Valuing flexibility in product platforms: An analytical framework

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Abstract

This thesis presents a new way of thinking about valuing flexibility in product platforms. It argues that by explicitly valuing flexibility, a product developer can, in many circumstances, bring a product to market faster and at lower cost, while maximizing expected economic returns over the product's lifecycle.

This possibility is developed by considering an analytical model which explores three cases: A single-purpose product, a dual-purpose product, and a single-purpose product which has the flexibility to be adapted to a second purpose. In comparing these three scenarios, the model considers development costs and simulates changes in the markets these products serve. In the case of the flexible product, the model considers whether the product's developer is likely to take the managerial decision to adapt the product for a second purpose. Finally, the model compares all costs and expected returns from each scenario, and finds that in many cases the flexible strategy both minimizes initial costs while maximizing expected returns.

Underpinning this procedure is a combination of statistics, cash flow modeling and methods of analyzing flexibility related to real options analysis. Real options analysis typically applies the methods of financial options analysis to valuing options in large-scale projects, including those in infrastructure, natural resource extraction and aerospace. This thesis draws concepts from this field and extends them to serially-produced products, providing a method of valuing flexibility in a product's scope as opposed to on a project's scale.

The thesis confirms the value of flexibility by presenting the results from a field study. The study confirms the appropriateness of the method proposed, and provides guidance on the situations where flexibility does and does not increase expected returns.

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"The intuitive mind is a sacred gift and the rational mind is a faithful servant. We have created a society that honours the servant and has forgotten the gift."

- Einstein

"Whatever you can do, or dream you can, begin it. Boldness has genius, power, and magic in it."

- Goethe

It is only with considerable help that I have traversed the steps that culminated in my signature on the cover of this document.

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To the many wonderful professors, instructors and lecturers who I have learned from during my time at MIT, I thank you for sharing your wisdom with me. In particular, to Michael Davies and Tom Steenburgh – thank you for leading me to discover that it is neither the courses, the research, nor the degree that make this journey worthwhile; rather, that the greatest gift of my time here will be a lifetime of intellectual curiosity and the boldness to take on incredible projects. To Jim Utterback – thank you for leading me to appreciate that intellectual, technological and managerial practice are, at their core, humanistic pursuits. Finally, thank you to Pat Hale and the SDM staff for the incredible job you do in pulling together the phenomenal System Design and Management Fellows program.

To the friends that I've made at MIT, thanks for continuously pushing me to learn more, work harder, and be smarter; I look forward to hearing about, and sharing in, the incredible exploits that await you in years to come. To my friends in Vancouver and scattered around the world, know that I draw strength from your existence, and that I look forward to seeing you again soon.

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Introduction

The intent of this thesis is to develop an analytical framework for valuing flexibility in a product's platform, by applying the methods and tools taught in MIT's System Design and Management program. Specifically, the framework draws on concepts associated with product platforms design, product development, economics, accounting and the adoption of innovative products into new markets. It also draws extensively on the concept of flexibility in engineering design.

This thesis proceeds in five sections. Section One describes the motivation behind this work, highlighting both the situation that faces product developers in deciding whether to build flexibility into their products, and the complication they face in making such decisions. This section concludes by presenting the hypothesis that this thesis will prove.

Section Two briefly describes the theory combined to develop the framework. This includes details of the set of methodologies that are combined to prove the hypothesis, and includes references to the prior work that informs the framework's structure.

Section Three describes the framework's implementation in Microsoft's Excel software. This incorporates details of the model itself, including all relevant functions, data structures, equations and outputs.

Section Four presents several use cases – one detailed, and six more general – that illustrate the outputs from the model. The detailed case is drawn from the author's own experience, while the six general cases are drawn from a variety of industries.

Finally, Section Five discusses the results of the case studies, uses those results to suggest the limitations of where this procedure is appropriate, presents conclusions on the value of flexibility, and presents recommendations for future work.

Motivation and hypotheses

When planning a new product, the product's developer must decide which market or markets the product will address. Made effectively, these decisions can have a critical impact on the product's success. Typically, the developer will consider a product's technological feasibility, its market demand and costs incurred to serve those markets, and on that basis will determine which markets to serve.

However, feasibility, demand and costs are dynamic variables that shift over the product's lifecycle; and while feasibility and costs can be reasonably estimated, predictions of changes in demand are much less accurate. This dynamic characteristic can mean that it is not clear to a developer which markets a product should be designed to serve.

This situation, and a method for how it can be clarified, is the subject of this thesis. This section will describe the motivation behind the thesis in greater detail, discussing the situation that developers find themselves in, and proceeding to the question of what they can do to resolve the complications within that situation.

1.1 Situation

In the product development process, product developers (hereafter "developers") have to make decisions about what markets their products will and will not address. In general, these decisions should take into account:

- Technological feasibility
- Market demand
- The cost of implementing a certain set of capabilities.

When considering whether to design their products to serve a given market, developers should thus compare the cost of implementing the features required for that market against the benefits of selling into that market, and on the basis of that comparison decide whether a set of market-specific features should be incorporated.

However, costs, demand and technological feasibility are dynamic characteristics of the product system, and may evolve differently from the developer's projection. In particular, though costs and feasibility are endogenous to the developer and can be estimated with reasonable certainty, market demand is an exogenous variable over which the developer often has little control. Thus estimates of market demand are often highly uncertain.

This leaves the developer with three options. They can either

1. Design the product with a limited feature-set strictly to serve a primary market,
2. Design the product with an expanded features-set to serve both a primary and a secondary market (or possibly several markets), or
3. Design the product to serve the primary market with the flexibility to serve a secondary market at a future time, should the state of that market evolve in the developer's favor.

Accordingly, developers frequently build flexibility into a new product. Such flexibility allows the product to adapt as new technologies become available, as new opportunities emerge in the market, and as implementation costs fall over time.

There are many ways of incorporating such flexibility, including:

- Modularization of the design
- Developing an extensible, adaptable platform as the basis for the product
- Incorporating linkages designed to connect future elements to the whole.

These, and similar tools, are well known within the product development literature.

Because the cost of developing a new product is proportional to its complexity (all else being equal – *ceteris paribus*), the product designed with additional features to serve multiple markets will have a higher development cost than the product designed for a single market. Similarly, the flexible design will cost more to develop than the single-market design. However, because the flexible design incorporates just the flexibility to develop features for multiple markets and not the features themselves, the flexible design will likely cost less to develop than the complete multiple market design.

The flexible option does, however, come at some cost to the product developer. Typical costs may include the:

- Additional development costs related to designing the flexible option
- Increase in cost of goods sold for each instance of the product
- Cost to incorporate the flexible option, once that decision is made
- Incremental lifetime cost of supporting a more complex product
- Marginal decrease in customer interest as the product becomes more complex.

1.2 Complication

The challenge the product developer faces in considering including this flexibility is that the analytical models used to evaluate the product's expected value typically do not adequately reflect a flexible product's total costs nor likely returns. Product developers will often use a Net Present Value ("NPV") model to predict the economic outcome of their project. This presents several complications.

First, NPV models are deterministic, in that they are based on single estimates of future cash flows. This deterministic view is insufficient, as predictions of future market conditions are frequently inaccurate. A stochastic model, one that accounts for the randomness of future market conditions, could much better arrive at a reasonable prediction of the product's expected value.

Second, NPV models generally do not take into account the cash flows that may accrue from secondary markets; markets that may be addressed by executing flexible options later in the product's lifecycle. Conversely, a NPV model typically does include the cost of incorporating such flexibility into the product design at the initial development stage.

Finally, not considering the potential benefit of a flexible element means that returns from the product are underreported in the analytical process. Executing the option afforded by the flexible element will be the result of a managerial decision; a decision we can assume will (on balance) improve the product's expected returns. Not including the positive impact of these decisions thus undervalues the project overall. This may make it more difficult for the developer to secure sponsorship (financial or otherwise) for the project.

The result of these complications is that the developer's decision to include flexible elements will not be based on expected economic returns. Instead, the developer must rely on experience, intuition or similarly vague measures in combination with rudimentary economic analysis to make a decision. This makes it difficult for the developer to arrive at accurate conclusions about whether the flexible element should be included.

1.3 Question

The question, then, is whether a framework can be developed to improve managerial decision-making in new product development. Such a framework should:

- Inform decisions around what flexible elements should be included in the product system
- Inform the decision of whether to proceed with a product development project, once the flexible elements are considered.

Such a framework should reflect the

- Cost of developing an inflexible product to serve multiple markets
- Costs of incorporating the flexible option into the product's architecture
- Costs of carrying the flexible option through the lifecycle of the product
- Costs of the managerial decision to exercise the flexible option
- Additional revenues that are expected to flow from having executed the option.

1.4 Hypotheses

This thesis will argue that a framework can be developed to make such decisions, and will develop the details of that framework. The framework will draw on analytical tools derived from statistics, cash flow modeling and the analysis of flexible options.

The hypotheses to be explored are:

- ***Hypothesis 1:*** *By considering elements of a product's design as flexible options, a product developer can <u>make effective decisions</u> on which markets a product should be designed to serve, based on costs to serve and anticipated returns from those markets;*
- ***Hypothesis 2****: By incorporating functions representing managerial decisions into a conventional product cash flow model, a product developer can effectively <u>assess expected returns</u> over the product's entire lifecycle; and*

- ***Hypothesis 3**: By implementing this managerial flexibility, a product developer may be able to bring a flexible product to market at <u>substantially lower cost</u> than comparable inflexible designs.*

This thesis explores these hypotheses by developing a model for conducting such analysis, using tools commonly available to product development practitioners.

Note that this framework is intended for manufacturer-side decision making only. Though a customer for large, technologically complex products may well consider the value of flexibility of a new product within their enterprise's architecture, this thesis does not specifically consider that related viewpoint.

Theoretical foundation

This thesis explores the hypotheses posited above by developing a comprehensive model, then testing that model against real-world scenarios to ensure that the goals underlying the hypotheses can actually be achieved.

Before building the model itself, it is necessary to understand the theoretical basis on which the model is developed. The model draws on knowledge from seven different fields, including

- Flexibility
- Flexible options
- Options valuation
- Monte Carlo simulation
- Statistical distribution of likely outcomes
- Rates of product adoption
- Cost modeling.

The theories supporting these seven categories are described briefly in the sections that follow.

2.1 Flexibility

The concept of flexibility within a product platform is well established within the engineering and systems design disciplines; see for example (Baldwin and Clark 2000), (Saleh, Mark and Jordan 2008) or (Suh, de Weck and Chang 2007). What is not as well established is how value flows from that flexibility, and how that value can be quantified.

Within the options literature, the value of flexibility is perhaps defined best by Hassan, who stated that “Flexibility (is) the ability of the system to be actively managed against uncertainty by hedging risk and exploiting upside opportunities in order to maximize a system’s value over its lifecycle” (Hassan 2007).

Within the engineering disciplines, flexibility is usually defined in terms of developing products that are better able to serve a broader set of markets, applications or mission than more rigidly-defined products. This flexibility is sometimes defined in a broader sense: In their 2005 paper “Design for Changeability, Fricke and Schulz defined flexibility as one aspect of a product’s “Changeability” or ability to react to change in the environment (physical, environmental or economic) in which it operates, shown graphically in Figure 1.

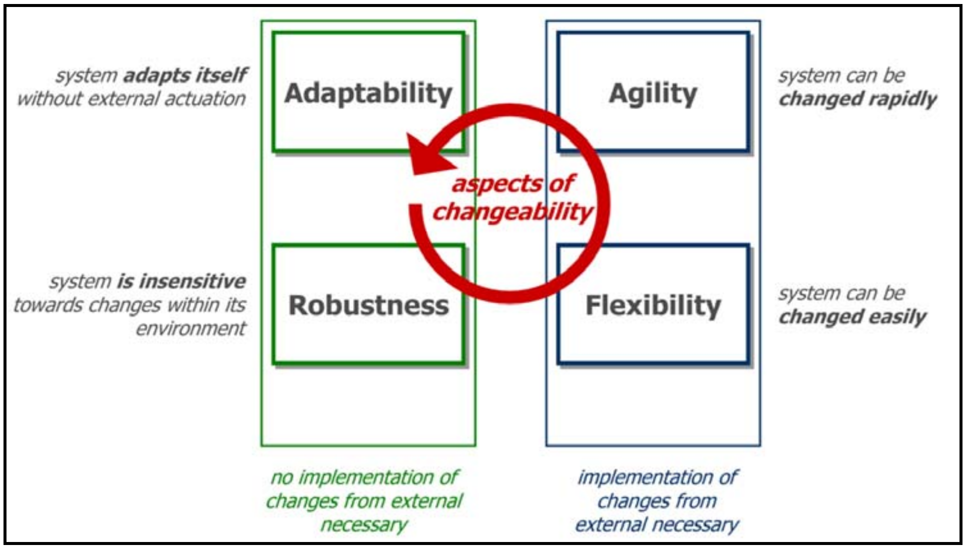


Figure 1: Flexibility as an aspect of changeability

(Fricke and Schulz 2005)

Within product development, the concept of flexibility is also closely related to “product platforms” and “product families”. To quote Meyer and Lehnerd’s book “The Power of Product Platforms”:

> *Product families do not have to emerge one product at a time. In fact, they are planned so that a number of derivative products can be efficiently created from the foundation of common core technology. We call this foundation of core technology the “product platform”, which is a set of subsystems and interfaces that from a common structure from which a stream of derivative products can be efficiently developed and produced. A platform approach to product development dramatically reduces manufacturing costs and provides significant economies in the procurement of components and materials, because so many of these are shared among individual products. Perhaps as important, the building blocks of*

> *product platforms can be integrated with new components to address new market opportunities rapidly"* (Meyer and Lehnerd 1997, xi)

Most importantly, as is the focus of this analysis, flexibility allows the product developer to eliminate the up-front cost of developing a product to serve multiple markets, while ensuring that the product platform can, through flexible elements, reap the full benefits of all possible markets should they develop favourably over time.

By way of illustration, consider the following example: A car company is considering developing a new compact car. The primary market for the car is commuters; however, the company feels there may be a market for the car to be used for more utilitarian purposes by families and small business owners. This market may develop in particular if fuel prices rise and buyers in this secondary market no longer consider it economically feasible to operate larger vehicles. The carmaker has two choices: They can develop a vehicle to serve both markets, or they can develop a vehicle that, though initially designed for a first market, can be used as a platform for developing a variant to serve the secondary market should that market evolve favourably. This flexible option will be much less expensive both to develop (since the initial design requires fewer features) and to manufacture (since features not explicitly needed for the primary market are not included in the initial product offering). This strategy could yield substantial savings, by allowing the carmaker to address the primary market comparatively quickly and at lower cost, while still providing the opportunity to capture value from the secondary market at a later time.

Despite all of the above, there remain few analytical methods for assigning value to flexibility itself. None of the references noted above provide a method for discretely valuing flexibility, beyond identifying that it is beneficial. In their 2008 article "Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems", Saleh, Mark and Jordan state that:

> *"…there is not yet a coherent set of results that demonstrates how to embed flexibility in the design of engineering systems, nor how to evaluate it and trade it against other system attributes such as performance, risk, or cost."* (Saleh, Mark and Jordan 2008, 9)

To build this link between flexibility and an engineering system's cost attributes, we can turn to the concept of flexible options valuation.

2.2 Flexible options

The concepts underlying the valuation of flexible product options derive largely from the field of "real options", which in itself originates from methodologies developed in the field of financial options analysis.

Options theory originates from methodologies developed in the field of financial analysis. Starting in the early 1970s, a body of work began to emerge that put explicitly values on *the right, not the obligation* to either acquire or dispose of a financial asset (Black and Scholes 1973). These methods have found widespread use in financial markets.

Real options are an extension of this theory, applied in general to "real world" instead of financial instruments. Real options allow managers to build options into products and projects in the real world. The methodology has found widespread use in industrial practice, notably in

> *"pharmaceutical drug development, oil and gas exploration and production, manufacturing, e-business, start-up valuation, venture capital investment, IT infrastructure, research and development, mergers and acquisitions, e-commerce and e-business, intellectual capital development, technology development, facility expansion, business project prioritization, enterprise-risk management, business unit capital budgeting, licenses, contracts, intangible asset valuation, and the like."* (Mun 2006, 17)

Though the theory underpinning real options is similar to financial options, because of the multidimensional nature of decision making in real projects the scope of decisions to which real options analysis can be applied is much broader. In his book *Real Options in Practice*, Marion Brach identifies six basic managerial options that can be analyzed using a real options approach:

1. The option to Defer: Wait until further information reduces market uncertainty.
2. The option to Abandon: Dispose of an unprofitable project.
3. The option to Switch: Exchange input / output parameters or modus operandi
4. The option to Expand/Contract: Alter capacity depending on market conditions

5. The option to Grow: Entertain future-related opportunities
6. The option to Stage: Break up investment into incremental, conditional steps. (Brach 2003, 67)

The analytical challenge in assessing real as opposed to financial options is that financial options exist within a narrowly defined space – the "market" – and have well defined identifying characteristics. By contrast, real options exist "in the world", and thus have a much more complex set of attributes associated with them. Mun's "Real Options Analysis" suggests the following as the major differentiation between the two.

Table 1: A Comparison of Financial And Real Options

Financial Option	**Real Option**
Short maturity, usually in months	Longer maturity, usually in years
Underlying variable driving its value is equity price or price of a financial asset	Underlying variables are free cash flows, which in turn are driven by competition, demand, management
Cannot control option value by manipulating stock prices	Can increase strategic option value by management decisions and flexibility
Values are usually small	Major million- or billion-dollar decisions
Competitive or market effects are irrelevant to its value and pricing	Competition and market drive the value of a strategic option
Have been around and traded for more than three decades	A recent development incorporate finance within the last decade
Usually solved using closed-form partial differential equations and simulation / variance reduction techniques for exotic options	Usually solved using closed-form equations and binomial lattices with simulation of the underlying variables, not on the option analysis.
Marketable and traded security with comparables and pricing information	Not traded and proprietary in nature, with no market comparables
Management assumptions and actions have no bearing on valuation	Management assumptions and actions drive the value of a real option.

(Mun 2006, 110)

Perhaps the most critical aspect of real options, though, is that the option itself implies a manager's right, but not obligation, to exercise a particular decision at a future time. This means that in a product developer's cost modeling, the value of future decisions can be explicitly incorporated in calculating expected returns from a project. As Guthrie states in "Real Options in Theory and Practice":

> *"Under static decision making, the manger's actions at every future date n depend only on information available to the manager at date 0. In contrast, under dynamic decision making the manager's actions depend on all information available at date 0 as well as all new information revealed between dates 0 and n.* (Guthrie 2009, 20)

Since we can reasonably assume that any manager's future decisions are likely to improve the performance of the project over time, we can conclude that incorporating flexible options into the project plan can increase the financial performance of the project over its entire lifecycle.

2.3 Option valuation

Within the real options and flexible options valuation literature there are three general categories of methods for valuing options:

- Models based on closed form and partial differential equations
- Models based on binomial functions, and
- Models based on simulations of stochastic models.

The following sections describe these three groups.

2.3.1 Closed form and partial differential equation solutions

The Black-Scholes equation was first proposed by Fischer Black and Myron Scholes in 1973 (Black and Scholes 1973), then expanded into the "Black-Scholes option pricing model" by Frank Merton later that year (Merton 1973). This method can "be used to price the various elements of the firm's capital structure…we can use the total value of the firm as a "basic" security (replacing the common stock in the formulation of this paper) and the individual securities within the capital structure (e.g., debt, convertible bonds, common stock, etc.) can be viewed as "options" or "contingent claims" on the firm and priced accordingly" (Merton 1973, 178).

Unfortunately, the Black-Scholes-Merton method makes several critical assumptions that invalidate its direct use with real options problems. Specifically, the Black-Scholes equation requires that

- "Returns must be log-normally distributed,

- Securities must be continuously traded, and
- There must be complete markets that provide an unlimited number of options to trade with." (Brach 2003, 331)

While these may be reasonable assumptions in financial markets, they are simply not practical for physical projects or products. It is hard to imagine a "continuously traded" market for the expansion of a copper mine, for example. However, the Black-Scholes-Merton method was critical to the later development of real options methods, as it formalized the use of many of the inputs to our analysis, including the costs to acquire and to execute the option.

2.3.2 Binomial functions

Because of the limitations of the Black-Scholes-Merton method, real options practitioners have sought an alternative form of modeling options without relying on the limitations of the continuous model. This is done by considering the option as a series of discrete steps, where at each step the option may be executed.

This binomial method, first developed by John Cox and Stephen Ross in their 1975 paper "The Valuation of Options for Alternative Stochastic Processes", is currently in widespread use (see, for example, (Rocha and Delamaro 2007), (Jiao, Kumar and Lim 2006), (Brach 2003) or (Guthrie 2009)). Because closed-form solutions can be developed from binomial models, and because they are comparatively simple to understand, they are likely to remain a common means for modeling some real options problems. An example of a binomial options model, showing its closed-form solutions, is as shown in Figure 2.

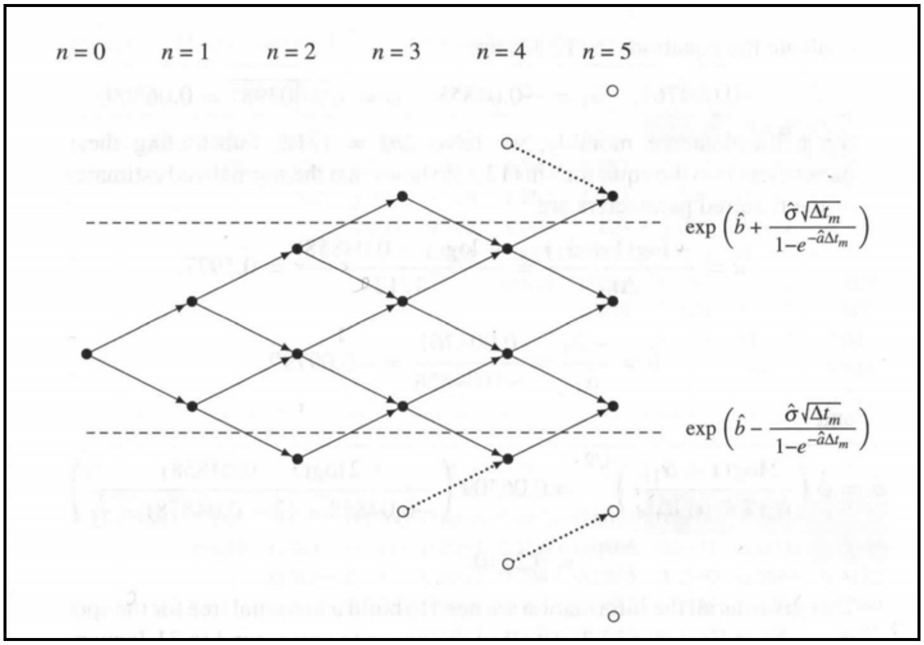


Figure 2: Binomial option

(Guthrie 2009, 277)

2.3.3 Stochastic simulations

The third common way of modeling flexible options is to use the so-called “random walk” over time. The random walk is defined as “the stochastic process formed by successive summation of independent, identically distributed random variables” (Lawler and Limic 2010, ix). This procedure essentially repeatedly projects the next in a sequence of steps by taking the current value and projecting forward in some way. Random walks are sometimes referred to as Brownian motion, although Brownian motion refers specifically to the physical process of particle diffusion in space, not the mathematical model by which that motion is defined. Mathematically, the additive random walk can be described by the following relation:

$$X(t) = X(t-1) + \varepsilon(t) \text{ (de Neufville and Scholtes 2011)}$$

When $\varepsilon(t)$ takes a fixed value, the random walk will appear to take the same step size at each instance. This yields a fairly regular random walk, as shown in Figure 3.

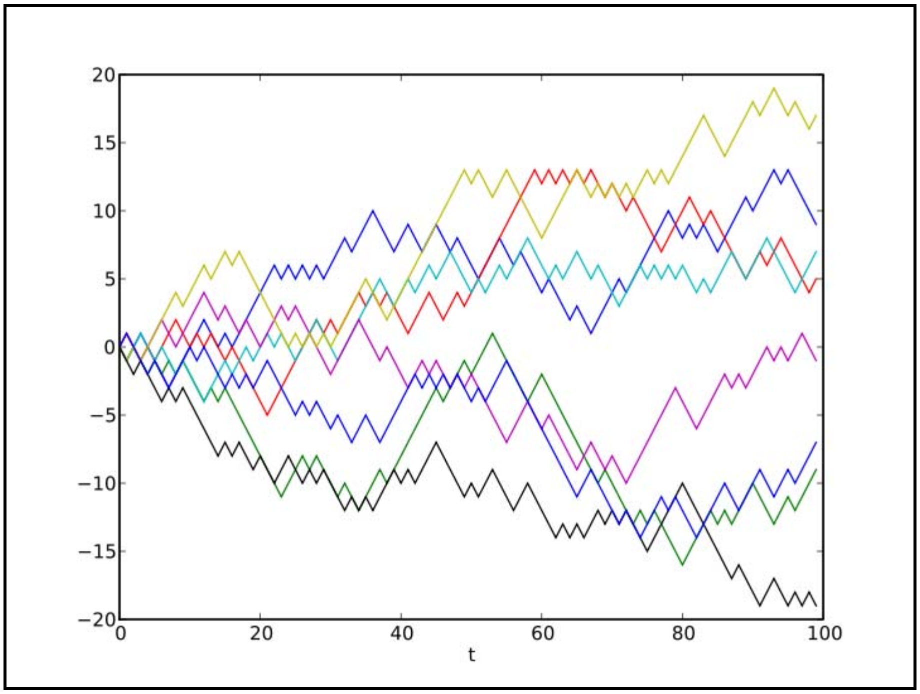


Figure 3: Random walk; note identical step sizes

(Wikipedia 2011)

Though this is a good way of modeling some processes – for example, the outcomes of a series of coin tosses – it is limited in that step sizes are fixed.

To allow the steps in a random walk to vary randomly, we can model the step size as a distribution of outcomes. If the step size is normally distributed the function becomes known as a "gaussian random walk"; this model is one of the more commonly used functions for modeling financial decisions (Magoc and Kreinovic 2009)

As compared with the basic random walk, the Gaussian random walk appears more random; in Figure 4, note how both the direction and magnitude of each step forward vary.

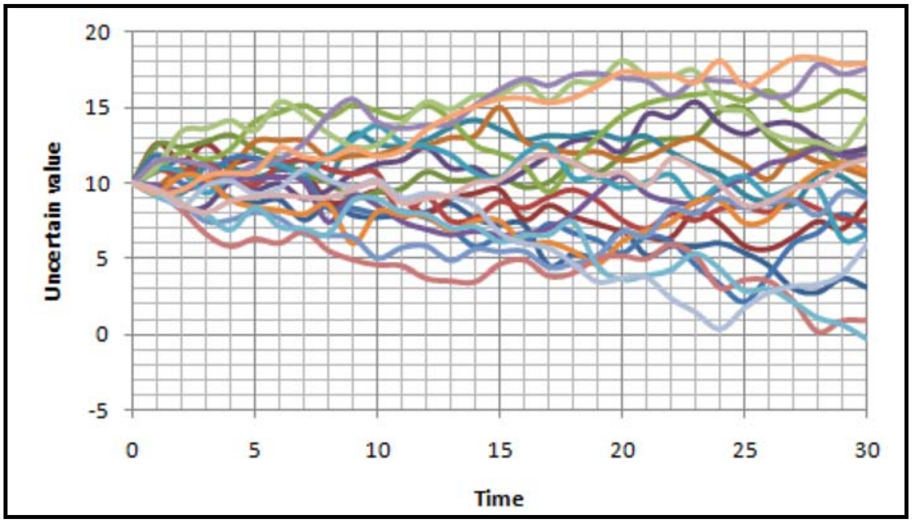


Figure 4: Gaussian random walk

(de Neufville and Scholtes 2011, Figure E.7)

On the basis of these three descriptions, it would seem that the Gaussian random walk is the best form for our particular model, specifically because it

- Does not require the strict conditions of the Black-Scholes-Merton method
- Does not conform to the rigid step shapes of the binomial form
- Is cited as being a frequently used model for financial analysis
- Appears intuitively to follow the random path that one would expect from the complex, multivariable system that is a product's target market.

For the Gaussian random walk to be useful, it needs to be combined with a statistically significant number of iterations, and then those iterations need to be aggregated in a way that provides information on the model's overall performance. This is the function of Monte Carlo simulation.

2.4 Monte Carlo simulation

The goal of Monte Carlo simulation is to develop a model which contains some form of uncertainty, then to execute that model a great many times. Given a sufficiently large number of trials, and assuming the model is built correctly, Monte Carlo simulation leads to a distribution that represents the probability of outcomes from any given instance of the situation represented by the model.

The use of Monte Carlo simulations in options analysis dates back to 1977, and work originally published by Phelim Boyle at the University of British Columbia. Boyle sought to develop an alternative to the closed-form equations derived from partial differential equations that had previously been the focus of Black and Scholes' work; a technique that is "simple and flexible in the sense that it can be easily modified to accommodate different processes governing the underlying stock returns" (Boyle 1977, 324). The major limitation at the time was computing power: Boyle limited his models to 5000 iterations only, and devoted a good part of his paper to analyzing and proposing methods for improving on the possible errors given this limited number of iterations.

One of the most powerful reasons for using Monte Carlo simulation is that it allows complex problems to be solved without arriving at very complicated closed-form solutions, the sort of which require advanced mathematical skills. In another section of his book "Real Options", Jonathan Mun summarizes this situation as follows:

> *"…for the practitioner, simulation opens the door for solving difficult and complex but practical problems with great ease. Monte Carlo creates artificial futures by generating thousands and even millions of sample paths of outcomes and looks at their prevalent characteristics. For analysts in a company, taking graduate level advanced math course is just not logical or practical. A brilliant analyst would use all available tools at his or her disposal to obtain the same answer the easiest and most practical way possible. And in all cases, when modeled correctly, Monte Carlo simulation provides similar answers to the more mathematically elegant models."* (Mun 2006, 316)

2.5 Distribution of outcomes

Having combined the Gaussian random walk with Monte Carlo simulation to yield valuable results, there remains one final question: whether a normal distribution best represents the individual steps within the random walk. It is conceivable that other uniform or log-normal distributions could be appropriate – especially since the Black-Scholes model assumes a log-normal distribution (Boyle 1977). Other more exotic distributions could also be considered.

However, in his book “Real Options”, Jonathan Mun proposed that the normal distribution is typically the best distribution, as

> *“Decision makers can use the normal distribution to describe uncertain variables such as the inflation rate or the future price of gasoline. The three conditions underlying the normal distribution are:*
>
> 1. *Some value of the uncertain variable is the most likely (the mean of the distribution);*
> 2. *The uncertain variable could as likely be above the mean as it could be below the mean (symmetrical about the mean);*
> 3. *The uncertain variable is more likely to be in the vicinity of the mean than further away.”* (Mun 2006, 370)

These three conditions are generally true of the changes over time in a product’s market. Moreover, the normal distribution is easily implemented in most spreadsheet and other analytical tools. Thus it is reasonable to select this distribution.

Practically, though, there are limits that need to be applied to the normal distribution. This stems from the fact that the distribution is, on its own, unbounded in the extreme values that it can produce. This can produce one of two results – either the size of a market may become negative, which has no reasonable meaning, or the size of the market may become far larger than is practical, if many consecutive trials indicate significant growth. Thus the model should place appropriate, rational boundaries on the values for market size that can be returned in each iteration.

2.6 Product adoption

In order to analyze the rate at which products are sold into a market, it is necessary to understand how quickly new products are adopted. A very simple model will consider this rate of adoption, the ultimate size of the market, and the relative maturity of the market to project anticipated sales at a given time.

Much modern thought on the rate and timing of the adoption of new products is based on Everett Rogers’ book “Diffusion of Innovations”, first published in 1962. Rogers calls diffusion “The process by which (1) an *Innovation* (2) is *Communicated* through certain *Channels* (3) over *Time* (4) among the members of a social system.” (Rogers 1995, 11)

Rogers was the first to extend this notion of diffusion to product adoption, and proposed the s-shaped logistic curve that has been widely adopted by many influential authors in the field of product and market development, including Clayton Christensen in "The Innovator's Dilemma" (Christensen 1997) and Geoffrey Moore in "Crossing the Chasm" (Moore 1991).

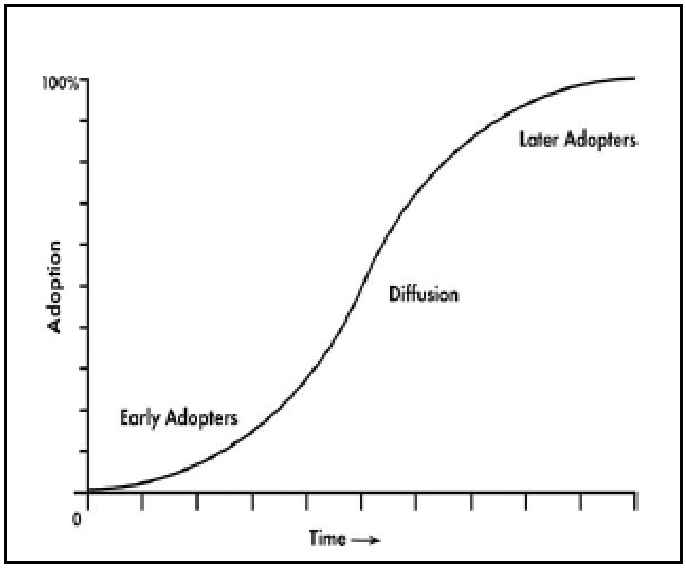


Figure 5: Rogers' diffusion model

(Rogers 1995, 11)

More recently, several authors have refined this basic logistic curve to reflect a variety of mathematical models, including those by Bass and Lotka-Volterra. However, for the purposes of this work we are interested only in the gross shape of the adoption curve, not the details of its mathematical formulation. Thus Rogers' original assertion – that diffusion of new products starts slowly, accelerates over time then eventually decreases as the product matures – will be sufficient for the model under consideration here.

2.7 Economic Analysis

The final element of this model is perhaps the most widely understood, but also the most critical. For the value of a flexible product platform to be reported, the simulated random events underpinning the model must be used as inputs to a model of the product's economic performance over time.

It is beyond the scope of this work to consider the fundamentals of product cash flow modeling; textbooks on both product development (such as (Ulrich and Eppinger 2008)) and accounting (see, for example, (Weygandt, Kimmel and Kieso 2003)) cover this subject in great detail.

The critical component of the cost model from our perspective is the point of execution of the option itself. In order for a Monte-Carlo based options simulation to work, the “managerial decision” that is the option itself must be incorporated into the cost model. This allows the cost model to automatically be adjusted depending on whether the option is executed or not. If the option is executed, the economic analysis automatically calls into play the costs of bringing the flexible product option to market, while at the same time calculating the expected returns from that product once it is launched.

Method: Model development

This section presents the elements of the analytical framework that allow the exploration of this thesis's hypotheses, based on the theory discussed in the previous section. This framework, implemented in Microsoft Excel, incorporates the factors considered and discussed below.

A major reason for developing this model in Excel as opposed to in other analytical packages is that Excel is a tool that is both almost universally available to and easily understood by product development managers. This fact, combined with the emphasis in the following sections on making the model comprehensible and usable, will allow practitioners to fully understand the model and use it to drive real managerial decisions.

This section of the thesis is divided into four sections. First, immediately below is a discussion of the overall structure of the model, including a description of the strategic decisions facing the product developer, one of which will be selected on the basis of the model's output. Second, a section is included which discusses the inputs to the model, and why they are needed. The third section details the Monte Carlo simulation that will form the basis of the model's output; this includes a discussion of the sales forecasting and cash flow models that form a critical part of the simulation. Finally, the fourth section presents the methods by which the model's output can be compared, allowing the manager to assess the model's outcome and decide on an appropriate course of action.

3.1 Overall structure

The model presents three potential strategies that the product developer may implement at the outset of the product's development. The first possible strategy is for the product developer to address the primary market only. This has the likely benefit of minimizing development cost, but does not allow the developer to capture value from the secondary market.

The second possible strategy is for the product developer to address both the primary and secondary markets with a single product. This will, in most cases, increase the cost of product development since features required for both markets need to be included in the product's design. It may also increase the cost of goods sold into that market, for similar reasons. However, this strategy ensures that the developer is able to capture value from both markets.

The third possible strategy is for the product developer to develop a product that addresses only the primary market, but that has the flexibility to be extended to serve the secondary market at a future time. This strategy will combine the lower development cost and cost of goods of the first strategy, but will retain the ability to capture value in the secondary market should the manager decide to address that market at a later time. Because only the costs for the primary market are incurred up-front, and costs for the secondary market may never be incurred, this strategy will allow the product to be brought to market at significantly lower cost than the second, multi-market strategy.

A flowchart detailing the overall model structure and elements is as shown in

Figure 6.

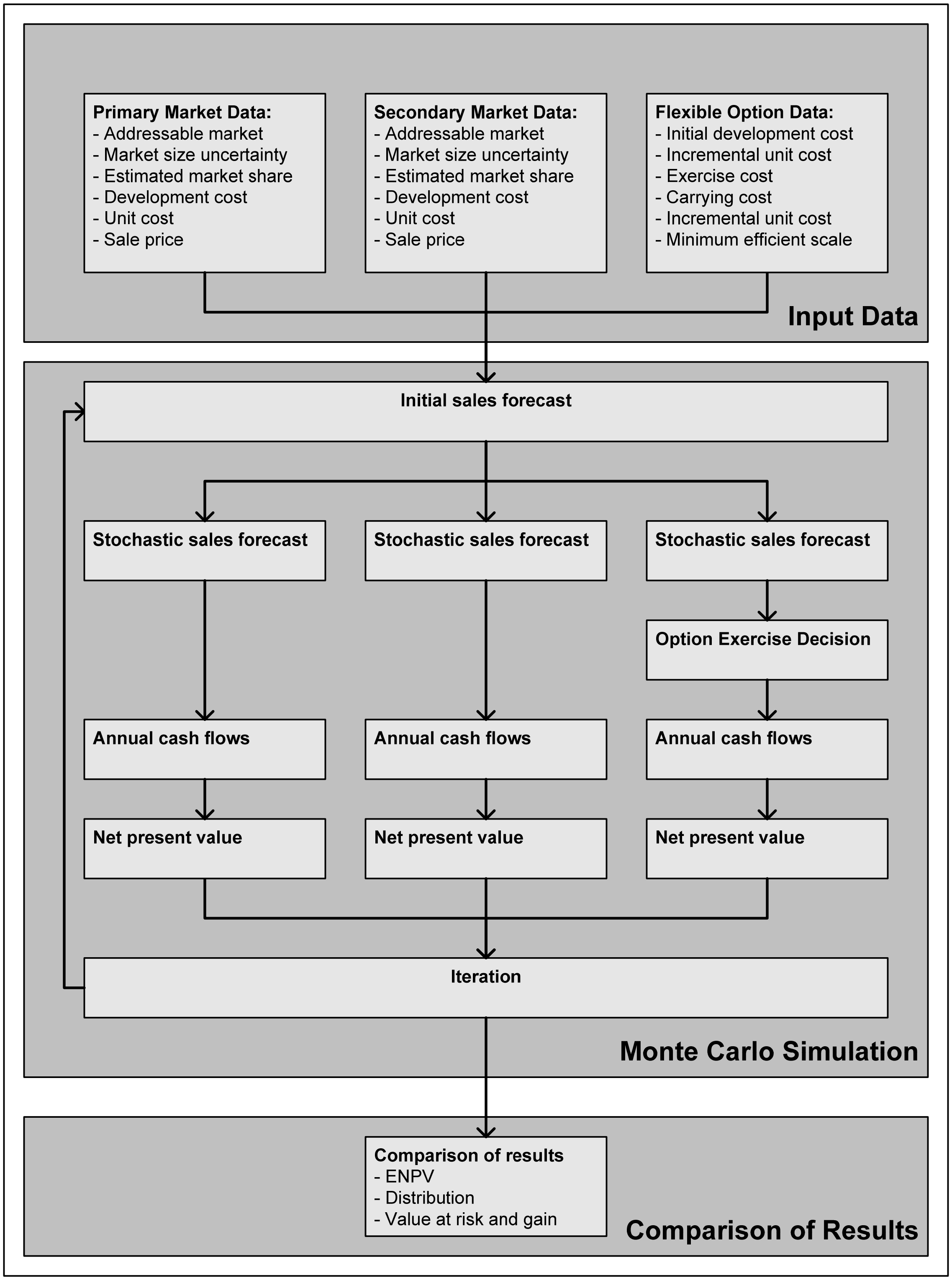


Figure 6: Model overview

3.2 Input data

The first step in developing the analytical model is to gather information about the markets that the product could potentially serve. This is done for the two separate markets, and for the option characteristics of the flexible product.

The Primary market is the one that the product will first serve; most typically, this is the market that both spurred the original product concept or has come to be regarded by the developer as the most important. The Secondary market is the one which the developer is considering designing for, which, given the outcome of the model, the developer may choose to develop the flexible option to enter at a future time.

For both the primary and secondary market, the following information is required:

- Addressable market
- Market size uncertainty
- Sale price
- Estimated market share
- Time to maturity.

Then, the products that address these primary and secondary markets have the following data associated with them:

- Development cost
- Cost of goods sold.

The flexible option that addresses the secondary market based on the product developed for the first has the following characteristics:

- Incremental development cost, initial
- Incremental development cost, at execution
- Carrying cost, per unit
- Minimum efficient scale.

Finally, there are several data that are endogenous to the product developer's organization that need to be considered, including:

- Discount rate
- Learning curve effects on the cost of goods sold.

For each of these data, the following will be discussed:

- The theory underpinning the element's inclusion in and relation to the model
- The mathematical relationship between the element and the model
- The nature of the data required from the element
- The managerial work needed to arrive at a value for the element.

Details of these data are discussed in the sections that follow.

3.2.1 Market size

This is the product developer's estimate of the total forecast market for the current product. Forecasting is a notoriously inaccurate process; 'the forecast is "always wrong"' (de Neufville and Scholtes 2011, 5). However, some reasonable forecast is required as an input to most strategic planning activities, particularly in product development. In "Real Options", Jonathan Mun suggests the following methodologies and rationales that a manager may choose to use to generate a market forecast:

- "Time series – Performs time-series analysis on past patterns of data to forecast results. This works best for stable distributions where conditions are expected to remain the same.
- Regression – Forecasts results using past relationships between a variable of interest and several other variables that might influence it. This works best for situations where you need to identify the different effects of different variables. This category includes multiple linear regression.
- Simulation – Randomly generates many different scenarios for a model to forecast the possible outcomes. This method works best when you might not have historical data but you can build the model for your situation to analyze its behavior
- Qualitative – Uses subjective judgment and expert opinion to forecast results. These methods work best for situations for which there are no historical data or models available." (Mun 2006, 375)

No matter which technique a manager chooses, their estimates will merely be inputs to the simulation developed here; the results that will eventually be considered will incorporate both this estimate and the uncertainty in market outcomes.

3.2.2 Market size uncertainty

A key strength of a flexible approach to product development is that it allows the product developer to take advantage of opportunities that arise when market circumstances swing unexpectedly in the developer's favor. Put simply, a developer adopting a flexible approach can take advantage the upside of uncertainty, while being protected against the potential downside.

The challenge in building a model is that it is very difficult to predict what the uncertainty is in a given market. One of the difficulties lies not so much in the magnitude of the uncertainty itself, but in expressing that uncertainty in a way that is intuitive and comprehensible to the average practitioner.

In "Real Options", Jonathan Mun suggests a methodology whereby the uncertainty in a market can be approximated by determining both the expected market size and the reasonable best case scenario for what the market size could be. As shown in Figure 7, this reasonable upper boundary is defined as the value which will only be exceeded by a small percentage of potential outcomes. Analytically, this value can then be converted into a variance for the distribution, which can then be used to conduct statistical analysis.

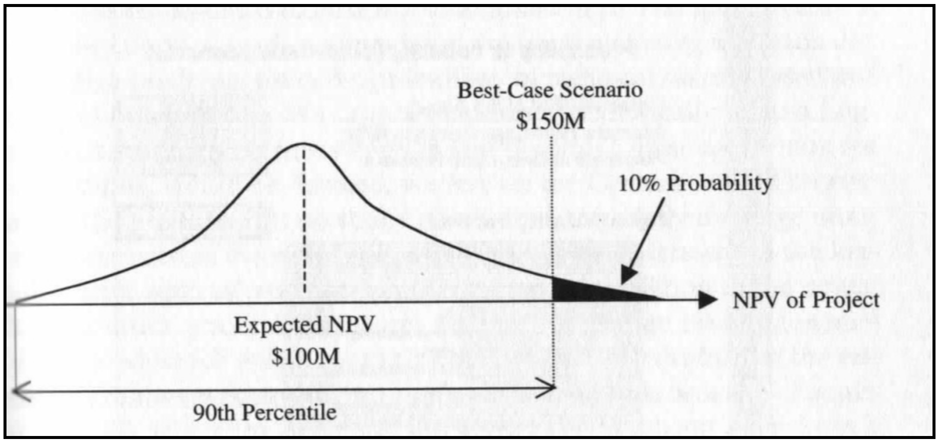


Figure 7: Manager's estimate of volatility

(Mun 2006, 207)

Details of how this method is implemented in this the framework developed here is discussed in the sections below. However, in terms of inputs, the manager in this case is expected to predict the upper 5% confidence band – that is, the possible market size that may be exceeded only approximately 5% of the time.

3.2.3 Sale price

This is the price at which the product developer believes that the product may be sold. This can vary over time, or may be static. The model developed here assumes a static sale price, though it could easily be modified to incorporate changes in price over time according to the developer's beliefs.

3.2.4 Estimated market share

The estimated market share represents the degree of dominance that the developer feels they have within the particular market. It is the absolute fraction of all sales into the market which they feel they will capture. This value is again subject to the manager's assumptions, and may be determined by factors such as:

- Number of firms selling competitive products
- Comparative dominance of the developer's brand over competitors
- Comparative performance of the developer's product over competitors
- Historical values for the developer's comparable products.

3.2.5 Time to obsolescence

Except in industries where good historical data on existing products exist, or for products where replacement is planned in advance, the time to obsolescence is again likely to rely on the manager's best estimates. In this model, "obsolescence" is taken to mean the point where the product is either rendered uncompetitive by improved products available on the market or is replaced by a company's new offerings. In either case, this time is the effective duration of the product sales cycle. Once the product is obsolete, this model assumes no further sales will occur.

3.2.6 Development cost

The development cost is the cost that the developer invests to develop the product to the point where it can be manufactured. It may include:

- Product planning
- Market research
- Product engineering
- Prototyping
- Testing
- Certification
- Facility development
- Production startup. (expanded from (Ulrich and Eppinger 2008))

3.2.7 Cost of goods sold

The cost of goods sold (or COGS) represents the total cost of a single unit of production – including all direct material, direct labor and allocated overheads.

This model makes one significant assumption about this figure. A product's COGS typically includes the overheads directly related to production only. This model, however, assumes that the COGS includes all costs related to the company executing an individual sale. This assumption is atypical in commercial practice, where a company will typically report overhead costs (particularly sales, general and administrative charges) separately (Weygandt, Kimmel and Kieso 2003). However, as a means of allowing the overall costs of bringing a product to market, and allowing that cost to scale with the number of units sold, this simplification is effective and realistic. Care must be taken, however, to ensure that this difference is explained to any practitioner using the model, as it varies from the accepted convention.

3.2.8 Flexible product incremental development cost, at execution

The option exercise cost is the cost to develop the features for the new market once the manager makes the decision that that market should be addressed. In many cases, this will be very similar to the cost to build features for the secondary market into the inflexible product; that is, the costs that are deferred by building an option for possible exercise at a later date. However, specific circumstances (such as costs to re-certify a regulated product, for example) may increase this cost substantially over the initial savings.

3.2.9 Flexible product incremental development cost, initial

Despite having saved a significant amount on not developing features for the secondary market, the developer may incur some costs at the time the product is initially developed that accrue explicitly to the flexible option. Such costs may include:

- The cost to analyze whether the option should be included as part of the product's architecture
- The cost to design the interfaces to features that may eventually exist should the flexible option be brought to market
- The cost to verify that the flexible option's elements have been designed correctly.

3.2.10 Flexible product carrying cost

The option carrying cost is the component of the flexible product's cost that accrues to the option, but that is present even when the option has not been exercised. For example, a physical product may include structural reinforcements to support features that make up the flexible option; those structural reinforcements will be present even when the option is not exercised. In order to make a reasonable comparison against the single-market strategy, these costs must be included.

3.2.11 Minimum efficient scale

The minimum efficient scale ("MES") is the product developer's estimate of how big a the opportunity needs to be in a secondary market in order to enter that market. This will frequently be based on the costs to enter and expected returns from that secondary market, though there may be other factors the developer wishes to take into account. If the market for the flexible option exceeds the MES, the option should be executed.

3.2.12 Discount rate

The discount rate is the rate at which the firm discounts future cash flows back to the present for the purposes of financial analysis. The specific means by which this figure is determined varies from firm to firm, typically includes the expectations of returns on working capital used to fund the project, as well as some measure of risk.

3.2.13 Magnitude of learning curve effects

Learning curves are a way of including in the model the ability of an organization to improve its operational performance over time, thus delivering identical products at progressively lower costs. In this instance, the function incorporated into the model decreases costs over time by a fixed amount for every doubling of the total number of units produced, according to the following formula:

$$Y= Y_0 * x^n$$

Where:

- Y = cost to produce unit x
- n = log b/log 2
- b = learning curve factor (~80-100%).

Having proposed the formula above, (de Weck 2010) proceeds to recommend the following learning curve factors:

- Fabrication 90%
- Assembly 75%
- Material 98%.

Thus for each instance of the model, the manager must choose an appropriate value for the learning curve factor based on the dominant costs contained within the final product.

One necessary adjustment to this formula is that, in serially-produced products, development managers will have a very good understanding of the costs of the first production article; however, the costs associated with a first prototype article are both harder to assess and less likely to be reflective of the ultimate product cost. Since the exponential model presented here decreases costs rapidly in the first few units, to be used effectively the learning curve equation must be used as follows:

1. The first production article unit cost is determined;
2. The total number of prototype articles is determined;
3. The learning curve equation is used to project back to get an estimated first prototype article cost; and
4. Finally, the learning curve equation is then used to project forward to any period, using the cumulative production to that period to assess the actual unit costs.

Details of how this equation is implemented in the framework developed here can be found in Appendix 2.

3.2.14 Other considerations

There is one further cost that could be considered significant – the cost of product sales not realized because of a negative impact of the flexible option to the product's overall performance or perceived value. For example, if a flexible option built into a commercial airliner increases the mass of that airliner, how many sales will the manufacturer lose to competitors because of that increased weight?

In the preparation of this thesis, no evidence was found directly linking such flexibility with loss in market share. However, this effect could be significant; future work in the field may seek to further elucidate this relationship.

3.3 Monte Carlo simulation

The Monte Carlo simulation executed in this model contains four steps:

1. Stochastic projection of actual sales;
2. Determination of cash flows based on the actual sales;
3. Summation of the project's net present value; and
4. Iteration.

The details of how these steps are executed are detailed in the following sections. Note that, for brevity, the entire spreadsheets used in the calculations are not included in this section; please see *Appendix 1: Model Results for Detailed Case* for an illustration of the complete model.

3.3.1 Project of actual sales

Market size

The first step in projecting actual sales involves using the Excel's random number generator to arrive at a predicted market size for both the primary and secondary markets. The exact procedure for doing so is as follows:

1. The manager's estimate of market size is used as the estimate market size at year 1;
2. The developer's 5% upper confidence boundary (as discussed in 4.2.2, above) is used to determine the standard deviation of potential market sizes;
3. Excel's Rand() function is used to generate a random number between 0 and 1;
4. Finally, Excel's norminv (inverse normal distribution) function combines these three values to generate a single instance of projected market size.

In subsequent steps, the use of the developer's estimate of market size for the mean of the distribution is replaced by the market size generated at the previous step. This is what allows the random walk to "evolve" over time.

The Excel formula used to achieve this step is:

=NORMINV(RAND,MEAN,(STDEV))

Where:

- NORMINV is the inverse normal distribution function
- RAND is the random number generator
- MEAN is the market size in the previous time step
- STDEV is the standard deviation of the market's size.

The one practical challenge of using this procedure is that, because the normal distribution is unbounded, it is possible for the model to return extreme values that are simply not realistic. For example, the model could easily show that a market size had become negative; conversely, a string of very positive results could compound on one another and lead to an unreasonably large market size.

To account for this behavior, the model developed here implements a limit to the potential market size at two values – zero, and at the manager's estimate of the largest possible outcome. As the market size approaches each of these two limits, the model looks at the MEAN value at every given step, and at whether the step is going to increase or decrease the projected market size. If the MEAN is approaching one of the two limits, and if the step is going to push the MEAN further towards that limit, the model scales the STDEV value used in the NORMINV function. This allows the model to continue to behave randomly, but to only gently approach the model's boundaries.

An illustration of this method is shown in Figure 8; the method used to implement this technique are reported in Appendix 2.

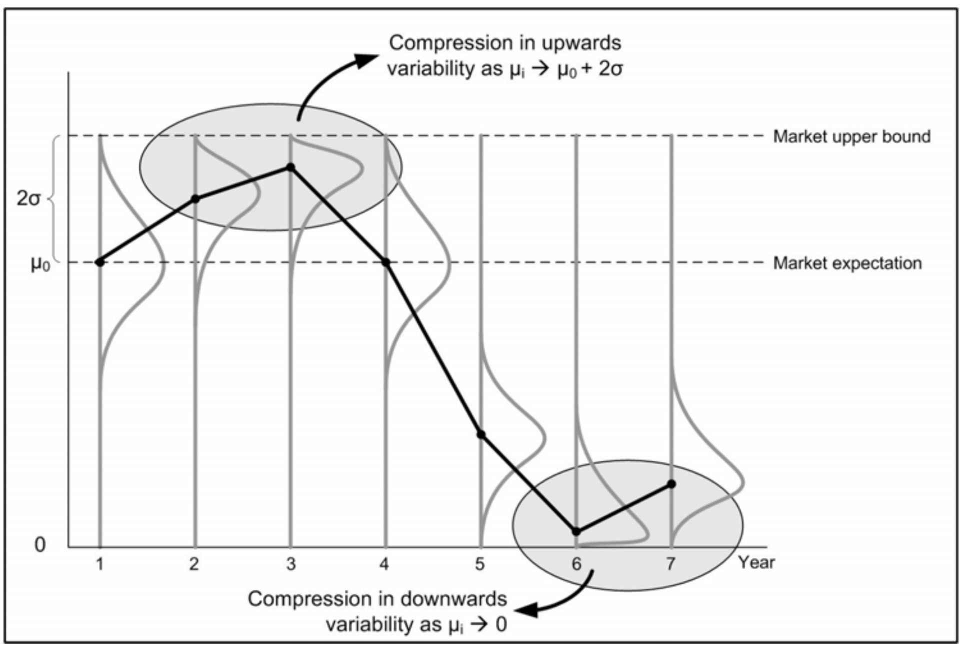


Figure 8: Variability compensation at market extremes

With this adjustment included, the model can begin to make predictions about the expected market size. An example of one instance of the outcome from the model is shown in Figure 9.

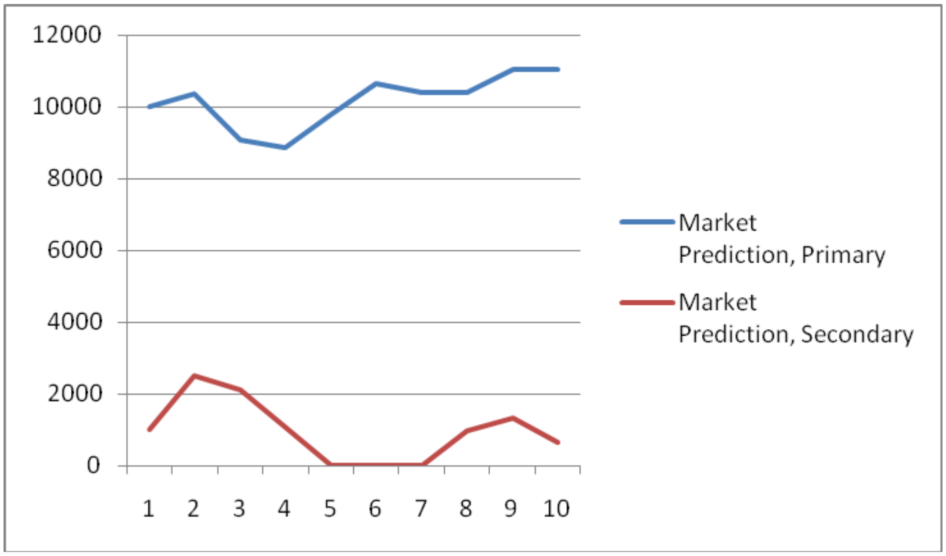


Figure 9: Flexible options model prediction of market sizes

Sales into market

The next step is to project the actual sales. How the model does this varies depending on which market, and which product strategy, is being considered.

For the primary market for both flexible and inflexible strategies, and for the secondary market for the inflexible strategy, the model takes the predicted market size at that time step and applies the adoption fraction curve to that market size to determine how many sales are made in a particular year. Recall from Section 2.6 that Rogers' S-shaped logistic curve is used for this purpose, in combination with the following data:

- Total market size
- Estimated market share
- Duration of product lifecycle to obsolescence.

As implemented in Excel, the logistic curve appears as shown in Figure 10.

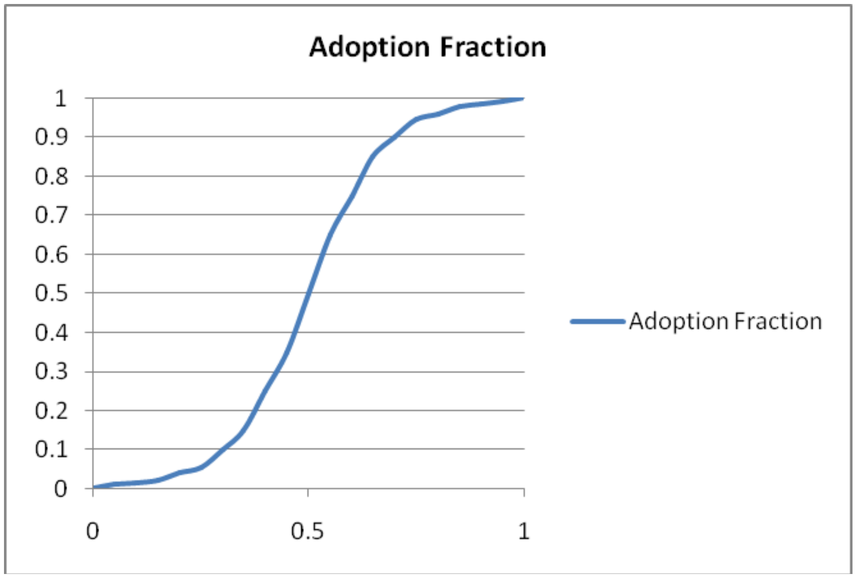


Figure 10: Flexible options model adoption curve for all product variants.

X-axis represents the fraction of the product's lifecycle (in years) that has passed, whereas the y-axis represents the fraction of the total market that has been addressed.

Note that the adoption fraction graph shown here is normalized; this is because the model allows for both market size (the y-axis) and relative product maturity (the x-axis) as variables. If one were to graph a single instance of a single product, the y-axis would be the total sales into the market over its lifecycle, and the x-axis would show the number of years until obsolescence.

This curve yields the total sales for the inflexible markets. Determining sales for the flexible products is more complex; for it is here that the flexible option may or may not be exercised.

Finally, note that because of the stochastic nature of the random walk function it is possible for the total market size to drop to zero. If this happens, the product adoption curve is assumed to be stalled; that is, the product neither resets back to the beginning of the curve nor proceeds further towards obsolescence.

Flexible option

To determine whether the option on the flexible product should be executed to serve the secondary market, the model looks at the secondary market size for each year in each step of the simulation and compares that value against the minimum efficient scale as reported by the product developer. If the projected market at any given time exceeds the MES, the option is executed.

Once the logistic curve has been applied, the model can combine the results for both sales into the primary market, sales into the secondary market in an inflexible scenario, and sales into the secondary market in a flexible scenario. Two likely outcomes are shown in Figure 11 and Figure 12. In Figure 11, the secondary market develops nicely. Because of the delay in starting development until the market exceeds the minimum efficient scale, sales of the flexible product lag the multi-market product in the secondary market slightly. In Figure 12, by contrast, the secondary market never exceeds the flexible product’s minimum efficient scale. The option is never exercised; and though any incremental returns from that market are not realized, the costs to serve that market are never incurred. Depending on the magnitude of development costs, this can yield a substantial savings to the product developer.

Once the option is executed, it can be sold no matter what happens to the secondary market. In rare instances with high volatility, it is possible that the secondary market will grow sufficiently large to trigger the option, then collapse suddenly. In this instance, as soon as the market recovers, sales will resume since the option has already been executed. This situation is shown in Figure 13.

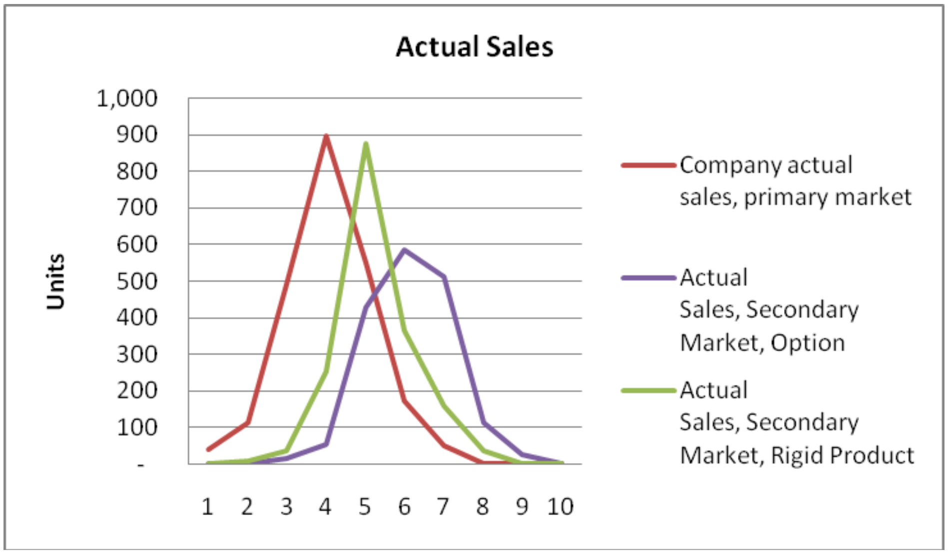


Figure 11: Flexible options model prediction of actual sales (I)

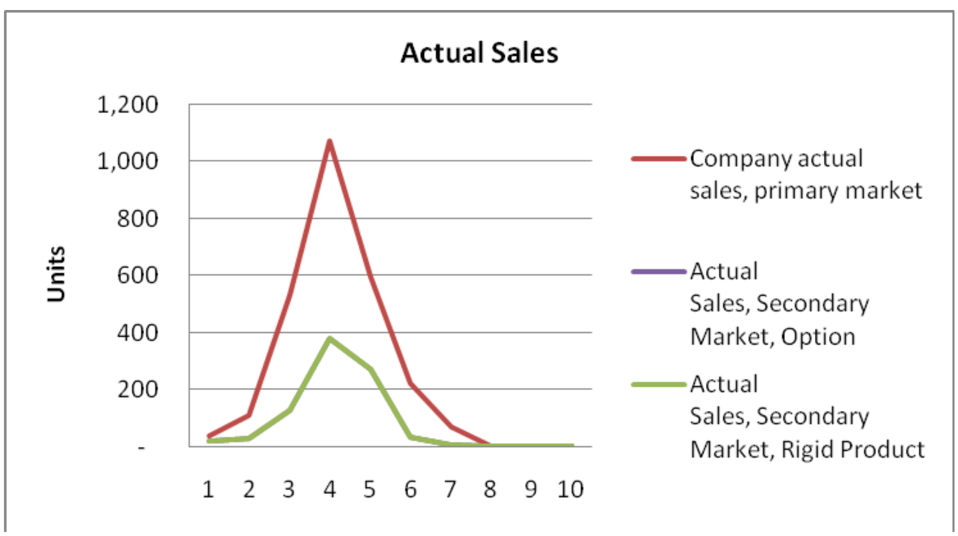


Figure 12: Flexible options model prediction of actual sales (II)

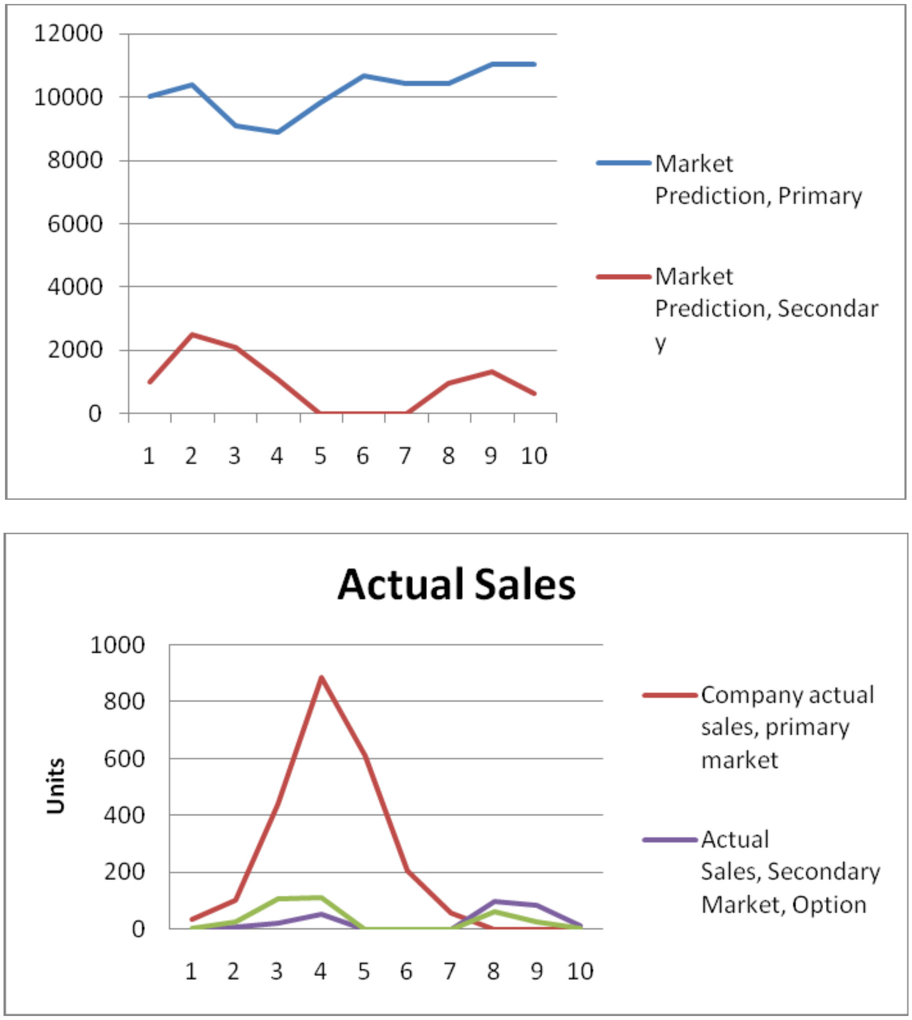


Figure 13: Model behavior in a highly volatile secondary market

Note that flexible product sales resume immediately once the market demand recovers.

3.3.2 Cash flow model

Once the sales of the rigid single-market, rigid multi-market and flexible products are established, these sales figures are compiled into a cash flow model. The first four years of the rigid multi-market and flexible strategies are as shown in Figure 14 and Figure 15.

Rigid Model, Multi Market						
	Period	Year 0	Year 1	Year 2	Year 3	Year 4
Income, Primary Market	Sales, period	0	37	113	526	1038
	Sales, cumulative	0	37	151	677	1715
	Sale price	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600
	Development cost	$ 2,120,000	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77
	Unit cost	$ 10,600	$ 10,600	$ 9,803	$ 9,044	$ 8,151
	Revenue, base	$ -	$ 397,500	$ 1,200,687	$ 5,577,259	$ 10,998,707
	Expenses, base	$ 2,120,000	$ 397,500	$ 1,110,428	$ 4,758,801	$ 8,457,092
	Total income, base	-$ 2,120,000	$ -	$ 90,259	$ 818,457	$ 2,541,616
Incremental Income, Secondary Market	Sales, period	0	4	4	28	0
	Sales, cumulative	0	4	8	36	36
	Sale price	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720
	Incremental Development cost	$ 212,000	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77
	Variable cost, per unit	$ 10,600	$ 10,600	$ 9,803	$ 9,044	$ 8,151
	Revenue	$ -	$ 47,700	$ 49,756	$ 356,197	$ -
	Expenses	$ 212,000	$ 39,750	$ 38,346	$ 253,271	$ -
	Total income	-$ 212,000	$ 7,950	$ 11,409	$ 102,926	$ -
Net Cash Flows	Net Income	-$ 2,332,000	$ 7,950	$ 101,669	$ 921,383	$ 2,541,616
	Discount rate	0%	25%	25%	25%	25%
	Discount multiplier	1.00	1.25	1.25	125%	1.25
	Discount Factor	100.00%	80.00%	64.00%	51.20%	40.96%
	Discounted cash flow	-$ 2,332,000	$ 6,360	$ 65,068	$ 471,748	$ 1,041,046
	Net present value	**$ 254,445**				

Figure 14: First years of cash flow model for rigid multi-market product

Note that this view (and the view below) is truncated at year 4, hence NPV values reflect results from additional years not shown here. For a complete table, see Appendix 1.

Flexible Model						
	Period	Year 0	Year 1	Year 2	Year 3	Year 4
Income, Base Model	Sales, Base	0	37	113	526	1038
	Cumulative Sales, Base	0	37	151	677	1715
	Sale price, Base	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600
	Development cost	$ 2,162,400	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77
	Cost of goods sold, per unit	$ 9,752	$ 9,752	$ 9,019	$ 8,321	$ 7,498
	Option carrying cost, per unit	212	$ 212	$ 196	$ 181	$ 163
	Revenue, base	$ -	$ 397,500	$ 1,200,687	$ 5,577,259	$ 10,998,707
	Expenses, base	$ 2,162,400	$ 373,650	$ 1,043,802	$ 4,473,273	$ 7,949,666
	Total income, base	-$ 2,162,400	$ 23,850	$ 156,885	$ 1,103,985	$ 3,049,041
Income, Option	Sales, Option	0	0	0	0	0
	Cumulative Sales, Option	0	0	0	0	0
	Sale price, Option	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720
	Execution cost, Option	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	1.00	1.00	1.00
	Incremental unit cost, Option	848	848	848	848	848
	Cost of goods sold, per unit	10,812	10,812	10,063	9,350	8,509
	Revenue, Option	$ -	$ -	$ -	$ -	$ -
	Expenses, Option	$ -	$ -	$ -	$ -	$ -
	Total income, option	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	Net Income	-$ 2,162,400	$ 23,850	$ 156,885	$ 1,103,985	$ 3,049,041
	Discount rate	0%	25%	25%	25%	25%
	Discount multiplier	1.00	1.25	1.25	1.25	1.25
	Discount Factor	100.00%	80.00%	64.00%	51.20%	40.96%
	Discounted cash flow	-$ 2,162,400	$ 19,080	$ 100,406	$ 565,241	$ 1,248,887
	Net present value	**$ 738,123**				

Figure 15: First years of cash flow model for flexible product

The cash flow model is fairly standard, with the exception of the following details.

Cumulative sales

The total cumulative sales are calculated here, as it is this figure that is used to calculate the learning curve factor by which the cost of goods falls over time.

Learning curve

This is the factor by which the cost of goods is reduced as the developer gains experience building the product. The underlying formula is somewhat complex to implement in Excel, as it requires "backing out" the number of prototype units the developer builds prior to production launch. However, the implementation follows the mathematical theory presented in section 3.2.13, above.

Details of the exact implementation of this technique, including appropriate Excel formulae, are reported in Appendix 2.

Cost of goods

The cost of goods is calculated by multiplying the developer's original cost of goods estimate and multiplying it by the learning curve factor.

Option carrying cost

The option carrying cost is the incremental cost that is added to the basic inflexible primary-market product that allows the flexible option to be executed. This cost is carried through the entire life of the product whether the flexible option is executed or not. Note that because of this, the carrying cost is subject to the same learning curve factors as the primary market product.

Option learning curve factor

Because the flexible option is only constructed once the option is executed, the incremental cost of the flexible product that is related to serving the secondary market is subject to a learning curve factor that is initiated only on the units of production that incorporate the exercised flexible option. Thus if 1000 flexible units without the option exercised have been sold into the primary market and 200 flexible units with the option exercised sold into the secondary market, there is a different learning curve factor applied to the product with the flexible option and the product that incorporates the exercised option.

Discount rate multiplier

Most cash flow models use a static discount rate, since these models have historically been developed and studied within the context of large, well-established companies. However, in the dynamic markets where this flexible options approach may well be used, products are frequently brought to market by entrepreneurial startups. Because the discount rate is, in large part, based on the cost of capital, and because the cost of capital for a startup can be very much higher than for an established company, this model includes the ability to include a discount rate that varies over time. Thus the developer for a startup company could, for example, set the cost of capital to 50% for the first three years (while the company is funded by venture capital); decrease the rate to 20% for years four through seven (when the company is funded by a bank debt); then finally decrease to 15% in subsequent years when the company is profitable and the cost of capital is based on shareholders' expected returns.

Note that in the modeling done below, the discount rate is set to a constant rate of 25%.

3.3.3 Net present value

Once the annual cash flows have been calculated as described above, they are discounted back to the present and summed. This determines the net present value for the product given this single set of market inputs.

3.3.4 Iteration

Once the net present value has been determined for a single iteration of the model, this entire process is repeated. For the purposes of this thesis, 2000 iterations are executed. By observing the behavior of the output curves described below it can be seen that the individual curves are reasonably stable across successive model runs; thus the results returned should be fairly reasonable. Especially since the developer's inputs to the model are estimates in any case, it does not seem necessary to run the model through further iterations.

3.4 Comparison of results

Finally, once all 2000 iterations have been run, the model produces several outputs for the developer to analyze.

The first, and possibly most useful, of these outputs is a graph representing both the expected net present value (that is, the average of all simulations – the ENPV) and the cumulative distribution (CDF) of probabilities for the three different strategies. An example of this graph is shown in Figure 16.

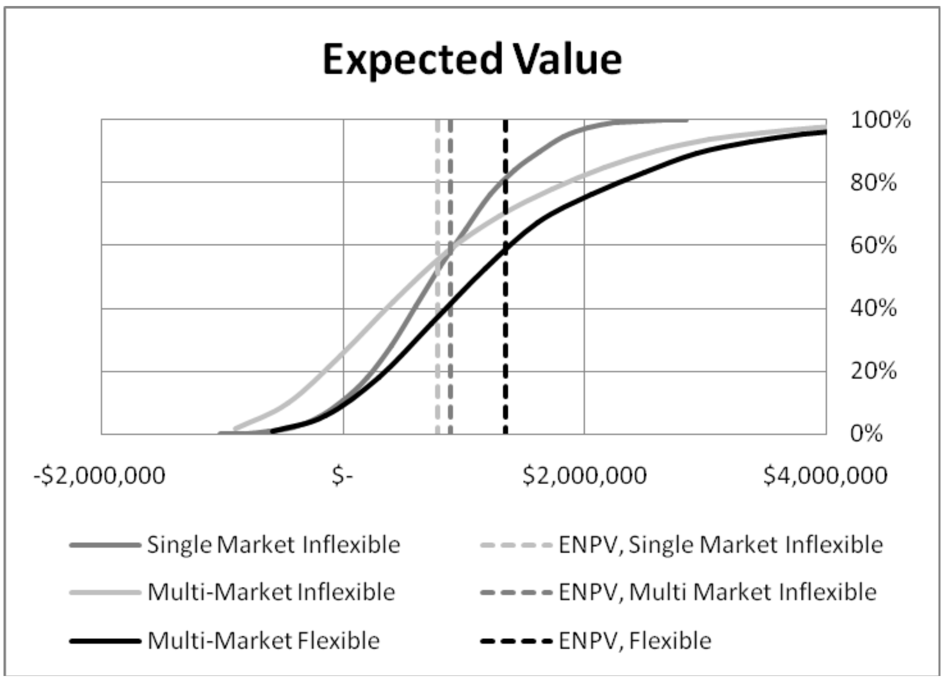


Figure 16: Model output – expected value graph

As a final step to assist the product developer in their analysis, the model compiles the mean expected net present values for the three strategies. This table also gives a sense of the limits of likely outcomes by presenting the figures below and above which only 5% of all outcomes fall. This is intended to give the developer a sense of the value at risk (and the value that could be gained) in each scenario. An example of this output is shown in the following table.

Table 2: Sample comparison of results	
Single Market Inflexible	
Min	-$ 1,505,640
Mean	$ 794,118
Max	$ 2,882,242
5% chance of NPV below	$ -221,808
5% chance of NPV above	$ 1,860,149
Multi-Market Inflexible	
Min	-$ 1,417,935
Mean	$ 835,090
Max	$ 6,428,660
5% chance of NPV below	$ -683,675
5% chance of NPV above	$ 3,159,317
Multi-Market Flexible	
Min	-$ 1,363,822
Mean	$ 1,297,947
Max	$ 6,833,124
5% chance of NPV below	$ -214,847
5% chance of NPV above	$ 3,614,719

Case studies

The fourth part of this thesis applies the methods and model developed in the sections above and applies them to information provided by product development practitioners. The goal of these case studies is not so much to validate the model's effectiveness; such proof would require *ex post* analysis of many projects' performance many years after the analysis was made – an exercise beyond the scope of this thesis. Rather, these case studies are intended to verify that the model returns believable results that give insight into the actual managerial decisions under consideration. This will both indicate that the framework is useful across a broad set of scenarios, and will give a preliminary indication of general guidelines on where flexibility is and is not valuable.

The discussion of each case study includes:

- A brief overview of the product, the market for which it was developed and the technologies that were used to develop it;
- The managerial data that was required as input to the model;
- The outcomes from the model; and
- Reflections by the industrial partner on the inputs, the process and the applicability of the results.

This section begins with a detailed study from the industrial battery industry, before presenting seven short cases including data provided by practicing product development managers. Finally, the results of both the detailed case and the cases described by the industrial practitioners are compared, and some general conclusions suggested.

4.1 Detailed study: Industrial Battery Development

This section reviews the development of a product in the remote energy storage industry. Specifically, it asks the question: Would a flexible approach to the battery's design have made the project likely to provide higher economic returns?

The details of this study have previously been published by the author in (Harper 2009) and (Harper 2010). General information about the technology is available either via Wikipedia (en.wikipedia.org/wiki/vanadium_redox_battery) or at the website of one developer of the technology, Prudent Energy (www.pdenergy.com). To protect the confidentiality of company information, figures presented here have been normalized against a randomly generated constant value; however, the relative magnitude of figures has been maintained, thus ensuring the analytical outcome from the model remains qualitatively accurate.

4.1.1 Background

Prudent Energy, formerly VRB Power Systems, builds large scale energy storage devices known as “Vanadium Redox Batteries”, or “VRB-ESSs”. These are moderately complex industrial products containing electronic (controls), structural (metal framework), process (pumps, valves, sensors) electric (DC circuits up to 250A) and electrochemical (acid electrolyte, electrochemical cell stacks) components. These systems measure approximately 2m x 2m x 4m, weight about 4000kg, and are sold for approximately $11,500. The VRB-ESS differs from conventional batteries in that it is a “flow battery”, where the battery electrolyte is continuously pumped through a reaction chamber to facilitate the charge and discharge reactions.

Figure 17: Typical kW-Class VRB-ESS Installation, Njambini, Kenya

(Author's collection)

Initial examples of the VRB-ESS were focused on much larger installations. The technology was first developed in the late 1990s by Sumitomo Electric in Japan. Their equipment was built at the scale of a small industrial plant; for example, one early 4MW unit filled a building approximately 60m x 40m. While these systems incorporated some standardized electrochemical parts, they were generally custom-engineered units.

VRB Power Systems initially took that same route. In 2004, having licensed the VRB technology from Sumitomo they designed and commissioned a 250kW system in Moab, Utah. Shortly thereafter, a prospective customer came to them with a potentially very lucrative proposal. That company saw a market for the VRB-ESS at a much smaller scale, targeting the telecoms industry. That industry makes extensive use of lead-acid batteries, devices that are expensive to maintain, hard to dispose of and prone to unexpected failures – hence operators were open to alternatives.

The market for the VRB-ESS was primarily in remote, off-grid telecoms applications. Historically, such remote sites have been powered by diesel generators, using lead-acid batteries as backups in case one generator (of the two typically on-site) failed. More recently high fuel prices and environmental concerns had led telecoms operators towards renewable energy technologies, whose prices were falling rapidly, to power remote sites. (GSMA 2009)

In fall of 2005, then, VRB Power Systems launched into the process of taking this industrial-scale, custom-built technology and repackaging it as a transportable, serially-manufactured product – what eventually came to be known as the Mark-I kW-Class VRB-ESS. This product was narrowly focused on a single customer; more product options would be needed if the product was to become commercially viable on a wider scale. This narrow focus ultimately led to a second generation of the product, the Mark-II kW-Class VRB-ESS.

4.1.2 Market challenge

The challenge facing the development team was that there were two possible application scenarios for the product, both of which had slightly different technical requirements. The primary market for the product was in the remote markets noted above, where the battery would be required to be cycling continuously. This was the primary benefit of this technology over other battery types – that the VRB-ESS could charge and discharge for many thousands of cycles without any degradation of performance. This was in contrast to the batteries typically on the market at the time; these were typically limited to several hundred cycles before their performance started to suffer.

However, a secondary market for the VRB-ESS also existed – one where cycling was limited, and thus where the battery would be required to rest for long periods of time between discharges. This operating mode presented a particular challenge to the VRB-ESS. Because of the nature of the electro-chemical-mechanical process that underlies the battery's operation, performance would suffer significantly in long stretches between discharges, increasing the battery's operating costs significantly. An alternative solution was needed.

The solution that the design team developed (and patented – see US Patent 7,740,977 – "Vanadium Redox Battery Incorporating Multiple Electrolyte Reservoirs") was to incorporate a second, smaller set of electrolyte tanks into the system. When the system was running at its full rated capacity electrolyte would be drawn from large storage tanks. Conversely, between discharges when the battery was idle, only the smaller set of tanks would be in use.

The product was brought to market incorporating both sets of tanks, and was successfully launched in mid-2007.

4.1.3 Tanks as options

The question in this instance is should VRB Power Systems have developed the product to serve both of these markets, or should a product have been developed for one market first, with a flexible option incorporated to address the secondary market if time could prove that that market was necessary?

The framework developed in this thesis can be used to analyze this problem. Table 3 shows the inputs to the model, as described above.

Table 3: Market and product data for kW-Class VRB-ESS	
Description	**Value**
Primary market data	
Total addressable market (units)	10 000
5% upper confidence bound (units	12 000
Sale price	$10 600
Company market share	25%
Time to maturity (years)	7
Product development cost	$2 120 000
Cost of goods sold	$9 752
Secondary market data	
Total addressable market (units)	1 000
5% upper confidence bound (units)	5 000
Sale price	$11 500
Market share	25%
Time to maturity (years)	7
Incremental product development cost	$424 000
Incremental cost of goods sold	$850
Flexible option data	
Development cost, initial	$42 400
Development cost, at execution	$424 000
Carrying cost, per unit	$212
Minimum efficient scale	2 500
Learning curve effects	
Cost reduction factor per doubling of net production	0.95
Units built prior to production	20

Inserting this data into the model developed in this thesis yields the following results.

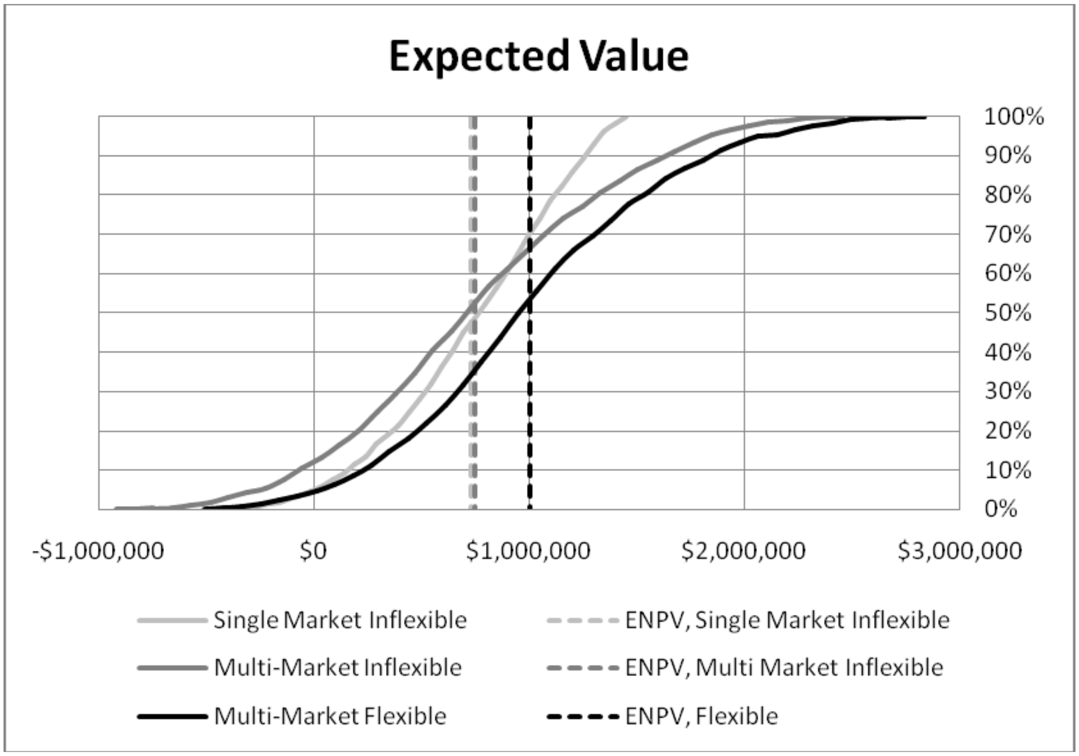


Figure 18: Expected value, single-market, multi-market and flexible VRB-ESS

4.1.4 Discussion

On the basis of these results, it would clearly have been beneficial for the VRB development team to consider developing a flexible platform instead of one designed initially to serve multiple markets.

It is worth observing the curves above qualitatively, and noting that the flexible option allows the product developer to take advantage of the upside potential of selling to multiple markets, while minimizing development costs until it is known that the less certain secondary market will develop favourably. This is exactly what one would expect from a flexible option, which provides *the right but not the obligation* to enter a second market.

4.2 Practitioner surveys

The second step in verifying the performance of the completed model was to use it to analyze several sets of data, provided by practitioners in a variety of product development fields. These surveys served three primary purposes.

First, it was intended to "exercise the model" using a inputs from a diverse set of product development practitioners within the industry. As reported below, several input cases that were not considered in developing the initial model; for example, the case where including the flexible option in the model decreases unit costs instead of increasing them. These provided the impetus for modifications to the model that increased its robustness overall.

Second, using data from diverse industries was intended as a first step towards developing some general guidelines on where flexibility is and is not valuable. The practitioners interviewed came from industries with wildly varying gross margins on sales; industries that are mature and some that are rapidly emerging; and product development cycles that stretch from months to decades. Including this broad spectrum was intended to start to identify the boundaries of where flexibility may not be valuable, and thus where the framework developed here should and should not be considered. This ensures that the validity of the method developed truly depends on economic and market factors, and not just on the characteristics of a particular set of circumstances within which the product exists.

Finally, the surveys were intended to begin to identify general trends about what factors are most important to consider when deciding whether to incorporate a flexible design into a new product development effort. While practitioners may well use rigorous numerical analysis to support decisions to enter a particular market, in discussion with many of these practitioners it came to light that the ultimate "go / no-go" decision came down to a subjective decision by senior managers. If general trends can be identified in these surveys, those trends can be applied as heuristics to these more general managerial decisions.

4.2.1 Practitioner survey 1

Practitioner 1 is a senior technology manager in the industrial power equipment industry. This individual provided the following data.

Input data

Table 4: Market and product data for practitioner 1	
Primary market data	
Total addressable market (units)	2 000
5% upper confidence bound (units)	4 000
Sale price	$538 000
Company market share	25%
Time to maturity (years)	7
Product development cost	$5 382 000
Cost of goods sold	$358 000
Secondary market data	
Total addressable market (units)	1 000
5% upper confidence bound (units)	5 000
Sale price	$538 000
Market share	25%
Time to maturity (years)	7
Incremental product development cost	$1 794 000
Incremental cost of goods sold	-$72 000
Flexible option data	
Development cost, initial	$179 000
Development cost, at execution	$1 794 000
Carrying cost, per unit	$5 600
Minimum efficient scale	100
Learning curve effects	
Cost reduction factor per doubling of net production	0.9
Units built prior to production	5

Results

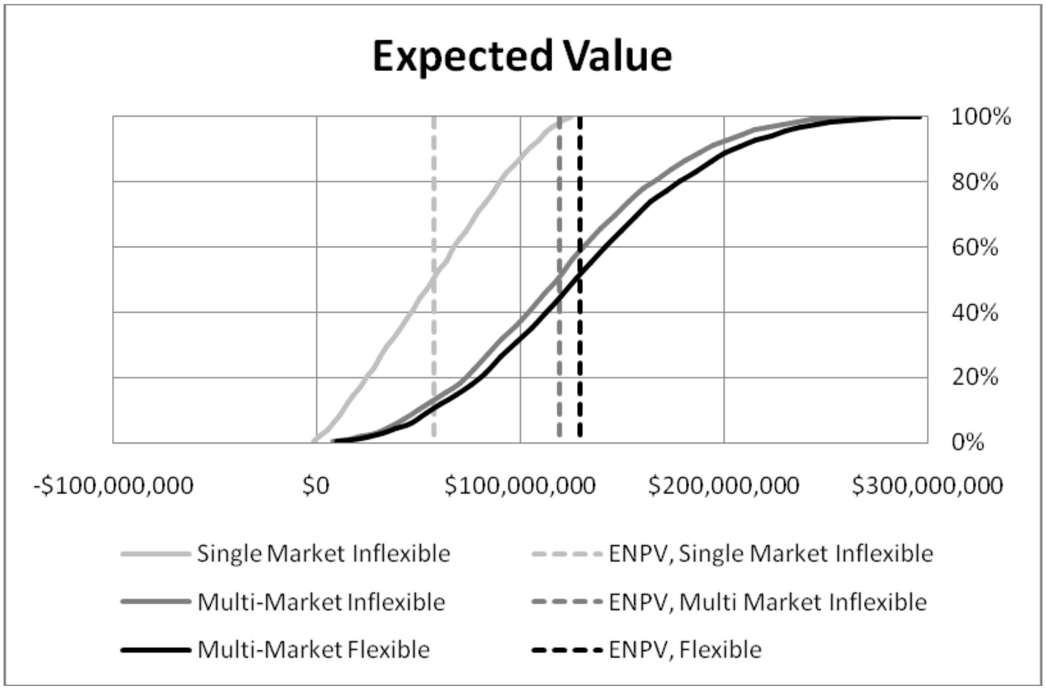


Figure 19: Expected value, Practitioner 1 example

Discussion

The dramatic improvement in economic returns by selling into the secondary as well as primary market here is not surprising, given that the product enjoys much higher profit margins in the secondary market. Essentially the secondary market is one where a major feature of the primary market may not be needed; therefore the change to enter the secondary market is simply to remove that feature. These positive economics mean the minimum efficient scale for developing a product for the secondary market in the flexible scenario is low; thus the spread between the flexible and inflexible multi-market products is quite narrow. In this instance, the developer would want to adopt the flexible strategy, but would almost certainly execute that option immediately.

Practitioner 1 felt that the methodology was good, but that customer preferences were likely to be an important factor not accounted for in the model. Especially where the economic difference between the flexible and rigid multi-market outcomes is small, these qualitative factors could easily determine which strategy is better.

4.2.2 Practitioner survey 2

The second practitioner is a senior R&D manager, also in the industrial power equipment industry.

Input data

Table 5: Market and product data for practitioner 2	
Description	**Value**
Primary market data	
Total addressable market (units)	10 000
5% upper confidence bound (units)	15 000
Sale price	$170 000
Company market share	25%
Time to maturity (years)	7
Product development cost	$6 360 000
Cost of goods sold	$254 000
Secondary market data	
Total addressable market (units)	10 000
5% upper confidence bound (units)	50 000
Sale price	$153 000
Market share	25%
Time to maturity (years)	7
Incremental product development cost	$848 000
Incremental cost of goods sold	-$42 000
Flexible option data	
Development cost, initial	$42 000
Development cost, at execution	$848 000
Carrying cost, per unit	$42 000
Minimum efficient scale	500
Learning curve effects	
Cost reduction factor per doubling of net production	0.9
Units built prior to production	10

Results

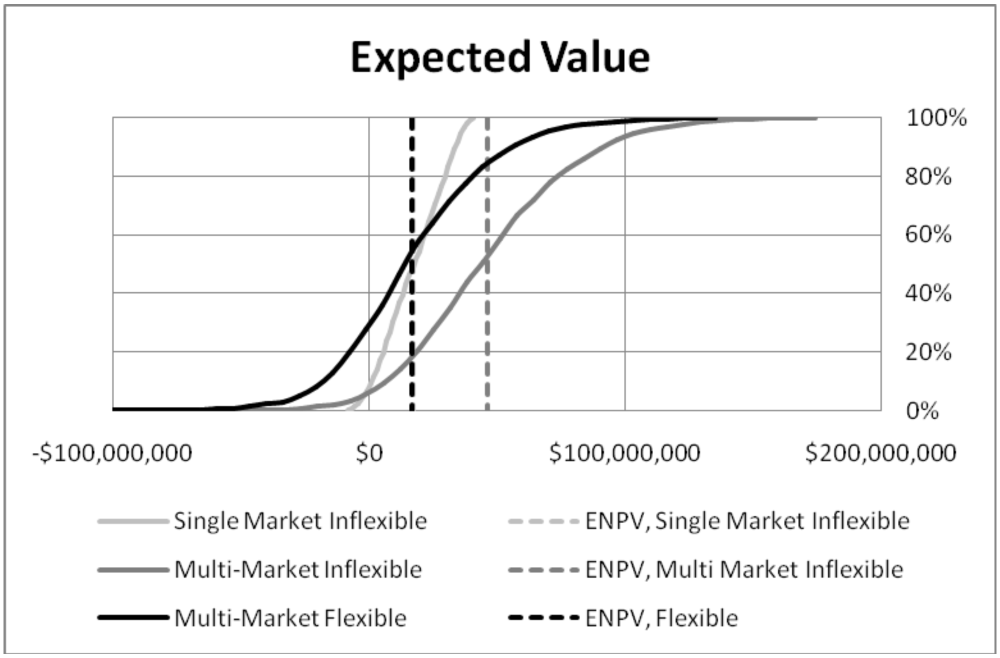


Figure 20: Expected value, Practitioner 2 example

Discussion

Here, the case for proceeding with the product itself is less clear, and the flexible option only makes the situation worse. The only option with clear positive expected value is the multi-market inflexible version, and even it has a significant value at risk – the simulation shows a 5% chance of losses exceeding $2.5MM. Though selling into a single market reduces the value at risk slightly, the returns from that strategy are comparatively small. This performance is largely because the product itself costs significantly more to build than it can be sold for at the beginning of its lifecycle; only once costs come down by learning curve effects are positive margins achieved in a per-unit basis.

The reason the flexible option is not appealing here is because the carrying cost for the option on products where the option is not exercised is comparatively high. In this product, the developer thus has to choose between a low-risk, low return single-market strategy, or a higher-risk, higher-return multi-market strategy. Perhaps the best strategy is to return to the drawing board, to develop a product whose costs are in line with its market value early in its lifecycle.

4.2.3 Practitioner survey 3

The practitioner in survey 3 is a senior program manager for a large multinational industrial equipment company.

Input data

Table 6: Market and product data for practitioner 3	
Description	**Value**
Primary market data	
Total addressable market (units)	10 000
5% upper confidence bound (units)	20 000
Sale price	$60 000
Company market share	25%
Time to maturity (years)	5
Product development cost	$6 009 000
Cost of goods sold	$15 000
Secondary market data	
Total addressable market (units)	1 000
5% upper confidence bound (units)	4 000
Sale price	$60 000
Market share	25%
Time to maturity (years)	5
Incremental product development cost	$601 000
Incremental cost of goods sold	$1 500
Flexible option data	
Development cost, initial	$300 000
Development cost, at execution	$601 000
Carrying cost, per unit	$10
Minimum efficient scale	1 000
Learning curve effects	
Cost reduction factor per doubling of net production	0.95
Units built prior to production	20

Results

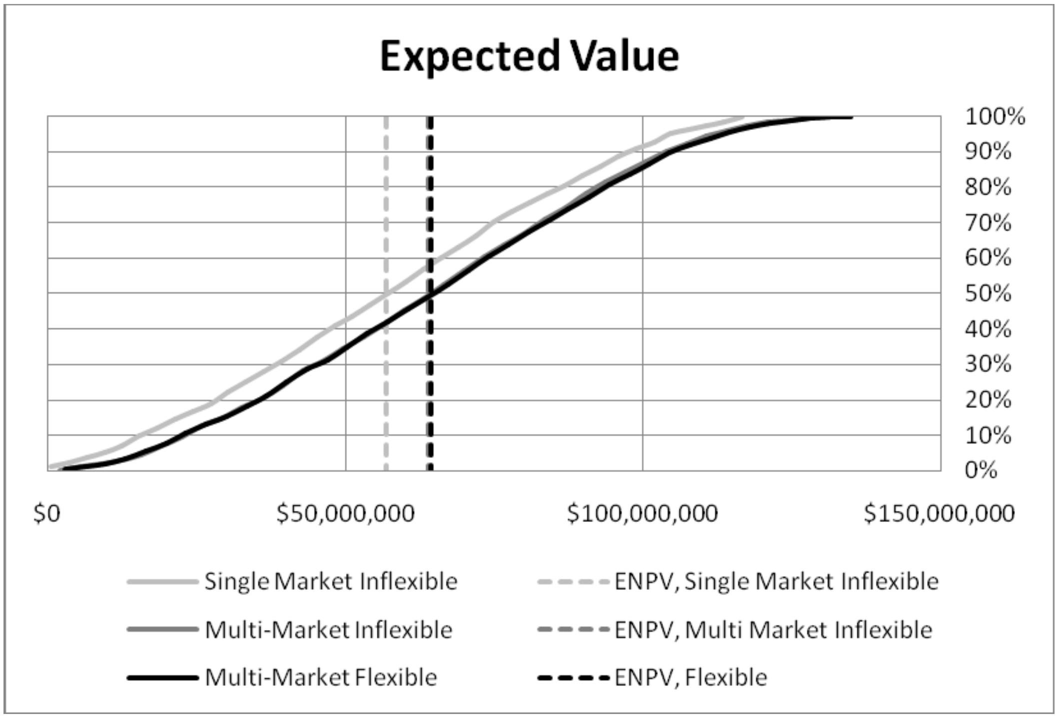


Figure 21: Expected value, Practitioner 3 example

Discussion

The product being developed by Practitioner 3 enjoys high margins on sales – though in subsequent discussions the individual noted that the cost reported did not include sales, service and administrative overheads.

Despite this anomaly, the product is still likely to have a positive expected value, because of the combination of good margins on sales and comparatively small development costs. Because of this, the minimum effective scale for the flexible version is the same as the initial expected size of the secondary market; thus unless the model returns a lower-than-expected market size in the first year the flexible option is always executed. Because the carrying cost for the flexible option is low, there is little penalty carried on flexible products where the option has not been executed. Thus the flexible strategy earns only very slightly better returns than the multi-market inflexible strategy.

4.2.4 Practitioner survey 4

The practitioner in survey 4 is a senior product architect for a manufacturer of specialized medical diagnostic equipment.

Input data

Table 7: Market and product data for practitioner 4	
Description	**Value**
Primary market data	
Total addressable market (units)	1 600
5% upper confidence bound (units)	1 680
Sale price	$573 000
Company market share	30%
Time to maturity (years)	7
Product development cost	$6 338 000
Cost of goods sold	$229 000
Secondary market data	
Total addressable market (units)	2 566
5% upper confidence bound (units)	2 874
Sale price	$357 000
Market share	30%
Time to maturity (years)	7
Incremental product development cost	$4 934 000
Incremental cost of goods sold	-$86 000
Flexible option data	
Development cost, initial	$393 000
Development cost, at execution	$4 934 000
Carrying cost, per unit	$1 970
Minimum efficient scale	1 000
Learning curve effects	
Cost reduction factor per doubling of net production	0.95
Units built prior to production	20

Results

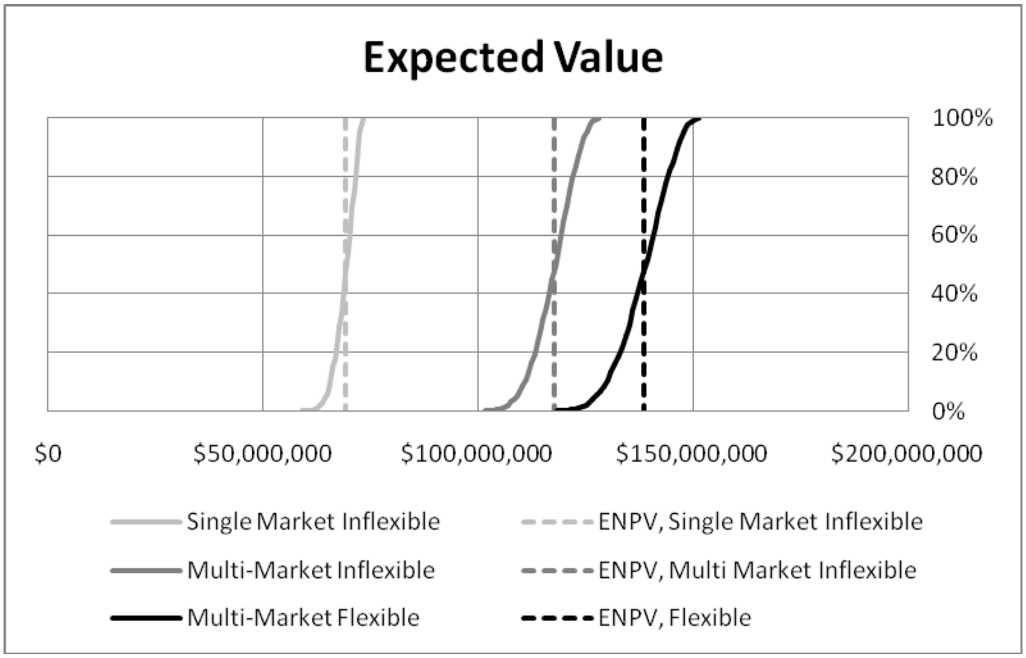


Figure 22: Expected value, Practitioner 4 example

Discussion

The product that practitioner 4 is helping to develop is a piece of diagnostic equipment designed to go into a variety of locations. Because the market is large and well established, downside potential is comparatively low. The two markets considered here are differentiated by device throughput – one market is in high-volume settings such as large hospitals, whereas the second is in smaller clinics with lower volume needs.

In this case it is fairly obvious that a flexible platform is the best choice: a product developer could (and, in this case, indeed did) intuitively observe that a smaller unit with lower cost of goods will best serve the smaller throughput market. The practitioner here noted that the company's development of these products was limited by their product development resources – the primary market was addressed first, then successive generations of the product focused on smaller secondary markets. While it may thus seem efficient to sell a de-tuned version of the base product into the secondary market, the model suggests that the resources used to develop a flexible platform that can reduce costs in the secondary market yields a significantly increased expected value.

4.2.5 Practitioner survey 5

The practitioner in survey 5 is a product planning manager for a large multinational agricultural equipment and services provider.

Input data

Table 8: Market and product data for practitioner 5	
Description	**Value**
Primary market data	
Total addressable market (units)	250 000
5% upper confidence bound (units)	300 000
Sale price	$2 690
Company market share	50%
Time to maturity (years)	10
Product development cost	$7 176 000
Cost of goods sold	$359
Secondary market data	
Total addressable market (units)	250 000
5% upper confidence bound (units)	600 000
Sale price	$5 380
Market share	13%
Time to maturity (years)	10
Incremental product development cost	$7 176 000
Incremental cost of goods sold	$381
Flexible option data	
Development cost, initial	$300 000
Development cost, at execution	$601 000
Carrying cost, per unit	$180
Minimum efficient scale	1 000
Learning curve effects	
Cost reduction factor per doubling of net production	0.95
Units built prior to production	20

Results

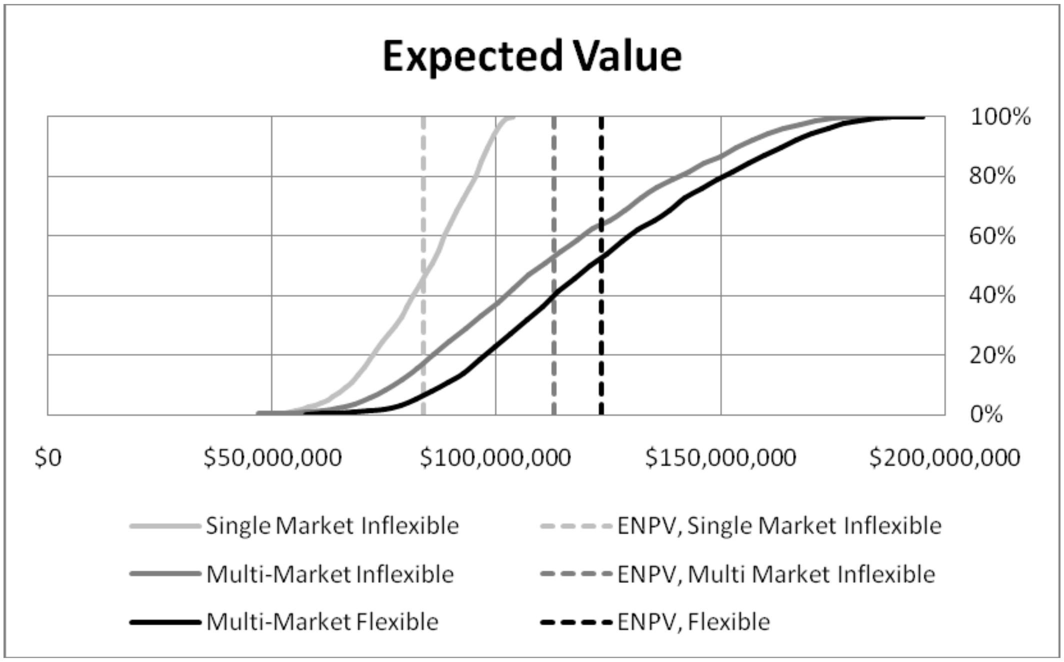


Figure 23: Expected value, Practitioner 5 example

Discussion

Practitioner 5's market is large and mature. As the dominant player in that market, any new product stands a reasonable chance of success with limited downside possibility.

The opportunity that flexibility provides is not in addressing a different market but rather as a way of providing an enhanced service offering to existing customers. The hardware needed to serve that application can be developed in one of two ways – either by developing two successive generations of the hardware, or by designing flexibility into the hardware so that it can be easily modified to serve either market.

Considering the opportunity in the secondary service, it is clear that the developer should seek to serve that market. However, the decision that was actually made was to develop the rigid, single-market product in the interests of saving costs. Had the developer had access an analytical framework as presented here, they could more easily have made the case for a flexible approach, thus increasing expected returns.

4.2.6 Practitioner survey 6

The practitioner in survey 6 is a senior technology strategist and planner for a specialized enterprise software development company. The company has a small but growing share of their market, and products easily adopted to serve similar applications.

Input data

Table 9: Market and product data for practitioner 6	
Description	**Value**
Primary market data	
Total addressable market (units)	2 000
5% upper confidence bound (units)	3 500
Sale price	$62 700
Company market share	7%
Time to maturity (years)	5
Product development cost	$73 150
Cost of goods sold	$10 450
Secondary market data	
Total addressable market (units)	6 000
5% upper confidence bound (units)	10 500
Sale price	$67 000
Market share	7%
Time to maturity (years)	5
Incremental product development cost	$16 720
Incremental cost of goods sold	$-1 570
Flexible option data	
Development cost, initial	$14 630
Development cost, at execution	$8 360
Carrying cost, per unit	$10
Minimum efficient scale	500
Learning curve effects	
Cost reduction factor per doubling of net production	0.99
Units built prior to production	20

Results

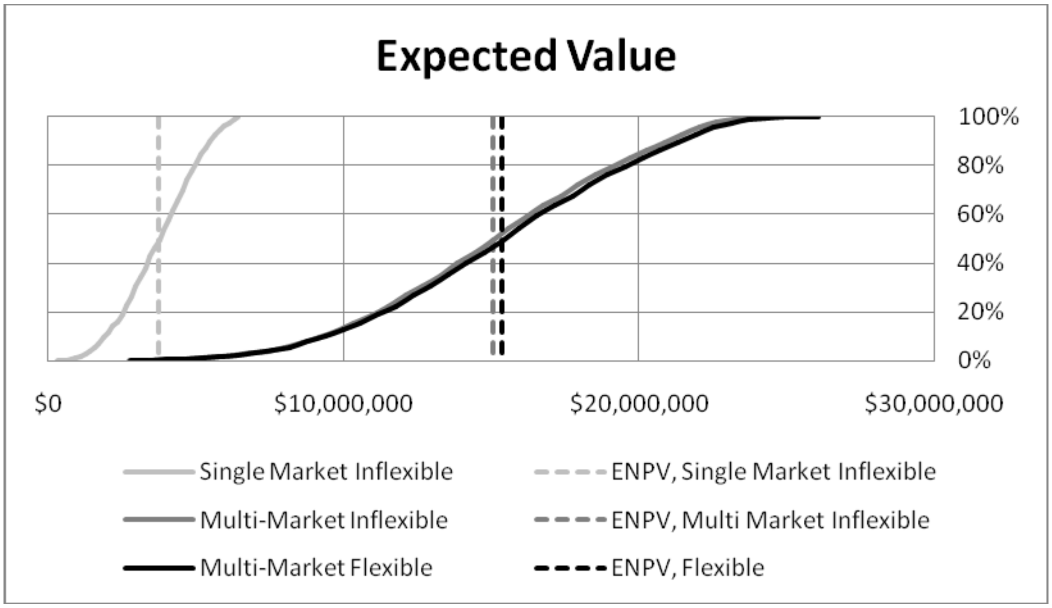


Figure 24: Expected value, Practitioner 6 example

Discussion

The most significant characteristic of both the primary and secondary markets in this case is that both can be served at a comparatively low development cost – in both cases, development costs are recouped after just two sales. Thus the products are almost always profitable, and the spread between the expected value of serving the primary and both the primary and secondary markets is nearly equal to the expected revenue streams from the secondary markets.

The difference between the rigid, two-market product and the flexible product is also very small. The reason for this is that the incremental development cost for a completely new product, as compared with the cost of developing the flexible platform, is very small. However, flexibility here does yield some additional value, suggesting that good practice in such projects would be to design the software in a way that it can be extended into new applications as they emerge. This could be particularly valuable as markets for software tend to evolve comparatively quickly; with a flexible platform implemented, developers can quickly adapt existing platforms to new applications.

4.2.7 Practitioner survey 7

The practitioner in survey 7 is a business development manager in an industrial electronics company.

Input data

Table 10: Market and product data for practitioner 7	
Description	**Value**
Primary market data	
Total addressable market (units)	5 060
5% upper confidence bound (units)	7 590
Sale price	$47 000
Company market share	40%
Time to maturity (years)	10
Product development cost	$1 415 000
Cost of goods sold	$35 380
Secondary market data	
Total addressable market (units)	600
5% upper confidence bound (units)	4 000
Sale price	$59 000
Market share	40%
Time to maturity (years)	10
Incremental product development cost	$235 900
Incremental cost of goods sold	$2 360
Flexible option data	
Development cost, initial	$47 000
Development cost, at execution	$235 900
Carrying cost, per unit	$240
Minimum efficient scale	200
Learning curve effects	
Cost reduction factor per doubling of net production	0.95
Units built prior to production	100

Results

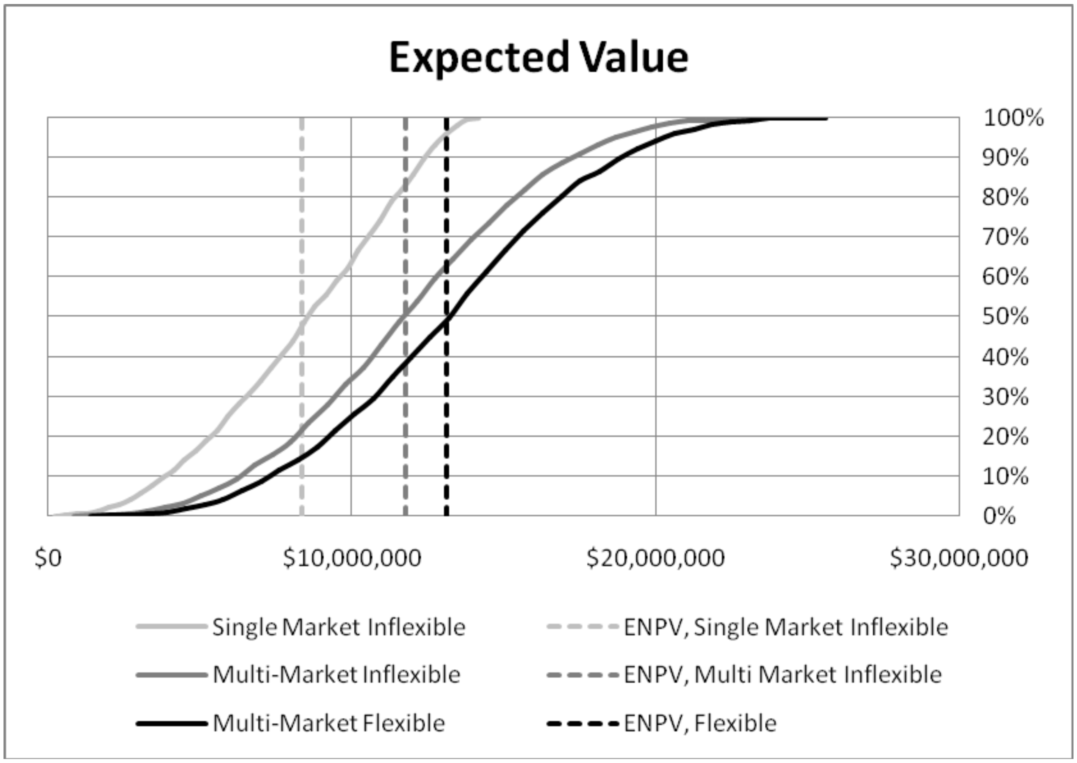


Figure 25: Expected value, Practitioner 7 example

Discussion

The company that Practitioner 7 works for is a well established player in a fairly specialized market; as such, incremental developments of new products build on a well established set of knowledge and experience. So, while the products may not be built on a platform per se, they do benefit from the company's existing capabilities and can be developed quite profitably.

In this case, we again see that serving both primary and secondary markets is of benefit, and that designing the product with a flexible option rather than simply including all needed features improves expected returns overall. Also, because the minimum efficient scale for the secondary market is quite small we are almost always likely to execute the option to serve that market; hence the shape of the curve for the expected returns from the flexible version is similar to for the multi-market, inflexible version.

4.3 Discussion of results

The one detailed and seven short cases presented above are summarized in the following table.

Boxes highlighted in grey show which of the three scenarios provide the highest expected net present value. In cases where two ENPVs are very similar, both boxes are highlighted.

Table 11: Summary of results

Results	Base	Practitioner 1	Practitioner 2	Practitioner 3	Practitioner 4	Practitioner 5	Practitioner 6	Practitioner 7
Single Market Inflexible								
Min	($ -568,755)	($ -4,305,840)	($ -9,286,280)	($ -2,403,680)	$ 58,688,483	$ 34,822,013	$ 160,930	$ 202,858
Mean	$ 730,271	$ 57,820,255	$ 17,396,529	$ 56,960,679	$ 69,209,101	$ 83,329,248	$ 3,751,074	$ 8,298,064
Max	$ 1,450,771	$ 125,306,563	$ 40,929,443	$ 116,556,457	$ 73,405,307	$103,355,968	$ 6,449,794	$ 14,120,528
5% of NPV below	$ 3,062	$ 7,407,282	($ -2,106,322)	$ 9,533,378	$ 64,774,801	$ 61,498,079	$ 1,529,871	$ 2,943,819
5% of NPV above	$ 1,329,641	$ 112,012,112	$ 36,220,421	$ 104,613,346	$ 72,653,609	$ 99,664,253	$ 5,863,653	$ 12,983,119
Multi-Market Inflexible								
Min	($ -1,007,120)	$ 1,497,093	($ -85,171,978)	($ -1,293,448)	$ 100,976,981	$ 31,210,745	$ 2,182,048	($ -10,692)
Mean	$ 747,463	$ 119,556,299	$ 46,326,338	$ 63,947,240	$ 117,682,043	$ 112,878,691	$ 15,072,282	$ 11,684,249
Max	$ 2,454,512	$ 277,330,037	$174,392,847	$ 134,412,907	$ 128,149,637	$ 184,499,419	$ 25,547,221	$ 23,411,263
5% of NPV below	($ -251,929)	$ 36,562,418	($ -2,466,354)	$ 16,420,470	$ 109,094,699	$ 67,219,736	$ 7,875,968	$ 4,865,454
5% of NPV above	$ 1,833,398	$ 210,609,974	$105,550,335	$ 111,488,440	$ 125,321,194	$ 159,955,307	$ 21,950,168	$ 18,620,682
Multi-Market Flexible								
Min	($ -592,312)	$ 2,354,485	($ -124,388,111)	($ -480,697)	$ 117,465,144	$ 34,495,825	$ 2,220,857	$ 575,243
Mean	$ 998,976	$129,532,551	$ 16,740,944	$ 64,461,324	$ 138,549,371	$ 116,358,007	$ 15,396,192	$ 12,993,950
Max	$ 2,832,201	$296,334,253	$ 135,324,314	$ 134,849,798	$ 151,342,911	$ 187,228,782	$ 26,111,354	$ 24,925,464
5% of NPV below	$ 33,396	$ 41,091,107	($ -27,223,371)	$ 16,147,657	$ 127,397,891	$ 70,763,345	$ 7,957,283	$ 5,771,936
5% of NPV above	$ 2,073,285	$226,763,049	$ 67,798,468	$ 113,262,438	$ 148,047,557	$ 162,504,141	$ 22,442,395	$ 20,213,665

In each one of these cases, expected returns are maximized by serving both primary and secondary markets. The example provided by Practitioner 2 is the only example where the multi-market, inflexible version performs better than the flexible version of the product. Referring back to the input data for that case, one can see that this is because the ratio of the “carrying cost” to the cost of goods is high compared with other practitioners’ examples.

In the case of the examples provided by practitioner 3 and 6, there is little difference between the expected returns from a flexible product strategy and a rigid product designed to serve both markets. There are two reasons for this. First, in both cases the cost – benefit ratio of the product development investment is very high; that is, both projects produce high expected net present values. Because of this, the incremental cost to develop a totally unique product to serve a secondary market is comparatively small. Second, both of these products have a very small carrying cost for the flexible option itself. This indicates that there is little downside to the flexible product as compared with the rigid multi-market version. In this case, the developer may want to consider other factors – such as the value at risk – to decide which option to pursue.

These conclusions suggest that one could look at these two factors – product development cost-benefit ratio and flexible option carrying cost – as overall indicators of whether a flexible platform is an appropriate strategy for serving a secondary market. If the relative costs of product development are comparatively high, a flexible strategy may significantly increase the expected value of a whole product family in a given market. Conversely, if the costs to develop a new product are low compared with the revenues expected from that product, the best option may be to develop individual products for both markets, as this will allow the products to be exactly tailored for the markets they are intended to serve. Finally, in cases where the costs of carrying such flexibility in a primary market are comparatively high, this flexibility may excessively burden costs in that market and decrease the expected returns from the product overall.

Conclusions

5.1 Review of hypotheses

Recall that this thesis set out to explore three hypotheses.

Hypothesis 1: *By considering elements of a product's design as flexible options, a product developer can make effective decisions on which markets a product should be designed to serve, based on costs to serve and anticipated returns from those markets.*

This hypothesis is supported since the model applies rigorous analysis based in economics, product development theory and statistics to compare the strategic options open to the product developer. By reviewing the results from a detailed simulation rather than simply considering mean estimates of market size, the developer can avoid the "flaw of averages" and get an accurate indication of which alternative they should pursue.

Incorporating flexibility into the product's design does, in several of the examples reviewed, yield greater returns. Conversely, the model also indicates where this flexibility is not valuable, and where the developer's best choice for maximizing expected returns is to develop a product tailored for a specific market.

Hypothesis 2*: By incorporating functions representing managerial decisions into a conventional product cash flow model, a product developer can effectively assess expected returns over the product's entire lifecycle.*

This hypothesis is supported since the decisions incorporated into the cash flow model do indeed have an effect on the expected returns from each strategy for the proposed new product. The model combines these decisions with a comprehensive set of inputs to arrive at an expected value for the project. Finally, the output from the model is presented in a way that allows the product developer to assess both mean expected returns, and the probably distribution of outcomes.

Hypothesis 3*: By implementing this managerial flexibility, a product developer may be able to bring a flexible product to market at substantially lower cost than comparable inflexible designs.*

This hypothesis is supported reviewing the results of these studies, where we can clearly see where flexibility reduces projected costs: In allowing a product developer to incur development costs only if and when they are required. This means that development costs are not incurred for markets that never emerge. Moreover, since flexible options are developed only *when* the market emerges, development costs are reduced by discount rates similar to the returns from related sales. Combined, these two effects can considerably reduce overall costs.

Overall, the method presented is an effective way of approaching the problem of determining whether to include flexible options in a product's platform. In most of the cases developed, applying a flexible design methodology would indeed allow practitioners to lower their costs to bring new products to market. Each of the practitioners interviewed found the model intuitive and easy to understand. It is the author's hope that this will lead to more widespread adoption of this type of modeling, and that models which explicitly value flexibility and managerial decisions will empower future product developers to make better, more profitable decisions.

5.2 Recommendations for future work

Three directions of future study would continue to refine and improve upon the methods presented in this thesis.

First, it is recognized that the results achieved through these simulations are highly dependent on the developer's analysis of the circumstances surrounding their development activities. For example, one can look at the overwhelmingly positive returns predicted by the developers questioned, and wonder whether a more comprehensive set of cost or risk inputs are required. The detailed study of appropriate inputs, and the correlation of those inputs against statistically valid results from real world projects, would be of great value to practitioners wanting to use this model.

Second, the number of practitioners surveyed in this thesis was limited by the time available while this work was being produced. Further studies that could expand on the base of practitioners surveyed – both qualitatively and quantitatively – on the use of this model would further enhance this method's robustness. The ultimate proof of the methods proposed herein would be to test the framework's predictions against the performance of actual products in the market over time. To do so effectively would require a study conducted across a number of industries and over many years.

Finally, the distillation of the findings of a more comprehensive study into some more subjective heuristics would open the results of this methodology to application by a wide range of product development practitioners. While some practitioners may go to the depth of analysis presented in this study in order to determine whether they should design their products on a flexible platform, many will not. For those who do not, providing guidance based on this study would allow them to apply the concepts presented here within general guidelines. While some of the analysis above points to, for example, a comparatively high product development cost and comparatively low carrying cost of flexibility as circumstances where flexibility has a high inherent value, this relationship should be further explored and evaluated before being adopted as a rule of thumb for product development practitioners in general.

Works Cited

Baldwin, Carliss Y, and Kim B Clark. *Design Rules - The Power of Modularity.* Cambridge: MIT Press, 2000.

Balgos, V, interview by Matthew Harper. *Practitioner model utilization survey* (April 25, 2011).

Black, Fischer, and Myron Scholes. "The Pricing of Options and Corporate Liabilities." *Journal of Political Economy* 81, no. 3 (1973): 637 - 655.

Borison, Adam. "Real Options Analysis: Where are the Emperor's Clothes?" *Journal of Applied Corporate Finance* 17, no. 2 (2005): 17-31.

Boyle, Phelim P. "Options: A Monte Carlo Approach." *Journal of Financial Economics* 4, no. 3 (1977): 323-338.

Brach, Marion A. *Real options in practice.* Hoboken: John Wiley & Sons, 2003.

Christensen, Clayton M. *The Innovator's Dilemma.* Boston: Harvard Business School Press, 1997.

de Neufville, Richard, and Stefan Scholtes. *Flexibility in Engineering Design.* Cambridge: MIT Press, 2011.

de Weck, Olivier. "Learning Curve Effects." *Course Notes, ESD.36 - System Project Management.* Cambridge: Massachusetts Institute of Technology, October 2010.

Faulkner, Terrence W. "Applying "Options Thinking" to R&D Valuation." *Research Technology Management* 39, no. 3 (May - June 1996): 50 - 57.

Fricke, Ernst, and Armin P Schulz. "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle." *Systems Engineering* 8, no. 4 (2005): 342-359.

Gil, Nuno. "On the value of project safeguards: Embedding real options in complex products and systems." *Research Policy* 36, no. 7 (2007): 980-999.

GSMA. *Green Power for Mobile - Top Ten Findings.* White Paper, London, UK: GSMA Development Fund, 2009.

Guthrie, Graeme. *Real Options in Theory and Practice.* New York: Oxford University Press, 2009.

Harper, Matthew A M. "Field Data from VRB Flow Batteries in Remote Telecoms Applications." *Electrical Energy Storage Applications and Technologies.* Seattle: Sandia National Laboratories, 2009.

Harper, Matthew A M. *Reassessing the development of the VRB-ESS.* Term Paper, 15.969 - User Centered Innovation, Cambridge: MIT, 2010.

Hassan, Rania. *Flexibility versus Robustness: What's in a Name?* Course Notes, ESD.344, Cambridge: MIT, 2007.

Howell, Sydney, et al. *Real options.* Harlow: Pearson Education Limited, 2001.

Iheagwara, C, interview by Matthew Harper. *Practitioner model utilization survey* (April 27, 2011).

Jiao, Jianxin, Arun Kumar, and Ching Moi Lim. "Flexiblity valuation of product family architecture: a real-option approach." *Internation Journal of Advanced Manufacturing Technology* 30, no. 1-2 (2006): 1-9.

Klassen, A, interview by Matthew Harper. *Practitioner model utilization survey* (March 25, 2011).

Kluza, J, interview by Matthew Harper. *Practitioner model utilization survey* (April 28, 2011).

Ko, J, interview by Matthew Harper. *Practitioner model utilization survey* (March 25, 2011).

Lawler, Gregory F, and Vlada Limic. *Random Walk: A Modern Introduction.* Cambridge: Cambridge University Press, 2010.

Leiblein, Michael J. "The Choice of Organizational Governance Form and Performance; Predictions from Transaction Cost, Resource-based, and Real Options Theories." *Journal of Management* 29, no. 6 (2003): 937-961.

Lepp, G, interview by Matthew Harper. *Practitioner model utilization survey* (March 25, 2011).

Luehrman, Timothy A. "Investment Opportunities as Real Options: Getting Started on the Numbers." *Harvard Business Review*, July - August 1998.

—. "Strategy as a Portfolio of Real Options." *Harvard Business Review*, September - October 1998.

Magoc, Tanja, and Vladik Kreinovic. "Empirical Formulas for Economic Fluctuations: Towards A New Justification." *Proceedings of the 28th North American Fuzzy Information Processing Society Annual Conference.* Cincinnati: NAFIPS, 2009.

Merton, Robert C. "Theory of Rational Option Pricing." *The Bell Journal of Economics and Management Science* 4, no. 1 (1973): 141-183.

Meyer, Marc H, and Alvin P Lehnerd. *The Power of Product Platforms: Building Value and Cost Leadership.* New York: The Free Press, 1997.

Moore, Geoffrey A. *Crossing the Chasm.* New York: Harper Business Essentials, 1991.

Moran, M, interview by Matthew Harper. *Practitioner model utilization survey* (April 29, 2011).

Mun, Johnathan. *Real Options Analysis: Tools and Techniques for Valuing Strategic Investments and Decisions, Second Edition.* Hoboken: John Wiley & Sons, 2006.

Newton, David P, Dean A Paxson, and Martin Widdicks. "Real R&D Options." *International Journal of Management Reviews* 5, no. 2 (June 2004): 113-130.

Roark, H, interview by Matthew Harper. *Practitioner model utilization survey* (April 27, 2011).

Rocha, Henrique Martins, and Mauricio Cesar Delamaro. "Product development process: Using real optiosn assessments to support decision-making at decision gates." In *Complex Systems Concurrent Engineering*. Springer, 2007.

Rogers, Everett M. *Diffusion of Innovations, 4th Edition.* New York: Free Press, 1995.

Saleh, Joseph H, Gregory Mark, and Nicole C Jordan. "Flexibility: a multi-discilpinary literature review and a research agenda for designing flexible engineering systems." *Journal of Engineering Design* 20, no. 3 (2008): 1-17.

Suh, Eun Suk, Olivier L de Weck, and David Chang. "Flexible product platforms: framework and case study." *Research in Engineering Design* 18, no. 2 (2007): 67-89.

Ulrich, Karl T, and Steven D Eppinger. *Product Design and Development, 4th Edition.* New York: McGraw-Hill Higher Education, 2008.

van Bekkum, Sjoerd, Enrico Pennings, and Han Smit. "A real options perspective on R&D portfolio diversification." *Research Policy* 38, no. 7 (2009): 1150-1158.

Weygandt, Jerry J, Paul D Kimmel, and Donald E Kieso. *Managerial Accounting: Tools for Business Decision Making.* Hoboken: John Wiley & Sons, 2003.

Wikipedia, Contributors. *Random Walk - Wikipedia, the free encyclopedia.* April 5, 2011. http://en.wikipedia.org/w/index.php?title=Random_walk&oldid=422458411 (accessed April 5, 2011).

Appendix 1: Full model results for detailed case

7.1 Inputs

Key:

Inputs	
Calculated values	
Randomization factor	(Hidden)
Static randomization	(Hidden)

Data	**Random Normalized**
Discount Rate	25%
	15%
	10%
Market Data	
Addressable market, Primary	10,000
5% Upper confidence bound, Primary	12,000
Sale price, Primary	$10,600
Market share, Primary	25%
Time to maturity, Primary	7
Addressable market, Secondary	1,000
5% upper confidence band, Secondary	5,000
Sale price, Secondary	$11,448
Market share, Secondary	25%
Time to maturity, Secondary market	7
Product Data	
Primary market	
Development cost	$2,120,000
Cost of goods to serve primary market	$9,752
Secondary market	
Incremental Development cost	$424 000
Incremental cost to serve Secondary	$848
Cost of goods to serve secondary market	$10 600
Rigid Multi-Market Product	
Cost of goods sold	$10 600
Option Characteristics	
Development cost, Initial	$42 400
Development cost, at execution	$424 000
Option carrying cost, per unit	$212
Minimum efficient scale, Option	2 500
Incremental unit cost, Option	$ 848
Learning Curve Effects	
Learning curve slope	0.95
Units built prior to introduction	20
LC Curve Starting Factor	1.248179301

7.2 Adoption fraction modeling

Expected Demand

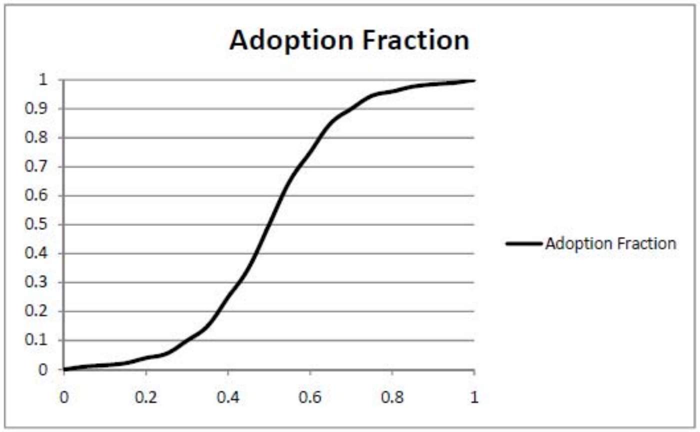
Base model

Total market	10000	units
Market share	25%	of total
Time to maturity	7	years

Option model

Total market	1000	units
Market share	25%	of total
Time to maturity	7	years

Time Fracti	Adoption Fraction
0	0
0.05	0.01
0.1	0.015
0.15	0.022
0.2	0.04
0.25	0.055
0.3	0.1
0.35	0.15
0.4	0.25
0.45	0.35
0.5	0.5
0.55	0.65
0.6	0.75
0.65	0.85
0.7	0.9
0.75	0.945
0.8	0.96
0.85	0.977
0.9	0.985
0.95	0.99
1	1



Lead product adoption

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fraction	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.00	1.00	1.00
Adoption Fraction	0%	2%	6%	25%	65%	90%	98%	100%	100%	100%	100%
Yearly Adoption		2%	4%	20%	40%	25%	8%	2%	0%	0%	0%

Option product adoption (calendar only)

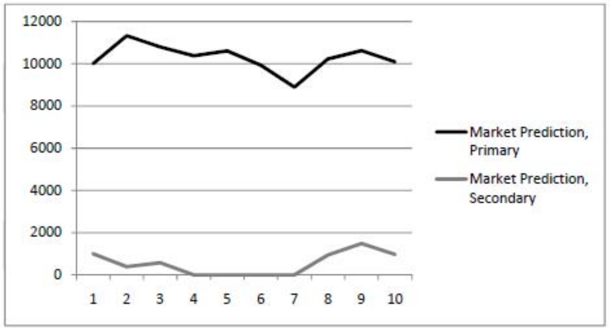
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Lifecycle Fraction	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.00	1.00	1.00
Adoption Fraction	0%	2%	6%	25%	65%	90%	98%	100%	100%	100%	100%
Yearly Adoption	0%	2%	4%	20%	40%	25%	8%	2%	0%	0%	0%

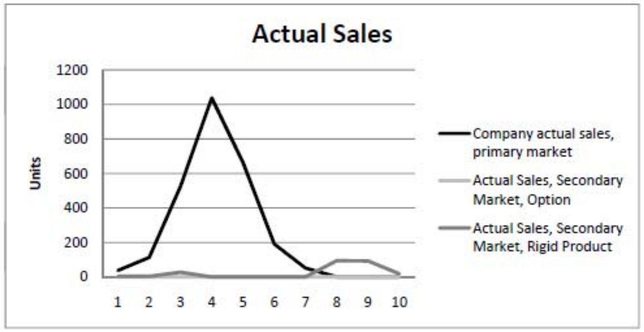
7.3 Stochastic sales forecast (single instance)

Sales Forecasts and Option Execution

	Year	0	1	2	3	4	5	6	7	8	9	10	Total
Primary Market	5% Upper Bound on Confidence	12,000											
	Base Standard Deviation	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	1020.4	
	Random number		0.31713135	0.90331735	0.300281	0.341461	0.6103935	0.252614	0.1533138	0.9048253	0.6672076	0.3009356	
	Market above expectations?		0	0	1	1	1	1	0	0	1	1	
	Market below expectations?		0	1	0	0	0	0	1	1	0	0	
	Market growing?		0	1	0	0	1	0	0	1	1	0	
	Market shrinking?		1	0	1	1	0	1	1	0	0	1	
	Above and growing?		0	0	0	0	1	0	0	0	1	0	
	Below and shrinking?		0	0	0	0	0	0	1	0	0	0	
	Standard Deviation Adjustment		0.000	1.000	1.000	1.000	0.812	1.000	0.993	1.000	0.885	1.000	
	Standard Deviation Adjusted		0	1020	1020	1020	829	1020	1013	1020	904	1020	
	Market prediction, unbounded		10000	11327	10793	10376	10608	9929	8893	10229	10620	10087	
	Market Prediction, Primary	10000	10000	11327	10793	10376	10608	9929	8893	10229	10620	10087	
	Market maturity		0.02	0.04	0.20	0.40	0.25	0.08	0.02	0.00	0.00	0.00	
	Market share		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
	Company actual sales, primary market		37	113	526	1038	663	191	51	0	0	0	2620
Secondary Market	Initial prediction	1000											
	5% Upper Bound on Confidence	5,000											
	Base Standard Deviation	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	2040.8	
	Random number		0.9067068	0.382725028	0.535776	0.131347	0.3547214	0.4116615	0.4094676	0.6781568	0.6049497	0.4003003	
	Market above expectations		1	1	0	0	0	0	0	0	0	1	
	Market below expectations		0	0	1	1	1	1	1	1	1	0	
	Market growing		1	0	1	0	0	0	0	1	1	0	
	Market shrinking		0	1	0	1	1	1	1	0	0	1	
	Above and growing?		1	0	0	0	0	0	0	0	0	0	
	Below and shrinking?		0	0	0	1	1	1	1	0	0	0	
	Standard Deviation Adjustment		0.000	1.000	1.000	0.574	0.000	0.000	0.000	1.000	1.000	1.000	
	Standard Deviation Adjusted		0	2041	2041	1172	0	0	0	2041	2041	2041	
	Market prediction, unbounded		1000	391	574	-739	0	0	0	944	1487	972	
	Market Prediction, Secondary	1000	1000	391	574	0	0	0	0	944	1487	972	
	Sales into market		1	1	1	0	0	0	0	1	1	1	
	Lifecycle year		1	2	3	3	3	3	3	4	5	6	
	Market maturity		2%	4%	20%	20%	20%	20%	20%	40%	25%	8%	1.76
	Market Share		25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	
	Actual Sales, Secondary Market, Rigid Product		3.8	3.9	28.0	0.0	0.0	0.0	0.0	94.4	93.0	18.7	242

Option Decision	MES	2500											
	Execute Option?		0	0	0	0	0	0	0	0	0	0	
	Sales into market		1	0	1	0	0	0	0	1	1	1	
	Option lifecycle year		0	0	0	0	0	0	0	0	0	0	
	Adoption fraction, Option		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	Market Share		25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	
	Actual Sales, Secondary Market, Option		0	0	0	0	0	0	0	0	0	0	0





7.4 Cash flow, rigid single- and multi-market products

Rigid Model, Single Market

	Period	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Income		0	37	113	526	1038	663	191	51	0	0	0
	Cumulative Sales, Base	0	37	151	677	1715	2378	2569	2620	2620	2620	2620
	Sale price, Base	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600
	Development cost	$ 2,120,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77	0.72	0.70	0.70	0.70	0.70	0.70
	Unit cost	$ 9,752	$ 9,752	$ 9,019	$ 8,321	$ 7,498	$ 7,009	$ 6,843	$ 6,805	$ 6,795	$ 6,795	$ 6,795
	Revenue, base	$ -	$ 397,500	$ 1,200,687	$ 5,577,259	$ 10,998,707	$ 7,028,068	$ 2,025,915	$ 542,016	$ -	$ -	$ -
	Expenses, base	$ 2,120,000	$ 365,700	$ 1,021,593	$ 4,378,097	$ 7,780,524	$ 4,647,284	$ 1,307,919	$ 347,942	$ -	$ -	$ -
	Total income, base	-$ 2,120,000	$ 31,800	$ 179,093	$ 1,199,161	$ 3,218,183	$ 2,380,784	$ 717,995	$ 194,074	$ -	$ -	$ -
Cash Flows	Net Income	-$ 2,120,000	$ 31,800	$ 179,093	$ 1,199,161	$ 3,218,183	$ 2,380,784	$ 717,995	$ 194,074	$ -	$ -	$ -
	Discount rate	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Discount multiplier	100%	125%	125%	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
	Discount Factor	100.00%	80.00%	64.00%	51.20%	40.96%	32.77%	26.21%	20.97%	16.78%	13.42%	10.74%
	Discounted cash flow	-$ 2,120,000	$ 25,440	$ 114,620	$ 613,971	$ 1,318,168	$ 780,135	$ 188,218	$ 40,700	$ -	$ -	$ -
	Net present value	**$ 961,252**										

Rigid Model, Multi Market

	Period	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Income, Primary Market	Sales, period	0	37	113	526	1038	663	191	51	0	0	0
	Sales, cumulative	0	37	151	677	1715	2378	2569	2620	2620	2620	2620
	Sale price	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600
	Development cost	$ 2,120,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77	0.72	0.70	0.70	0.70	0.70	0.70
	Unit cost	$ 10,600	$ 10,600	$ 9,803	$ 9,044	$ 8,151	$ 7,619	$ 7,438	$ 7,396	$ 7,386	$ 7,386	$ 7,386
	Revenue, base	$ -	$ 397,500	$ 1,200,687	$ 5,577,259	$ 10,998,707	$ 7,028,068	$ 2,025,915	$ 542,016	$ -	$ -	$ -
	Expenses, base	$ 2,120,000	$ 397,500	$ 1,110,428	$ 4,758,801	$ 8,457,092	$ 5,051,396	$ 1,421,651	$ 378,198	$ -	$ -	$ -
	Total income, base	-$ 2,120,000	$ -	$ 90,259	$ 818,457	$ 2,541,616	$ 1,976,673	$ 604,263	$ 163,818	$ -	$ -	$ -
Incremental Income, Secondary Market	Sales, period	0	4	4	28	0	0	0	0	94	93	19
	Sales, cumulative	0	4	8	36	36	36	36	36	130	223	242
	Sale price	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720
	Incremental Development cost	$ 212,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77	0.72	0.70	0.70	0.70	0.70	0.70
	Variable cost, per unit	$ 10,600	$ 10,600	$ 9,803	$ 9,044	$ 8,151	$ 7,619	$ 7,438	$ 7,396	$ 7,386	$ 7,386	$ 7,386
	Revenue	$ -	$ 47,700	$ 49,756	$ 356,197	$ -	$ -	$ -	$ -	$ 1,200,744	$ 1,182,329	$ 237,944
	Expenses	$ 212,000	$ 39,750	$ 38,346	$ 253,271	$ -	$ -	$ -	$ -	$ 697,185	$ 686,492	$ 138,157
	Total income	-$ 212,000	$ 7,950	$ 11,409	$ 102,926	$ -	$ -	$ -	$ -	$ 503,560	$ 495,837	$ 99,788
Net Cash Flows	Net Income	-$ 2,332,000	$ 7,950	$ 101,669	$ 921,383	$ 2,541,616	$ 1,976,673	$ 604,263	$ 163,818	$ 503,560	$ 495,837	$ 99,788
	Discount rate	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Discount multiplier	1.00	1.25	1.25	125%	1.25	1.25	1.25	1.25	1.25	1.25	1.25
	Discount Factor	100.00%	80.00%	64.00%	51.20%	40.96%	32.77%	26.21%	20.97%	16.78%	13.42%	10.74%
	Discounted cash flow	-$ 2,332,000	$ 6,360	$ 65,068	$ 471,748	$ 1,041,046	$ 647,716	$ 158,404	$ 34,355	$ 84,483	$ 66,550	$ 10,715
	Net present value	**$ 254,445**										

7.5 Cash flow, flexible product

Flexible Model												
	Period	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Income, Base Model	Sales, Base	0	37	113	526	1038	663	191	51	0	0	0
	Cumulative Sales, Base	0	37	151	677	1715	2378	2569	2620	2620	2620	2620
	Sale price, Base	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600	$ 10,600
	Development cost	$ 2,162,400	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	0.92	0.85	0.77	0.72	0.70	0.70	0.70	0.70	0.70
	Cost of goods sold, per unit	$ 9,752	$ 9,752	$ 9,019	$ 8,321	$ 7,498	$ 7,009	$ 6,843	$ 6,805	$ 6,795	$ 6,795	$ 6,795
	Option carrying cost, per unit	212	$ 212	$ 196	$ 181	$ 163	$ 152	$ 149	$ 148	$ 148	$ 148	$ 148
	Revenue, base	$ -	$ 397,500	$ 1,200,687	$ 5,577,259	$ 10,998,707	$ 7,028,068	$ 2,025,915	$ 542,016	$ -	$ -	$ -
	Expenses, base	$ 2,162,400	$ 373,650	$ 1,043,802	$ 4,473,273	$ 7,949,666	$ 4,748,312	$ 1,336,352	$ 355,506	$ -	$ -	$ -
	Total income, base	-$ 2,162,400	$ 23,850	$ 156,885	$ 1,103,985	$ 3,049,041	$ 2,279,756	$ 689,562	$ 186,510	$ -	$ -	$ -
Income, Option	Sales, Option	0	0	0	0	0	0	0	0	0	0	0
	Cumulative Sales, Option	0	0	0	0	0	0	0	0	0	0	0
	Sale price, Option	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720	$ 12,720
	Execution cost, Option	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Unit cost learning curve factor		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Incremental unit cost, Option	848	848	848	848	848	848	848	848	848	848	848
	Cost of goods sold, per unit	10,812	10,812	10,063	9,350	8,509	8,010	7,840	7,800	7,790	7,790	7,790
	Revenue, Option	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Expenses, Option	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Total income, option	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	Net Income	-$ 2,162,400	$ 23,850	$ 156,885	$ 1,103,985	$ 3,049,041	$ 2,279,756	$ 689,562	$ 186,510	$ -	$ -	$ -
	Discount rate	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Discount multiplier	1.00	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
	Discount Factor	100.00%	80.00%	64.00%	51.20%	40.96%	32.77%	26.21%	20.97%	16.78%	13.42%	10.74%
	Discounted cash flow	-$ 2,162,400	$ 19,080	$ 100,406	$ 565,241	$ 1,248,887	$ 747,031	$ 180,765	$ 39,114	$ -	$ -	$ -
	Net present value	**$ 738,123**										

7.6 Simulation results, sheet 1

Simulation Spreadsheet

Simulations			
#	NPV_{std}	NPV_{multi}	NPV_{flex}
1	$ 961,252	$ 254,445	$ 738,123
2	$ 1,080,027	$ 671,092	$ 851,045
3	-$ 238,386	-$ 181,315	-$ 383,138
4	$ 1,209,408	$ 1,074,148	$ 1,222,235
5	$ 1,081,178	$ 1,694,216	$ 2,254,324
6	$ 727,313	$ 1,247,026	$ 1,650,484
7	$ 897,421	$ 850,723	$ 979,529
8	$ 1,044,645	$ 420,050	$ 861,304
9	$ 832,634	$ 250,424	$ 616,056
10	$ 111,832	-$ 402,265	$ 118,878
11	$ 601,238	$ 1,401,600	$ 1,694,138
12	$ 1,169,873	$ 1,432,428	$ 1,383,805
13	$ 666,133	$ 1,664,486	$ 1,873,435
14	$ 915,732	$ 1,319,574	$ 802,489
15	$ 927,264	$ 127,879	$ 706,008
16	$ 1,142,046	$ 1,975,241	$ 1,312,944
17	$ 686,568	$ 43,259	$ 476,627
18	$ 579,637	-$ 251,690	$ 374,500

Results		
Single Market Inflexible	Min	-$ 568,755
	Mean	$ 730,271
	Max	$ 1,450,771
5% chance of NPV below		$ 3,062
5% chance of NPV above		$ 1,329,641
Multi-Market Inflexible		
	Min	-$ 1,007,120
	Mean	$ 747,463
	Max	$ 2,454,512
5% chance of NPV below		$ -251,929
5% chance of NPV above		$ 1,833,398
Multi-Market Flexible		
	Min	-$ 592,312
	Mean	$ 998,976
	Max	$ 2,832,201
5% chance of NPV below		$ 33,396
5% chance of NPV above		$ 2,073,285

7.7 Simulation results, sheet 2

19	$ 959,436	$ 1,035,935	$ 846,006
20	$ 38,673	$ 476,568	$ 348,235
21	$ 172,087	-$ 379,419	-$ 12,725
22	$ 447,019	-$ 130,234	$ 247,843
23	$ 874,186	$ 1,215,286	$ 1,808,212
24	$ 1,134,172	$ 1,132,315	$ 969,159
25	$ 905,300	$ 1,392,746	$ 1,436,345
26	$ 518,223	$ 1,967	$ 306,840
27	$ 1,279,267	$ 1,112,779	$ 1,784,646
28	$ 432,638	$ 911,488	$ 904,330
29	$ 875,640	$ 1,007,890	$ 1,522,862
30	-$ 352,149	-$ 1,007,120	-$ 511,360
31	$ 151,487	$ 988,951	$ 1,182,486
32	$ 970,826	$ 1,200,957	$ 1,448,575
33	$ 385,669	$ 777,988	$ 989,601
34	$ 175,024	$ 133,980	$ 234,548
35	$ 244,297	$ 563,692	$ 646,896
36	$ 572,417	$ 751,268	$ 1,222,953
37	$ 792,246	$ 1,173,281	$ 1,584,403
38	$ 957,622	$ 1,065,833	$ 1,184,463
39	$ 696,156	-$ 180,814	$ 485,924
40	$ 717,458	$ 929,420	$ 1,192,549
41	$ 692,669	$ 1,219,446	$ 940,245
42	$ 891,347	$ 1,079,355	$ 1,270,734
43	$ 1,443,464	$ 1,141,682	$ 1,327,579
44	$ 754,085	$ 751,443	$ 1,269,823
45	$ 393,275	-$ 122,697	$ 411,542
46	$ 1,116,130	$ 2,077,545	$ 2,333,164
47	$ 1,369,379	$ 2,176,128	$ 2,560,520
48	$ 868,525	$ 516,529	$ 689,457
49	$ 1,365,706	$ 1,899,955	$ 1,958,355
50	$ 723,309	$ 930,446	$ 722,792
51	$ 1,317,718	$ 1,213,389	$ 1,248,007
52	$ 652,240	$ 1,540,564	$ 1,688,005
53	$ 598,625	$ 538,159	$ 911,870
54	$ 673,765	$ 1,188,438	$ 1,040,537
55	$ 385,357	$ 743,737	$ 1,045,582
56	$ 775,228	-$ 98,796	$ 560,527
57	$ 1,248,478	$ 1,133,844	$ 1,448,820
58	$ 1,189,591	$ 1,685,290	$ 2,160,054
59	$ 365,271	$ 1,618,662	$ 1,854,220
60	$ 778,332	$ 748,534	$ 897,382
61	-$ 211,055	-$ 151,626	-$ 257,014
62	$ 368,862	-$ 322,671	$ 172,930

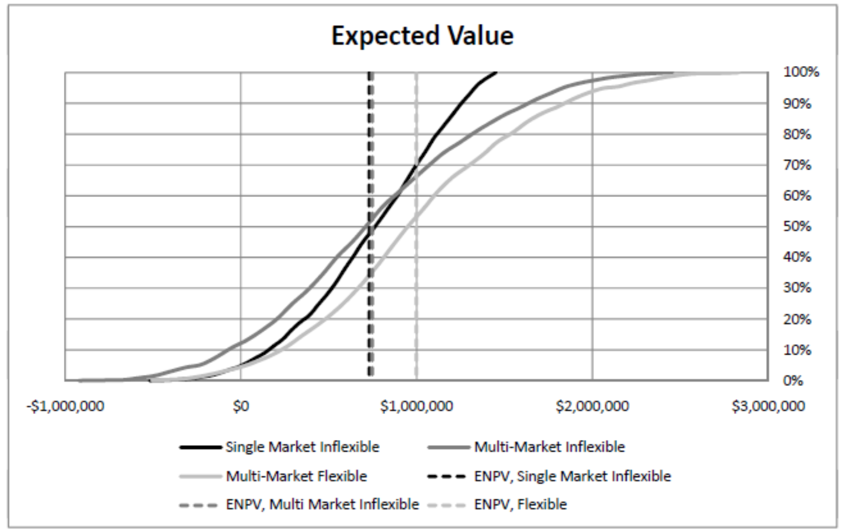
Building the Cumulative Distribution Function

	Single Market			Multi Market			Flexible		
#	Bound	Count	CDF	Bound	Count	CDF	Bound	Count	CDF
1	-$ 518,266	1	0%	-$ 920,579	1	0%	-$ 506,699	3	0%
2	-$ 467,778	2	0%	-$ 834,038	2	0%	-$ 421,087	6	0%
3	-$ 417,290	4	0%	-$ 747,497	4	0%	-$ 335,474	11	1%
4	-$ 366,802	7	0%	-$ 660,957	6	0%	-$ 249,861	24	1%
5	-$ 316,314	11	1%	-$ 574,416	19	1%	-$ 164,248	43	2%
6	-$ 265,826	16	1%	-$ 487,875	33	2%	-$ 78,635	66	3%
7	-$ 215,338	26	1%	-$ 401,334	60	3%	$ 6,978	91	5%
8	-$ 164,850	35	2%	-$ 314,793	86	4%	$ 92,590	126	6%
9	-$ 114,361	52	3%	-$ 228,253	104	5%	$ 178,203	168	8%
10	-$ 63,873	72	4%	-$ 141,712	152	8%	$ 263,816	223	11%
11	-$ 13,385	90	5%	-$ 55,171	212	11%	$ 349,429	293	15%
12	$ 37,103	118	6%	$ 31,370	262	13%	$ 435,042	361	18%
13	$ 87,591	150	8%	$ 117,911	326	16%	$ 520,654	437	22%
14	$ 138,079	183	9%	$ 204,451	400	20%	$ 606,267	527	26%
15	$ 188,567	227	11%	$ 290,992	498	25%	$ 691,880	632	32%
16	$ 239,056	270	14%	$ 377,533	585	29%	$ 777,493	748	37%
17	$ 289,544	330	17%	$ 464,074	690	35%	$ 863,106	875	44%
18	$ 340,032	382	19%	$ 550,615	807	40%	$ 948,719	999	50%
19	$ 390,520	426	21%	$ 637,155	905	45%	$ 1,034,331	1109	55%
20	$ 441,008	495	25%	$ 723,696	1018	51%	$ 1,119,944	1227	61%
21	$ 491,496	562	28%	$ 810,237	1134	57%	$ 1,205,557	1321	66%
22	$ 541,984	639	32%	$ 896,778	1223	61%	$ 1,291,170	1392	70%
23	$ 592,472	728	36%	$ 983,319	1311	66%	$ 1,376,783	1466	73%
24	$ 642,961	812	41%	$ 1,069,860	1398	70%	$ 1,462,396	1552	78%
25	$ 693,449	899	45%	$ 1,156,400	1481	74%	$ 1,548,008	1611	81%
26	$ 743,937	971	49%	$ 1,242,941	1544	77%	$ 1,633,621	1683	84%
27	$ 794,425	1048	52%	$ 1,329,482	1611	81%	$ 1,719,234	1738	87%
28	$ 844,913	1129	56%	$ 1,416,023	1671	84%	$ 1,804,847	1779	89%
29	$ 895,401	1209	60%	$ 1,502,564	1727	86%	$ 1,890,460	1828	91%
30	$ 945,889	1305	65%	$ 1,589,104	1773	89%	$ 1,976,072	1868	93%
31	$ 996,377	1397	70%	$ 1,675,645	1823	91%	$ 2,061,685	1898	95%
32	$ 1,046,866	1481	74%	$ 1,762,186	1866	93%	$ 2,147,298	1909	95%
33	$ 1,097,354	1573	79%	$ 1,848,727	1907	95%	$ 2,232,911	1933	97%
34	$ 1,147,842	1645	82%	$ 1,935,268	1933	97%	$ 2,318,524	1949	97%
35	$ 1,198,330	1718	86%	$ 2,021,808	1952	98%	$ 2,404,137	1968	98%
36	$ 1,248,818	1792	90%	$ 2,108,349	1969	98%	$ 2,489,749	1982	99%
37	$ 1,299,306	1858	93%	$ 2,194,890	1980	99%	$ 2,575,362	1993	100%
38	$ 1,349,794	1923	96%	$ 2,281,431	1990	100%	$ 2,660,975	1994	100%
39	$ 1,400,283	1965	98%	$ 2,367,972	1996	100%	$ 2,746,588	1996	100%
40	$ 1,450,771	2000	100%	$ 2,454,512	2000	100%	$ 2,832,201	2000	100%

7.8 Simulation results, sheet 3

63	$	391,473	$	815,304	$	931,504
64	$	484,396	-$	69,879	$	285,221
65	$	950,792	$	1,480,050	$	2,022,893
66	$	917,510	$	1,435,779	$	1,392,031
67	$	616,299	$	1,093,395	$	1,344,670
68	$	636,294	$	398,938	$	700,826
69	$	968,085	$	674,061	$	698,319
70	$	904,556	$	548,522	$	968,804
71	$	1,161,644	$	1,520,159	$	1,606,929
72	$	972,410	$	281,074	$	786,597
73	$	138,398	-$	404,022	-$	45,813
74	$	1,184,024	$	1,466,607	$	1,858,283
75	$	1,365,032	$	1,131,665	$	1,123,596
76	$	994,896	$	630,210	$	773,453
77	$	812,670	$	1,176,984	$	1,076,538
78	$	1,059,181	$	492,903	$	831,677
79	$	528,158	$	190,092	$	452,554
80	$	1,344,177	$	1,053,995	$	1,109,171
81	$	251,872	$	408,275	$	405,396
82	$	1,129,445	$	1,589,729	$	1,650,787
83	-$	43,703	$	22,012	-$	137,622
84	$	1,057,903	$	152,154	$	830,283
85	$	663,702	$	189,030	$	897,124
86	$	856,972	$	190,286	$	656,327
87	$	14,989	-$	32,819	$	292,067
88	$	293,554	$	166,681	$	217,103
89	$	483,161	$	546,718	$	780,471
90	$	558,560	$	1,244,365	$	832,187
91	$	603,314	-$	75,950	$	396,766
92	$	1,123,427	$	941,216	$	1,129,726
93	$	260,511	$	1,076,918	$	934,804
94	$	1,121,842	$	1,309,136	$	2,207,486
95	$	1,113,458	$	1,815,773	$	1,780,860
96	$	744,513	$	1,197,810	$	1,540,017
97	$	540,930	$	794,003	$	663,464
98	$	380,582	$	224,288	$	351,974
99	$	878,504	$	548,504	$	602,010
100	-$	4,942	$	894,544	$	1,014,954
101	$	492,568	-$	342,381	$	290,799
102	$	1,206,300	$	853,181	$	1,544,271
103	$	196,272	$	860,073	$	962,354
104	$	98,302	$	206,399	$	806,215
105	$	780,220	$	837,583	$	737,666
106	$	558,867	$	11,676	$	355,653
107	$	432,653	-$	174,648	$	233,235
108	$	466,851	$	1,488,576	$	1,435,516
109	$	253,516	-$	287,231	$	64,025

$	730,271	1	$	747,463	1	$	998,976	1
$	730,271	0	$	747,463	0	$	998,976	0



7.9 Simulation results, final sheet

1990	$ 995,778	$ 2,145,086	$ 1,986,551
1991	$ 742,374	$ 1,099,530	$ 929,466
1992	$ 524,645	$ 1,425,888	$ 1,708,222
1993	$ 1,008,168	$ 1,914,770	$ 2,348,579
1994	$ 944,199	$ 682,133	$ 749,173
1995	$ 983,841	$ 758,004	$ 860,816
1996	$ 8,930	-$ 205,002	-$ 179,174
1997	$ 707,961	$ 925,217	$ 986,968
1998	$ 1,333,793	$ 1,485,532	$ 1,602,134
1999	$ 477,565	$ 574,281	$ 724,590
2000	$ 256,582	$ 209,885	$ 463,680

Appendix 2: Selected Excel Formulae

8.1 Learning curve effects

The learning curve equation included here is derived from the one presented by Professor de Weck in “System Project Management”, MIT course ESD.36, in Fall, 2010.

The basic form of the equation is as follows:

$$Y = Y_0 * x^n$$

Where

- Y = cost to produce unit x
- n = log b/log 2
- b = learning curve factor (~80-100%).

Having proposed the formula above, (de Weck 2010) proceeds to recommend the following learning curve factors:

- Fabrication 90%
- Assembly 75%
- Material 98%.

Essentially what this equation does is to multiply the cost of production by the learning curve factor for each doubling of production, as shown in Figure 26.

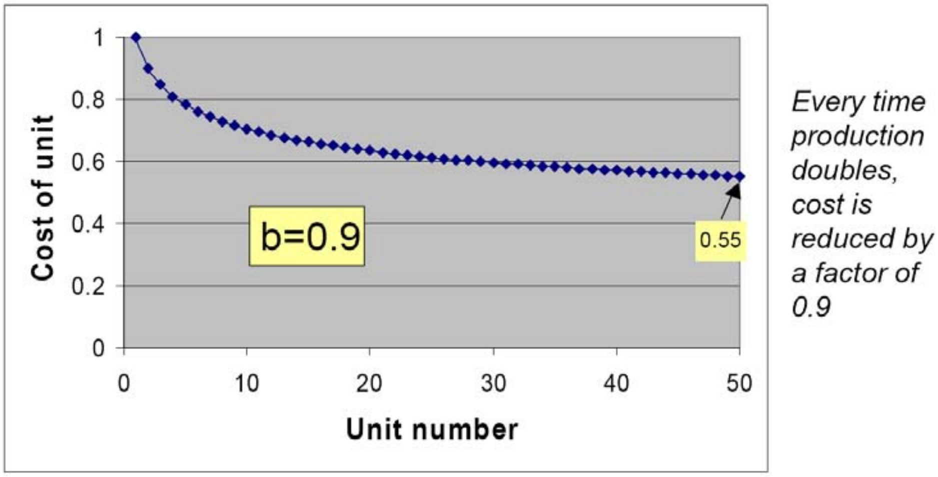


Figure 26: Product cost learning curve

(de Weck 2010)

To implement this in the framework developed here, though, one must consider the first part of the curve represented by this equation, where costs fall very quickly. Product developers are unlikely to know the true manufacturing costs of early prototypes; what is much more common is for them to have an understanding of the cost of the first production article. However, that article already has a great deal of the “learning” represented by the learning curve built into it. Hence, to apply this equation, we need to project backwards to determine the likely true cost of the first prototype. This is done in the following five steps.

First, the practitioner identifies the first production article unit cost.

Second, the practitioner identifies the number of articles produced before production is initiated.

Third, a derivative of the learning curve equation presented above in reverse to get an estimated Learning Curve “Starting Factor” (the factor by which the cost of the first prototype exceeded the cost of the first production unit). This is accomplished by using the equation

LC_START = 1/LC_UNITS^(LOG(LC_SLOPE)/LOG(2))

Fourth, the learning curve factor is calculated for each individual step in the model, using the equation

LC_FACTOR = (LC_START)*((UNITS+LC_UNITS)^(LOG(LC_SLOPE)/LOG(2)))

Note that here "UNITS" is the cumulative number of units sold.

Finally, this "LC_FACTOR" – the learning curve factor for each individual step – is multiplied by the initial production cost per unit to get the unit cost of goods at any given step in the model. This applies to all costs of goods sold, including base products, flexibility carrying costs and the incremental unit cost of the flexible option itself once that option is executed.

The implementation of this factor can be seen in Sections 7.4 and 7.5. Note that for the instance of the flexible product cash flow model shown in that section the option is never exercised, hence the learning curve factor remains at unity throughout the period analyzed.

8.2 Stochastic model variance compression

As discussed in Section 3.3.1, one of the challenges with the stochastic model that was implemented in this framework was that it had the possibility of yielding very large or negative numbers for market size. This is a result of using a normal distribution to represent the variance in market size. Though this distribution was proposed in the literature and seems intuitively reasonable, because it is unbounded at its limits some modifications were needed to produce believable results.

The approach taken was to compress the value of variability as the model approached either the practitioner's estimate of the largest possible market size or zero. This behavior is shown in Figure 27.

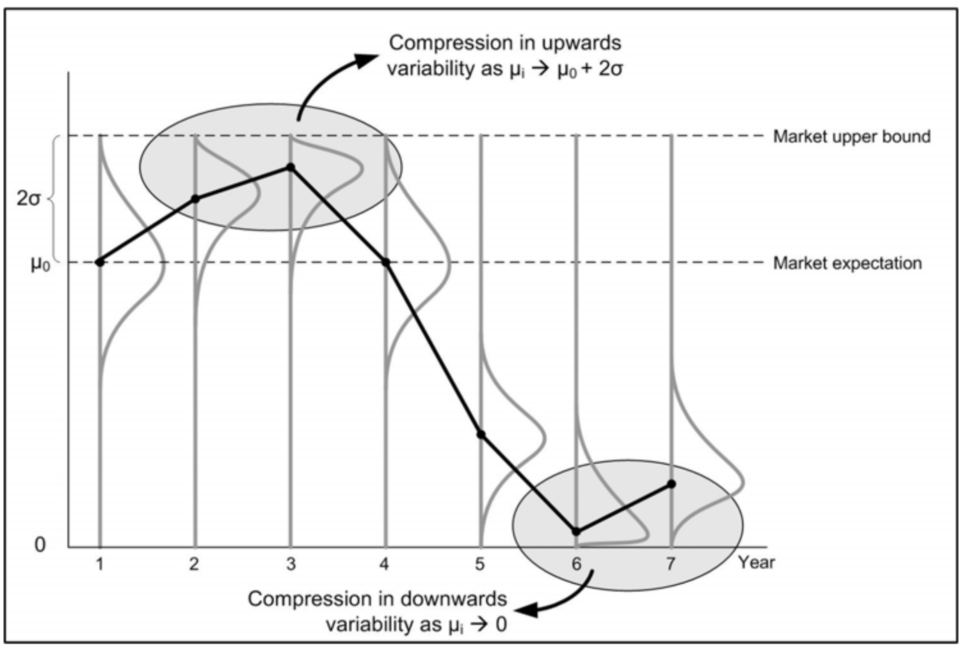


Figure 27: Variability compensation at market extremes

In excel, a series of logical tests were applied to the model's results at each step to determine where this compression should be applied. This yielded two tests:

1. If μ_i was above μ_0 and increasing, the variance was decreased; and
2. If μ_i was below μ_0 and decreasing, the variance was decreased.

In both cases, if an adjustment was called for the variance would be decreased by the ratio of the distance between μ_i and the market size limit and μ_0 and the market size limit. This returned a value between 0 and 1; that factor was then multiplied by the standard deviation and the model incremented one step forward.

In Excel, this was implemented as follows.

SD_ADJUST=IF(UPWARDS_TEST=1,((MKT_LIM-MEAN)/(MKT_LIM-MKT_INITIAL)),(IF(DOWNWARDS_TEST,(MEAN/MKT_INITIAL),1)))

Where:

- SD_ADJUST is the Standard Deviation adjustment factor;
- UPWARDS_TEST is the logical test to see if the market size is above expectations and increasing;
- DOWNWARDS_TEST is the logical test to see if the market size is below expectations and decreasing;
- MKT_LIM is the upper boundary of the potential market size, assessed by the practitioner and modeled as 2 standard deviations above the reported market average;
- MEAN is the current market estimate; and
- MKT_INITIAL is the practitioner's initial estimate of market size.

Implementing this algorithm allows extreme values to be avoided while retaining the fundamental character of the normal distribution in assessing randomness in product market behavior.