A Model for Exploration of Factors Affecting Parallel Research and Development Strategies

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Abstract

Early stages of product development are critical to success of the final product. Decisions made in the early stages will affect the design choices available during the entire development cycle. This thesis examines two research and development strategies. One product development strategy is to make critical decisions as early as possible to manage costs and coordinate work. Making decisions early can help control costs. Early decisions can also limit the potential value of the product. The value of decisions made at the beginning of the development cycle when the least is known about the problem and the potential solutions are most susceptible to uncertainty. An alternate approach is to employ a parallel research and development strategy. Multiple alternative designs are pursued as if they were the final choice. Decision makers can then make more informed choices for the design of their product. This approach has higher development costs. The net benefit of the project can be higher due to increases in quality and decreases in schedule. Understanding when to apply parallel research and development strategy is an important consideration for those facing uncertainty in their product development cycle. A systems dynamics model was used to illustrate how the intensity and commitment to a parallel research and development strategy affects the efficiency and effectiveness of product development. The model shows that the number of alternatives and the time alternatives are developed before one alternative is chosen are both important factors for effectiveness and efficiency. The model also shows that it is important to strive for variety in the alternatives added.
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1 Introduction

Product and research development organizations face many decisions about what to develop. During development they will define the product characteristics, the technology used, and the how the product will be sold. These decisions define the value of the product. Product research and development organizations also face decisions on how that product will be developed. The strategy chosen will also affect the value of the product. Most organizations rely on a sequential strategy where decisions are made early to control costs. These organizations will not consider benefits of a parallel research and development strategy because of the misperception that the added development cost will always outweigh the benefits. This thesis introduces parallel research and development and compares the benefits of following a parallel strategy versus a sequential strategy.

In a sequential strategy, critical decisions are made near the beginning of the project. These critical decisions are based on the incomplete information that is available early in the product development. These decisions limit the solutions that will be explored during development. However, this is the period where the least is known about the problem to be solved and the possible solutions. One alternative approach is the parallel research and development strategy. In a parallel strategy, multiple alternatives are developed as if they were the winning alternative chosen. Development of all the alternatives continues until a decision point is reached. By this time more information on the various alternatives has been gathered and a better decision can be made on which alternative will generate the highest value. Parallel research and development strategies have been used successfully in high risk, high criticality and high cost projects in the past. Two high profile examples are the development of the atomic bomb during World War II and the Apollo Project during the 1960s.

The strategy has been less popular in the development of commercial products. The apparent cost of the approach makes it a less attractive choice. Nevertheless, case studies of organizations that do employ a parallel research and development strategy have shown that it can be a strong differentiator in a competitive environment and result in more profitable projects. Higher quality and shorter development time offsets the costs of a parallel strategy. New modeling, simulation and data analysis technologies have
lowered some of the economic barriers to pursuing parallel strategies in early design stages of product development. Increasing modularity can also lower the development cost associated with parallel research and development.

Decision makers may find that pursuing a parallel strategy can improve their bottom line. Using a systems dynamics model developed by David Ford and Durward Sobek II to illustrate “The Second Toyota Paradox”, this thesis explores the factors affecting the decision to use a parallel R & D strategy. Ford and Sobek found that the convergence time, the time at which the final design is chosen, has a profound effect on quality. In addition to the convergence time, Ford and Sobek’s original model has been modified to allow variation in the number of lines of development at the beginning of a project for this thesis.

The thesis focuses on exploring these factors in finding the optimal degree of parallel R & D for different project characteristics. The resulting model could also be calibrated to specific projects and alternatives to build a better understanding of the key factors for consideration by decision makers to make use of parallel development strategies.

1.1 Research Agenda

The purpose of this research is to build a better understanding of the effects of various product development controls to consider when evaluating the application of a parallel research and development strategy. The two controls the model focuses on optimizing are the number of parallel research and development lines and the length of time to maintain them over the course of a three phase project. For these two control factors, different profiles of technological complexity of the alternatives and tractability of the alternatives are explored.

This model can be used to gain a better understanding of parallel research and development costs during the course of the project. As noted by Abernathy and Rosenbloom, the costs associated with parallel development are much more apparent than the benefits. (Abernathy and Rosenbloom 1969) To make a convincing argument to pursue parallel research and development, a model can be used to show the cost versus benefit during the course of the project. It can also be used to test perceptions of barriers to applying a parallel research and development strategy. (Marschak 1962)
perception is that parallel research and development will always be more costly. While it is true that the development costs will be greater, the value of a higher quality product is also greater. In some cases, the added value of a higher quality product will offset the development cost.

2 Overview of Parallel Research and Development

Abernathy and Rosenbloom describe parallel research and development as “the simultaneous employment of two or more distinct approaches to a single task when successful completion of any one would satisfy the task requirements.” The alternative would be the sequential strategy which is the “commitment to the best evident approach with other possibilities to be pursued only if the first proves unsuccessful.” (Abernathy and Rosenbloom 1968) The advantages of pursuing a parallel strategy are:

- Increases in quality (Ward, Liker et al. 1995)
- Decreases in research and development time (Thomke, von Hippel et al. 1998)
- Higher and more effective coverage of the value landscape (Thomke, von Hippel et al. 1998)
- Higher reactivity to changes in the requirements and competitive environment (Klein and Meckling 1958)

On the other hand, parallel research and development has significant disadvantages:

- Higher cost of overall development (Thomke, von Hippel et al. 1998)
- Lower learning opportunities between implementation of alternatives (Loch, Terwiesch et al. 2001)
- Larger overhead for overall project coordination (Thomke 2003)
- Perception of “wasted” work (Nelson 1959)

These disadvantages are much more visible to the organization during development than the potential benefits of higher quality in the end product. However, the benefits of a parallel research and development strategy are particularly important for new product development where there is high uncertainty for customer preferences, competitive products and technological performance. A parallel strategy can be used to hedge against these uncertainties until a more informed decision can be made. A savvy
decision maker should consider the potential benefits of parallel research and development over a sequential strategy before committing to an approach.

The framework for evaluating the merit of a parallel research and development strategy is based in decision analysis. Utility of the project is weighed against the accumulated cost to evaluate the relative merit of each approach. Unfortunately, an analysis based on utility and net benefit of the project would be highly dependent on the nature of the individual project. This makes it difficult to make detailed predictions for all projects based on the net benefit of the approach. However, general conclusions based on the effects of control factor of projects on effectiveness and efficiency can be drawn through analysis of an uncalibrated model.

3 Literature Review and Research Questions

3.1 Parallel versus Sequential Research and Development Strategies

General work on parallel research and development strategies started during the late 1950s at RAND Corporation. Richard Nelson built the framework for evaluation of parallel research and development versus sequential strategies based by considering the economics of parallel research and development. This research was based on parallel research and development projects in the public sector and the military. Criteria for the evaluation of the sequential versus parallel strategies was tied to: (Marshall and Meckling 1959)

- costs (development and production)
- performance
- time of availability of the final product
- utility of the project

Two assumptions are made about projects for which parallel research and development should be considered.

"First, at the start of the development program, estimates of cost, time, and performance of a proposed system are subject to great uncertainty. Second, these estimates improve and become more reliable as development proceeds." (Nelson 1959)
The utility of a sequential strategy could be weighed against the utility for a project with improved performance that could be delivered within a shorter time frame. The difference between these two utilities can be used to justify a parallel strategy. Nelson also explored the factors that determine the number of projects that should be run in parallel. He identifies the following as key factors:

1) "the cost of running a project during the period of competition
2) the expected improvement in estimates during the period of competition
3) the difference among the cost and performance estimates of the competing projects
4) The design similarities and differences in the competing projects

If the early stage development costs are small and the expected improvement in the estimates is large, and if the competing projects are quite similar in their estimated cost and performance because there is little data on which to base estimates, but quite different in design; then it certainly pays to run several projects in parallel." (Nelson 1959)

If the development cost or technical performance of an additional alternative is correlated with one of the current alternatives, it is a poor candidate. If two alternatives are correlated there will be less new information gained by adding the second alternative.

Abernathy and Rosenbloom then proposed that there need to be two distinct types of analysis for considering the use of a parallel research and development strategies.

"In the first category, called a parallel synthesis strategy, the uncertainty is broad; the cost of information is relatively low, and there may be only a limited commitment to further work. In the contrasting case, the parallel engineering strategy, the bounds of uncertainty are more definite; the information cost is relatively high; and there is a strong commitment to satisfy developmental objectives." (Abernathy and Rosenbloom 1969)

The parallel synthesis strategy is usually found in the beginning stages of a development project where design choices are being made free from the constraints of prior decisions. The goal is to make better choices in initially unknown value landscape so
that the final design might be more successful. The decision maker is willing to consider the cost of multiple alternatives in return for a gain in quality.

Conversely, the parallel engineering strategy is found later in the development cycle where prior decisions have already limited the design choices available. In particular these prior decisions may increase the cost of changes or negate some alternatives from use without extensive rework. In the parallel engineering strategy, the costs and potential benefits are known and multiple alternatives would be developed to decrease the time to completion for a known benefit. The decision maker is willing to trade additional development cost for a decrease in development time.

This thesis focuses on the case of the parallel synthesis strategy. The parallel engineering case depends largely on a cost benefit analysis based on largely known information and falls into established project management protocol. The parallel synthesis case is more difficult to advocate to a product development organization since so much of the benefits of the strategy are intangible at the point a decision would be made to use it.

Klein and Meckling make a theoretical case for the use of parallel research and development within the commercial space. (Klein and Meckling 1958) They compare the decision making process between two fictional project managers, one who is committed to a sequential approach versus one who is open to parallel research and development. It is shown that the sequential approach is doomed to provide inferior results because too many of the decisions are made with uncertain information available at the beginning of the project.

A number of these early researches in parallel research and development based their analysis on case studies of actual projects. The projects which employed parallel research and development discussed in early literature by RAND Corporation’s Richard Nelson are military in nature. He cites examples such as the atomic bomb project which successfully employed five competing alternatives in a parallel research and development strategy during its development. He also uses the development of military aircraft to demonstrate how one might construct criteria for choosing a winning alternative during the product development cycle. (Nelson 1959)
Allen, while exploring the nature of information flow during research and development, studied 17 pairs of parallel research and development projects in the aerospace industry. He finds that organizations producing high performing projects tend to continue to communicate at a higher level and resist commitment to a winning alternative until late in the development cycle. Organizations that considered multiple alternatives with more depth produced higher quality products. Teams continued to modify the design parameters throughout the development cycle and therefore continued to communicate outside their immediate project teams. Poorer performing teams generally had a high period of communication at the beginning of the project to agree on design parameters and then a second burst of activity later in the development cycle to resolve interface issues resulting from unforeseen issues during the development cycle. However, this burst of activity later in the cycle is not as effective as continued communication and effort to optimize the product as a whole over the development cycle. Ongoing communication enabled teams to optimize the entire systems they were building rather than just the individual components. (Allen 1984)

With a sequential strategy decisions which limit the potential performance of a system are made at the beginning of the project when there is the least amount of information. The theory is that making design decisions early will help control costs. Unfortunately, making these decisions limits the potential value of the system. Furthermore, the designs are inflexible to changing information from the marketplace and changes in understanding of unproven technologies. (Bhattacharya, Krishnan et al. 1998)

Similarly, MacCormack, Verganti and lansiti studied pairs of companies working on products for the same market. They found that companies that remained flexible throughout the development cycle to changes in customer requirements found higher value in the marketplace. Surprisingly, companies that felt they had a well run product development cycle with well defined requirements early on produced lower ranked products. Conversely, companies that felt they had a chaotic development cycle due to flexibility in their design process often produced higher ranked products. (MacCormack, Verganti et al. 2001).

Another concrete example of the benefits of parallel research and development was described in a study on Toyota’s product development cycle in 1995. This study highlighted extended parallel research and development periods as a key differentiator...
for Toyota. This quote highlights the importance Toyota places on gathering information before making product development decisions.

“The general manager of body engineering remarked that delaying the decision on critical dimensions until the last possible moment is necessary to ensure that customers’ expectations are fully understood, that they will be fully satisfied by preventing engineers from making premature design decisions as a critical part of his job.” (Ward, Liker et al. 1995)

This closely mirrors Nelson’s original economic argument for the benefits gathering better information through a parallel research and development strategy prior to committing to a single alternative. Bhattacharya, Krishnan and Mahajan later applied these economic arguments specifically to new product development. They contend that flexibility in design is especially important in “highly dynamic environments, characterized by changing customer preferences and uncertainty about competitive products”. (Bhattacharya, Krishnan et al. 1998) Krishnan and Bhattacharya later went on to evaluate parallel research and development against a sufficient design approach. In sufficient design, a single product is over-designed to accommodate multiple options to gain design flexibility rather than pursuing multiple product designs with parallel teams. They conclude that parallel research and development is most useful when the variance of viability of a solution is low but the estimated viability is high since development costs are high. (Krishnan and Bhattacharya 2002)

Loch and Terweisch have discussed the changes in the economics of pursuing parallel research and development in the advent of cheaper prototyping and testing. Technology for prototyping has become cheaper and testing has shifted to computer simulations. Gaining information is now cheaper allowing additional experimentation without as much impact to the development cost. This changes the dynamics of parallel research and development for these stages that can use these new technologies making it a more viable prospect. (Loch, Terwiesch et al. 2001)

For the stages of development that can make use of these more economical solutions the prospect of using a parallel research and development strategy can become very compelling. The pharmaceutical industry is one where cheaper testing technology has transformed the economics of parallel research and development. Mass screening of
has made it possible to screen many more potential drug candidates more quickly. This information improves success rates downstream in the expensive clinical trial stage. By front-loading the discovery process, costly resources are focused on better alternatives. (Thomke 2003)

Furthermore, organizations that fail to make use of new technologies will fail to innovate as quickly as those that do. Thomke studied the differences between firms using application specific integrated circuits (ASIC) and electrically programmable logic devices (EPLD) for integrated circuit design. ASICs have much higher costs associated with changes and experimentation but lower manufacturing costs than EPLDs. However, EPLDs are more flexible. "It was found that projects using flexible design technologies outperformed projects using inflexible technologies by a factor of 2.2. 23% of that difference can be attributed to differences in managing risk of design changes: high flexibility enabled designers to tolerate high levels of risk, whereas low flexibility resulted in significantly higher resource investments that were aimed at minimizing risk of design changes. Thus design managers who operate in uncertain and unstable environments will find that increasing design flexibility and adjusting the respective development strategy accordingly will provide them with a significant competitive advantage over other firms." (Thomke 1997)

Similarly, increasing sophistication in modular designs could also make parallel research and development more viable for commercial research and development. One of the largest concerns is the massive development cost of pursuing a parallel research and development strategy for a large integrated project. However, if only critical portions of a product were pursued with a parallel research and development strategy the net benefit could be larger for the project as a whole. In fact, the possibility of parallel experimentation and substitution of modules with better alternatives is the key to the value of modularity. Baldwin and Clark state that the true potential of a modular design "lay in combining its modular structure with much higher levels of experimentation." They go on to state that "large investments involving modularization alone or experimentation alone have negative values. It is only when splitting and substitution are combined that the modular design takes on positive net option value." Concerns driving this conclusion are the larger "cost of achieving modularity, which include the cost of specifying design rules, the cost of experimentation, and the cost of testing and system integration. Taken
as a whole, these costs may substantially reduce or even wipe out the option value of a modular design." (Baldwin and Clark 2000)

However, parallel experimentation and the optimization of critical modules can greatly enhance the value of the system as a whole. This gain in system value through experimentation can be thought of as mapping a landscape of designs. Each point on the landscape represents a combination of design choices. Highpoints in the landscape represent combinations of design choices that result in a high value product. Baldwin and Clark predict that changing the modularity of a product would shift these peaks or create new peaks. Without experimentation the product could get trapped in a low value state or at a local peak rather than the global peak in the value landscape. Moreover, parallel research and development maps the contours of the landscape more quickly by exploring alternatives at many points on the value landscape at the same time.

4 Summary of Research Questions

Based on the research above, the expectation is that a correct model will exhibit the behavior described. The model should also build a more tacit understanding of the concepts and their applicability to product development situations.

4.1 Parallel Research and Development Effectiveness

Hypothesis 1: Quality increases with additional alternatives.

Quality should increase as the number of parallel research and development alternatives are pursued. The more alternatives that are pursued, the larger the coverage of the value landscape and the more likely it is that the true optimal solution is found. These alternatives should be uncorrelated in cost and performance or the addition of an alternative will not be cost effective.

Hypothesis 2: Quality increases with later convergence times.

Choosing the correct time at which alternatives are thinned out is critical to the effectiveness of a parallel research and development strategy. In fact a sequential strategy can be thought of as a special case of parallel research and development.
strategy where the winning alternative is chosen at the beginning of the project when there is the least amount of information. The expectation is that by delaying this decision and allowing the alternatives to be developed a better decision can be made later in the cycle.

Despite high development costs delaying design decisions can benefit the overall net value of the system. As work continues on an alternative more information on its potential is gained making it possible to choose a better alternative. Marshall and Meckling studied the error associated with estimates made during the course of a project. They found that:

"'Early' estimates of important parameters are usually quite inaccurate. First, such estimates are strongly "biased" towards overoptimism. Second, aside from the bias, the errors in estimates evidence a substantial variation. The accuracy of estimates is a function of the stage of development, i.e. estimates improve as development of the item progresses. "(Marshall and Meckling 1959)

Some of the bias towards overoptimism can be attributed to project advocates attempts to sell the project to decision makers. There is motivation to skew initial estimates at the beginning of a project to justify the launching of a product development effort. However, later estimates need to be more accurate to raise enough resources to finish the project. In addition from the bias from launching the product development effort, unexpected costs associated with uncertainties in the project or changes in the requirements are more likely to be uncovered as the development cycle continues. Choosing a later time to make a decision among alternatives should help organizations make a decision for a more cost effective and better quality alternative.

**Hypothesis 3: More alternatives will generate higher quality more quickly.**

The more alternatives followed the more information is available about possible solutions. Loch, Terwiesch, and Thomke discuss the parallel versus sequential testing strategies. In their opinion, as additional parallel tests are added, the time to completion is shortened. However, the opportunity for learning from one test to the next is diminished since the testing is run in parallel. (Loch, Terwiesch et al. 2001)
This has some implications to the overall project that are explored by Thomke, Von Hippel and Franke. They defined three types of experimentation: Parallel Experimentation, Rapid Learning Serial Experimentation and Minimal Learning Serial Experimentation. For a completely parallel approach, there is no learning between testing periods only one testing cycle is needed. For the rapid learning serial experimentation, the possibilities are narrowed after each period as information from the previous round of tests informs subsequent rounds. This leads to more testing cycles than the completely parallel approach but less than the minimal learning serial experimentation. With minimal learning serial experimentation, previous tests do not inform subsequent tests leading to the highest number of iterations of testing cycles. (Thomke, von Hippel et al. 1998) If we extend this reasoning to the overall development process, parallel research and development strategy should result in the highest quality in the shortest period of time but also with the highest cost.

4.2 Parallel Research and Development Strategy Efficiency

For this discussion, parallel research and development strategy efficiency is defined as the ratio of quality gained per unit of development cost per task of the parallel strategy over the sequential strategy. The larger the ratio the more efficient the strategy is for generating additional quality. Since the model is uncalibrated only a relative comparison of efficiency is meaningful. To compare actual development and net benefit between strategies actual development cost would have to be identified. This measure will help evaluate the amount of parallel research and development to employ as defined by number of alternatives and time to choose the winning alternative.

Hypothesis 4: Efficiency decreases as the number of alternatives increases.

Since the solution space is limited, as the number of alternative increases it is expected the additional alternative is more likely to have characteristics that are already represented within the alternatives chosen. As Nelson writes, "Most of the arguments against parallel R and D efforts are arguments against duplication." (Nelson 1959) There is a danger of wasted effort due to duplication of technical approaches as well as duplication in project characteristics such that more than one alternative will accomplish the goal with little advantage in terms of cost, schedule or performance as additional alternatives are pursued.
Hypothesis 5: Efficiency can be maximized at one convergence time.

The longer the alternatives are pursued, the higher the development cost and the more “wasted” effort is accrued for alternatives that are not ultimately chosen. Near the beginning of the project efficiency should increase as information improves the choice of alternative. Near the end of the project, it is expected that the value of that information decreases as it become more likely that enough is known to choose the best alternative.

5 Modeling and Testing Methodology

5.1 Original Model

The model used to test these hypotheses is a slightly modified version of the model developed by Ford and Sobek for their paper “Adapting Real Options to New Product Development by Modeling the Second Toyota Paradox”. (Ford and Sobek 2005) This model demonstrates how delaying decisions can increase the net value of a project.

The core of the model is the product development model developed by Ford and Sterman to explore “the dynamic concurrence relationships that constrain the sequencing of tasks as well as the effects of and interactions with resources (such as labor), project scope, and targets (such as delivery dates).” (Ford and Sterman 1998) This model expands on the standard work cycle by introducing more complex constructs for the:

- precedence constraints on tasks to be completed
- sharing of resources between phases of work
- technological and market risk
- schedule pressure from release targets
- project scope

The result is a more realistic model of work progression. There is lumpiness in work flowing through the development cycle due to task precedence relationships and sharing of resources across the phases of the project. Work is released into the next phase of development in work packages. There is also a more complex rework cycle due to uncertainties in technology and changes in customer requirements. Finally the schedule
pressure introduces variation in the amount and quality of work accomplished by a resource due to the project scope and schedule targets.

The following is adapted from Ford and Sterman's article "Dynamic Modeling of Product Development Processes". The structure below is the core of the model used for testing for this thesis. (See Figure 5-1) For each alternative, this structure shows the flow of work through one phase of the development cycle. In particular, take note of the rework loop which is governed by the probability of generating a change and the probability of discovering a change. The probability of generating a change is a measure of the complexity of the system. This affects the rate at which internal tasks needing changes are created. Similarly, this also affects the rate at which external tasks needing changes are created. Also, take note of the probabilities to discover a change. This represents the tractability of the alternative. This probability affects the rate of discovering internal and external changes. Tractability represents the ease of which the QA resources will be able to find defects either generated within the current development phase or from downstream tasks. During the product development cycle these probabilities vary randomly around an average value. Each simulation has unique results due to the random nature of the probabilities to generate and discover change.
Figure 5-1: Work flow model with shared resources and concurrent work. Adapted from Ford and Sobek's Second Toyota Model (Ford and Sobek 2005) and Ford and Sterman's Multiple Phase Dynamic Concurrence Model (Ford and Sterman 1998)
Ford and Sobek, added another layer of complexity by linking multiple parallel projects together through a shared pool of resources to simulate parallel research and development. For their research, they held the initial number of alternatives constant at four during their testing. I expanded the model to allow variation in the number of alternatives giving us the following structure.

![Shared Phase Resources](image)

**Figure 5-2**: Resource allocation across alternatives and tasks. Adapted from Ford and Sobek. (Ford and Sobek 2003)

To evaluate the net benefit of the project overall, Ford and Sobek applied real options analysis. Development cost is tracked across the lifetime of the project. Quality as measured by the percentage of tasks with known imperfections is also tracked. By then assigning a marginal value of quality to the project, a net benefit of the project can be calculated. Ford and Sobek found that the convergence time, the time at which the winning alternative is chosen had a profound effect on the overall quality of the project, and therefore the net benefit of the project as well.

The winning alternative is chosen by considering the known imperfection fraction of each of the alternatives and eliminating the worst alternative at the convergence time. Each alternative is given a grace period to be the worst alternative after which it is eliminated. This process continues until there is only one alternative left. The alternatives are
differentiated by increasing complexity paired with decreasing tractability. The true complexity and tractability is not known to a product development organization at the beginning of a development cycle. It is only through development that they are revealed through the quality of work produced. The best alternatives have lower complexity which generates the least amount of rework. They also have high tractability which means that any rework needed is more likely to be found. The worst alternatives have high complexity and low tractability meaning that completed work is more likely to need rework and these imperfections will be more difficult to discover. With this alternative selection setup, there is a bias towards choosing a worse alternative in the sequential development case since the imperfections generated are hard to find leading to an impression of a better quality alternative early in the development cycle.

This model was originally calibrated against the product development cycle at Toyota to illustrate their product development cycle as described in “The Second Toyota Paradox: How delaying Decisions Can Make Better Cars Faster”. Consequently, important exogenous variables such as the number of alternatives, the marginal value of quality, and the scope of the projects were chosen to reflect Toyota’s development cycle. For this thesis, the values of these variables have been changed to make data analysis easier. Despite the lack of calibration, the model structure is based on generalizable product development research.

In the model, quality is defined as the percentage of tasks without known imperfections at the end of the project. The project has a fixed deadline at which the final quality is assessed rather than letting the project continue until a target quality is reached. The convergence time is the milestone during the project at the winning alternative is chosen. The corresponding sequential development case for comparison is modeled by setting this milestone to choose the best apparent alternative before any work is completed.

5.2 Modifications to the Model

Earlier work by Abernathy and Rosenbloom focused around optimization around the number of alternatives. In order to explore the effect of the number of alternatives along side convergence time, Ford and Sobek’s set-based design model was extended to enable the user to specify the number of alternatives for the project. Five versions of the
model were generated corresponding to 2, 4, 6, 8, and 10 alternatives. The original three phase product development cycle was kept for each of these alternatives.

5.3 Experiment Design

The model has quite a few variable inputs that can be controlled to model different situations. The main control variables focused on here are:

- Number of alternatives
- Convergence time

For these control variables the distribution of complexity and tractability of the alternatives was varied.

5.3.1 Effectiveness Experiments

In order to explore the effect of these control variables on the effectiveness of development, the follow hypotheses are proposed:

- Hypothesis 1: Quality increases with additional alternatives.
- Hypothesis 2: Quality increases with later convergence times.
- Hypothesis 3: More alternatives will generate higher quality more quickly.

The number of alternatives was varied from 2 through 10 parallel alternatives and convergence times were varied from 0 to 900 days at 50 day intervals for a 1000 day project for 3 different profiles of complexity and tractability:

- Constant range and constant average complexity and tractability
- Expanding range and constant average complexity and tractability
- Improving average complexity and tractability

The first series of tests held the range of complexity and tractability constant as the number of alternatives and convergence times were varied. In this set of tests, as the number of alternatives was increased from 2 to 10, the best and worst alternatives had the same complexity and tractability and remaining alternatives were added at regular intervals in between. Alternative 1 is the best alternative with the lowest technical complexity and the highest tractability. See Table 5-1 for a comparison of complexity and tractability between (a) two alternatives and (b) ten alternatives. Notice that the best
alternative Alt 1 has the same complexity and tractability as the best choice in the two-alternative case. Note that Alt 10, the worst alternative, has the same characteristics as the worst choice in the two-alternative case. Using Baldwin and Clark’s mental model of a value landscape, two alternatives explore the same area of the value landscape as the ten alternatives but ten alternatives give better coverage between the best and worst alternative. This might represent a case where alternatives added to the parallel research and development strategy added have similar characteristics to the original two.

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Alt 1</th>
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<tbody>
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<tr>
<td>Phase 2</td>
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<td>Phase 3</td>
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Table 5-1a: Complexity and tractability for two alternatives.

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<th>Complexity</th>
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<th>Tractability</th>
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<td>0.633</td>
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Table 5-1b: Complexity and tractability for ten alternatives.

The second group of tests held the average complexity and tractability constant while widening the range of complexity and tractability as more alternatives are added. This corresponds to adding alternatives that widen the search area in the value landscape but keeping it centered on the same average complexity and tractability. See Table 5-2 for a
comparison of the settings for two alternatives and ten alternatives. Notice that the best alternative Alt 1 has the lower complexity and higher tractability than the best choice in the two-alternative case. Alt 10, the worst alternative, has a higher complexity and lower tractability than the worst choice in the two-alternative case. This might represent the case where increasing the number of alternatives pursued increases the risk of introducing both better and worse alternatives. Of the complexity and tractability profiles, this is the most realistic. The literature on parallel research and development suggests that practitioners should strive to gain information when adding of alternatives. It is likely that alternatives added would widen the range of complexity and tractability rather than remaining focused on the same area of the design space.

<table>
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<td>Phase 1</td>
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<td>Phase 2</td>
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<tr>
<td>Phase 3</td>
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</tbody>
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Table 5-2a: Complexity and tractability for two alternatives as the average complexity and tractability are held constant but the range between the best and worst alternative increases.

<table>
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<tbody>
<tr>
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<td>Phase 1</td>
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<tr>
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<table>
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<td>Phase 1</td>
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<tr>
<td>Phase 2</td>
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<tr>
<td>Phase 3</td>
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</table>

Table 5-2b: Complexity and tractability for ten alternatives.

The third series of tests skewed the range of alternatives towards more favorable complexity and tractability characteristics as more alternatives were added. See Table 5-3. This corresponds to shifting the focus of the search area on the value landscape.
closer to a maximum with the addition of alternatives. As alternatives are added, the average complexity decreases and the average tractability decreases skewing the portfolio of design alternatives toward better choices. It is unlikely in practice that as the number of alternative grow only more favorable alternatives would be chosen, but it is interesting to see the effects of a favorable if unrealistic complexity and tractability profile on quality.

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>Phase 2</td>
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Table 5-3a: Complexity and tractability for two alternatives as the average complexity and tractability are steadily improve with the addition of more alternatives.

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<thead>
<tr>
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<th>Tractability</th>
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<tr>
<td>Phase 1</td>
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<td>0.233</td>
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<td>Phase 3</td>
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<td>0.833</td>
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Table 5-3b: Complexity and tractability for ten alternatives. Note that the best alternative is now Alt 10. It has lower complexity and higher tractability than the best choice in the two-alternative case.

5.3.2 Efficiency Experiments

For this set of experiments, efficiency is defined as the quality gain per development dollar per task. The efficiency is tested with the most realistic risk profile: The addition of alternatives widens the range of complexity and tractability. Results from this series of
tests help define the effect these factors have on efficiency by testing the following hypotheses:

- Hypothesis 4: Efficiency decreases as the number of alternatives increases.
- Hypothesis 5: Efficiency can be maximized at one convergence time for a given number of alternatives.

Though efficiency is not the only factor in deciding the extent of parallel research and development to pursue, it is important to understand how it changes in response to the number of alternatives and the convergence time chosen.

6 Analysis and Results

6.1 Exploring Research and Development Effectiveness

The following graphs show results varying the number of alternatives, convergence time and the profile of complexity and tractability for the alternatives. The results from the testing done across a constant range of complexity and tractability can be found in Graph 6-1. Each data point represents 100 simulations with the same convergence time and number of alternatives. The average quality over those 100 simulations is plotted.
The sequential research and development strategy can be found when the winning alternative is chosen at the beginning of the development cycle. This occurs at convergence time 0 for each of these graphs. At low convergence times there is very little change in quality between the sequential and parallel research and development strategies regardless of the number of alternatives. This is expected since at very low convergence times no information has been gained that would dissuade the decision maker from choosing the same alternative that was chosen in the sequential strategy. Note that for this profile of complexity and tractability adding alternatives does not necessarily improve quality. These results show that the overall quality is maximized for at later convergence times with 8 alternative rather than 10 alternatives as might be expected. With earlier convergence times the maximum quality is with even fewer alternatives.

**Graph 6-1:** Constant average and constant range of complexity and tractability as alternatives are added.
The next set of tests show results when the average complexity and tractability are held constant as more alternatives are added but the range increases. Tractability is the likelihood of discovering an imperfection. The worst alternatives are the most attractive near the beginning of the product development cycle since they have the lowest tractability. For this profile as alternatives are added the worst alternative has a higher complexity and a lower tractability. So if the alternatives are thinned early on in the development cycle a higher number of alternatives generate poorer quality. If the alternatives are allowed to develop sufficiently the alternatives can be ranked correctly. Therefore adding alternatives generates better quality.

**Quality vs. Convergence Time**

![Graph 6-2: Constant average widening range as alternatives are added.](image)

Finally, the last set of tests show the quality gains as additional alternatives improve the portfolio of alternatives. In this case, the addition of alternatives dramatically improves quality even with little development. However, it is unlikely that this profile is particularly realistic. With the true complexity and tractability of an alternative hidden from product
development team until development has progressed it would be difficult to continue to add progressively better and better alternatives to the portfolio. This last set of tests serves only to demonstrate the relationship between the range of complexity, tractability and quality.

**Quality vs. Convergence Time**

![Graph 6-3: Average complexity decreases and average tractability increases with the addition of more alternatives.](image)

**Hypothesis 1: Quality increases with additional alternatives.**

Adding more alternatives should enable a more informed decision on the final design resulting in higher quality for the overall project. The model shows that while generally true, there are some caveats.

First, if the parallel research and development paths are not allowed to continue long enough there is a little difference between following a sequential strategy and following a
parallel strategy. The model is structured such that bad alternatives start out looking like good alternatives with good quality until later in the development cycle. Over time the bad alternatives reveal themselves as the project generates higher amounts of rework due greater complexity of the alternative. If the convergence time occurs before the rework accumulates for the worst alternatives the effect of a parallel strategy on quality is negligible. If development is allowed to progress until information about the amount of rework generated by an alternative is available overall quality does improve dramatically with a parallel strategy versus a sequential strategy.

Second, if additional alternatives do not widen the probability distribution of complexity and tractability, adding more than one alternative does not necessarily increase quality. In the test where alternatives are added within a constant range of complexity and tractability, adding alternatives does not guarantee increased quality. When the range of complexity and tractability is widened, we see quality decreasing prior to a critical convergence time when enough information is gathered during the development cycle to identify the worst alternatives. Quality increases with the addition of alternatives after the critical amount of development to identify rework is performed. Only when additional alternatives skew the distribution of complexity and tractability favorably do we see the addition of alternatives increase quality from the very beginning of the development cycle.

**Hypothesis 2: Quality increases with later convergence times.**

In theory, the longer the alternatives are developed the higher the quality. In general, this hypothesis is proven true. However, the relationship between convergence time and quality is not linear. Referring back to the graphs shown above, within this model, we see that near the beginning of the development cycle quality gains remain flat. The flat area represents the time alternatives are pursued during which there is not enough information to choose a better alternative than in the sequential strategy. Once the convergence time is late enough that development has progressed enough to influence the choice of alternatives, there is a period of rapid growth in quality as new information improves the choice of alternative. This rapid growth in quality represents the period where, rework is being discovered and the true nature of the each of the alternatives is revealed. Finally, quality gains are more modest as the project continues. This leveling off later in the project represents the period where the worst alternatives have been
identified and more information about the true ranking of alternatives is not obtained by continuing the parallel strategy. An S-shaped pattern was seen regardless of the number of alternatives followed or the profile of complexity and tractability.

The model limits the tasks that can be worked on by creating precedence relationships between tasks from phase to phase. Quality problems in the first phase can affect future phases with a delay in the information. This delay in the discovery of rework causes the true nature of the alternative to be hidden until a later date. The worst alternatives are ones with the lowest level of tractability and the highest complexity at the beginning of the project. Later convergence times allow these problems to be discovered. In this model, by the second phase most of these problems have been discovered and the quality increases begin to level off during this phase.

The choice of the optimal convergence time should depend on when a particular product reaches a point where the worst alternatives can be identified. This optimal convergence time depends on the characteristics of the alternatives. The complexity and tractability of the alternative will govern when defects are discovered and the severity of the defects. It should be noted that the optimal convergence time may be affected not only by the inherent project characteristics but also unforeseen changes in the marketplace for which the project is undertaken. Changes in the marketplace can shift performance goals for the product. More alternatives provide more alternatives that may meet the needs of changes in marketplace.

**Hypothesis 3: More alternatives will generate higher quality more quickly.**

For the most part, more alternatives will generate higher quality more quickly. In the second and third group of tests the ten-alternative test shows more rapid improvement than two-alternatives. The result is inconclusive for the first set of tests where additional alternatives do not cover a different part of the value landscape. Adding alternatives generates higher quality when the new alternatives are more differentiated from the current alternatives. Correlation in the technology or resources used for more than one alternative will lead to duplication of effort. This duplication will not improve overall quality of the project appreciably.
Hypothesis 4: Efficiency decreases as the number of alternatives increases.

The factor analysis from the design of experiments matrix show a correlation in the decrease of efficiency as the number of alternatives is increased. Two factors were tested as part of this experiment, the number of alternatives and the convergence time. The number of alternatives accounted for 35% of the total sum of squares variation versus 34% from convergence time. Graph 6-4 shows the decline of efficiency as alternatives are added.

Graph 6-4: Efficiency versus the number of alternatives. As alternatives are added the efficiency decreases.

Part of this is the design of the distribution of complexity and tractability of the alternatives. These results used the constant average but increasing range for complexity and tractability profile for testing. Efficiency is shown to be very high for two alternatives because there is a guaranteed gain in quality from the sequential case to the two alternatives due to the bias towards the worst alternative in the sequential case.
However, the results do show that even without this effect as alternatives are added, the efficiency of gaining quality decreases with the addition of alternatives.

Hypothesis 5: Efficiency can be maximized at one convergence time for a given number of alternatives.

The convergence time also has a strong effect on final quality of the system. The convergence time chosen contributed for 34% of the effect on the total sum of squares in this test. Graph 6-5 shows that the efficiency increases to a peak and then falls off as convergence time increases.

Graph 6-5: Efficiency versus convergence time. The efficiency peaks and then declines as later convergence times are chosen.

This behavior is caused by the delay in discovering the true nature of the various alternatives. As development proceeds more is known about the various alternatives. The later the convergence time the more likely it is that enough is known to rank the
alternatives correctly. After the peak in efficiency, the value of knowing the correct ranking of alternatives is outweighed by the cost of continuing development of the alternatives.

7 Discussion and Conclusion

7.1 Lessons Learned

Both of the control factors explored, number of alternatives and the convergence time, had a strong effect on the effectiveness and efficiency of parallel research and development. In general, quality does increase with more alternatives and with later convergence times. However, the increase is non-linear. A parallel strategy builds quality slowly at early convergence times. This rate increases sharply once enough information has been generated to reliably rank the alternatives. It becomes less effective once the alternatives are correctly ranked.

Adding alternatives was much more effective when the range of complexity and tractability was increased. Quality did not necessarily increase when alternatives were added if they occupied the same area of the value landscape. When more of the value landscape was explored and the convergence time was late enough in the development cycle the addition of alternatives did increase quality. Practitioners should choose to add alternatives that differ from existing alternatives in the parallel strategy.

The efficiency of a parallel strategy also changes with the number of alternatives and the convergence time. Efficiency decreases with the addition of alternatives. There is a convergence time at which the efficiency is maximized. It is a balance between the increase in accuracy in ranking the alternatives and the increased cost of gaining the information.

The decision maker should understand the following:

- Commitment is important to successfully implement a parallel strategy. If the convergence time is too soon very little is gained by pursuing more than one alternative.
- Adding alternatives with very different characteristics than the existing alternatives will be more effective than exploring variations of the same design.
• Efficiency in improving quality decreases as alternatives are added. However, the importance of quality can offset added development cost.

7.2 Theory versus Practice – Challenges of Parallel Development

A parallel research and development strategy should not be considered for all projects. Nelson writes:

“Parallel development of alternative designs seems called for when the technical advances sought are large, much additional information can be gained by prototype testing, and the cost of a few prototypes is small relative to the total system cost.” (Nelson 1959)

Advances in computing and simulation have increased the ability to gain more information about alternatives and has made extensive experimentation more affordable and more effective in generating useful information about alternatives. Technology has lowered two of the barriers to effective use of a parallel strategy highlighted by Nelson: the cost of prototyping and the ability to analyze gain information about the alternatives. Thomke discusses the implications to innovation:

“New technologies now enable more learning to be created more rapidly, and the results can be incorporated in even more experiments at less expense. In other words, information-based technologies drive down the marginal costs of experimentation just as they have decreased the marginal costs in many production and distribution systems. Moreover, an experimental system that integrates new information-based technologies effectively does more than lower costs; it also increases the opportunities for learning and innovation. Thus, some technologies can make existing experimental activities more efficient, while others introduce entirely new ways of discovering novel concepts and/or solutions.” (Thomke 2003)

Organizations are also becoming more sophisticated about implementing modularity as well. Modular architectures lend themselves to parallel experimentation since the development cost of a parallel strategy is reduced with the scope of the project. Applying a parallel strategy to critical modules may still improve quality of the overall product greatly. Optimization of critical parts of a product through a parallel strategy can be more
cost effective than an optimization of an integrated product. Also, the value landscape itself shifts with modularity. Customized products that may not have been profitable with an integrated architecture may now be viable products. Parallel experimentation can uncover the potential of these customized products. Parallel experimentation is essential to identifying the potential value of a modular architecture. (Baldwin and Clark 2000)

However, in practice, securing ongoing commitment to a parallel strategy may be difficult unless management truly understands the benefits of a strategy. It is important to understand which situations they should be applied. The model presented here could be used to persuade project stakeholders to support the strategy.

7.3 Use of the Model

For the general user, the current model remains uncalibrated for a specific project and unvalidated against real projects. Only the most general of trends are explored as part of this thesis. Calibrating this model for a specific project could help the user explore their particular situation and recommend whether a parallel research and development strategy could be beneficial to the project. The model could be used as a tool to convince others within the organization to pursue a parallel research and development strategy. The decision to pursue a parallel research and development strategy is rarely intuitive. It is much easier to focus on the immediate costs and benefits of a sequential strategy and incremental improvements. However, organizations that wish to win in a competitive market need to make decisions based not only on the apparent development costs but also on cost of opportunities lost. Tools such as this model help clarify the true costs and benefits for a better informed decision.

7.4 Recommendations for Further Research

This model was built to assume that there was a fixed schedule for the project and that alternatives would be evaluated based on the schedule. Alternatives are evaluated on based alternative can deliver the highest quality within the confines of the schedule. However, some of the more compelling reasons for pursuing a parallel research and development strategy include capitalizing on the shorter development time by releasing a project of acceptable quality into the market earlier and by savings on development costs for a shorter development cycle. This model might again be extended to evaluate
the net benefit of the project based on the alternative with an acceptable quality and the shortest development time.

The model also does not explicitly take into account the added flexibility that having additional alternatives could give an organization facing uncertain requirements in the product definition. It assumes that the target product remains static over the course of the development cycle. In reality, the understanding of market needs especially for new product development often changes during the development cycle. Real options analysis could be applied when choosing alternatives to pursue in a parallel research and development strategy.

Finally, the model assumes that decision makers will have only one decision point at which the winning alternative is chosen. In practice, there are likely to be multiple decision points at which some of the alternatives are passed on to the next phase of development. This more gradual narrowing down of the design alternatives gives additional flexibility to help balance out development costs versus benefit of information gained through a parallel research and development process.

### 7.5 Closing Remarks

A parallel research and development strategy is a viable option for organizations facing an environment of high uncertainty. It can offer gains in flexibility and schedule at admittedly higher development cost. However, the overall quality of the project is improved through a parallel strategy. In cases where the net value of a product is highly sensitive to the quality a parallel strategy should be considered. Detractors may argue that a parallel strategy wastes resources on alternatives that will not become the final design. However, the true product of following those alternatives is information. Even though these designs will not be part of the final product, they contribute to the decisions made for the final product, thereby increasing its value. These alternatives may also provide a measure of flexibility in the face of changing information. In some cases an alternative that wasn’t chosen because of a design constraint may become a viable option again if that constraint is relaxed later in the development cycle.

Organizations that consider parallel research and development as an option will find that they are capable of making better decisions for their products. However, they must be prepared to support the strategy. The model has shown abandoning alternatives
prematurely does waste the resources used for a parallel strategy. The decision makers must be committed to following the strategy through for it to successfully influence the final design. Defining useful criteria for the comparison and ranking of the alternatives is critical to the success of the strategy. In some cases these criteria can be based on historical projects. However, for new product development it can be difficult to predict which criteria should be used to judge the alternatives.

Also, the organization must be ready to make use of the information that is generated from the parallel strategy. The amount of information compounds with each alternative added. The resources needed to coordinate the work also increase. Without preparation, the organization will not be able to truly benefit from the strategy.

However, new technology and design practices are also shifting the value of pursuing a parallel research and development strategy. Cheaper technology for experimentation and data analysis can mean that a parallel strategy may no longer require the capital investment it once did. Similarly, more modular designs mean that a parallel strategy can be more limited in scope thereby reducing the cost of the overall strategy. This shift in the economics of following parallel strategy makes it a more viable option to consider.

Organizations that consider a parallel research and development strategy and apply it to appropriate situations will produce higher quality products. They will also have greater flexibility to react to changing technologies and market forces. Barriers to applying a parallel strategy successfully are being lowered by new modeling and simulation technologies, and more modular designs. This shift makes understanding the factors affecting the parallel research and development strategy even more important to the development organization.
Bibliography


