Managing Flexibility in the Supply Chain

by

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Abstract

Supply chain flexibility is introduced and its importance is discussed. This is followed by a review of the flexibility literature in manufacturing, supply chain, economics, strategy, organizational design, and industrial networks. Next, tools for evaluating flexibility are discussed: Decision analysis, decision trees, and real options. Lastly, an analysis of the literature and tools is incorporated into a set of guidelines for dealing with flexibility decisions.

Acknowledgements

First, my thanks go to my advisor, Jim Masters, for his valuable comments and direction (and a certain pedagogical absence of direction at times). Second, a general thanks to the professors and staff at MIT who do such a good job preparing and delivering great courses. Professor Richard de Neufville's class on Engineering Systems Analysis was inspirational for this thesis. Next, thanks go to my classmates in the MLOG program, at the engineering school, and at the business school. I do believe that the students are the most valuable assets of a school like MIT. I count myself very fortunate to have had a chance to study and learn at such a place with such people. Lastly, I would like to thank my wife Liesa Jean, who not only puts up with my oscar-the-grouchiness, but also does a bang up job of keeping me happy and interested in life. I have become happily dependent upon her company, sharing, and love.

You can't communicate complexity, only an awareness of it.

—Alan J. Perlis

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Chapter Outline

Chapter I provides a brief history of flexibility and offers two anecdotes to illustrate why the topic deserves management attention. This chapter presents compelling reasons for the study of flexibility; the *raison d'être* for the thesis. The importance of time as an element of competitiveness is discussed.

Chapter II presents a summary of the available literature on flexibility. These readings come from a wide area of literature, from economics to manufacturing. Specifically, these readings impart on the reader an awareness of supply chain flexibility in several dimensions: Range versus Mobility, Operational versus Strategic, and others. Chapter two gives the reader an intelligent way to communicate the various types flexibility and their implications. The reader learns to place specific problems regarding flexibility into their appropriate contexts.

Chapter III provides tools that can be used to evaluate solutions. Decision Analysis and Real Options Analysis are presented as tools to further define the problem, model scenarios, and in some cases produce numerical answers. Further, the use of DA and ROA is suggested as a way of further refining the meaning and uses of flexibility. In this way, these tools act as an inductive complement to the deductive tools gathered in chapter two.

Chapter IV incorporates learnings from chapters one, two, and three into summary guidelines that can be used to manage flexibility in the supply chain.

Chapter 1. Introduction: An awareness of flexibility

Flexibility has a positive and significant impact on growth and performance. This flexibility allows firms to respond to changes in customers' tastes, declining product life cycles, and uncertainty in sources of supplies and, thus, enables it to become a time-bases competitor.

—Gupta *&* Somers, 1996

Supply chain flexibility is a popular topic among practitioners and academics alike. A look thru popular press, trade journals, and advertisements finds the term *supply chain flexibility* used often:

- "[Our Product] Empowers Users with Maximum Supply Chain Flexibility"[1]
- "Delivering B2B Supply Chain Flexibility" [2]
- "Collaboration among supply chain partners can deliver significantly lower inventory levels, lower process costs and greater supply chain flexibility" [3]

But what is meant by supply chain flexibility? And more importantly, how does one ensure that it is managed correctly?

Flexibility is often compared to the quality charge of the 1970's and 80's in American manufacturing. Prior to that time it was thought that there was an unavoidable cost-and-quality tradeoff and besides, quality was "too squishy" an

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[1] Red Prairie sales & marketing material

[2] Supply Chain Technology website, `www.inboundlogistics.com`

[3] HP white paper, *Realizing the Value of Collaboration*

attribute to be measured—and managed—effectively. Like quality was then, flexibility is currently considered something that always comes with a price, and something that may be too ambiguous to effectively manage.

Of course, today it is widely accepted that quality *is* manageable. In fact, parity in cost reduction and quality management has moved the competitiveness of firms to new frontiers. One of these new frontiers is flexibility [Duclos *et al,* 2000].

This frontier of flexibility as a competitive advantage is important to supply chain managers because in many industries firms won't compete against one another; rather, supply chains will compete against one another [Hoppe *&* Rice, 2001].

Further, Gupta and Somers find that there is a relationship between flexibility, strategy, and firm performance. They write:

> [Flexibility has] a positive and significant impact on growth and performance. This flexibility allows firms to respond to changes in customers' tastes, declining product life cycles, and uncertainty in sources of supplies and, thus, enables it to become a time-bases competitor [1996].

Stalk and Hout agree, and they find that time-based competitors perform significantly better than companies that do not compete on a time basis [Stalk *&* Hout, 1991]. The role of flexibility as part of a broader, time-based competitive strategy will be covered in this paper. But first, additional background on the importance of flexibility will be covered.

1.1 Background

1.1.1 History of flexibility

At a very high level, this section can be summarized as three waves of evolution in industrial production: The first wave was efficiency; the second, quality; the third, flexibility [Suarez *et al,* 1995].

Starting in the industrial revolution—the beginning of modern industry—the emphasis in production systems was on mechanization of processes and specialization of labor. Production runs were long and batch-oriented, and the firm operated in a stable environment. As operations became larger, firms enjoyed significant economies of scale. Many industries were vertically integrated. Products were made in large quantities, without much differentiation. Forecasts were very long and drove extended production schedules. This is often called the era of mass production.

Then lean systems—also called "Japanese" systems, after their country of origin—further wrung-out waste to find new orders of efficiency. Anything deemed non-value-added was removed. Systems became more continuous instead of batch-oriented. Instead of a broad range of products, focused product offerings were the goal. Reducing the product line by half at a factory could increase labor productivity by 30% and decrease costs by 17% [Stalk, 1991]. As before, production was intended to run in a stable, extended forecasting environment.

The next major movement was to quality of production. Popular implementations included Total Quality Management (TQM), Continuous improvement, and Statistical process control. These systems were still forecast driven, but the forecasting horizon had become much shorter.

Most recently, systems of production have become more responsive by emphasizing speed and flexibility. Industries are characterized by an accelerated cycle of repeated vertical integration followed by horizontal disbandment [Fine, 1998]. Instead of batches, the goal is a production lot size of one. This allows for greater variety in the product line; production systems have gone from economies of *scale* to economies of *scope*. In place of forecasts, many supply chains are driven by real-time market data or actual orders (make-to-order). Some systems go so far as to practice pro-active "demand management," molding demand to match production capacities (sell-what-you-have).

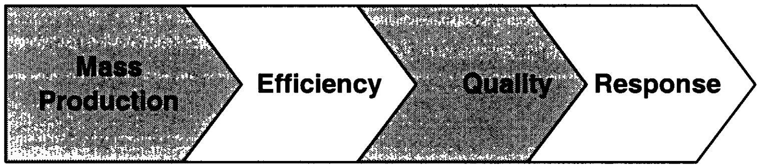

Exhibit 1.1: Evolution of Production Systems.

The current frontier for leading companies—and supply chains—is response. Customers see this in terms of responsiveness to their needs. The supply chain implements this in terms of speed and flexibility.

Exhibit 1.1 displays the evolution of production systems. Greis and Kasarda write about the role of the supply chain at companies that evolve into this new mode of responsiveness:

> Forecast-based production systems are no longer adequate to organize their operations around real-time information about shifting customer needs and about the availability of their productive capacity. They require not only up-to-date and immediate information about the location and disposition of all productive assets, but also information linking the location of the asset with available transportation opportunities. Under such conditions, logistics[4] is becoming a primary enabler of real-time response to customer needs. [1997]

1.1.1.1 Zara

An example of a company that has embraced this new mode of competition is Zara, a brand of Spanish company Inditex. In an industry described as having a long, inflexible supply chain, fashion retailer Zara has used innovative practices to become the darling of the industry.

In an industry where the design-to-sales cycle time is often over one year, Zara goes from design to manufacture to distribution to stock out in fewer than 20 days. Zara makes room for these new products by immediately obsolescing old ones. In

[4] In this thesis, the terms logistics and supply chain may occasionally overlap.

fact, most designs are produced only once. To sustain this rate of introduction, Zara creates five to eight designs per day, for a total of 12,000 new products per year. Zara is considerably faster than any other company in its industry [INSEAD Case, 2002].

In supply chains that move more car parts than bell-bottom pants, or more office supplies than knitted cashmeres, what can be learned from a fashion company such as Zara? The answer is "time." Time can be used two ways: Defensively and offensively. Historically, the former has driven improvements in the supply chain. More recently, the latter has been the impetus for supply chain innovation. Both will be discussed briefly.

1.1.2 Management of time as a defensive measure

More than forty years ago Forrester launched the field of Systems Dynamics by describing a typical retail supply chain, which had a lead-time of 18 days to replace stocked out items [Forrester, 1960]. In this simple system, it took the supply chain nearly five years to stabilize volumes after a one-time increase in consumer demand of 10%. When the system was fed a more realistic pattern of random, up-and-down demand, the results were predictably even worse.

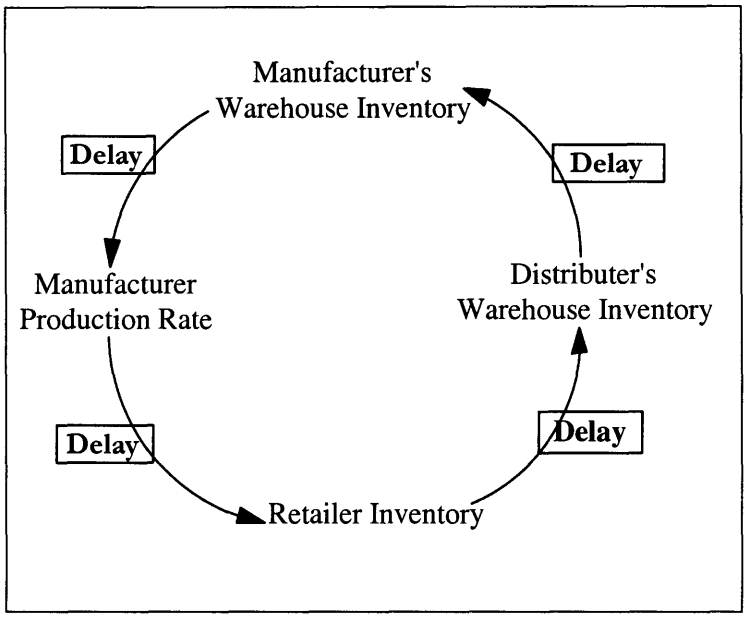

Exhibit 1.2: Planning Loop

What appears to be a simple, innocuous supply chain design actually leads to wild fluctuations in inventories and service levels. The information delays create waves of "phantom" demand. Loops such as these can be explored by using The Beer Game and other learning tools.

The loop delays described by Forrester in Exhibit 1.2 lead to what is now commonly called the "bullwhip effect." The problem is the time delay of demand (sales) information from the point of sale to the factory. Instead of transmitting the information explicitly and quickly—e.g., EDI or fax—the sales information is transmitted slowly and indirectly as a series of amplifying inventory purchases. From this example, one can see that time, when not managed properly, can be very damaging to the supply chain.

1.1.3 Management of time as an offensive measure

Flexibility, responsiveness, and variety can be used together in order to create a "time-based advantage" for businesses and supply chains. Stalk writes, "as a strategic weapon, time is the equivalent of money, productivity, quality, even innovation" [1988].

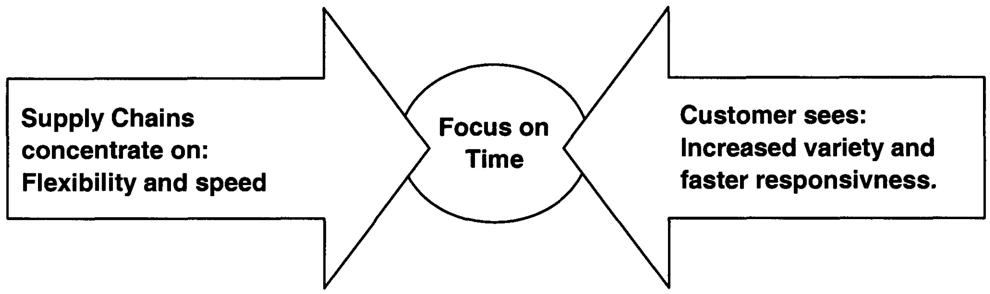

Exhibit 1.3: Focus on Time

A time-based approach emphasizes flexibility and speed on the supply side, which the demand side rewards as improved variety and response.

Andy Grove of Intel is credited with the saying "If you measure it, it will improve" [Intel Capital, 2000]. Consider these measurements: In a traditional manufacturing system, products spend over 97% of their time in the system waiting for something to happen [Stalk, 1988]. Likewise FedEx, long regarded as a top operation in transportation logistics, found in a study that a package in its system (including the customer's drop box) is actually moving only 25% of the time. One should consider the improvements possible if time were accounted for and managed-to as closely as COGS and labor hours in most companies. FedEx's COO comments:

> Good companies are becoming aware that management of time is as important as management of money. They are able to react more quickly and capitalize on change [Smith *et al*, 1988].

Similarly, Hammer and Champy decry the "inbox problem" where unneeded specialization of labor (a leftover of the Mass Production Era) creates a chain of wasted time as forms are passed from worker to worker to worker across the organization [1993]. Innovative supply chain practitioners must ask: What other holdovers from a bygone era are limiting the competitiveness of companies? It can be said that supply chain management is not just about managing resources and relationships; it's also about managing time.

1.2 Anecdotes

In this section, two examples of flexibilities in the supply chain are examined briefly to provide some context for the rest of the discussion. The first example concerns flexibility of a specific type at one location. The second concerns flexibility at a higher level, and its competitive implications. These two examples, the first tangible and local, the second, abstract and disparate, reflect the diversity of contexts where flexibility occurs.

1.2.1 The automated warehouse

The first anecdote is about a warehouse tour at a personal products manufacturer. A professor leading his students through the facility asks the tour leader about the large amount of unused track running around the warehouse.[5] The students on the tour keep stepping around and tripping on it, and more importantly it appeared to be impeding the laborers in the warehouse.

Over the years, the supervisor responds, the warehoused boxes of product got larger and heavier—either due to changes to the products inside or over-riding cost efficiencies elsewhere in the logistics system—and the automated system could no longer move them. Now, humans do the work of the abandoned, robotic track system instead. The warehouse is a busy, efficient operation based on the inordinate flexibility of human labor. When the warehouse manager is asked if he would like a

[5] The warehouse example is from a conversation with Jim Masters at MIT's Center for Transportation and Logistics about a tour he and a class of students took at a large distribution center

new, improved automated system—or an upgrade of the existing system—he quickly answers with an emphatic *no*.

There is theoretical backing for what happened in this warehouse. Many reviews of flexibility, including computer-driven FMS[6], that appeared in journals such as the Harvard Business Review in the late 1980's and early 1990's are harshly critical of those who mistake technology or automation for flexibility. As an example, Whitney finds that computer automation cannot compete with the flexibility of humans [1986]. Gerwin finds that factories—much like the warehouse in the example above—starting from a labor-intensive technology already have a high degree of flexibility [1983].

1.2.2 The Lolita apparel company

The next anecdote is about a women's fashion apparel company named Lolita. Lolita is an apparel company in South America that contracts and imports production from several countries, including India and China.[7] They compete in some of the same geographic markets as Zara (pp. 12). Because of the nature of the fashion-retail business, it is very hard to predict which styles and colors will sell well during the season. In fashion apparel, customers are famously fickle, and supply lines are notoriously long—often more than one year.

In the past, Lolita had been a net importer of goods, but with the devaluation of the peso, they now have a potential cost advantage in becoming a net exporter. The executive team had done some research and found that some forward-thinking companies were paying a little bit more to get faster turnaround from local companies

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[6] A Flexible Manufacturing System. An FMS is "a computer-controlled grouping of semi-independent work stations linked by automated material handling systems. The purpose of an FMS is to manufacture efficiently several kinds of parts at low to medium volumes" [Jaikumar, 1986]

[7] Lolita example is from Doshi *et al* (2003)

[Fisher *et al*, 1994]. Effectively, these companies are buying time—deferring the decision of what to produce until they can use early sales data to correctly select the best fabrics, styles, and colors.

The best in the business was Zara, the Spanish company that could take a garment from artist's concept to the store shelves in only 10 days [Hausman, 2002]. Could Lolita reconfigure their supply chain to be more like Zara's? If so, would Lolita need to make extensive investments in factories, computers, and other assets like Zara had? Just which portions of the Zara chain produced the flexibility that Lolita coveted? And how could Lolita avoid falling into the same trap as the warehouse manager, who found that the old way was more flexible than the new?

Furthermore if the peso revalued, could Lolita move back to an import-based model—or were these decisions irreversible? Did choosing flexibility require inflexible commitment? Indeed, so many questions to be answered.

It is questions like these, at companies such as Lolita, which have given birth to this thesis. The literature review in chapter two and the tools discussed in chapter three will help answer these questions. But first, the goal of the thesis will be defined more formally in the next section.

1.3 Formal Problem Statement

It is not enough to say, "Go forth and be flexible" or "Flexibility is good. Be flexible." Indeed, in the following chapters, it is found that flexibility is not always a good thing. **In response, managers need to develop an awareness of flexibility, learn how to communicate that awareness, and strive to find ways to objectively evaluate it.**

It is the author's contention that a way of comprehending and evaluating supply chain flexibility will be more valuable to practitioners than a complete definition. To this end, this paper will attempt to find a useful way to discuss and manage the concept of supply chain flexibility. This also means that flexibility will be examined from the supply chain *manager's* perspective, for "flexibility must be planned and managed" [Sethi & Sethi, 1989].

The end result will be a set of guidelines that can be used to structure the thought process when evaluating supply chain flexibility. These guidelines will not be a closed-form, "plug and chug" formula that takes a set of inputs describing a situation and spits out an answer. Rather, the guidelines will aim to provide a useful way to identify and intelligently discuss flexibility in the supply chain. These guidelines will be based on a collection and analysis of the flexibility literature and other related literature conducted in the course of preparing this thesis.

Chapter 2. Communicating Flexibility: A literature review

Strategic flexibility, thus, depends jointly on the inherent flexibilities of the resources available to the firm and on the firm's flexibilities in applying those resources to alternative courses of action

—Sanchez, 1995

The first half of this literature review has three major sections: Manufacturing literature, Supply Chain literature, and Economics literature. First, the manufacturing literature will provide a detail-oriented, bottoms-up perspective on the notion of flexibility in the supply chain, specifically the manufacturing and assembly portions of the supply chain. Second, the supply chain literature will provide a summary of the available publications on the topic to date. Third, the economics literature will provide a more theoretical, top-down perspective that will describe the competitive context in which supply chain flexibility decisions must be made.

In the second half of the literature review, Strategy literature, Organizational literature, and Industrial Networks literature will be reviewed. This literature will reveal some of the less obvious implications of flexibility and its implementations.

2.1 Manufacturing Flexibility Literature

There is a very large but fragmented body of literature on manufacturing flexibility. For detailed treatment of the literature, two recent articles are recommended, D'Souza and Williams [2000] and Beach *et al* [2000]. The classic survey is Sethi and Sethi [1989].

Many authors cite Upton's flexibility definition "the ability to change or react with few penalties in time, effort, cost, or performance" [1994]. Beyond that vague definition though, there is still not a consensus about what manufacturing flexibility means, or how to measure it. Manufacturing flexibility "has come to be used for many purposes, each of which characterizes a different quality or capability of a system" [Upton, 1994]. Considering that this has been the topic of discussion and publication for more than 20 years—Slack published *Flexibility as a Manufacturing Objective* in 1983—it may be safe to say that no clear definition will ever be accepted.

In the manufacturing literature, there are many, many definitions of what constitutes manufacturing flexibility. Sethi and Sethi point out that there are no fewer than 50 combined flexibility types and dimensions described in the literature, and that the definitions "are not always precise and are, at times even for identical terms, not in agreement with one another" [1990]. Eight years later, Shewchuk *et al* found a combined 80 flexibility types and dimensions in their literature review [1998].

Beech assesses the situation from a "system level" as such:

> Without an agreement on issues such as what the constituent elements of manufacturing flexibility are, the effects of interrelationships which exist between them and the extent of the role of the enablers of flexibility, when viewed at the system level, is likely to continue to appear inconsistent and confusing [2000].

However Beech goes on to say:

> Nonetheless, the importance of being able to account for existing degrees of flexibility when making strategic and operational decisions is clearly evident [*ibid*].

In summary, a comment that could be fairly made of the literature is "endless debate." Instead of entering this debate though, this paper will consider only two articles in detail—articles that the author will use to pull out the important tenets of manufacturing flexibility that are needed for this paper. The first article will provide workable definitions of manufacturing flexibility. The second article is a graphical taxonomy of the available literature, and will give an overview of where work has been done and how supply chain flexibility relates.

2.1.1 Manufacturing flexibility definitions

This paper will use Upton's popular (often cited) approach to manufacturing flexibility types. While general, Upton's descriptions are good enough to "provide a common base of understanding, so that all involved know what is to be improved. Reaching such a commonality of purpose is a critical step…" [Upton, 1994].

Upton uses three dimensions of flexibility: Range, Mobility, and Uniformity. Each of these is described next.

2.1.1.1 Range

Range is the measure of the size of the set of alternatives available, *or* the distance between alternatives in that set. For instance, range could be the number of different products that can be produced; the variance in output volumes of those products; or the variance in input volumes to manufacture those products, as shown in Exhibit 2.1 below.

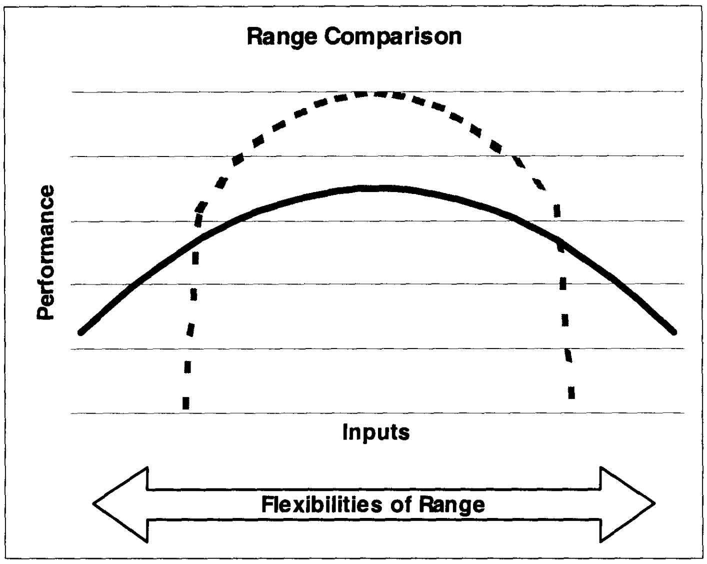

Exhibit 2.1: Flexibility of Range

The solid line represents a more flexible (wider) set of inputs that can be handled than that of the dotted line. This is because it handles a wider range of inputs, not because of its relative performance at any of the points on the range of inputs on the line.

2.1.1.2 Mobility

Mobility is a measure of how costly—in terms of dollars, time, or other performance measures—it is to move from one alternative in the range of flexibilities to another. Technically, it is the transient cost incurred when production moves from one state to another. An example of mobility is given in Exhibit 2.2 below.

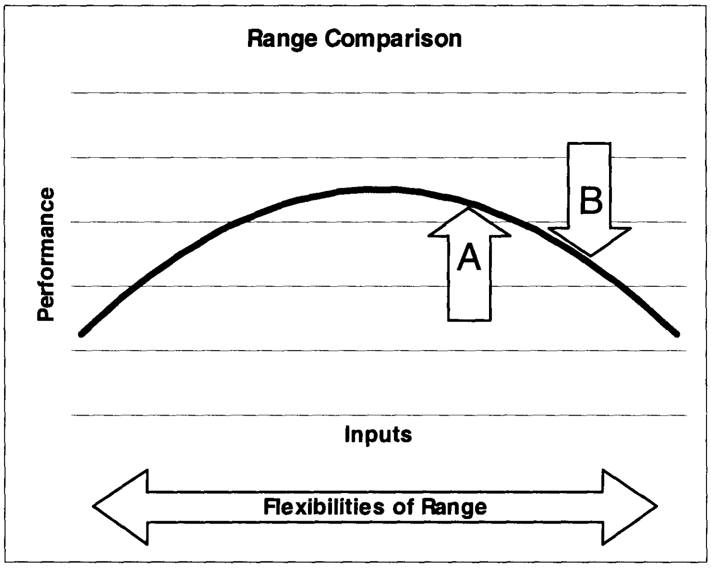

Exhibit 2.2: Flexibility of Mobility

Mobility is the cost of moving from one point on the range of possibilities to another. Re-using the example from the Range section, mobility would be represented by the ease at which production can move from point A to point B, one-time. Note that mobility is a one-time charge, and that the actual cost of making the move is not represented on the graph above. Rather, this graph is re-used to show the relationship between range and mobility.

2.1.1.3 Uniformity

Uniformity is the measure of constancy of performance across the range of alternatives. That is, production's ability to move across the range without much penalty in *continuing* performance. In perfect uniformity, performance is the same over the range of possible inputs or outputs. When considering uniformity, it may be helpful to picture the statistical distribution of the same name. When graphing performance versus input, a more uniform process will have a flatter line, as shown in Exhibit 2.3 below.

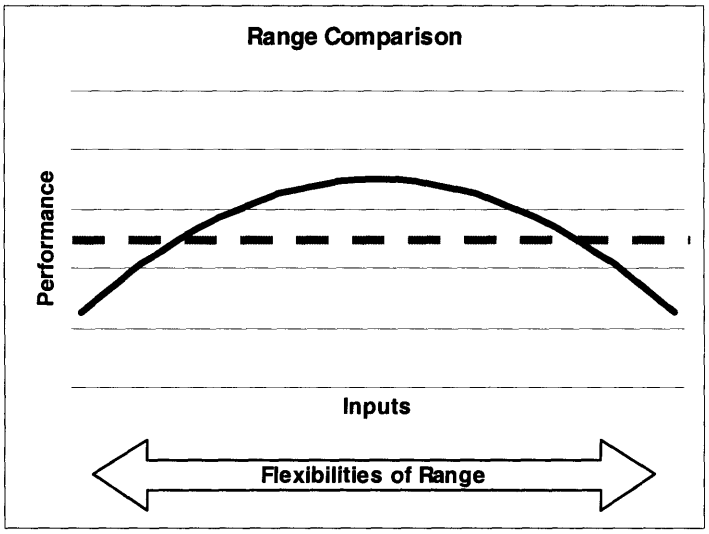

Exhibit 2.3: Flexibility of Uniformity

Comparison of the uniformity of two processes. The process represented by the dashed line is more uniform in its performance than the process represented by the solid line. So, across the uniform dimension, the dashed line represents a more flexible process.

Before leaving this topic, it is good to note that uniformity is probably closest to what some people call robustness: A system's ability to satisfactorily perform in a across a range of uncertainties. That is, what a system can handle, before needing to use flexibility techniques.

For more information on Range, Mobility, and Uniformity, including more examples, the reader is again referred to Upton [1994].

2.1.2 A graphical taxonomy

In the literature many frameworks have been proposed, and many of these are very good. But all are based on a necessary set of assumptions or limitations that constrain their scope and applicability. Basically, manufacturing flexibility depends much on context, and as the context changes, so does the necessary flexibility. However Koste and Malhotra's 1999 survey provides an excellent "meta-framework" of the literature. They include a matrix of results, and better yet, a graphical representation of that matrix [1999a].

Conveniently, Koste and Malhotra use Upton's three definitions of flexibility (see previous section) as the base for their study. There is one exception worth noting though. In the previous section, flexibility of range was defined as a "measure of the size of the set of alternatives available, *or* the distance between alternatives in that set." Koste and Malhotra are more careful, and divide this definition into Range-Heterogeneity (R-H) and Range-Number (R-N). R-H is the variety of products (size of product line or "size of the set of alternatives available"), and Range-Number is the variance in volume of products that can be produced ("distance between alternatives in that set").

Koste and Malhotra's article can be used to position supply chain vis-à-vis the rest of the manufacturing literature. The large graphic that comprises Exhibit 2.4 on page 27 has been taken from Koste and Malhotra, and modified for this thesis. Duclos *et al* also refer to Koste and Malhotra's work as way to position the supply chain flexibility discussion [Duclos *et al*, 2000].

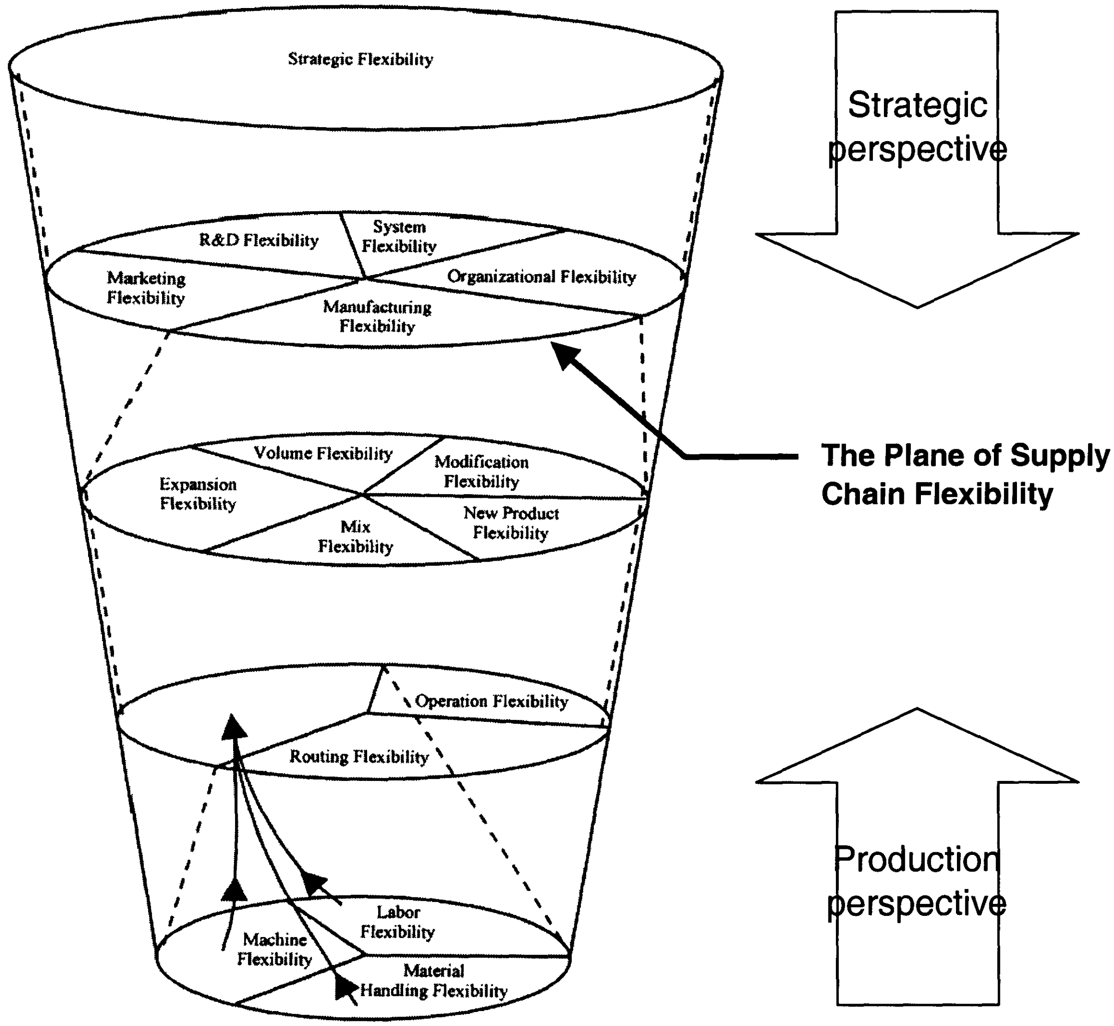

Exhibit 2.4: Flexibility Literature Funnel

This graphic, based on an extensive survey of the manufacturing literature, allows examination of the layers of flexibility.

As seen in Exhibit 2.4, there are different levels of flexibility, which seems intuitive, and also satisfies Gerwin's concern that when considering flexibility, one must first decide on what level [1993]. The second level from the top has been labeled the Plane of Supply Chain Flexibility in this thesis. This plane consists of Manufacturing Flexibility, Organizational Flexibility, System Flexibility, R&D

Flexibility, and Marketing Flexibility. The plane sits above three sub-levels of Manufacturing Flexibility, and below the level of Strategic Flexibility. Strategic Flexibility will be covered later in this literature review.

Note the inter-functional nature of the flexibilities on the Supply Chain level: R&D often belongs to marketing, while the human resources department would probably own organizational design. Manufacturing and Systems would have still other functional homes.

2.2 Supply Chain Flexibility Literature

The operational relevancy of supply chain flexibility is clearly stated by Beamon: "Indeed, flexibility is vital to the success of the supply chain, since the supply chain exists in an uncertain environment" [1999].

The competitive relevancy of supply chain flexibility is clearly stated by Duclos *et al*:

> As companies have improved their internal operations by increasing product quality while reducing costs, firms have achieved parity on these dimensions in many industries. These companies are now looking to develop competitive advantages in areas such as delivery, flexibility, and innovation [2000].

Compared to manufacturing flexibility, the body of literature on supply chain flexibility is younger and smaller. Indeed, the supply chain flexibility literature can be seen as the explosion of the more isolated, plant- and shop-specific manufacturing literature onto the larger, more interconnected network of suppliers and customers.

Duclos *et al* describe the vastness of the subject:

> A complete definition of supply chain flexibility components will include the flexibility dimensions required by all activities in the supply chain needed to successfully meet customer demand. Flexibility in the supply chain adds the requirement of flexibility within and between all partners in the chain including departments within an organization and the external partners

> including suppliers, carriers, third-party companies, and information systems providers [2002].

Given this onus, it is clear to see that defining supply chain flexibility is a daunting task indeed.

Also, as shown in the graphic from Koste and Malhotra (Exhibit 2.4, pp. 27), it is logical to include manufacturing flexibility as sub-component of supply chain flexibility. As an unfortunate consequence, the supply chain literature inherits all of the complexity and confusion of the manufacturing literature. Already one sees the same trend of fragmentation of literature and a proliferation of flexibility types and dimensions.

2.2.1 Types of supply chain flexibility

There are many types of flexibility defined in the literature; several are listed below to give the reader an idea of what is meant by supply chain flexibility. These names are largely self-explanatory—at a conceptual level—and their exact definitions will not be given here.

Beamon uses four types of supply chain flexibility: Volume flexibility, Delivery flexibility, Mix flexibility, and New Product flexibility [1999].

Vickery's review of the literature lists five types of supply chain flexibility: Product flexibility, Volume flexibility, New Product flexibility, Distribution flexibility, and Responsiveness flexibility [1999].

Duclos *et al* define six types of supply chain flexibility: Production System flexibility, Market flexibility, Logistics flexibility, Supply flexibility, Organizational flexibility, and Information Systems flexibility. Duclos *et al* also note: "It is clear that supply chain flexibility is taking the same path as manufacturing flexibility: fragmented and confusing" [2002].

2.2.2 Flexibility approaches

In this section some of the more popular supply chain designs that incorporate flexibility are mentioned briefly. The goal is not to comprehensively define what each of these is, but to acknowledge that flexibility takes many names.

2.2.2.1 Agile

Agile can usually be used as a synonym for flexibility when talking about the external face of supply chains. Supply chains that are flexible to meet, or mold, customer demand can be said to be agile. The Supply Chain Operations Research Council defines flexibility as "The agility of a supply chain in responding to marketplace changes to gain or maintain competitive advantage" [Wondergem, 2001].

2.2.2.2 Leagile

Another approach is the combination of a lean and agile supply chain into a "leagile" supply chain. In this configuration, the chain is lean until an explicit point of differentiation, or flexibility, and from that point forward the chain is agile. This is similar to postponement.

2.2.2.3 Postponement

Postponement is a technique that takes advantage of a "rule" that aggregate forecasts are more accurate than disaggregate forecasts. By using common components in product design (at the product family level), the company can delay the decision of which particular item (at the SKU level) to make until more detailed and accurate forecasts are available [Simchi-Levi *et al*, 2002].

A popular example of a postponement system is Italian apparel company Benetton's stocking of *greige* (gray) sweaters that are later dyed to match customer demand.

In postponement, as in the Benetton case, companies typically pay more per unit to delay the decision making, but that cost is more than recovered by the improved accuracy of the forecast: Companies reduce both the amount of overstock (obsolescent inventory) and understock (lost sales). Decision analysis tables will be discussed in chapter three as a way of evaluating pay-more-for-flexibility decisions such as Benetton's.

2.2.2.4 Accurate response

Accurate response entails figuring out for which items a company can accurately forecast demand, and for which items it cannot. For those items that it cannot, such as those sold in short, concentrated seasons with high rates of obsolescence, the company designs short lead-time replenishment into the supply chain. In this way, indicators of demand such as early sales results can be used to dramatically improve accuracy of the demand forecasts [Hammond *et al*, 1994].

2.2.2.5 Emergent approaches

There are also emerging flexibility articles appearing in the academic literature, on specific topics such as supply contracts and modeling emergency inventory. These tend to be well thought out and mathematically rigorous, but focused on a very specific part of the supply chain.

2.3 Economics Flexibility Literature

Economics flexibility examines the difference in cost, or profit, of having or not having flexibility. This literature is much older and less "operationalized," but it is a very strong precedent for the manufacturing and supply chain flexibility literature.

2.3.1 Cost curves and other traditional economic perspectives

The notion of flexibility in the economics literature is not new. According to Carlsson, Stigler may have been the first economist to introduce the notion of flexibility [Carlsson, 1988; Stigler, 1939]. Stigler defined flexibility as production's ability to accommodate variations in output. Stigler used cost curves, such as those shown in Exhibit 2.5 to demonstrate this. Cost curves that are steeper in slope are less flexible. This is similar to the notion of Uniform Flexibility expressed by Upton in the manufacturing section of this literature review (pp. 25).

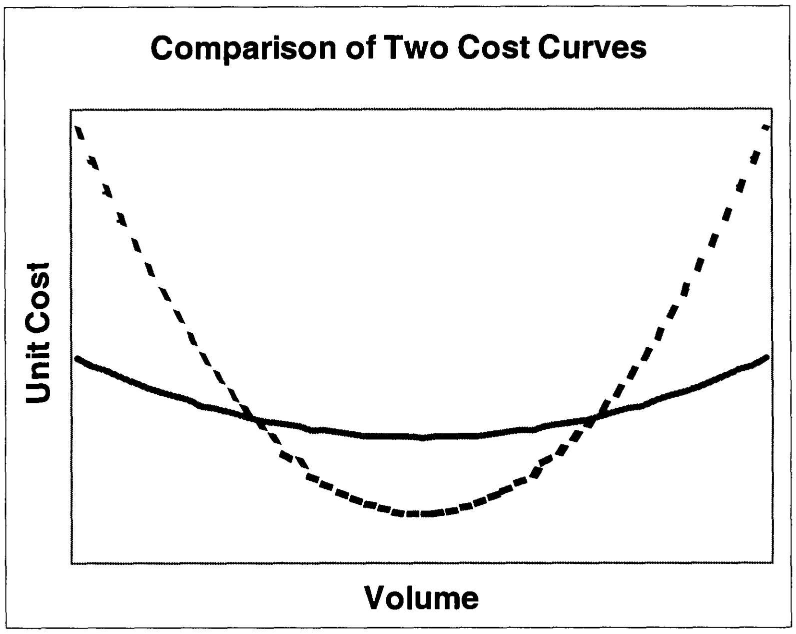

Exhibit 2.5: Comparison of Two Cost Curves.

The solid cost curve is optimal for a wider range of volumes (levels of output). However the dashed curve is optimal for the set of volumes near the middle of the volume range. The solid curve could be said to represent a more flexible production function, because its costs are more uniform across the range of volumes.

Stigler also stated that there is no free lunch:

> A plant certain to operate at X units of output per week will surely have lower costs at that output than will a plant designed to be passably efficient from X/2 to 2X units per week [1939].

This can be highlighted as the tension between flexibility (as secured by incremental increases in production capacity) and economies of scale provided by large investments. For example, consider a plant that makes an ordinary product such as clocks. If growth is certain to grow steadily over the next few years, it may be better to build a larger plant and enjoy economies of scale. But if demand is uncertain, it may be best to add capacity—as plant extensions or additional small plants—incrementally in small portions, even if it costs more per unit.

The next important economic step was made by Marschak and Nelson [1962]. They extended Stigler's original definition of flexibility to include two more definitions of flexibility. Compared to Stigler's cost curve, Marschak and Nelson suggest that the initial position of the curves is as important as their slopes. Marschak and Nelson's three definitions are basically the same as the three described by Upton in the manufacturing section of this thesis (pp. 22).

Even though Marschak and Nelson's definitions are similar to Upton's, it is important to consider their choice of words. What Upton calls "Range Flexibility," Marschak and Nelson describe as the size of the choice set. That is, a smart move in the present period ensures that more options will be available at a later period. This idea of a multi-period analysis will lead to the development of decision analysis and real options approaches for valuing flexibility in chapter three of this thesis.

Marschak and Nelson also consider the importance of flexibility not just at the production level, but also for other functions such as R&D and marketing. Their insight will turn out to be a precursor to the notion of supply chain flexibility that encompasses multiple functional areas in the firm.

For a more detailed discussion of economics flexibility literature, the reader is referred to Carlsson [1988].

2.3.2 Certainty, uncertainty, and risk

Before proceeding, it may be good to back up for a moment and talk about the language of chance; in particular the often used words Certainty, Uncertainty, and Risk. The greatest usage confusion seems to be with the words uncertainty and risk.

Many careful speakers defer to Knight's classic text [1928]. Knight defined risk as a known chance that is the product of repeatable operations. Risk could be calculated.

On the other hand, uncertainty was the unexpected. It was something for which there was not a determined probability of occurrence. As such, uncertainly—unlike risk—could not be calculated.

However, other authors choose to define risk and uncertainty as much the same thing. Merril and Wood define risk as the hazards (bad outcomes) that are posed by uncertainty [1991]. Ku defines risk as negative outcomes that are due to making the wrong decisions under uncertainty [1995]. These are probably closer to the definitions that are used most commonly in the business world today.

2.3.3 Type I and Type II flexibilities

Klein defines two types of flexibilities: Type I, and Type II [1984]. In terms of Wright's definitions of risk and uncertainty, Type I (also called continuous) flexibilities are used to account for *risk* and Type II (also called discontinuous) flexibilities are used to account for *uncertainty*.

Some suggest not using the term flexibility to cover both risk and uncertainty. Instead, flexibility could be used just for risk-related problems, while "adaptation" could be the term used to deal with problems of uncertainty. Still others prefer the alliterative combination "adaptability" for risk and "adaptation" for uncertainty. Using these terms, adaptability is used in the context of risk-related (or Type I, continuous) flexibility, and adaptation is used in the context of uncertainty-related (or Type II, discontinuous) flexibility.

2.3.4 Flexibility versus commitment

Economists contrast flexibility to *specificity* (sometimes called commitment). Ghemawat and del Sol [1998] offer that flexibility decisions come in two categories: Firm (as in the company) and Usage (as in purpose). Resources are firm-specific (non-flexible) when their value to the firm is greater than their value on the market. Resources are usage-specific (non-flexible) when they are less valuable when applied to a different purpose.

Ghemawat and del Sol propose a matrix, Exhibit 2.6, for plotting flexibility versus specificity.

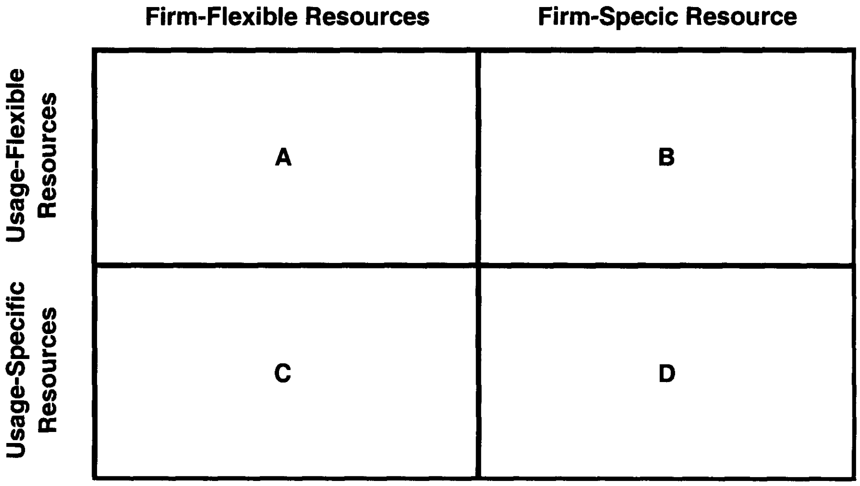

Exhibit 2.6: Resource Specificity Matrix

A look at the quadrants for plotting firm and usage flexibilities. Flexibilities can be firm- or usage-level, or both. This graph depicts the relationships [Ghemawat & del Sol, 1998].

An example for each quadrant is given below.

Quadrant A—Examples of both firm and usage flexible resources found in Quadrant A include cash and other short-term assets, as well as some information technology components (off-the-shelf hardware and software).

Quadrant B—An example of a firm-specific but usage-flexible resource could be the historical relationship a company enjoys with a distributor in a given geographical market. The firm can use this relationship to distribute many different products, but this relationship is not transferable to another firm, nor does another firm easily replicate the relationship.

Quadrant C—An example of firm-flexible but usage-specific resource could be a commodities contract that is used to set a fixed price for an input into manufacturing process. For instance, cane sugar is a commodity used in consumer vices such as candy, soft drinks, and tobacco products. Because it is a marketable contract, and not the bulky and clumsy commodity itself, transferring it would be relatively easy.

Quadrant D—Examples of both firm and usage specific assets could be as intangible as a brand name for a specific type of product, such as *Atari* in video game consoles, or as concrete as a specialized factory that is used to produce a unique product.

When looking at the Resource Flexibility Matrix, it is important to note the strategic importance of the X-axis. Because successful strategy involves investing in different activities or doing those activities differently from your competitors [Porter, 1996], competitive advantage *requires* some investment in firm-specific (non-flexible) resources. To ensure these differences, the supply chain must consciously make defensible, permanent investments that discourage competitors from following by imitation. By their very nature, these decisions are inflexible. **The requirement for committed, non-flexible investments to ensure superior firm performance is at the heart of the flexibility/non-flexibility trade-off.**

Consider this in terms of Porter's classic article on the Five Forces: Firm flexible resources lower the exit barriers for the firm, allowing the firm to plan over a shorter horizon [1979]. But the other side of this coin is that these flexible resources also lower the barriers to entry of other firms. The end result is that any competitive advantage based on firm flexibility will not be sustainable.

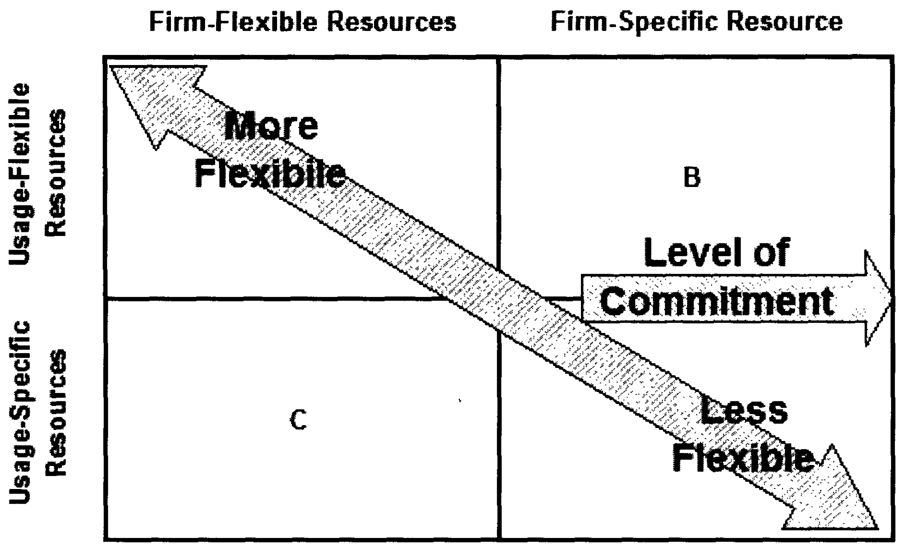

Exhibit 2.7: Flexibility versus Commitment

The areas of the Resource Specificity Matrix that are more flexible, less flexible, and those requiring more commitment (i.e., strategic thinking) [Ghemawat *&* del Sol, 1998].

The Y-axis of the Resource Flexibility Matrix covers usage resources. These resource decisions tend to be less strategic. Most of the existing manufacturing literature covers usage resources. But Ghemawat and del Sol contend that **without firm-specific resources, the firm is unable to exploit usage-flexible resources to their competitive advantage.**

An interesting aside is the value of techniques such as real options—covered in chapter three of this thesis—for valuing the delay of commitment to resources. Because usage-flexible resources can be re-tasked at a later date, there is a lower value of delay. In other words, it pays to delay investment in usage-specific resources, but not usage-flexible resources. There is a direct tradeoff between time and flexibility—an important insight that will be revisited later in the paper through real options analysis. Dixit and Pindyck, authors of an oft-referred book on real options, comment on this flexibility versus commitment decision:

> [In some cases] strategic considerations can make it imperative for a business to invest quickly in order to preempt investment by existing or potential competitors. In most cases, though, it is at least feasible to delay. There may be a cost—the risk of entry by other companies or the loss of cash flows—but the cost can be weighed against the benefits of waiting for new information. And those benefits are often substantial [1994]

Before closing this section, the curious reader is encouraged to examine Ghemawat and del Sol's two intriguing and original examples of strategic flexibility based on examples from the historical Spanish Armada.

2.3.5 Operational versus strategic flexibility

At a high level, Gerwin writes about the basic difference between operational and strategic flexibility:

> At the strategic level it is easy to concentrate on flexibility's role in handling uncertainties. At the operational level however, concern is with designing specific methods of delivery [Gerwin, 1983].

Carlsson divides flexibility into three time horizons: Operational, Tactical, and Strategic [1988]:

- **Operational flexibility** is a set of procedures—"the organizational software" on which the company runs—that is pliant enough to accept changes in scheduling, sequencing, and other daily tasks.

- **Tactical flexibility** is the production technology and organizational rules that permit changes to production rate, re-assortment of product mix, and minor changes to product design.

- **Strategic flexibility** is the ability to introduce new products at a fast pace and low cost, to permit major updates to existing products, and to positively encourage "most importantly, the nature of the organization of the firm and the people in it, their attitudes and expectations, particularly with respect to risk-taking and change."

2.4 Other Related Literature

In researching the topic of supply chain flexibility, there is a great deal of thought that has been borrowed from, or is based on, literature in other fields. A small sampling of that literature is presented here.

Probably the most important section is Strategy, as it provides the motivation for much of the flexibility movement. The Organizational Design and Industrial Networks sections also provide a very brief summary of related ideas from those areas.

2.4.1 Strategy

Gerwin comments on the implications of flexibility to strategy: "Flexibility is not just an adaptive response to an uncertain environment. It has a proactive function in creating uncertainties that competitors can not deal with" [1993].

Similarly, Sanchez proposes that firms can use a strategy of flexibility to quickly take advantage of new technologies and market opportunities. A flexible strategy means keeping open several alternative courses of action, also called the *set of strategic options.* Along these lines, Solgaard and Trolle-Schultz write:

> The current approach to strategic planning has been to answer the question `What should the firm plan to do?' but this approach may be too narrow. There are other approaches to the problem of ensuring the responsiveness of the firm. For instance, the firm could become quite flexible in what it can do. That is, it could develop a capacity to adopt a large set, or portfolio, of alternative potential activities for the future. Rather than trying to plan what to do, strategic planning should consider the question, `What should the firm be able to do?' When considered in terms of the purpose of strategic planning, the latter approach is equally as appropriate as the former [1988].

This idea of "what should the firm be able to do" seems to run counter to Porter's definition of competitive advantage in one of only three—critics call these static—forms: Cost leader, differentiation, or focus [1980]. Fine also agrees with Sanchez and Solgaard and Trolle-Schultz: the markets in which firms are competing are becoming more dynamic, and any competitive advantage gained can only be temporary [1998]. Therefore, flexibility itself becomes a new competitive advantage.

A firm's set of strategic options are based on capabilities to introduce more new products, offer a wider selection of those products, and shorten the product lifecycles [Sanchez, 1995]. Flexibility enables this strategy by allowing real-time market research via learning models, by allowing product proliferation, by allowing rapid product upgrades, and by allowing mass customization and/or personalization.

In order to appreciate the extent to which customization takes place, consider Gilmore and Pine's article on the subject [1997]. They suggest that customers can no longer be crudely segmented and described by a set of bell curves. Rather, these tools are artifacts of the mass-production era, when the wants of the individual customer were subsumed by the powerful scale economies that drove production, and thus, marketing.

Taken to its logical end, this may lead to the notion of a "segment of one", where product and service offerings are developed and delivered to individuals. This would be incorrect. Gilmore and Pine point out that even individual customers can be segmented. For instance, newspapers recognize that many readers have more leisure time on Sundays; therefore they make a larger—and more expensive—paper on Sunday. Another example could be airlines, who might be able to take advantage of a businessman's preference for caffeine drinks—such as a Coca Cola—on the way *to* a meeting, but his preference for an alcoholic drink—such as a scotch on the rocks—on the way *back* from a meeting [Gilmore *&* Pine, 1997].

At this level of customization, it is important to note the importance of the temporal dimension. In both these examples, the market opportunities changed with the day of week and time of day, respectively. With flexibility, companies can change their offerings and capitalize on these temporal opportunities. To do this, Gilmore and Pine identify four types of customization: Transparent, Collaborative, Adaptive, and Cosmetic. All four of these approaches—especially Adaptive—depend on flexibility.

However, authors such as Weick and Porter seem to disagree with the notion that flexibility should be the rule. Similar to Ghemawat and del Sol, they suggest that strategic stability can be as important as strategic flexibility. Weick elaborated upon this tension early:

> Flexibility is required to modify current practice so that non-transient changes in the environment can be adapted to. This means that the organisation must detect changes and retain a sufficient pool of novel responses to accommodate to these changes. But total flexibility makes it impossible for the organisation to retain a sense of identity and continuity. Any social unit is in part defined by its history, by what it has done repeatedly and chosen repeatedly [1982].

Porter responds that these new patterns of competition based on flexibility and other attributes are "dangerous half-truths" and contends that the notion of temporary strategic competitive advantage is an exaggeration [1996]. Three points may resolve the tension among Porter and the others: First, Porter says that there is a difference between operational effectiveness and strategy. Second, Ghemawat and del Sol's Resource Flexibility Matrix helps explain that competitive flexibility and strategic commitment can coexist. Third, flexibility can be seen as a way to help deliver speed and variety. In this way, flexibility does use time "as a strategic weapon" that gives firms new ways to differentiate themselves in the marketplace.

2.4.2 Organizational Design

It is important to consider the organization (system-wide) as a whole when evaluating flexibility. Carlsson notes:

> Given that there is a tradeoff between productivity and flexibility, the decision whether to emphasize one or the other must be made depending on the particular purpose of each production system. Therefore, the system has to be evaluated in terms of the overall efficiency of the company, not merely the efficiency of the production system [1988].

Sanchez suggests that there are two types of flexibility needed: Resource flexibility and coordination flexibility. These two types of flexibility agree with Penrose's view that is not just a firm's resources, but how the firm uses those resources that matter [Penrose, 1959].

Therefore, the firm must not only acquire flexible resources, but also acquire the abilities necessary to coordinate deployment of those flexible resources along the entire value chain. The combination of resource and coordinative flexibilities gives rise to flexibility at a strategic level:

> Strategic flexibility, thus, depends jointly on the inherent flexibilities of the resources available to the firm and on the firm's flexibilities in applying those resources to alternative courses of action [Sanchez, 1995].

As shown in Forrester's retail supply chain example (pp. 13), the timely movement of information is critical to effectively run the supply chain. Therefore, an organization that employs supply chain practices must share information throughout and—technology investment notwithstanding—this is a new paradigm for most firms. Greis and Kasarda contrast the information-sharing needs of the modern firm against the predominant models of the past:

> In traditional customer-supplier relationships, inter-organizational information exchanges were controlled by functions located on the periphery of the organization, such as sales and marketing. As we have noted, information sharing in the mass production environment was minimal. The organization of mass production systems around large-size batches masked true information about demand and its variability. Lean production required logistics arrangements that

> were more closely tuned to the rhythm of the manufacturing floor, but true information-sharing for the joint benefit of supplier and customer did not occur. [1997]

Significant attention needs to be paid to issues of incentives and alignment as well. Byrnes and Shapiro write that some of strongest resistance to developing close operating ties with suppliers and buyers can come from, ironically, the company trying to introduce cooperation into the channel.

> Incentive compensation is crucial both to facilitate change and to foster ongoing cooperation. As one executive put it, "In working with people, you can see the vision, you can explain the vision, [but] then they will go do what they are paid to do" [Byrnes *&* Shapiro, 1991]

It may be that some functions in a firm may welcome a more flexible approach, while others may not. As Gerwin notes: "The marketing department, for example, is likely to aim for a wider range of products than the manufacturing unit" [1993]. This would certainly be the case when production management and line workers are compensated on non-flexibility metrics such as throughput (e.g., tons per hour) or cost (dollars per unit).

To counter detrimental behavior, successful companies in the survey conducted by Byrnes and Shapiro had to re-invent performance review and compensation standards to ensure that management and employees were given goals that were consistent with the company's new strategy. Sometimes the changes can be large:

> Coordinative arrangements may lead to the elimination of some facilities, the reconfiguration of others, and significant changes to long-established procedures and prerogatives [Byrnes *&* Shapiro, 1991]

2.4.3 Industrial Networks

Araujo and Spring suggest that an Industrial Networks approach to flexibility is important because it emphasizes the importance of the relationships among firms.

This seems especially important to supply chain managers. These relationships become assets that are as important as production technologies or financial resources. Like factories and other assets, they require active investment:

> To become aware of others' contexts requires significant investments and the prospect of continuity of association. In this type of interface, investments in relationships become substantial. The development of joint resource combinations can only be achieved with reciprocal investments by customer and supplier, enabling each party to learn about each other's capabilities. Over time, the costs of maintaining an interactive interface can be assumed to decrease once the counterparts have gone through a learning curve on how to make best use of each other's capabilities [2002].

Like Penrose, Araujo and Spring suggest that flexibility is as much a product of the procedures and learning that are put in place *around* the resources as it is *in* the resources [Penrose, 1959]:

> ...an industrial networks perspective on flexibility emphasises the connection between activity structures and the resources deployed in those activity structures. A firm based perspective is still crucial to understand flexibility but there is a need for an increased recognition of the role of firms as loosely coupled systems... [Araujo *&* Spring, 2002]

Chapter 3. Evaluation of Flexibility: Tools and techniques

Ultimately, options create flexibility, and, in an uncertain world, the ability to value and use flexibility is critical.

—Dixit and Pindyck, 1994

3.1 Introduction

This section reviews the tools that supply chain managers can use to evaluate flexibility. Two approaches are covered: the more traditional decision analysis (DA) and the newer real options analysis (ROA) [8]. These frameworks are included in this thesis because "One may consider flexibility as arising from a formal decision problem in which the choices among future options are affected" [Gerwin, 1993].

Flexibility is difficult to measure because of the key word in Gerwin's statement: "future." Flexibility is the measure of potential—and will be revealed only in the future—unlike other attributes, such as throughput, cost, or quality, which can be measured in the present. As a result, flexibility can only be estimated. Even so, it is important to evaluate it carefully, and to ensure that estimates are reasonable.

Decision analysis will be covered because it is familiar to many managers, and is regarded as easy to learn. Real options will be covered because of its rising popularity in academics and practice, and because "[real] options create flexibility, and, in an uncertain world, the ability to value and use flexibility is critical [Dixit *&* Pindyck, 1994].

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[8] For additional discussion on the similarities and differences of decision analysis and real options, the reader is referred to Smith [1999]

First, though, the ubiquitous Net Present Value methodology is covered. It is revealed that this popular methodology fails to account for—and value—flexibility. [9]

3.1.1 NPV cannot value flexibility

NPV is the predominant test used to evaluate capital usage and other decisions in most firms. If a series of predicted, discounted cash flows (DCF) has a positive (at least $0) net present value, then the project is given a "go-ahead." If not, then the project is cancelled or reworked.

NPV is no longer a tool used by just MBAs and finance professionals. Even in engineering and operations fields the use of NPV and similar valuation techniques is quite common. For more information on NPV, the reader is referred to any one of many good college-level finance textbooks.[10]

There are shortcomings when using NPV to account for flexibility. NPV assumes that decisions must be made now and these decisions are irreversible. In other words, NPV is predicated on two points:

1. That the investment is made at some fixed point in time (usually the present time) or not at all. Often, this now-or-never assumption does not hold—decisions can be delayed. NPV does not reflect this.

2. That once the decision is made it can't be reversed. NPV doesn't capture the opportunity to abandon the project, modify the project, or pause the project.

In short, NPV assumes management is active only until the decision is made, and forever after the management is inactive, and cannot affect the outcome.

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[9] Similar methods such as pay-back-period and Internal Rate of Return suffer shortcomings similar to NPV.

[10] For example, *Corporate Finance*, by Ross, Westerfield, & Jaffe, from Irwin McGraw Hill

As expressed by Mandelbaum and Buzacott, there is no opportunity for the decision maker to "learn" from one period to the next, which is key in valuing flexibility [1987]. Ideally, learnings from the previous period can be used to revise expectations and make new choices in the next period, and more importantly, provide a valuation of flexibility.

Some decision makers try to "fix" NPV by using artificially high discount rates to adjust for contingencies—not opportunities—in the future. But this only distorts the NPV further, and still does not accurately depict the reduction of uncertainty as time elapses. Again, management is assumed to be passive.

Finally, there is one more problem with NPV analysis: The choice of an appropriate rate at which to discount the future cash flows. This process can be highly politicized and subjective, and is subject to manipulation [de Neufville, 1990].

3.2 Decision Analysis

Decision analysis allows managers to actively manage scenarios involving risk and uncertainty. In this thesis, two types of decision analyses will be covered. First, a decision tree will model how multi-period choices can be refined over time. Second, a decision table will model how more detailed single-period decisions can be made.

3.2.1 Decision Trees

Decision trees acknowledge that projects and processes do not have a single line of development—there are possibly several paths and subsequent outcomes. Decision trees work for valuing flexibility because as time elapses, uncertainty typically decreases.

To deal with uncertain outcomes, the decision tree provides a logical way to structure a problem as set of *decision nodes* and *chance nodes* leading to *terminal nodes*. Once structured this way, the expected outcomes can be calculated, giving managers guidance in making difficult decisions. These outcomes can be measured as costs, accidents prevented, or as other pertinent metrics. Often decision trees are used in tandem with DCF and NPV.

3.2.1.1 Decision tree example: The XML ordering system

A supplier contacts a firm and suggests that the two companies begin conducting business transactions over a new XML-based, Internet ordering and procurement system.[11] The firm is initially reluctant; the system will cost $15K in hardware, software, and consulting fees to set up. Because the technology is so new, it is not known how much it will cost to maintain, in software upgrades, IT support, and consulting fees. By examining similar projects at other companies, the firm predicts that the average cost of maintenance is $60K. There is considerable variance however. About one-third of adopters have lower ($30K) costs, while another one-third have higher costs ($120K). It is suggested that the asymmetry exists because there are more ways to overspend on than underspend on IT projects. Once implemented, it is expected that cost savings will be either low ($50K) or high ($110K), depending on how well the company transitions to the new system (the "to-be" procurement process) from their current way of doing things (their "as-is" procurement process).

To help decide if they want to implement the new system, the firm does an NPV analysis:[12]

$$\begin{aligned}\text{NPV} &= -\text{ Setup Costs} + \text{Cost Savings} - \text{Maintenance Costs}\\ &= -15 + \left[\frac{1}{2}(50) + \frac{1}{2}(110)\right] - \left[\frac{1}{3}(30) + \frac{1}{3}(60) + \frac{1}{3}(120)\right]\\ &= -\$5\end{aligned}$$

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[11] Portions of this example are borrowed from Dixit & Pindyck, 1994

[12] In order to concentrate on the flexibility portion of the example, all dollar amounts are assumed to be brought back to present day dollars already. Typically the cash flows would need to be discounted to present day dollars.

According to the NPV analysis, the firm should not invest in the XML connection with their supplier. There is an expected loss of five thousand dollars over the life of the project.

However, suppose that during the setup phase, which costs $15K, the firm becomes familiar with the technology, and can predict the maintenance costs. Therefore, the firm would choose to use the system only if maintenance costs were to be average or low. The decision tree in Exhibit 3.1 on the next page structures the company's new view of the decision to be made, and recognizes the uncertainty that is eliminated after the setup phase. In particular, if the installation goes poorly, the company will choose to abandon the project.

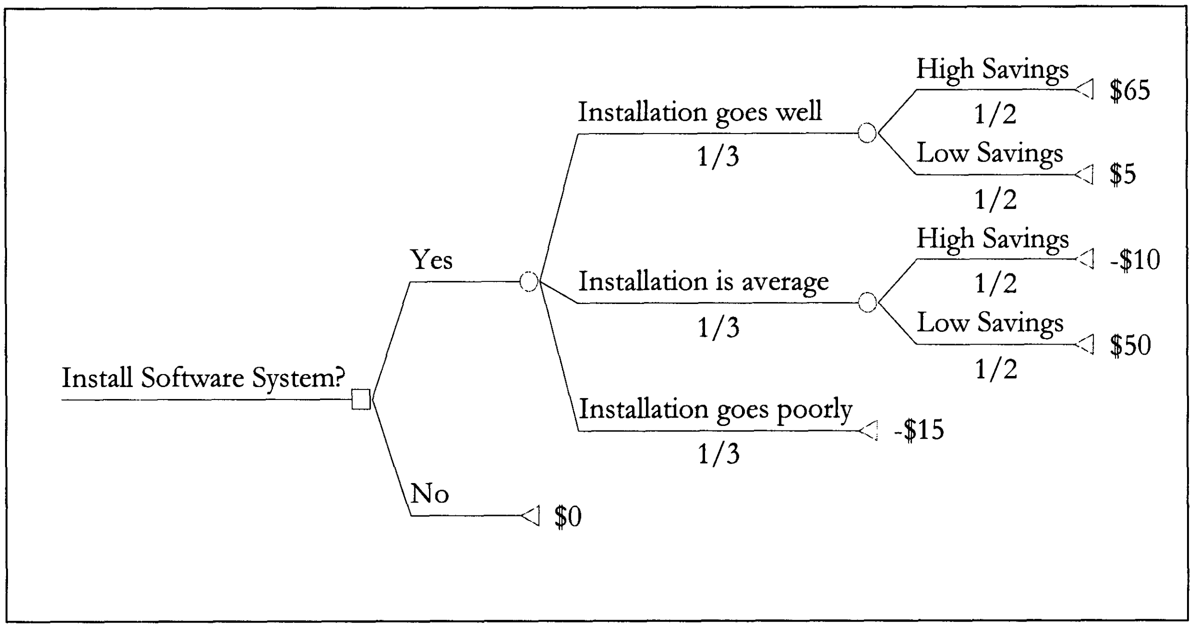

Exhibit 3.1: The firm's decision whether to install the XML ordering system

The boxed node represents the decision to be made, and the round nodes represent an uncertain outcome. The triangles are end states, also called terminal nodes. If the installation goes well, or average, it is assumed that the system will be used. If the installation goes poorly, the system will be abandoned.

The tree is then "rolled back" to find the path, and decision, that maximizes the expected value of the project. To roll back, each outcome is weighted by the probabilities along the path that precedes it. The sum of these weighted outcomes is the expected (average) outcome.

Using this improved way of structuring the decision, where the management can decide later whether or not to go forward with the project, results in a much different valuation of the project. The decision tree is rolled back, in Exhibit 3.2, to reveal that the project will result in an expected *gain* of $13K, instead of an expected *loss* of $5K.

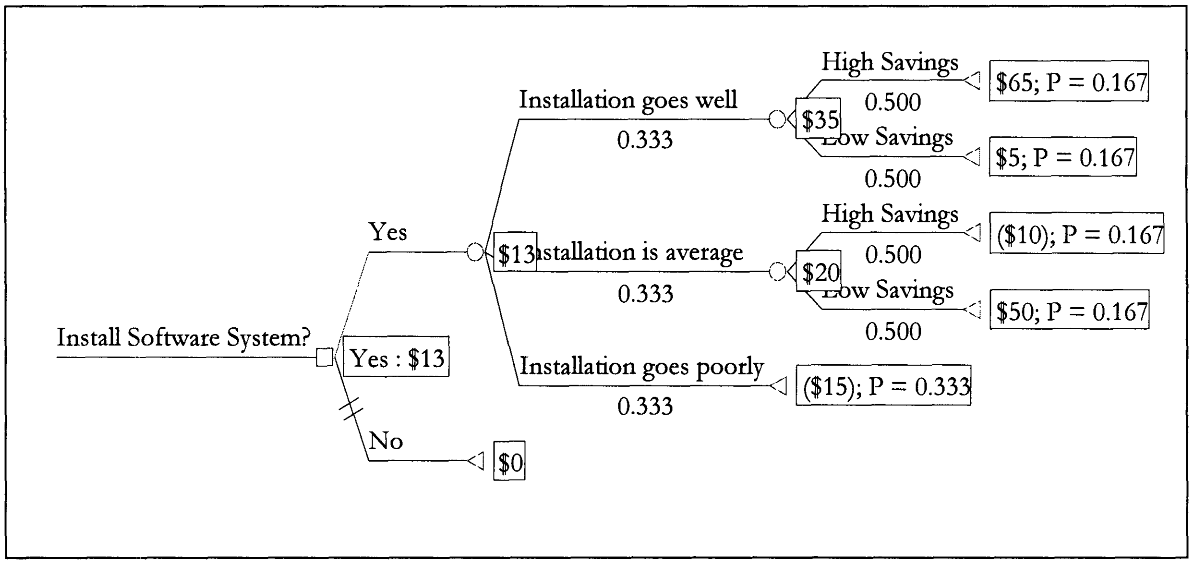

Exhibit 3.2: The firm's flexibility in deciding to install the XML ordering system

The decision tree is rolled back to reveal an expected gain of $13K on the new ordering system. The boxes on the far right of the tree contain dollar amounts and the cumulative probabilities by which they are weighted. The sum of these weighted dollar amounts is the expected value, $13K.

In this case, the investment in the technology created an option for the company to use the technology—but only if it looked viable. In this case, the ability to wait until more information was available makes what was a failed project—by NPV standards—a now worthwhile project.

Other options may exist as well. For instance, will the implementation also give the firm a better picture of the cost savings that the new system will bring? If so, the firm could add an additional decision branch to the tree to incorporate the new information. After rolling back this improved tree, the company will find an expected value *greater than* $13K.

Unfortunately, this type of weighted-outcome decision analysis often falls to the *flaw of the averages*. The net present values at the terminal nodes of the decision tree incorrectly assume a linear distribution of outcome values, which is rarely the case. In this example, the cost savings are probably not linear from $50K to $110K. If the outcomes are not linear, but are instead concave or convex, the results can be mistakenly deflated or inflated [Ramirez, 2002]. Note that this is an inherent limitation of NPV, not decision trees.

For more information about decision trees and their applications, the reader is referred to de Neufville [1990].

3.2.1.2 Decision tree extensions

There are several complementary analyses that can make decision trees more valuable. These include the Expected Value of Sample Information (EVSI), which gives the value of a test used to reduce uncertainty about outcomes; the Expected Value with Perfect Information (EVPI), which gives an upper limit for the value of information about expected outcomes; and Bayes' Theorem, which updates probabilities by incorporating more recent information as it becomes available.

Many decision trees use NPV. Like NPV, decision trees that use NPV are subject to the same discount rate manipulation as standard NPV analysis. Moreover, as time progresses left-to-right on the tree, the outcomes often become more certain and less risky. Constant discount rates that include a risk factor will not recognize this. For instance, if the implementation of a risky project is to be postponed for three years, the first three years of the cash flow should be discounted a risk-less rate, and only cash flows from year three on should be discounted at a risk-increased project discount rate. Some suggest adjusting probabilities at the chance nodes to "discount" for risk. Unfortunately, this does not lessen the opportunity for manipulation or confusion. Others suggest using sensitivity analysis to test for dependence on discount rate, but this does not seem to solve the problem of multiple discounts being necessary.

Lastly, decision trees can be extended by weighting outcomes to reflect the preferences of risk-averse, or risk-welcome, decision makers. Some utility function

U(x) can be used to incorporate risk-preference into the outcomes. For instance, a chance of losing $500 may, after adjusting for risk averseness, require the equivalent chance of profiting by $2500. Even though these outcomes are nominally asymmetric around $0, in the risk-adjusted arithmetic they net-out to $0. That is, U(-$500) + U($2500) = 0.

Before closing the discussion on decision trees, one should notice a subtle but nonetheless important heuristic that working with decision trees provides:

> In general "second best" strategies are not optimal for any one outcome, but are preferable because they offer flexibility to do well in a range of outcomes [de Neufville, 2002].

3.2.2 Single period decision analysis

Often, decision trees become very "bushy" and difficult to use if there are too many nodes and branches. Because of this, a tabular decision analysis approach can also be used to evaluate more detailed, one-time decisions (also called single period decisions). With the popularity and availability of spreadsheets such as Microsoft Excel, this becomes a good way to make decisions, including decisions involving flexibility.

While there are several ways to setup a decision analysis table, this is a common approach: Each row in the decision analysis table represents a choice that can be made, and the expected outcome given that choice. The left-most column is the potential choice that can be made, e.g., how much inventory to buy. Working left-to-right, the table calculates the result of that decision. In the right-most column, the expected result, in terms of costs, revenues, or other pertinent metric is revealed. The row with the best value (e.g., lowest cost) is the decision row to be chosen.

3.2.2.1 Decision analysis example: Newsstand inventory

In supply chains, a common problem is to determine how much inventory to carry. If there is too much inventory, then there is a greater chance of overstock:

Additional inventory is sold at a deep discount, or not sold at all. If there is too little inventory, then there is a greater chance of understock: Sales are foregone, customers are not happy, and customers may switch to other suppliers.

3.2.2.2 The inflexible solution

As an example inventory problem, the venerable newsstand is considered. The newsvendor must decide how many papers to buy in order to meet demand on a given day, e.g., Monday. By Tuesday, any leftover inventory of Monday papers will be worthless. The newsvendor sells between 1 and 100 papers per day, and demand is uniformly distributed: The newsstand is as likely to sell one paper as it is likely to sell 100 papers.[13] This demand distribution is depicted in Exhibit 3.3.

[13] A uniform distribution is used for simplicity. Other distributions, such as the Normal, are probably more appropriate in this scenario. In general, decision analysis works with any underlying distribution.

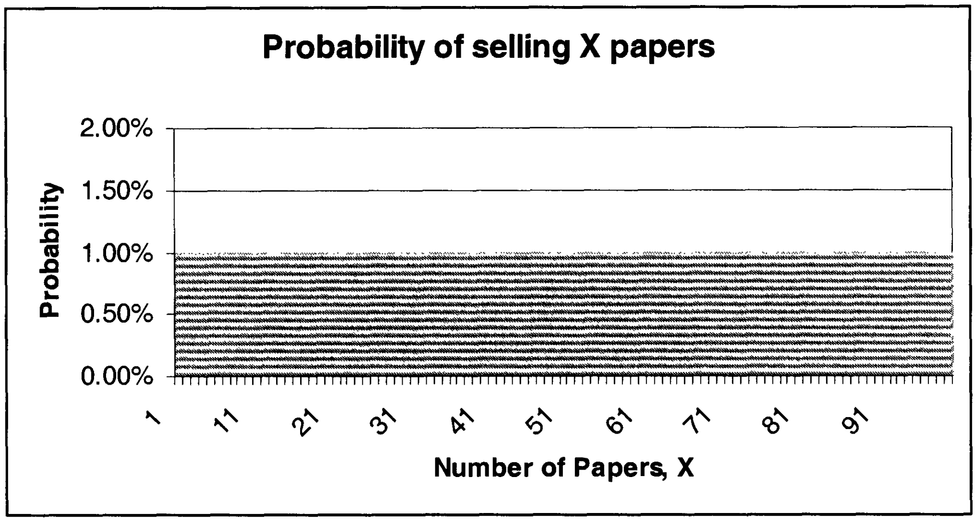

Exhibit 3.3: A simple demand distribution for newspapers

The newsvendor is equally like to sell each paper. There is a 90% chance of selling at least 10 papers, and a 10% chance of selling at least 90 papers. On average, the newsvendor will sell 50 papers.

The newsstand can pre-order papers three days before, on Friday, at a price of $0.50 per paper. In addition, the newsvendor can have newspapers rush delivered on Monday morning, from nearby newsstands, for $0.80 per paper. The selling price of a newspaper is always $1.00.

In tabular format[14], this inventory level problem could be expressed as Exhibit 3.4. In the first column, a given order amount, X, between zero and 100 is given. On the same row, the marginal probability of selling X papers is calculated, and added to

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[14] Non-tabular solutions also exist. For instance, if the newsvendor must decide on Friday how many papers to order, the newsvendor will order according to this formula: (Selling Price – Cost) / Selling Price. This formula gives the service level—which is the same as fill rate in this single period, one-product case. In this case, 50%, because at the mean, the marginal loss of understocking one paper equals the marginal cost of overstocking one paper: $.50. Calculus (first derivative), graphical (geometric areas under the revenue and cost lines), and linear programming solutions are also popular.

the cumulative number of expected papers sold. For instance, for the row X = 10, the Expected Number Sold column lists how many papers of those 10 will be sold on average. The Cost is calculated as X times the cost of a paper, $0.50. The Expected Revenue is calculated by multiplying the selling price by the Expected Number Sold. The Expected Profit is calculated by subtracting Expected Cost from Expected Revenue.

Order Amount X	Pecentage of the Time at Least X Units are Sold	Expected Number Sold	Cost	Expected Revenue	Expected Profit
0	-	-	-	-	-
1	100%	1.00	$ 0.50	$ 1.00	$ 0.50
10	91%	9.55	$ 5.00	$ 9.55	$ 4.55
20	81%	18.10	$ 10.00	$ 18.10	$ 8.10
30	71%	25.65	$ 15.00	$ 25.65	$ 10.65
40	61%	32.20	$ 20.00	$ 32.20	$ 12.20
50	51%	37.75	$ 25.00	$ 37.75	$ 12.75
60	41%	42.30	$ 30.00	$ 42.30	$ 12.30
70	31%	45.85	$ 35.00	$ 45.85	$ 10.85
80	21%	48.40	$ 40.00	$ 48.40	$ 8.40
90	11%	49.95	$ 45.00	$ 49.95	$ 4.95
100	1%	50.50	$ 50.00	$ 50.50	$ 0.50
101	0%	50.50	$ 50.50	$ 50.50	$ 0.50

Exhibit 3.4: The "Inflexible" Newsvendor

The newsstand pre-orders 50 papers, it will make an expected profit of $12.75.[15] Most table lines are hidden to conserve space.

[15] The theoretical answer is a quarter less: $12.50.

3.2.2.3 The flexible solution

However, if the newsstand waited until Monday morning, and ordered newspapers as they were being sold, it would eliminate the possibility of having overstock or understock. The newsvendor will order exactly the number that is sold. To do this though, the cost of papers increases by 60%, from $0.50 to $0.80. As shown in Exhibit 3.5, the expected profit will be $10.10.

Demand X	Pecentage of the Time that Demand equals X	Expected Number Sold	Cost	Expected Revenue	Expected Profit (Cumulative)
0	-	-	-	-	-
1	100%	1.00	$ 0.80	$ 1.00	$ 0.20
10	91%	9.55	$ 7.64	$ 9.55	$ 1.91
20	81%	18.10	$ 14.48	$ 18.10	$ 3.62
30	71%	25.65	$ 20.52	$ 25.65	$ 5.13
40	61%	32.20	$ 25.76	$ 32.20	$ 6.44
50	51%	37.75	$ 30.20	$ 37.75	$ 7.55
60	41%	42.30	$ 33.84	$ 42.30	$ 8.46
70	31%	45.85	$ 36.68	$ 45.85	$ 9.17
80	21%	48.40	$ 38.72	$ 48.40	$ 9.68
90	11%	49.95	$ 39.96	$ 49.95	$ 9.99
100	1%	50.50	$ 40.40	$ 50.50	$ 10.10
101	0%	50.50	$ 40.40	$ 50.50	$ 10.10

Exhibit 3.5: The Flexible Newsvendor

By waiting until Monday morning and ordering only as many papers as needed, the newsvendor makes an expected profit of $10.10. Most table lines are hidden to conserve space.

The "inflexible," order-ahead solution brings the newsvendor an expected profit of $12.75, but the completely "flexible," order-what-can-be-sold solution brings the newsvendor a lower expected profit of $10.10. In this simple case, the *in*flexible solution is better than the flexible solution.

At this point there are two more considerations. One of these is: At what cost will the flexible solution be more profitable? Certainly, if the papers ordered on Monday morning were to cost the newsstand only $0.50, then the newsvendor should wait until Monday to order all papers. The data tables feature in most spreadsheets can be used to create a matrix that reveals the maximum price the newsvendor should be willing to pay for "flexible" papers on Monday morning. For this example, the inflection point will be about $0.75. Other types of sensitivity analysis will also work.

The second consideration raised is for the possibility of a combined solution that borrows the best from each of the flexible and inflexible solutions.

3.2.2.4 The hybrid flexible/inflexible solution

If the newsstand orders 50 papers on Friday at $0.50 per paper, then it will make an expected profit of $12.75, as shown in Exhibit 3.4. If the newsstand also uses flexibility to cover demand that exceeds 50 papers, it will be able to sell up to 100 papers on days when the demand is higher than average. In this way, the customer demand has been segmented into two groups: One serviced by inflexible supply, and the other serviced by flexible supply.

Demand X	Pecentage of the Time that Demand equals X	Expected Number Sold	Cost	Expected Revenue	Expected Profit (Cumulative)
51	49%	0.49	$ 0.39	$ 0.49	$ 0.10
60	40%	4.45	$ 3.56	$ 4.45	$ 0.89
70	30%	7.90	$ 6.32	$ 7.90	$ 1.58
80	20%	10.35	$ 8.28	$ 10.35	$ 2.07
90	10%	11.80	$ 9.44	$ 11.80	$ 2.36
91	9%	11.89	$ 9.51	$ 11.89	$ 2.38
92	8%	11.97	$ 9.58	$ 11.97	$ 2.39
93	7%	12.04	$ 9.63	$ 12.04	$ 2.41
94	6%	12.10	$ 9.68	$ 12.10	$ 2.42
95	5%	12.15	$ 9.72	$ 12.15	$ 2.43
96	4%	12.19	$ 9.75	$ 12.19	$ 2.44
97	3%	12.22	$ 9.78	$ 12.22	$ 2.44
98	2%	12.24	$ 9.79	$ 12.24	$ 2.45
99	1%	12.25	$ 9.80	$ 12.25	$ 2.45
100	0%	12.25	$ 9.80	$ 12.25	$ 2.45

Exhibit 3.6: Hybrid Flexible and Inflexible.

The newsvendor uses a flexible supplier of papers—at cost increase of 60%—but is able to increase profits by $2.45, a margin of almost 20%. Most table lines are hidden to conserve space.

As shown in Exhibit 3.6, if the newsstand supplements the first 50 papers with additional papers, it can increase its expected profit by $2.45. This is then added to the $12.75 expected profit on the first 50 newspapers for a total expected profit of $15.20—a 19% increase over the inflexible solution.

On a given day, the newsstand will be able to meet all demand, up to 100 papers. By buying additional papers, the newsstand has expanded the **upside** of its business.

On another given day, if the newsstand sells less than 50 papers, then the flexible solution may, depending on how low demand was, have been preferable. (In this example, if the newsstand sells less than the breakeven amount of 25 papers.) So this solution does not eliminate the **downside**. The only way to eliminate the downside was to buy only what the newsstand was certain of selling, by using the flexible solution. Unfortunately, this lowers expected (average) profits.

Though this was a simple example, it is powerful because it eliminates bric-a-brac and concentrates on the underlying probabilities and the decision to be made. The findings are this: In any situation, the best solution may be flexibility, no flexibility, or a combination of the two, depending on the terms, prices, and other features of the problem. Many decisions about flexibility may be tractable with a traditional decision analysis approach and familiarity with computer spreadsheets.

3.3 Real Options Analysis

ROA is a way to apply financial options techniques to engineering and business projects. Specifically, it provides a way of valuing flexibility. It also provides a new way to think about flexibility in general, commonly called "options thinking." It is different from NPV because it takes into full account irreversibility, uncertainty, and the timing of decisions.

Technically, an option is the right, but not the obligation, to get into, or out of, a situation. In finance these are called "call options" and "put options," respectively. For instance, car insurance is the right, but not the obligation, to file a claim for repair expenses with the insurance company. In financial terms, this is called a put option. One can "put" the expense of replacing a badly wrecked car to the insurance agency, and they will replace it with a new car. Of course, one has to pay a fee upfront for this right to file a claim with the insurance company. This upfront fee acquires the right to put the expense to the insurance company, in the event of a car accident.

Sometimes real options occur "naturally" in projects, and they only need to be incorporated into the analysis of the project. Other times real options must be added at an additional expense. Types of real options on projects include: Defer, abandon, switch inputs, alter operating scale, growth options, and staged investments [Lander *&* Pinches, 2002]. De Neufville points out that options can be "on" projects or "in" projects [2002]. That is, options can be speculative instruments about a component of a project, such as postponing a decision until more is known about fuel prices, or they can be physically embedded, such as building an engine that consumes either gasoline or diesel fuel.

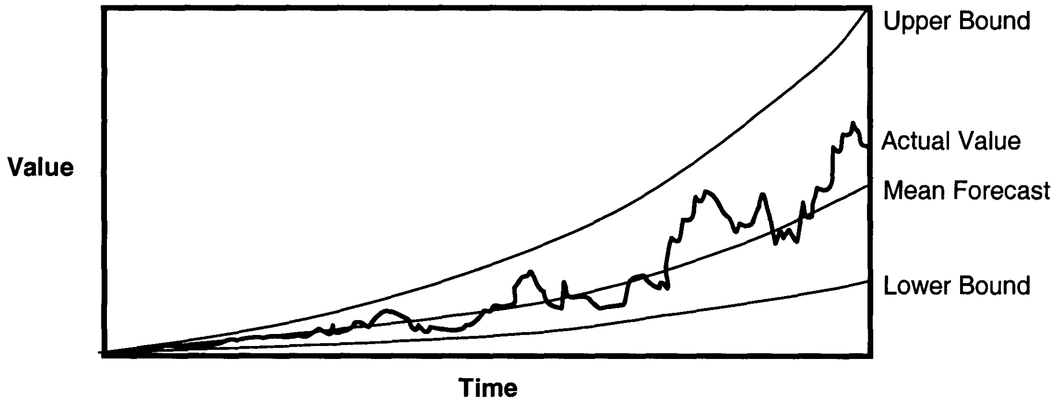

Exhibit 3.7: Option Value Asymmetry

High valuations are more likely than low valuations. The lower and upper bounds represent a statistical confidence interval. The actual value will be random continuous variable. This is called a Weiner Process or Geometric Brownian Motion.

Real options thrive on uncertainty; the more uncertain the outcome, the more useful real options become. Real options, because they are excericised only if the project has positive value, expand the upside, while limiting the downside. And as uncertainty about outcomes increases, the upside increases, while the downside does not. As shown in Exhibit 3.7, the upside, or maximum value, of an option (the top dotted line) grows quickly, while the downside of the option (the bottom dotted line) remains positive. Lander and Pinches comment:

> An option-based model is especially appropriate when the volatility of the underlying asset is high. Due to option asymmetry, the maximum possible gain increases while the maximum possible loss does not change [2002].

3.3.1 Quantitative real options

Using real options to evaluate decisions can be non-trivial. The underlying mathematics is beyond what most managers—even those with graduate business educations—are comfortable with. "As a result, corporate analyses that generate real numbers have been rare, expensive, and hard to understand" [Luehrman, 1998].

One of the more commonly used methods—because it is structurally similar to decision trees—is the Binomial Lattice[16]. With the lattice, each passing period is seen as a movement in one of only two directions: Up or down. The binomial approach can be quite a bit easier to learn, and explain to decision makers, than other ROA models.

An example of a one-period Binomial Lattice is shown in Exhibit 3.8. Like decision trees, binomial lattices are "rolled back" right-to-left to find the expected value. But unlike decision trees, there are no "chance" nodes that are based on probabilities. This is an important but counterintuitive distinction. For instance, in Exhibit 3.8, it does not matter what the distinct probabilities are that the movement will be up, or down, or even if these probabilities are known. The underlying mechanics—called Geometric Brownian Motion, or a Weiner Process—use parameters for volatility and time to generate "pseudo-probabilities" that are used instead.

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[16] Trinomial and other lattices are also used, but not as commonly

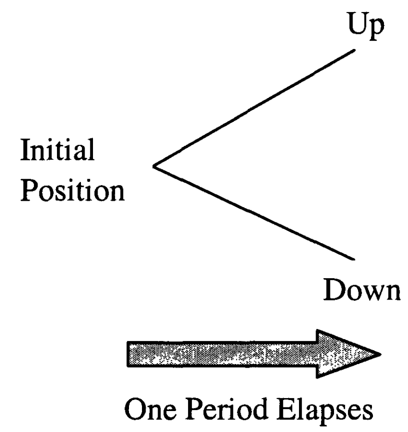


Exhibit 3.8: One Period Binomial Model

In the binomial model, each period is modeled as a move of up or down from the initial position. The period can be a day, week, month, quarter, year, or other time frame.

The pseudo-probabilities are determined by dividing the percentage factor that the asset price could increase by the percentage factor the asset price could decrease. These increase and decrease amounts are based on a growth rate that is calculated by multiplying volatility per period by the number of periods represented by the step. The pseudo-probabilities are then adjusted to be risk-neutral using the risk-free interest rate. Pseudo-probabilities can be thought of as weights that, when multiplied against the future values, yield a risk-neutral valuation of the asset.

After several periods of decisions like the one in Exhibit 3.8, a complete binomial lattice is built, as shown in Exhibit 3.9.

In the first period of Exhibit 3.9, the value of the project moves up. In the second period, the value moves down. In the third period, the project moves up again. This can be written briefly as Up/Down/Up. Equivalently the same end position could have been the result of the paths Up/Up/Down or Down/Up/Up.

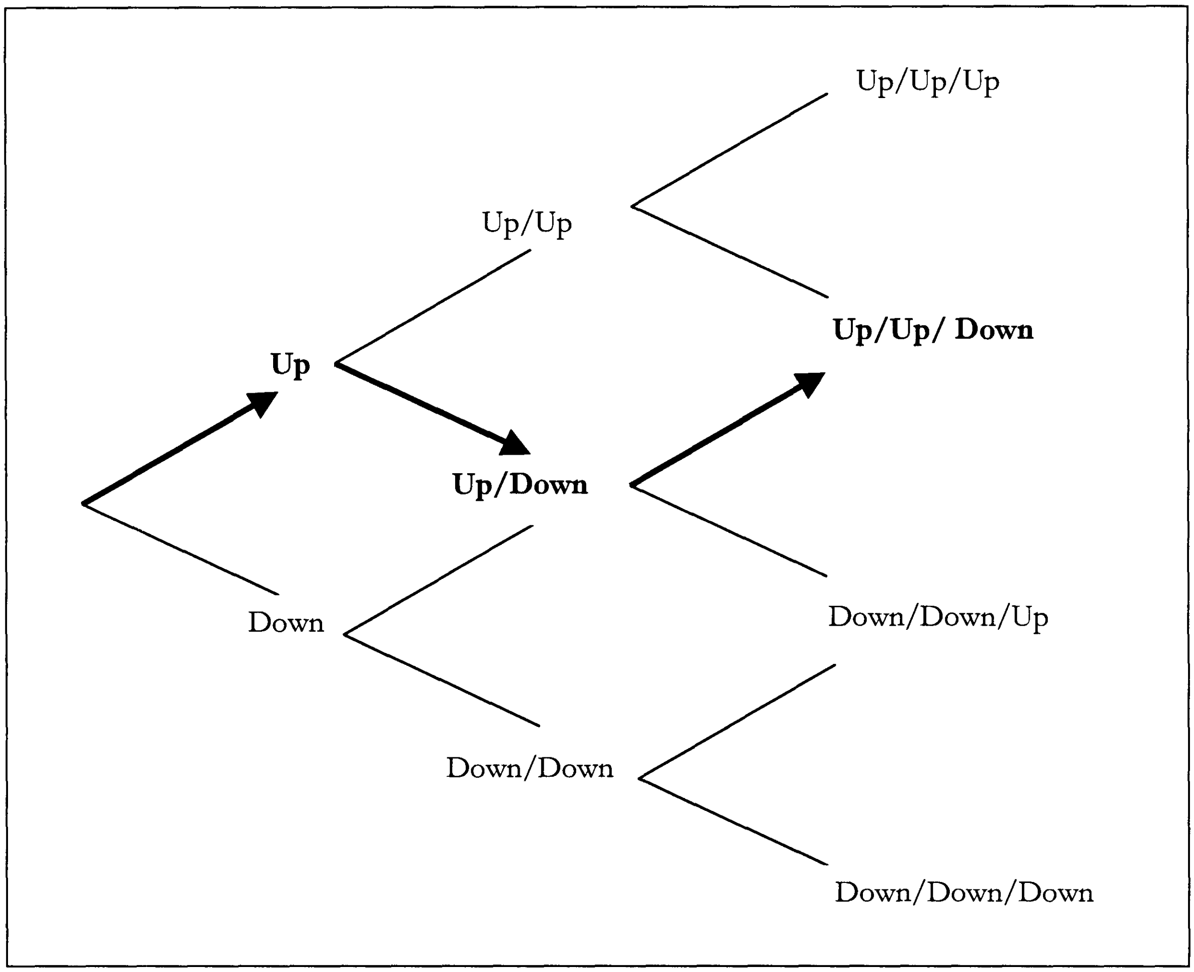


Exhibit 3.9: Three-Period Binomial Tree

Each period is modeled as an Up/Down movement, and over several periods the movement can be a combination of up and down movements. Though it appears discrete, when taken to the calculus limit the binomial tree converges with the Black-Scholes formula and other continuous pricing techniques.

For instance, an asset might be valued at $50 initially, at period 0. It could be determined—by historical or other means—that the asset has a volatility of plus or minus 10% per period. Therefore, after one period, if the asset moves up, it will be worth 110% of its original value, or $55 (50 * 1.10 = 55). If, in the second period the asset goes down, it will lose 10% of its present value. It is now valued at $49.50 (55 * .90 = 49.5). In the third period, if the asset moves up in value, the final value will be

$54.45 (49.5 * 1.10 = 54.45). This Up/Down/Up path is the path bolded in Exhibit 3.9.[17]

Calculations like these are done for every node on the lattice, and the nodes are rolled back, right-to-left, similar to a decision tree, to give the present value of the option on the underlying asset. Unlike a decision tree though, there are no probabilities at each node.

More importantly, at each time interval, each node of the lattice will reveal whether it is more valuable to retain the option, or to exercise it. So unlike other formulas, such as Black-Scholes, the binomial lattice reflects the possibility that management may have the chance to exercise the option early.

3.3.1.1 Real options example: Textiles contract

Suppose that Lolita, the South American women's apparel company mentioned in the introduction of this thesis (pp. 17) has decided to use local manufacturers to replenish stocks of popular women's knitted blouses, if needed, during the summer season. Lolita has reserved capacity with local short-cycle (small order size, fast turnaround) manufacturers, and can make a decision whether to use this manufacturing capacity at the beginning of each month during the peak summer selling season (November, December, and January).

The raw materials for the blouses—knitted cottons of various knits sizes (1 thru 12) and various colors—are imported from Asia because of the superior look and feel of the knitted cottons made there. Lolita will choose to import the knitted textiles and manufacture the garments only if there is sufficient demand for them. Lolita has contacted a knitted textiles manufacturer who is known to have surplus capacity, and Lolita has offered to set up a contract. Lolita would like to purchase a call option (the right, but not the obligation) on a bulk shipment of airfreight-delivered, knitted

[17] This simplified example ignores the adjusting of the 10% rate to be risk-neutral.

textiles, which Lolita could then send to its local, short-cycle blouse manufacturers to use as material for making blouses.

Historically, Lolita knows that demand for knitted blouses is Normally distributed and varies by 40%; it is notoriously hard to predict the fashion purchases of fickle Latin American *fashionistas*. The textiles manufacturer, seeing this as a way to potentially expand factory output, agrees to Lolita's offer to buy an option on textiles.

At today's prices, the Asian factory would deliver the blouses for $10K. If Lolita called the option today, the blouses would generate $10K in revenue, and Lolita would break even (all other costs are included in the $10K figure). Lolita and the textile manufacturer agree that the call option will lock in the current cost of goods, $10K. Lolita must now decide how much to pay for this option to reserve this expedited shipment of knitted textiles.

Lolita's decision can be modeled as a financial call option, with an underlying asset (the demand for fashionable blouses) that varies via a lognormal function (a modification to the Normal that prevents negative pricing of assets). The strike price—what it costs to exercise the option—is $10K, the cost of goods. Lolita's value of the option is modeled below in Exhibit 3.10.

Month	0	1	2	3
Price	$ 10,000.00	$ 11,224.01	$ 12,597.84	$ 14,139.82
Exercise Value	$ -	$ 1,224.01	$ 2,597.84	$ 4,139.82
Hold Value	$ 921.96	$ 1,589.17	$ 2,639.42	$ -
Option Value	**$ 921.96**	$ 1,589.17	$ 2,639.42	$ 4,139.82
Exercise?				**YES**
Price		$ 8,909.47	$ 10,000.00	$ 11,224.01
Exercise Value		$ (1,090.53)	$ -	$ 1,224.01
Hold Value		$ 290.50	$ 596.30	$ -
Option Value		$ 290.50	$ 596.30	$ 1,224.01
Exercise?				**YES**
Price			$ 7,937.87	$ 8,909.47
Exercise Value			$ (2,062.13)	$ (1,090.53)
Hold Value			$ -	$ -
Option Value			$ -	$ -
Exercise?				
Price				$ 7,072.22
Exercise Value				$ (2,927.78)
Hold Value				$ -
Option Value				$ -
Exercise?				

Exhibit 3.10: A three-period Binomial Options Analysis

The value of the option is $921.96. There are two cases in which the option should be exercised, both in the third month (top right, labeled **YES**).

At each node in Exhibit 3.10, the Option Value is defined as the function Max(Exercise Value, Hold Value). [18] The lattice is then "rolled back" right-to-left to calculate the expected value of the option. After being rolled back to the present day, the option to buy the textiles is valued at $921.96. This means that Lolita should not pay more than $921.96 for this call option—in fact, to do even better, Lolita can try to negotiate a price less than the calculated value of the option.

[18] In Exhibit 3.10, the top of the lattice is squashed 45° so that the top-most edge is parallel to the header and footer of the printed page. This format makes the lattice easier to work with in the row-column confines of a spreadsheet.

The option should be exercised only at nodes where the value of exercising the option is greater than the value of holding the option. In the 3rd period, there are two cases when the value of exercising the option is greater than the value of holding the option.[19] In all other cases, a wait-and-see approach is recommended, because the hold value is greater than the exercise value. In the two cases labeled "**YES**", Lolita should exercise the right to purchase the textiles rather than hold the option.

At nodes where the option value is greater than zero, the options are sometimes called "in the money." At nodes where the option value is less than zero, the options are called "out of the money."

3.3.1.2 Real options advantages

Unlike the NPV and DA, ROA does not have the flaw of the averages defect. ROA uses a "risk-free" discount rate combined with perfect "arbitrage" pricing of assets to ensure accurate results. This, along with the lack of a need for subjective probabilities, is an advantage of real options over decision trees. But ROA has shortcomings as well, chiefly:

1. The difficulty in determining the volatility of the asset (in the example above, Lolita was able to use historical data as an estimate, but often projects are unique, and do not have precedents or similar projects).
2. The difficulty of fitting a real world business problem into a framework originally intended to price derivatives of easily tradable, easily valued market securities. In the Lolita example, many simplyfing assumptions were made.

[19] Note that by the next period, the summer selling season is over, and the textiles themselves are not useful.

For more discussion of ROA, the reader is referred to any of the several books by Trigeorgis on the subject.[20]

3.3.1.3 Real options example: Other approaches

The Black-Scholes or other methods would yield similar results to the Lolita decision. Because the underlying asset, demand for knitted blouses, is a continuous random variable, the Black-Scholes and Binomial methods should yield the same results, at the limit. A visual conception of this is displayed in the exhibits on the next two pages.

[20] Trigeorgis, L. Real Options- Managerial Flexibility and Strategy in Resource Allocation, 1996, MIT Press, Cambridge, MA or Trigeorgis, L., ed. Real Options and Business Strategy: Applications to Decision Making, 1999, Risk Books, London, UK

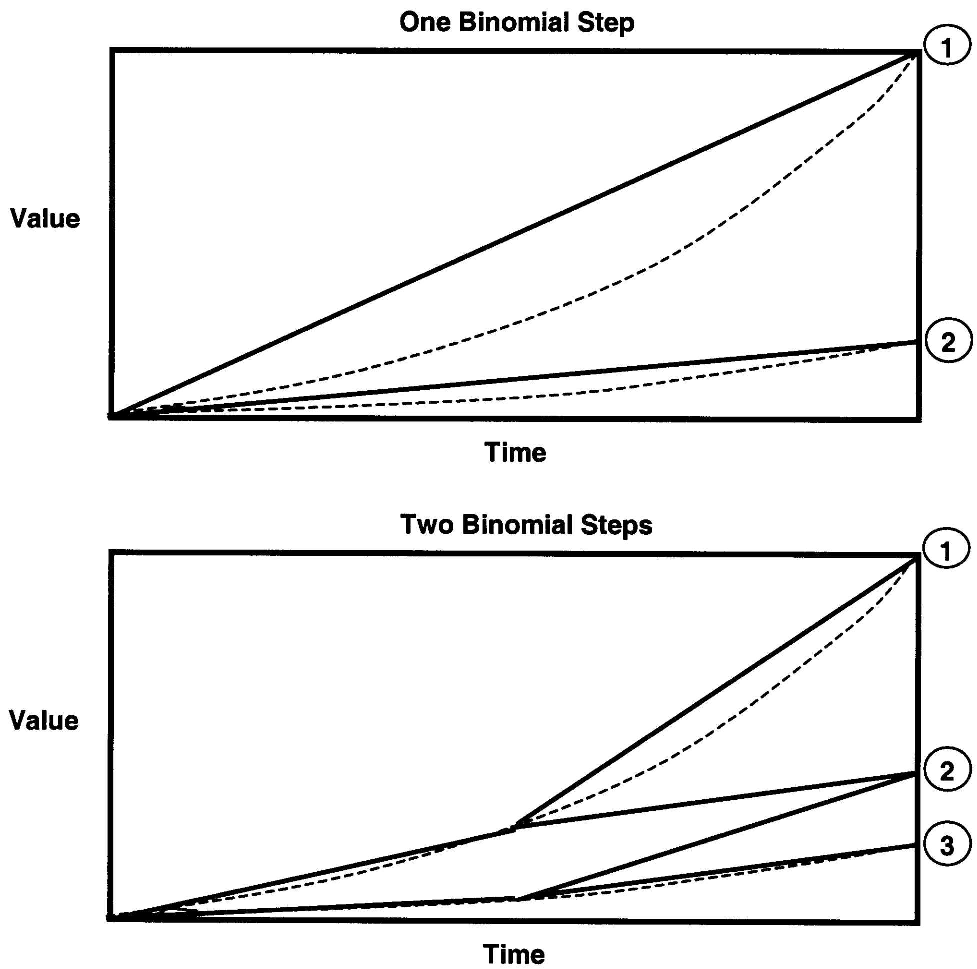
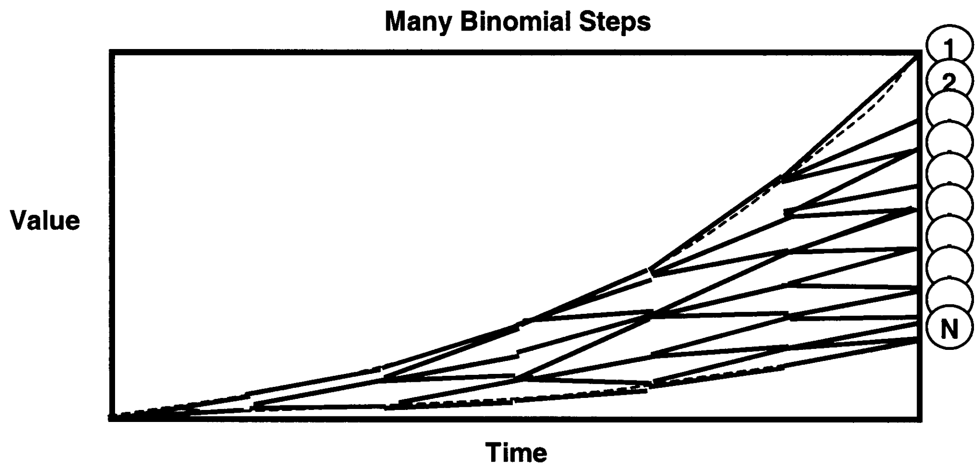


Exhibit 3.11: Binomial converges to the Black Scholes, Part 1

One and two step binomial lattices mapped onto the continuous distribution of option values. The dotted lines are the lower and upper bounds of the continuous distribution. The circled numbers represent the discrete number of outcomes calculated in the binomial lattice. The underlying Value vs. Time graph is from Exhibit 3.7 (pp. 61). See also next page.



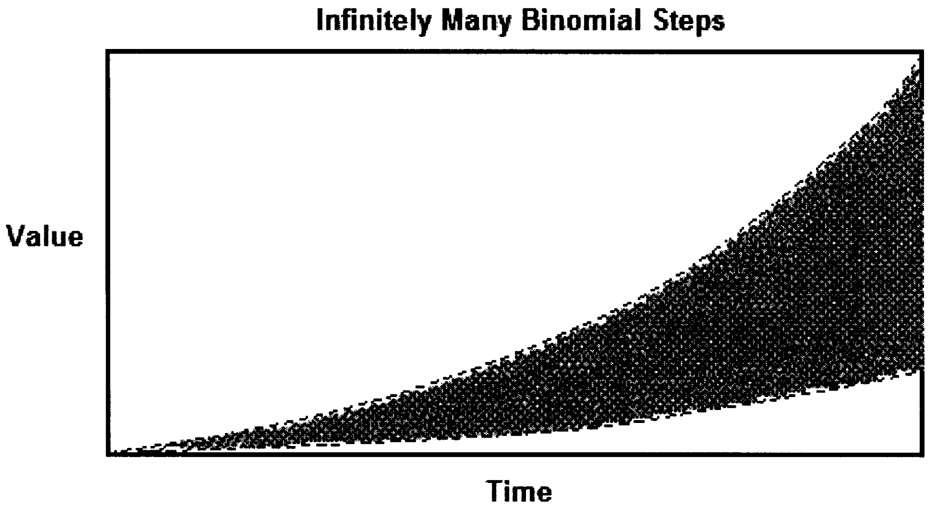


Exhibit 3.12: Binomial converges to the Black Scholes, Part 2

At the limit, the Binomial Lattice becomes infinitely dense and the Binomial Lattice and Black Scholes answers converge. See also exhibit on previous page.

A decision tree approach could also be used. For example, the demand distribution could be converted into three discrete variables by using the 5%, 50%, and 95% confidence level values (Z +/- 1.645) of the Normal. These point values would become terminal nodes on the decision tree. These terminal nodes would be preceded, to the left, by a three-way chance node with probabilities 18.5%, 63%, and 18.5%, respectively[21]. The decision tree could then be rolled back to calculate the value of the option. Many decision tree software packages now support such options as "discretizing" a Normal variable; spreadsheets can also be used.

Additionally, Luehrman suggests an intuitive way for managers more familiar with NPV to use real options valuations by using a conversion formula and a two-dimensional lookup table [1998].

3.3.2 Qualitative real options and "Options Thinking"

Real options analysis offers an ***inductive*** approach to supply chain flexibility: This is a well respected theory—it won a Nobel prize for its creators—that offers a new way to look at handling risk and uncertainty. Inductively, ROA provides managers a new lens through which to view the world, including supply chain flexibility. In contrast, the existing manufacturing and supply chain literature is largely ***deductive***, based on the study of theoretical models and observation of real world cases.

The inductive potential of real options is important because "Induction and deduction are both needed for scientific thought as the right and left foot are both needed for walking" [Marshall, 1929].

De Neufville suggests, "analysis of real options enables managers and designers to estimate the value of system flexibility"[2002]. Similarly, Meyer *et al* write:

> The notion of "real" options draws on the extensive theory of financial options to help managers think about the costs and benefits of flexibility. Flexibility is crucial in an age of uncertainty, whether that uncertainty is driven by natural

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[21] The Normal curve is trisected at +/- 1.645. Then the middle, 90%, trisection is divvied up 70/30. The 30% (30% of 90%, or 27%) is then divided into two 15% (13.5%) portions. These portions are then added to the 5% outlying areas to make 18.5%. The remaining middle section is 63%.

> disasters, terrorist attacks, or the changing needs of consumers. The essence of flexibility can be embodied by an option [2002].

As noted before, real options become more valuable as uncertainty about outcomes increases. Benefiting from uncertainty seems counter-intuitive at first, because in conventional decision analysis, wider ranges of possible outcomes reduce the accuracy of the expected value, attributable to an increase in variance, thus decreasing the value of the analysis. This can also be interpreted as the ***proactive*** stance that ROA takes, rather than the ***reactive*** stance that conventional DA takes.

Without the options perspective on decision-making, supply chain managers may ask: "What *will* happen?" However with an options view of the world, supply chain managers may ask: "What *could* happen? And, how can we respond?" [Pindyck, 2002]

This is a new stance, because traditional flexibility is an adaptive, reactive response to environmental uncertainty (what *will* happen) [Gupta *&* Goyal, 1989]. This does not have to be the case though; Gerwin writes:

> Management is accordingly not solely a passive reactor to environmental cues; it can also seize the initiative and try to bend the environment to its will [1994].

With options thinking, designers are encouraged to incorporate uncertainty—embodied as options—into their designs (what *could* happen). It is the view of some that this will fundamentally change how systems, such as supply chains, are constructed. Specifically, ROA takes into account options that reflect flexibilities, such as defer, shutdown, abandon, expansion, and switching among inputs. [Ramirez, 2002].

Indeed, the literature on real options suggests that the most important contribution of ROA may be changing the mindset of managers. According to Olmsted:

> The process of performing a Real Option Analysis tends to broaden one's view of future possibilities and sharpen the logic

> of one's thinking about various strategic alternatives. The process itself can be more important than the particular analytic results [Olmstead, *quoted in* Ramirez, 2002].

3.3.3 Portfolios of options

Another distinction of real options is the notion of portfolio management. Instead of considering each project individually, a project is considered amongst others as a "portfolio." Flexibilities could similarly be managed as a portfolio. Jordan and Graves found that a small number of flexibilities have nearly all the benefits of a large number (or even a complete set) of flexibilities [1995]. Gerwin also states that if utilities are independent and identically distributed—two big ifs—then most of the value of flexibility can be obtained from holding a small set of the what might be very large available set of options [1993]. These findings lend themselves well to portfolio management of a small set of well-selected options.

3.3.4 Real options in practice (or not)

Many cite a lack of penetration of ROA among practitioners. While it is seen as powerful, many consider it unwieldy. This results in a tentative, "plug-and-chug" approach, and little, if any of the qualitative "options thinking" is imparted.

Additionally, when educating peers in how to value flexibility, it can be a daunting task to teach the relatively esoteric ROA. Instead, many choose to use decision trees as the basis for evaluating flexibility decisions, or to ignore flexibilities altogether.

Further, getting real world data to fit into models that were originally intended to track marketable securities can be difficult. Accuracy may be a relative goal though, as Luehrman notes:

> When a very precise number is required, managers will still have to call on technical experts with specialized financial tools. But for many projects in many companies, a "good enough" number is not only good enough but considerably better than the number a plain DCF analysis would generate [1998].

Also, it may be difficult to model decisions as real options for "softer" reasons. Carr suggests that managers and other decision makers may become emotionally attached to projects, impairing their ability to make rational judgments [2002]. This makes it difficult to abandon projects—something that must be done. Carr says that "ruthless rationality" is important when managing projects as a portfolio of real options.

> Yet business projects are not purely financial instruments that are coldly traded on open markets. They are, instead, complex organizational constructs that, once initiated, tend to take on lives of their own and become notoriously difficult to kill [Carr, 2002].

3.3.5 Projects versus processes

Owing to its financial investments background, most ROA analyses have been used to evaluate projects, but many supply chain practitioners may want to use ROA to evaluate processes.[22] For companies that want to compete on speed and flexibility, it may stand to reason that more emphasis will be put on projects than processes because of the emphasis on innovation.

[22] De Meyer *et al* define projects as one-time, usually unique activities, and processes as the repetitive, systematic activities that run a company [2001].

Chapter 4. Analysis: Management of flexibility in the supply chain

How effectively a company implements flexibility is reflected in where their flexibilities initiatives are focused: On being reactive or pro-active. These guidelines are important because the extent of learning is reflected in a company and manufacturing strategy which attempts to defensively adjust to uncertainty or proactively control it.

—Swamidass, 1988

4.1 Introduction

It was not the goal of this thesis to describe specific dimensions or measures of flexibility, or to provide closed-form solutions that produce correct results for flexibility problems. A look at the mature manufacturing literature, which can be seen as smaller set of the supply chain literature, reveals that this is not possible. Instead, this thesis has aimed at A.) Giving managers the tools to communicate and evaluate flexibility, and B.) Acting as a starting point for further study of flexibility and its measurement.

4.2 Review

Chapter one provided a brief history of flexibility and the reasons it deserves management attention. It was intended that chapter one present a set of compelling reasons for the study of flexibility; a *raison d'être* for this thesis.

Chapter two presented a summary of the available literature on flexibility. These readings came from a wide area, from economics to manufacturing. Specifically, these readings impart on the reader an awareness of supply chain flexibility in several dimensions: Range versus Mobility, Operational versus Strategic, and others. On a whole they give the reader an intelligent way to communicate the various types flexibility and their implications. From here, the reader can place specific problems regarding flexibility into their appropriate contexts.

Whereas chapter two framed the problem, chapter three provided tools that can be used to evaluate solutions. Decision Analysis and Real Options Analysis can be used to further define the problem, model scenarios, and in some cases produce numerical answers. Further, the use of DA and ROA was suggested as a way of further refining the meaning and uses of flexibility. In this way, these tools act as an inductive complement to the deductive tools gathered in chapter two.

4.3 Recommendations

In this section the learnings from chapters one, two, and three are combined to give the supply chain manager new insights for managing flexibility. This is important, because flexibility is more and more often a word heard from vendors, upper management, academics and others.

However, it is hard to say what flexibility in a supply chain might be. For example, a list of current flexibility techniques might include:

- Safety stock inventory
- Product componentization and commonality
- Outsourcing
- Geographic dispersion of key resources
- Network-oriented organizational structures
- Forward positions on supply contracts
- Postponement

All of the techniques listed above deal directly with uncertainty in the supply chain, but do all of these techniques qualify as "flexibility?" If not, which do? Or do all of them qualify, but in different ways? And is there a way supply chain managers can evaluate cost-to-benefit, in dollars or otherwise, of any decision involving the addition or subtraction of flexibility? Additionally, several types of supply chain flexibility such as Mix flexibility and New Product flexibility were mentioned in the literature review. Where do these fit?

To tackle questions such as these, the following sections contain recommendations that are culled from an analysis of chapters one, two, and three. These sections intend to serve as guidelines for managing flexibility in the supply chain.

4.3.1 On communicating flexibility

First, the flexibility must be placed. Flexibilities can have different contexts, from floor-level flexibilities in the job shop to strategic-level flexibilities proposed in the boardroom. Koste and Malhotra's literature funnel (pp. 27) can be used to place these different levels of flexibility.

Second, the type of flexibility must be identified. Upton's three general types of flexibility (pp. 22) can be used to do this. This is important, because even a given machine in a given process could have any one of these flexibilities. It is important to define early on just which is meant.

Third, it must be decided if flexibility is to be used to account for things expected to happen, or things not expected to happen. While this is a subtle difference, in practice preparing for the former will be much easier than the latter. Klein called these Type I and Type II flexibilities (pp. 34).

Fourth, and last, the environmental goal of the flexibility must also be defined. Is it a flexibility meant to defensively absorb uncertainty from the environment, or is it intended to provide competitive, offensive advantage that can be used to capitalize on emerging or temporary market conditions? Defensive flexibilities will often be inward facing, but offensive flexibilities will be outward facing. Swamidass comments:

> How effectively a company implements flexibility is reflected in where their flexibilities initiatives are focused: On being reactive or pro-active. These guidelines are important because the extent of learning is reflected in a company and manufacturing strategy which attempts to defensively adjust to uncertainty or proactively control it.

4.3.2 On evaluating flexibility

Once an opportunity for flexibility has been identified, then analytical tools should be used to test the viability and value of the flexibility. Real Options Analysis and other methods can be a new "lens" thru which these opportunities for flexibility can be viewed. This will be difficult, because it requires one to think non-linearly, and to look past immediate efficiencies.

> Unfortunately, most organizations are poor at designing situations that offer choices for selection. It's hard to envision options, particularly when we've been told to be as efficient as possible. Creating options can be both unfamiliar and expensive. In fact, many organizations aggressively limit options to ensure efficiency, striving for standardized processes even when the environment is highly uncertain [Billington *&* Kuper, 2000]

Once found though, benefits of the flexibility should not be claimed before weighing the trade-off between flexibility and non-flexibility. These trade-offs occur in two ways. The first trade-off is an operational one; the second is a strategic one:

1. Operationally there is the trade-off between flexibility and *efficiency*, and

2. Strategically there is the trade-off between flexibility and *commitment.*

Knowledge of the company's competitive strategy or supply chain strategy should give the answer to the second trade-off; when examined in the context of the larger strategy, it should "fall out" naturally as to what the strategically best decision is. This, after all, is the intended benefit of strategy. The first trade off, however, can be more difficult.

The operational trade-off between flexibility and efficiency should be evaluated with tools such as DA and ROA. While a complete, precise model of the real world scenario may not be possible, a preliminary analysis can often tell whether it is indeed preferable to "pay more for flexibility," as is often the case. More precise models may also be able to tell exactly at what price flexibility pays for itself (a kind of flexibility break-even). **Flexibilities that cannot be modeled, even roughly, by DA or ROA should *not* be considered.** There are two reasons:

First, an evaluation with these tools provides a way to isolate just what the proposed flexibility does. For instance, these models would uncover which one of Upton's flexibilities—Range, Mobility, or Uniformity—is being asked for. Or the model would be able to locate the proposed flexibility on Koste and Malhotra's literature funnel. Without a model, it will not be clear to managers and employees just what is meant by "flexibility." As shown in the literature review, flexibility can mean many, many things to different people. In this way, the DA or ROA model acts not only as tool for churning out numeric answers but also as a model for collecting and refining the wants of management. As an example, Trigeorgis notes that decision trees make management "bring to the surface its implied operating strategy and to recognize explicitly the interdependencies between the initial decision and subsequent decisions" [1996].

The simple fact that the flexibility can be modeled acts as a validation that it is flexibility at all. So-called flexibilities that cannot be modeled by ROA or DA are more likely environmental uncertainties, misunderstandings, or management indecisions that are being masked by a purported need to be "flexible."

Second, the DA or ROA model provides a workable estimate of what is to be gained or lost by employing the flexibility. In the end, decisions about flexibility must be made, especially for companies that plan to use it as a competitive advantage. Because of the nature of flexibility, being revealed only the future, its value may not be perfectly quantifiable in the present, but an attempt to quantify its cost and benefits is usually much better than none, i.e., the improvement of decision trees over NPV analysis.

As for choosing the particular tool for evaluating flexibility, it seems somewhat arbitrary. ROA yields more precise answers, but at a price of stricter assumptions and the need for more sophisticated users (on part of the owners of the analysis *and* the consumers of the analysis). Decision trees, when used correctly, can also evaluate flexibility. Different tools and techniques (e.g., decision trees vs. binomial lattices) will yield different numerical answers. But whether decision trees, real options, or other tools are used, they should all lead to the same flexible strategies being recommended. Lander and Pinches suggest:

> When would the optimal strategies be different if a decision tree approach is employed instead of an option-based model? The authors' experience indicates that, in the vast majority of the time, the optimal strategy does not change even though the specific valuations do [2002]

The tools may not be precise, but the objective is not to find an exact estimate, but instead to create a strategy for the project. There is a subtle difference between a plan and a strategy, but it is an important one, and not just semantic. When envisaging the future, management will only naturally be conservative or optimistic about the future. Tools, though imperfect, remove some of this subjectivity and force the users to consider a broader range of outcomes. As de Neufville notes:

> In general "second best" strategies are not optimal for any one outcome, but are preferable because they offer flexibility to do well in a range of outcomes [2002].

In summary, this section suggests guidelines for dealing with flexibility. Once the flexibility is placed, then modeled, and then evaluated, it can be managed more effectively.

4.4 Closing Remarks

Going back to chapter one, the supply chain manager has a choice: reactively deal with uncertainty (and risk), or proactively take advantage of it. The latter can fundamentally change how an organization behaves, as well as offer competitive advantage over rival firms.

Chapters two and three, taken together, give the manager the requisite background and tools needed to successfully incorporate flexibility into his or her decision making. With these, the manager can more critically evaluate, or dismiss, claims of flexibility from various media, colleagues, vendors, suppliers, customers, and others.

Chapter four, this chapter, has attempted to summarize of the previous three chapters. Of course, this chapter is not an executive summary. The real learning is presented in those chapters, and the bibliography will point the reader in the right direction where clarification is needed.

From here, the reader is encouraged to use the bibliography to find out more about flexibility and its many meanings and uses. It will sometimes be the case that the reader will disagree with the author, and offer different interpretations and summaries, but this, after all, is good. This will lead to more discussion and study of a great topic.

4.5 Future Research

1. The learnings here should be used as the starting point for empirical research; additional quantitative study needs to be undertaken.
2. Is lead-time the most important measure of supply chain flexibility?
3. How can computer tools such as simulation help model flexibility?

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