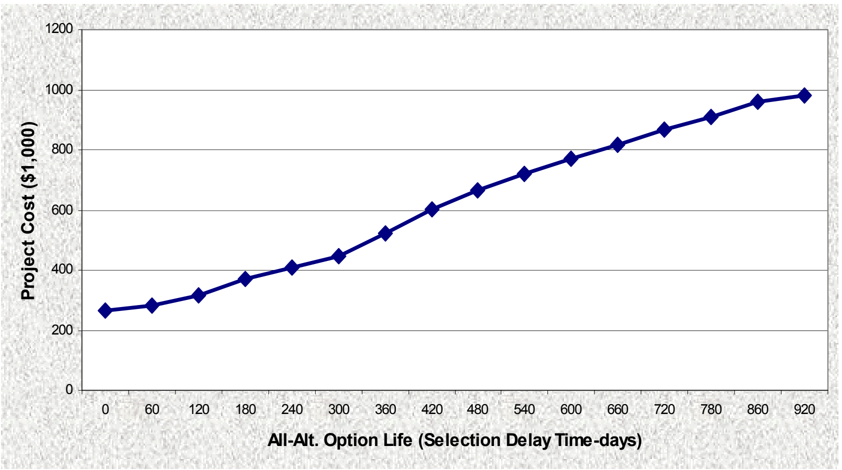

Figure 6: Average Project Cost using a Set-based approach

As expected, development costs increase as more alternatives are kept active longer. Assuming a value of $100,000 for each percent of quality in the final product, the average value of the point-based project is $9.7 million. Figure 7 shows the average value using set-based development.

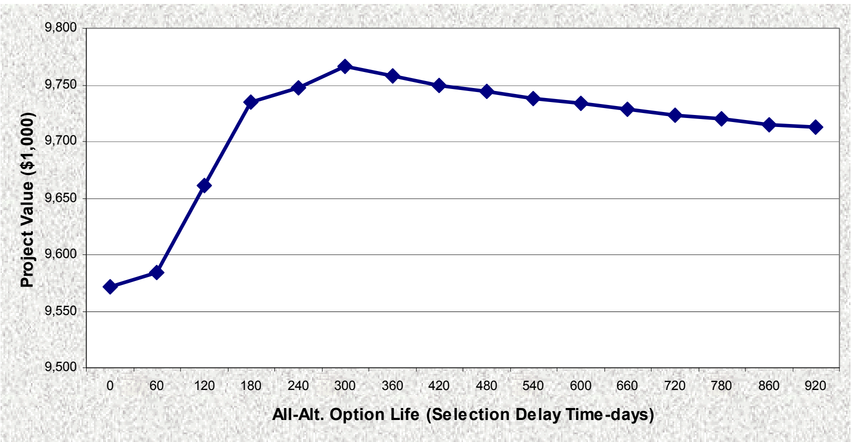

Figure 7: Average Project Value using Set-Based Development

Project values increase with the delay in beginning alternative elimination and then gradually decrease as the delay grows. The set-based value exceeds the point-based value for All-Alternatives-Available Life values greater than about 150 days. This supports our hypothesis that set-based project values will be greater than point-based project values *if it is assumed that the set-based approach is implemented effectively*. The increase of the set-based project values with increasing All-Alternative Option Life values up to a value of about 150 days supports the hypothesis that delaying the elimination of alternatives increases project values and that the Second Toyota Paradox add value by implementing real options. A comparison of Figures 4 and 7 reveal that the maximum project value occurs when the quality benefit of delaying has been obtained. Delaying the elimination of alternatives beyond that point increases development costs without adding value, causing the decline in project value. This causal explanation also supports our hypothesis that real options can explain the Second Toyota Paradox.

Conclusions

Based on this work we conclude that the Second Toyota Paradox adds value to new product development through the use of real options. Delaying managerial decisions can add value by keeping alternatives alive. That purposeful and structured management of flexibility can potentially increase new product development project value significantly. This suggests that there is a large potential for options use for increasing project value. However, improving the management of uncertainty in NPD requires understanding option designs and impacts on project value. Therefore a *managerial* approach to real options is needed to exploit the use of real options to recognize and capture latent project value. illustrates how real options theory can explain the Second Toyota Paradox. It also *how* (vs. that) the Second Toyota Paradox can increase new product development project value by managing uncertainty. The model explicitly includes development processes, resources, and management in an options model.

Future work can include the development of stylized representations of commonly used alternatives found at Toyota and in other, more accessible settings (e.g. student projects). These alternatives can reflect functional roles in development efforts such as a safe (“fall-back”) alternative based on incremental improvement of an existing and tested design and a high-risk, high-reward (“throw away”) alternative. Future work can also improve the model's calibration to

Toyota, model the impacts of other uncertainty characteristics, and multiple uncertainties and strategy designs.

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