Real Options in Composite Manufacturing Considering Demand Uncertainty and Staged Tool Investments

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Application Portfolio
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Introduction

An automaker’s decision to manufacture a vehicle body panel out of a certain material includes, among other concerns, the choice of a specific alloy or polymer system and the choice of a fabrication process that can shape the material into a finished part. Traditionally, vehicle body panels have been made from sheet steel and formed using a stamping process in which large presses “stamp” the metal into shape using custom designed steel molds.

While the same stamping presses can be used to form almost all the different sheet metal products that an automaker produces, the stamping molds (also known as “tools”) are necessarily part-specific because they take the shape of the part. Furthermore, stamping tools typically last at least 1,000,000 cycles (strokes of the press), meaning that one stamping tool is usually sufficient for the life of the product. As stamping tool investments can easily run into the millions of dollars for a product like a car body panel, manufacturers are driven to make as many parts as possible with a given tool in order to distribute the tool investment across as many finished parts as possible. Because the variable cost of sheet steel is relatively low compared to other material alternatives, steel stamping at high production volumes exhibits excellent economies of scale and is very attractive to mass production manufacturers like major automakers.

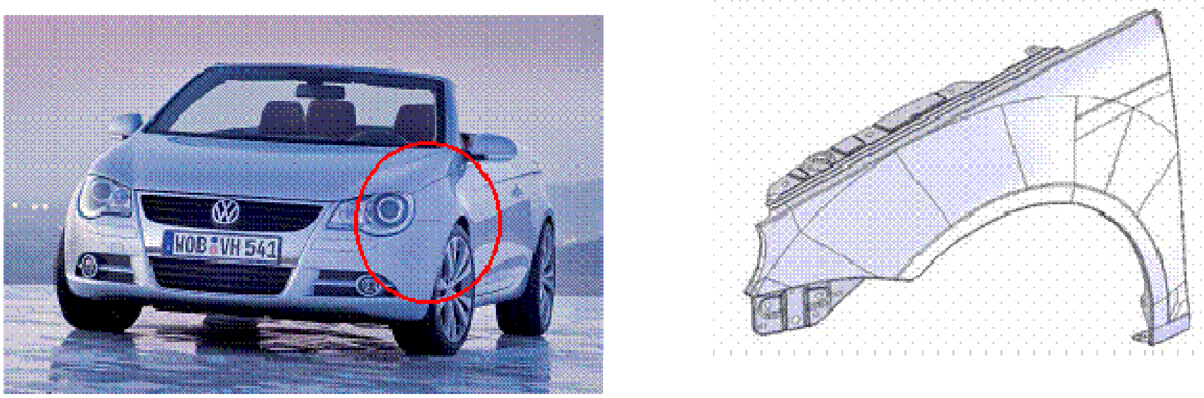


Figure 1. Volkswagen Eos and Eos fender. An example of a stamped steel part.

In recent years, though, several automakers have chosen plastic or reinforced composite materials instead of metals for body panel applications. One composite material system that automakers are investigating using in these applications is known as Resin Transfer Molding (RTM), which is a composite technique that reinforces a chemically-activated plastic with a fiber mat. Automakers usually consider using composites like RTM because they can offer significant weight-savings, which improves vehicle acceleration and/or fuel economy. This weight-savings comes at a price, though, which is the higher variable cost of the composite material itself. At high production volumes RTM is almost always more expensive than steel stamping (Figure 2).

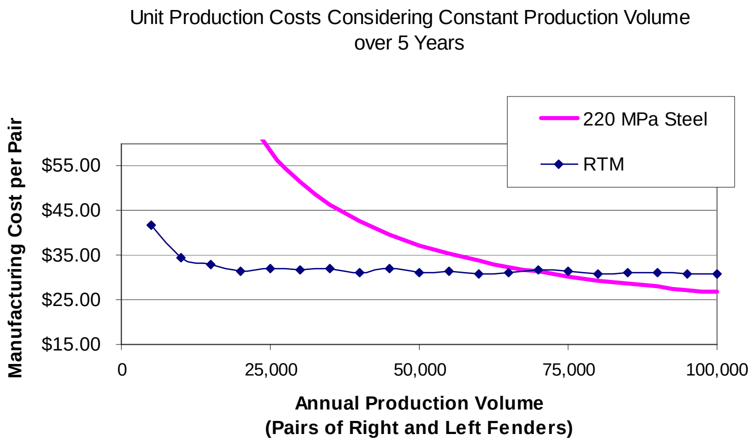


Figure 2. Steel vs. RTM production costs by production volume. Five-year total production

Yet there is some additional value to using RTM that most manufacturers are not considering: the flexibility to invest in tools in staged intervals. RTM, like stamping, uses presses and molds to form the part, but RTM presses are much smaller than stamping presses, and RTM molds—often made from plastic—are much cheaper and shorter lasting than steel molds (some last only a few thousand cycles).

This means that producing 1,000,000 steel body panels using a stamping process requires one large up-front tool investment whereas the production of 1,000,000 RTM body panels allows staged tool investments as the tools are cycled and wear out over the lifetime of part production. Moreover, the number of parts that a manufacturer will be able to produce and sell in a given year and over the life of the product is highly uncertain, meaning that the economic comparison between the fixed tool investment of the stamping approach and the staged tool investment of the RTM approach is largely uncertain as well. If demand is high and the automaker produces many parts the steel approach may be least expensive (and most profitable), but if demand is low the automaker can limit tool investments in the RTM approach, making it the better choice.

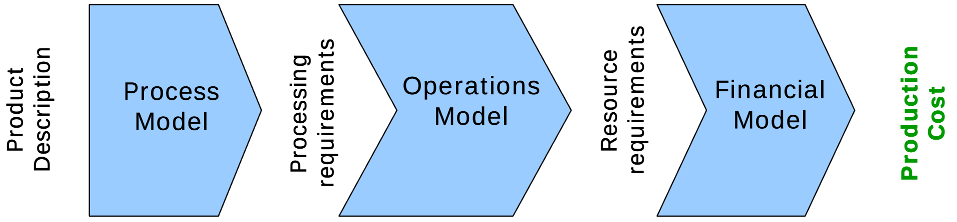
This paper investigates the value of flexibility inherent in the staged approach to tool investments in RTM manufacturing as market demand for a product varies during production lifetime, using the production of an automotive fender as a case study.

Systems and Technical Cost Models Overview

The two systems analyzed here represent a fixed approach (a steel fender produced using a stamping process) and a flexible approach (a composite fender using an RTM process). I used process-based technical cost models of the stamping and RTM processes developed by the Materials Systems Laboratory to project investments and manufacturing costs for every scenario that was analyzed in this work. This method combines three models: process, operations, and finance, to project manufacturing costs.

The first step in this approach utilizes a process model that incorporates engineering relationships between the part description and the materials processing technology to determine the necessary processing requirements. Next, an operations model combines the processing conditions with the desired production scale to determine plant resource requirements. Finally, a financial model applies factor prices and accounting principles to the set of resource requirements outputted from the operations model in order to determine the production cost.

A graphical representation of the entire cost modeling approach appears in Figure 3.



Process model
Incorporates engineering relationships between product description and processing requirements

Operations Model
Combines processing conditions and production scale to determine a set of resource requirements

Financial Model
Applies factor prices and accounting principles to assess costs over production life

Figure 3. Process-based technical cost modeling approach

The specific fender designs analyzed in this paper were developed as part of the Pilot Project for the Engineering Design and Advanced Engineering (EDAM) program within the MIT-Portugal alliance. The steel design is the current design of the Volkswagen Eos fender. The RTM fender was designed to fit the same package space of the steel fender and meet or exceed the structural performance of the steel design, although it is lighter. Note that all cost figures are given for producing a *pair* of fenders, because every car has a right and left one. A more complete description of the fender designs and cost models can be found in the EDAM Pilot Project Final Report.[1]

Fixed Approach: Steel Stamping Fender

Stamping Manufacturing Process and Process Model

Figure 4 illustrates the process steps included in the stamping cost model. Beginning from the left, steel sheet is fed through a blanking press which cuts trapezoidal blanks. After blanking, the blanks are rinsed and then the stamping line forms the fenders with six tandem press strokes, simultaneously stamping the left and right fenders from two blanks at a time. Each press has two tools (left and right), and the parts are transferred

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[1] To be released in early 2008.

from one press to the next by robotic manipulators. A fraction of the stamped fenders require rework to remove surface imperfections, and are then robotically stacked at the end of the line with the rest of the parts.

Process-level inputs and outputs appear above and below each process step, respectively, in the figure.

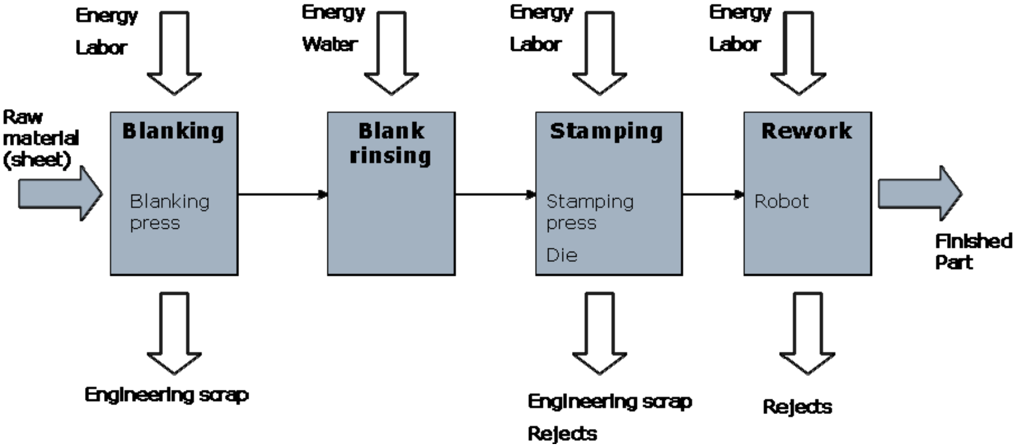

Figure 4. Stamping technical cost model.

Flexible Approach: RTM Fender

RTM Manufacturing Process and RTM Process Model

Figure 5 illustrates the steps involved in RTM manufacturing. The first steps involve two parallel paths: fiber preform making and foam core making. Fiber preform making consists of cutting layers of glass fiber fabric and placing them in the correct layup orientation, molding the layers together, and then trimming the preform. Foam core making consists of molding the foam core, curing the foam cure, and trimming excess material. After the fiber preform and foam core and made they are assembled. The resin and catalyst are then transferred to the assembly in the RTM step—which is where RTM presses and tools are utilized—and finally the part is inspected.

For the fender design considered here there is no foam core and so only the preform cutting, preform layup, preform molding, RTM, and final inspection steps were used.

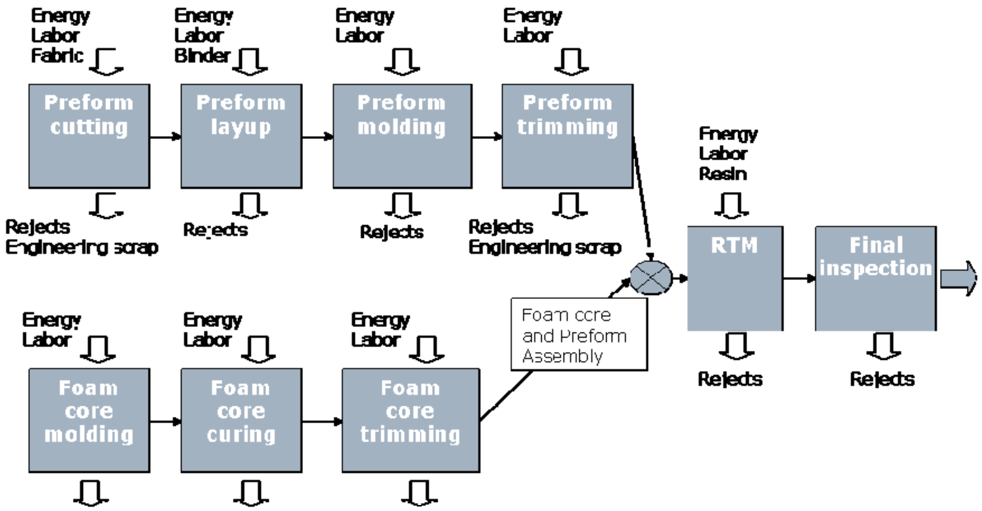

Figure 5. RTM technical cost model.

Fender Design Comparisons

As mentioned above, the RTM fender is designed as a substitute for the steel fender and it meets or exceeds several structural performance metrics as defined by the performance of the steel part. The primary design differences are material, thickness, and weight.

	Width x Length	Surface Area	Material System	Thickness	Weight
Steel	600 mm x 900 mm	0.34 m^2	220 MPa steel	0.65 mm	1.63 kg
RTM	600 mm x 900 mm	0.34 m^2	polyester resin glass fiber reinforcement	1.60 mm	1.04 kg

Characterization of Salient Uncertainties

Although many aspects of this analysis are uncertain, I have investigated just two important uncertainties—raw material prices and demand uncertainty—in some detail. Of these, I have explicitly modeled demand uncertainty and incorporated the demand uncertainty model in the latter sections of the paper.

Raw Material Price

While the analyses in this paper do not explicitly consider the uncertainty in future prices for raw materials, relevant raw material prices are certainly volatile and worth investigating as part of future work. To understand just how volatile raw materials can be, I plotted the price of steel sheet for the last decade in Figure 6.

Although I did not have direct access to historical steel sheet prices, the Department of Commerce publishes the producer price index (PPI) for steel mill products, which includes steel sheet. The price of steel sheet should scale with the steel mill products PPI, and so knowing the current value of steel sheet (about \$1.00/kg), I can relate the PPI to the actual cost of steel sheet. The resulting graph shows that after a period of relatively steady prices the price of steel sheet shot up in 2004 and has been very volatile since then. A robust comparison of steel stamping and RTM manufacturing should definitely consider the uncertainty in steel sheet prices, which could tip the balance one way or the other.

Figure 6. Historical steel prices

Market Demand

The primary uncertainty that this paper considers is uncertainty in the future demand for the fender, which is equivalent to uncertainty in future demand for the vehicle that the fender is a component of. As the project is analyzing a vehicle that hasn't been produced yet, there is no application-specific historical data available, though I do have access to historical sales data for comparable vehicles, which I will assume closely approximates vehicle demand.

The Normalized Annual Sales chart (Figure 7) presents normalized sales data for six vehicles over the first 6 full years of their production. Although each vehicle sold at very different volumes (some are low volume vehicles which sell about 15,000 per year, while others are high volume vehicles that sell more than 200,000 per year), all have been normalized so that the sales level in the first year of full production is set to 40,360. (This corresponds to the number of fenders that can be produced with four fully-utilized RTM presses, which is the initial capacity that later analyses in the paper assume.)

For example, according to the table, the Ford Focus hit the market during the middle of 1999 and the first full year of production began in 2000. So 2000 is year 0 and the 286,166 vehicles sold that year are reset to 40,360. Sales in all years after are recalculated by the same ratio.

Model	Year	Sales	Count	Normalized Sales
Ford Focus	1999	55,846		
	2000	286,166	0	40,360
	2001	264,414	1	37,292
	2002	243,199	2	34,300
	2003	229,353	3	32,347
	2004	208,339	4	29,384
	2005	184,825	5	26,067
	2006	177,006		

Table 1. Annual and normalized sales data for the Ford Focus. Source: Automotive News

Once this normalization has been done for all six vehicles the following graph can be obtained which shows the sales growth trend over five years and the sales volatility from year to year.

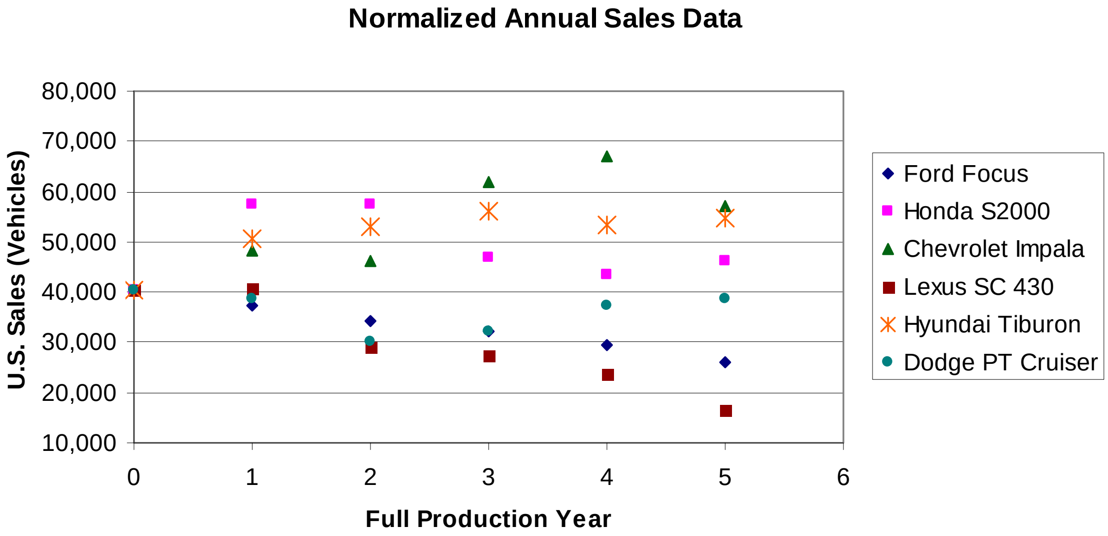

Figure 7. Normalized annual sales data. Source: Automotive News

On first inspection, there doesn't appear to be a consistent growth rate among the data. Some vehicles see their sales increase from year to year, some others do worse, and one or two oscillate around the initial 40,360 level. However, the data do suggest that if sales do very well in the first or second year, they are likely to follow that trend.

Furthermore, Figure 7 clearly shows that uncertainty increases over production life. For example, the sales volume range in year 1 is 37,292 – 57,491, a 20,199 vehicle range, and in year 5, the sales volume range is 16,472 - 57,055, a 40,583 vehicle range.

The following analyses make use of these characteristics regarding demand uncertainty in order to quantitatively model the uncertainty, first using a simple chance progression that demand will be high, medium or low (for the decision analysis), and then using a binomial lattice (for the options analysis).

Two-period Decision Analysis

Decision Analysis Scenario Description

The decision analysis scenario considers two types of decisions: 1) the initial decision to manufacture a pair of fenders from steel or RTM, and 2) if RTM is chosen, the decision regarding how many RTM tools to purchase for the upcoming year of production. The tool investment option is the key flexibility investigated in this work and as such RTM represents a flexible choice. Producing in steel is an inflexible choice because one tool must be purchased at the beginning at production and it will last for the entire production life.

For the RTM design, I have defined the system as being comprised of 4 RTM presses. The decisions in each year are to buy enough tools to utilize all 4 presses for the year (4 line-yrs of tools), or to buy only enough tools to utilize 3 presses for the year (3 line-yrs of tools). The chart below summarizes the options.

The chance events are the demand for the fender in each year. This can either be high, medium, or low. In the first year, the p(high) = 0.25, p(med) = 0.5, p(low) = 0.25. If the demand is medium in the first year the probabilities are the same for the second year. If the demand is high in the first year it is more likely to be high in the second year. The second year chances are then p(high) = 0.5, p(med) = 0.3, p(low) = 0.2. Similarly, if demand is low in the first year it is more likely to be low in the second year and correspondingly weighted probabilities hold.

These probabilities were chosen to roughly approximate two characteristics observed in the annual sales data: average annual growth of 0% (medium demand corresponds to no gowth), yet the tendency to stay high or low in successive periods if demand is observed to trend in those directions. The exact numbers chosen are only approximations to illustrate this behavior.

The medium demand corresponds to the capacity of the 4 line-yr RTM tool option; while the low demand corresponds to the capacity of the 3 line-yr RTM tool option. High demand will exceed the capacity of the RTM design, though the steel design will be able to capitalize on this event because its capacity is much higher.

Decisions in Year 1 and Year 2				
	Tool Decision Year 1	**Tool Decision Year 2**	**Capacity (parts/yr)**	**Tool Investment**
Steel	Steel tool	-	2,000,000	$2,112,248
RTM	3 line-yrs / 4 line-yrs	3 line-yrs / 4 line yrs	30,270 / 40,360	$312,500 / $414,500

Chance Events in Year 1 and Year 2					
Demand	**Parts/yr**	**Year 1 Probability**	**P(Y2 | Med Y1)**	**P(Y2 | High Y1)**	**P(Y2 | Low Y1)**
High	50,450	25%	25%	50%	20%
Medium	40,360	50%	50%	30%	30%
Low	30,270	25%	25%	20%	50%

Financial Model

I used a simple financial model to determine the net present value of each branch in the decision tree. The model assumes that a plant produces fenders to sell to an automaker, at a price of $45.00. The demand that the plant sees is the same as the demand for the vehicle that the automaker is producing. Each year, the plant will sell as many fenders as possible, which will either be limited by demand (if demand is lower than capacity), or capacity (if demand is greater than capacity).

Table 2 presents the variable costs for material, labor, and energy, the operating costs for the equipment (presses) and building, and the tool investments. Note that the steel tool investment is a one-time purchase, while the RTM tool investments are made every year, either for enough tools to utilize 4 presses or 3 presses for the year. Also, the number of tools that are purchased each year is the number that brings plant production *up to* 3 line-yrs of production capacity of 4 line-yrs of capacity. Depending on the previous year's capacity and demand, the plant may purchase 2, 3, or 4 line-years of tools to get up to the right level. The actual number of purchased tools appears in the decision tree at the decision nodes.

	Steel	**RTM**			
Material, Energy, Labor per part	$ 9.72	$ 27.90		Price	$ 45.00
				Discount Rate	10%
Plant Scale	N/A	40,360 parts/yr			
Annual Equipment Cost	$ 95,246	$ 53,726			
Annual Building Cost	$ 7,585	$ 4,249			
Tool Investment	$ 2,112,224	414,500	(4 line-years of tools)		
		312,500	(3 line years of tools)		
		216,500	(2 line years of tools)		

Table 2. Cost and price data for financial model

Table 3 presents an example of an NPV calculation for the highest decision tree branch, corresponding to RTM production with high demand in year 1 and year 2 and three line-years tool purchases in both years. Cost and revenue in each period are given by

Total Cost = Tool Cost + Equipment Cost + Building Cost +
*Variable Cost*Production Volume*

*Revenue = Price*Production Volume*

Year	0	1	2	
RTM Tool Decision		Buy 3LY	Buy 3LY	
Capacity (parts)	-	30,270	30,270	*NPV calculation for*
Demand (parts)	40,360	50,450	50,450	*highest branch in decision tree*
Production Volume (parts)	-	30,270	30,270	
Total Cost	$ -	$ 1,215,008	$ 1,215,008	
Revenue	$ -	$ 1,362,150	$ 1,362,150	
Net Revenue	$ -	$ 147,142	$ 147,142	
PV(Net Revenue)	$ -	$ 133,765	$ 121,605	
NPV	**$ 255,370**			

Table 3. Sample NPV calculation in decision tree

Decision Analysis Results

The decision tree is split into two parts, the flexible branches (RTM, Figure 8), and the fixed branches (steel stamping, Figure 9). The expected value of the steel approach is $348,293, slightly greater than the expected value of the RTM approach, $328,442. The steel has a higher expected NPV because the expected total production volume is 80,720 parts, which is high enough to allow steel to benefit from the economies of scale noted earlier in Figure 2.

The optimal strategy, on the basis of expected NPV, is thus to go with steel, the fixed approach. However, as the Value at Risk and Gain graph shows (Figure 10), the steel is much riskier than the RTM, having about a 15% chance of losing money. By contrast, the RTM is always profitable although it has a reduced upside potential. This reveals the benefit of the flexible RTM approach. While the RTM can never be as profitable as the steel because its costs can never get as low at high volumes (steel enjoys economies of scale), the RTM solution allows plant operators to adapt in cases of low demand and purchase less tools—thus reducing capital costs and improving downside conditions.

If you were to go with RTM—the flexible and less risky technology—the optimal strategy is to buy 4 line-years of tools before the first year and then buy enough tools to utilize 4 lines again if you observe that demand is high or medium in the first year, but buy only enough tools to utilize 3 presses if demand is low. The flexibility to purchase less tools because demand has been observed to be low improves the NPV of this scenario. These choices are highlighted in yellow in Figure 8.

Table 4 summarizes these results. Steel looks better on the basis of expected NPV and maximum NPV, but RTM is better on the downside. Because fewer RTM tools can be purchased if demand is low, potential losses can be attenuated and the minimum possible NPV will still be greater than steel. Moreover, the size of the total tool investment is smaller with the RTM solution even across the entire range of staged investments analyzed in the decision tree. This further reflects the less risky nature of the flexible RTM approach.

	ENPV	**max NPV**	**min NPV**	**Total Tool Investment**
Steel (fixed)	$348,293	$990,372	($245,244)	$2,112,224
RTM (flexible)	$328,442	$454,239	$235,199	$727,000 - $829,00

Table 4. Decision analysis summary results

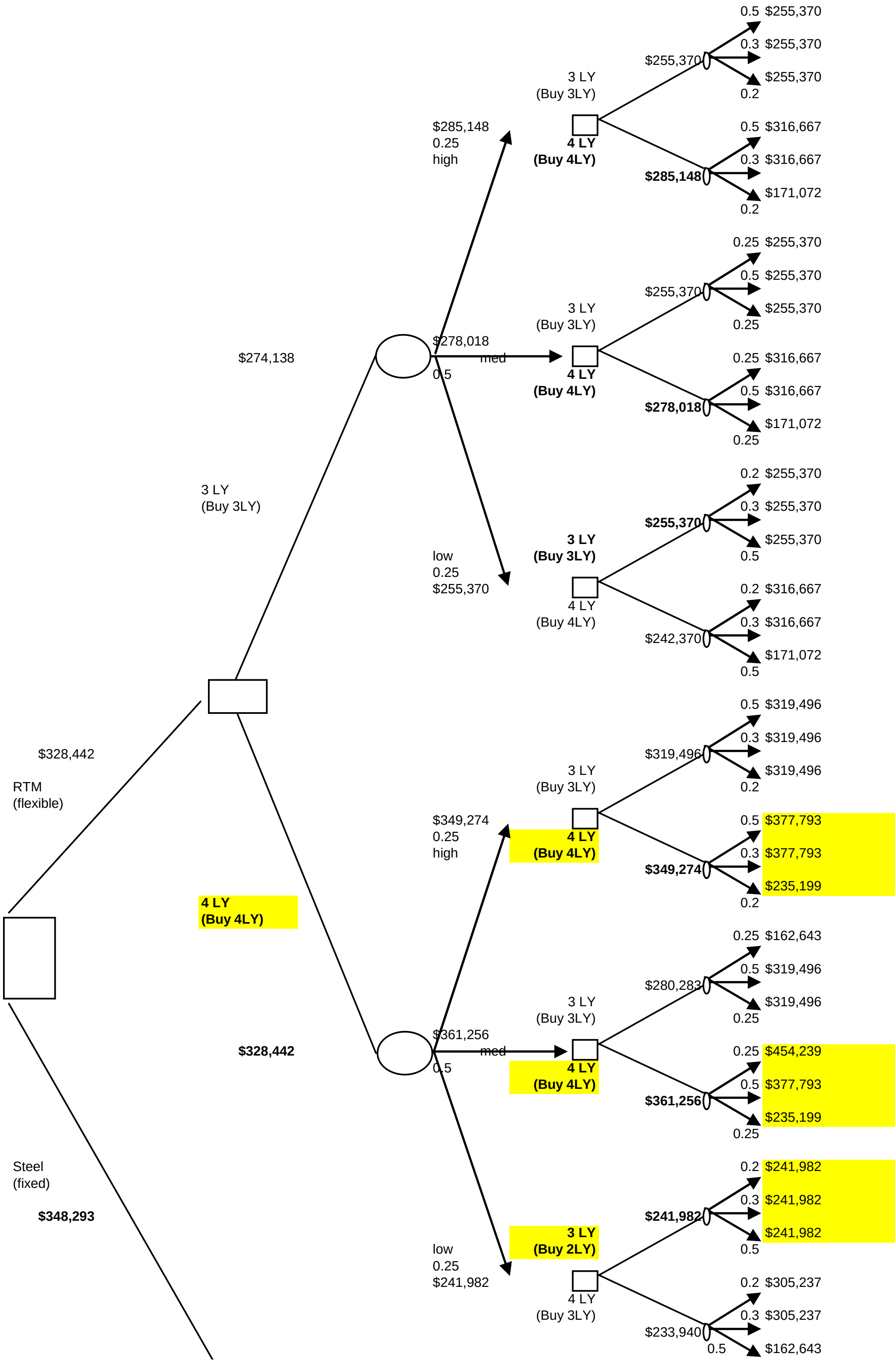

Figure 8. Flexible half of DA tree

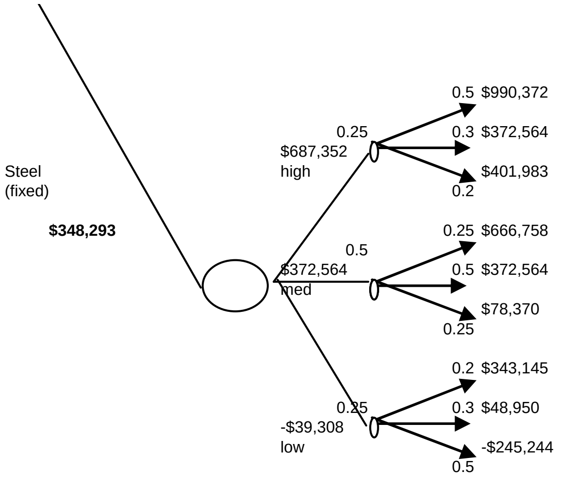

Figure 9. Fixed half of DA tree

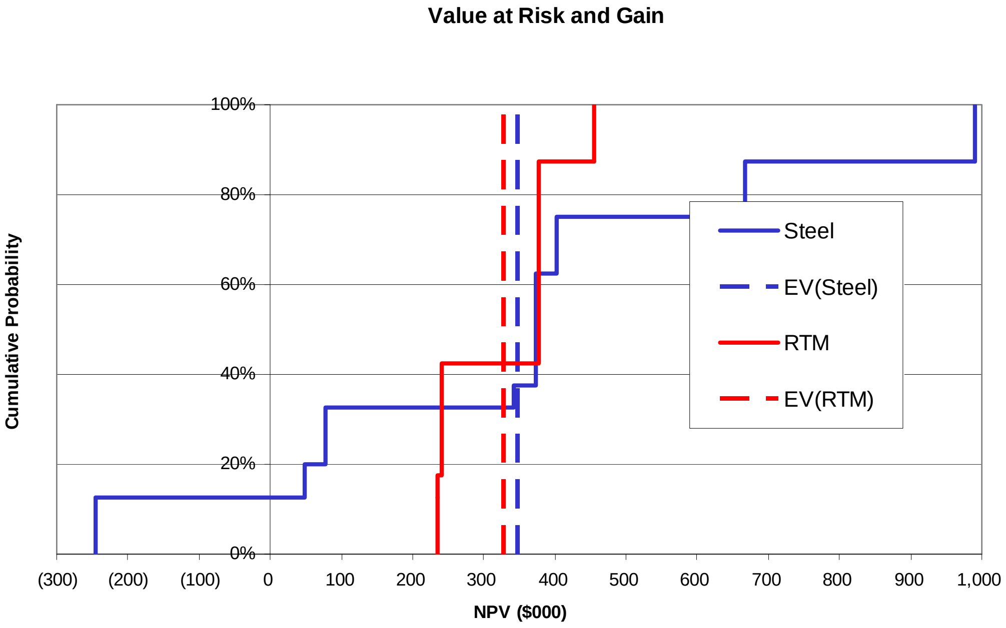

Figure 10. Value at Risk and Gain for decision analysis

Five-period Options Analysis by Lattice

Options Analysis Scenario Description

The options analysis scenario is different than the scenario previously investigated in the two-period decision analysis. For the options analysis, only RTM production is considered. The baseline, or fixed case in this analysis is a plant that has chosen to manufacture an RTM fender for 5 years, purchasing 4 line-years worth of tools just before the beginning of each year. This scenario could describe a plant that has engaged in a contract with a tool supplier to consistently deliver that many tools over production life.

The plant has the option to alter the contract and purchase only 3 line-years of tools. This option will be exercised if demand is significantly lower than expected, allowing the plant to contract capacity and reduce capital costs. In a sense, this is a “put” version of a real option.

Baseline Analysis: No Uncertainty

The baseline analysis considers the five-year production of the RTM fender as described above. In year 0 there is no production but demand for the car fender is 40,360 and this level is forecast to remain constant for the duration of the project. The fender will be sold for $45.00, and the project will be evaluated using a discount rate of 10%.

As before, the initial capacity of the plant is scaled to exactly meet the demand in year 0 (40,360 parts per year). The variable part costs and plant operating costs for the equipment and building are the same as in the decision analysis. Because the baseline analysis assumes steady demand and an unvarying production scale in years 1 to 5, plant capacity = market demand = 40,360 parts for each year of production.

The NPV of the baseline analysis is $825,182, shown in Table 5.

Material, Energy, Labor per part	$ 27.90	Price	$ 45.00
Plant Scale: 40,360 parts/year ==> 4 presses at 100% utilization needed			
Annual Equipment Cost (4 presses)	$ 53,726		
Annual Building Cost (4 presses)	$ 4,249		
Annual Tool Cost (40,360 parts)	$ 414,500	Discount Rate	10%

Year	0	1	2	3	4	5
Demand (parts)	40,360	40,360	40,360	40,360	40,360	40,360
Capacity (parts)	-	40,360	40,360	40,360	40,360	40,360
Production Volume (parts)	-	40,360	40,360	40,360	40,360	40,360
Total Cost	$ -	$ 1,598,519	$ 1,598,519	$ 1,598,519	$ 1,598,519	$ 1,598,519
Revenue	$ -	$ 1,816,200	$ 1,816,200	$ 1,816,200	$ 1,816,200	$ 1,816,200
Net Revenue	$ -	$ 217,681	$ 217,681	$ 217,681	$ 217,681	$ 217,681
PV(Net Revenue)	$ -	$ 197,892	$ 179,902	$ 163,547	$ 148,679	$ 135,163
NPV	$ 825,182					

Table 5. Baseline NPV for options analysis

Demand Uncertainty Model

I used a trial and error method to determine the appropriate binomial lattice parameters by experimenting with the lattice outcome of several different growth rates and standard deviations. I achieved the best result by fitting the sales data to an exponential growth curve using a starting value of 40,360, an annual growth rate of -0.3% and a standard deviation of 15%. This leads to binomial lattice parameters u = 1.162, d = 0.86, p = 0.49. Comparing the graph of the binomial model outcomes in Figure 11 to the graph of the normalized annual sales data in Figure 7 shows good correlation between the lattice prediction of demand uncertainty for 5 periods and the range of actual vehicle sales over 5 years of full production.

Yet although the outcomes and overall trend of the binomial model closely match the observed sales data, the individual probabilities for each observation are not necessary aligned. For example, the binomial model predicts that the highest and lowest outcomes in year 5 have only a 3% chance of occurring, yet the actual sales data shows that they are as likely to occur as the middle set of observations. (There are six sales data sets evenly distributed across the range of observations.) This shortcoming is one area for future work.

Exponential Growth Function

$\text{Sales}(t) = 40{,}360 * e^{-0.003t}$

Sales in Year 0 = 40,360

Standard deviation = 15%

v = -0.3% per year

Binomial Lattice Parameters

$u = e^{(\sigma\sqrt{t})} = e^{(0.15\sqrt{1})} = 1.162$

$d = e^{(-\sigma\sqrt{t})} = e^{(-0.15\sqrt{1})} = 0.861$

$p = 0.5 + 0.5(v/\sigma)\sqrt{\Delta t} = 0.5 + 0.5(-0.003/0.15)\sqrt{1} = 0.49$

Outcome and Probability Lattice

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Demand	40,360	46,898	54,496	63,324	73,583	85,503
		34,733	40,360	46,898	54,496	63,324
			29,891	34,733	40,360	46,898
				25,724	29,891	34,733
					22,137	25,724
						19,051

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Probabilities:	1.00	0.49	0.24	0.118	0.058	0.028
		0.51	0.50	0.367	0.240	0.147
			0.26	0.382	0.375	0.306
				0.133	0.260	0.318
					0.068	0.166
						0.035

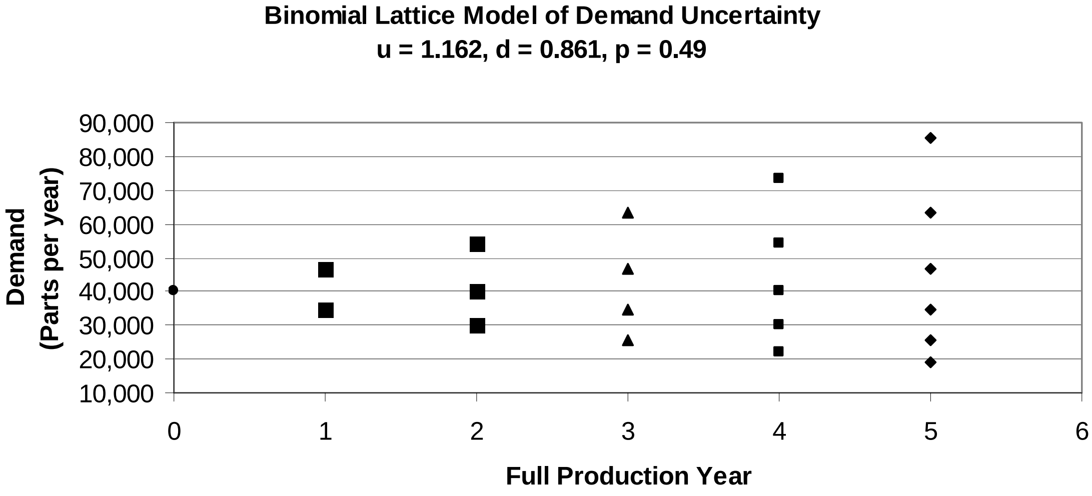

Figure 11. Binomial lattice model

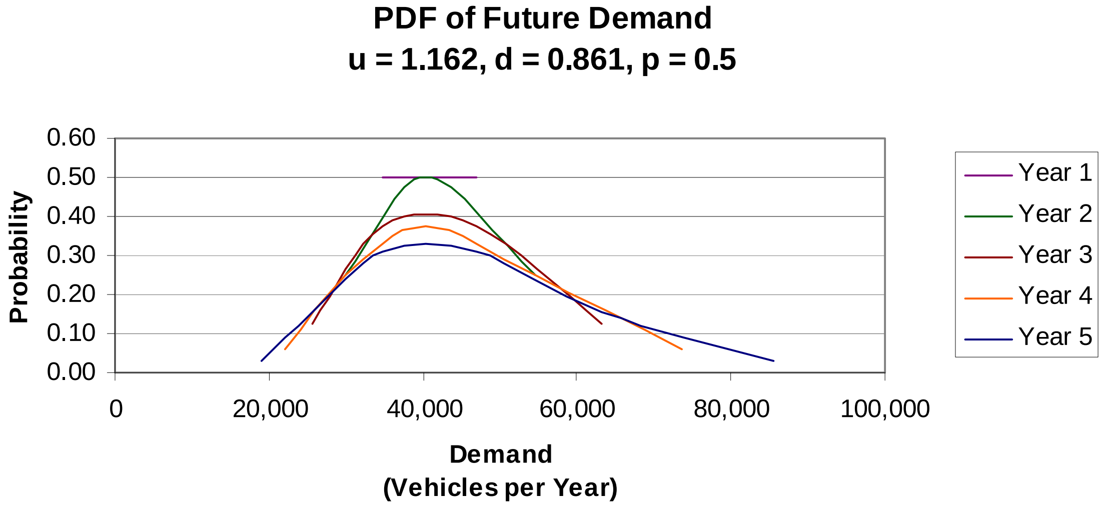

Figure 12. Binomial lattice model PDF

Analysis Recognizing Uncertainty

Assuming that the plant produces only as many fenders as it knows it will sell in a given year, actual annual production volume will be limited by the capacity of the plant (if demand is greater than capacity), or demand (if demand is lower than capacity). Formally,

Production Volume(t) = min(capacity(t), demand(t))

If the capacity of the plant is kept constant over the life of the project then this becomes

Production Volume(t) = min(40,360, demand(t))

The resulting production volume lattice is below.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Production Volume - 4LY	-	40,360	40,360	40,360	40,360	40,360
		34,733	40,360	40,360	40,360	40,360
			29,891	34,733	40,360	40,360
				25,724	29,891	34,733
					22,137	25,724
						19,051

Costs in each period are given by

Total Cost = Tool Cost + Equipment Cost + Building Cost +
*Variable Cost*Production Volume*

If the cost of four fully utilized presses and enough tools to produce 40,360 parts/yr are purchased every period, this becomes

Total Cost = $414,500 + $53,726 +$4,249 + $27.90 Production Volume*

The resulting cost lattice is below.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Costs - 4LY	-	(1,598,519)	(1,598,519)	(1,598,519)	(1,598,519)	(1,598,519)
		(1,441,532)	(1,598,519)	(1,598,519)	(1,598,519)	(1,598,519)
			(1,306,431)	(1,441,532)	(1,598,519)	(1,598,519)
				(1,190,165)	(1,306,431)	(1,441,532)
					(1,090,109)	(1,190,165)
						(1,004,002)

Revenue is given by

*Revenue = Price*Production Volume*

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Revenue - 4LY	-	1,816,200	1,816,200	1,816,200	1,816,200	1,816,200
		1,562,995	1,816,200	1,816,200	1,816,200	1,816,200
			1,345,090	1,562,995	1,816,200	1,816,200
				1,157,565	1,345,090	1,562,995
					996,183	1,157,565
						857,300

Net revenue is the sum of costs and revenue.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Net Revenue - 4LY	-	217,681	217,681	217,681	217,681	217,681
		121,463	217,681	217,681	217,681	217,681
			38,659	121,463	217,681	217,681
				(32,601)	38,659	121,463
					(93,926)	(32,601)
						(146,701)

To determine the relevant likelihood of each net revenue observation, the net revenue lattice is multiplied by the probability lattice.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
Probability Weighted Net Revenue - 4LY	-	106,664	52,265	25,610	12,549	6,149
		61,946	108,797	79,966	52,244	32,000
			10,055	46,441	81,565	66,611
				(4,325)	10,051	38,685
					(6,354)	(5,403)
						(5,062)

Summing the probability weighted net revenue lattice in each period gives the expected net revenue for each year. Taking the present value of expected net revenue for each year and summing over the life of the project gives an expected net present value of the project, $590,724.

4LY	**0**	**1**	**2**	**3**	**4**	**5**
E [Net Revenue]	0	168,610	171,117	147,692	150,055	132,980
PV(E[Net Revenue])	0	153,281	141,419	110,963	102,490	82,570
ENPV over 5 years	**590,724**					

The ENPV of the project considering demand uncertainty is smaller than the NPV of the baseline case because the plant is sized to perfectly meet expected demand in year 0, meaning than the value of any increases in future demand cannot be captured because the capacity of the plant is capped at 40,360—no more fenders can be produced and sold, even if the market grows. On the flipside however, if demand falls below 40,360 the project is worth less because the costs of the building, equipment, and tools are always set at the level needed to produce 40,360 parts/yr.

Valuation of Option to Purchase Fewer Tools

An option to purchase only 3 line-years of tools each year instead of 4 line-years of tools should improve the value of the project because this option acts like a shutdown or put option if demand falls in future periods.

Three line-years of tools represents the number of tools needed to operate three of the four RTM presses for the entire year. If this option is exercised, the capacity of the plant is 30,270 parts/yr, down from 40,360 parts/yr if 4 line-years of tools are purchased.

To determine when this option should be exercised, the production volume, cost, revenue, and net revenue lattices are developed for the 3 line-year case, using 30,270 parts/yr as the maximum plant capacity instead of 40,360 parts/yr. The net revenue lattice for the 3 line-year case appears below, along with the net revenue lattice from the previous 4 line-year case. Note that net revenue never gets as high as the 4 line-year case, but also never falls as low.

	t = 0	**t = 1**	**t = 2**	**t = 3**	**t = 4**	**t = 5**
Net Revenue - 3LY	-	147,142	147,142	147,142	147,142	147,142
		147,142	147,142	147,142	147,142	147,142
			140,659	147,142	147,142	147,142
				69,399	140,659	147,142
					8,074	69,399
						(44,701)

	t = 0	**t = 1**	**t = 2**	**t = 3**	**t = 4**	**t = 5**
Net Revenue - 4LY	-	217,681	217,681	217,681	217,681	217,681
		121,463	217,681	217,681	217,681	217,681
			38,659	121,463	217,681	217,681
				(32,601)	38,659	121,463
					(93,926)	(32,601)
						(146,701)

The decision controlling whether or not to switch from purchasing 4 line-years of tools to 3 line-years of tools can be solved by a dynamic programming approach. Before applying this approach to the option, though, we can use it to calculate the ENPV of the 4 line-year case without flexibility.

The dynamic programming approach to ENPV solves the net revenue tree from right to left, starting by sitting in year 4 and looking at year 5. If we are in the cell corresponding to the highest observation in the net revenue lattice in year 4 (217,681), the expected net present value at this point is the expected net revenue from year 5 discounted one year plus the net revenue in that cell.

$$ENPV_{(observation)} = [p*(Net\ Revenue_{up}) + (1-p)*(Net\ Revenue_{down})]/(1+0.1) + Net\ Revenue_{observation}$$

$$ENPV_{(highest\ Y4)} = [0.49*217{,}681 + 0.51*217{,}681]/1.1 + 217{,}681$$

$$ENPV_{(highest\ Y4)} = 415{,}572$$

This process is repeated for every other observation in year 0-4, and results in the lattice below. The ENPV of the entire project is the value in the t=0 cell, $590,724. This is equal to the ENPV from before, which was calculated by summing expected net revenues for each year, discounting them, and then adding up those discounted present values.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
ENPV(Net Revenue)	590,724	840,523	749,431	595,474	415,572	217,681
NO FLEXIBILITY		466,548	623,344	574,791	415,572	217,681
Dynamic programming			145,402	322,711	370,962	217,681
approach				(79,826)	77,650	121,463
(check next year)					(176,464)	(32,601)
						(146,701)

With Flexibility

To evaluate the ENPV of the project with the flexible option, I use the same general approach but include a check to see whether or not it makes sense to switch to a smaller tool purchase. Starting with the next to last year again and working backwards, the option to switch from 4 line-yrs of tools to 3 line-yrs of tools will be exercised at any observation (lattice cell) when the expected net present value of the 4 line-year case in following year is less than the expected net present value of the 3 line-year case in the following year. The decision rule is:

$$If([p*(\text{Net Revenue}_{up\ 4LY}) + (1-p)*(\text{Net Revenue}_{down\ 4LY}) <$$
$$[p*(\text{Net Revenue}_{up\ 3LY}) + (1- p)*(\text{Net Revenue}_{down\ 3LY})\ \text{, switch, otherwise stay)}$$

At the highest observation in year 4, this becomes

$$If(p*217{,}681 + (1-p)*217{,}681) < p*147{,}142 + (1-p)*147{,}142)\text{, switch, otherwise stay)}$$

217,681 < 147,141, false, ***stay***

The ENPV of the observation cell in a situation like this where the option to switch to 3 line-years of tools is not exercised is equal to the expected net revenue of the 4 line-year case in the next year (because we did not switch) discounted one year, plus the net revenue of the 4 line-year case at that point in the lattice. So,

$$ENPV_{stay} = [p*(\text{Net Revenue}_{up\ 4LY}) + (1- p)*(\text{Net Revenue}_{down\ 4LY}]/(1.1)$$
$$+ \text{Net Revenue}_{observation}$$

At this point in the lattice,

$$ENPV_{stay} = [217{,}681]/(1.1) + 217{,}681 = 415{,}572$$

If the option is exercised then the ENPV for the cell is given by

$$\text{ENPV}_{\text{switch}} = [p*(\textit{Net Revenue}_{up\ 3LY}) + (1- p)*(\textit{Net Revenue}_{down\ 3LY}]/(1.1) + \textit{Net Revenue}_{observation}$$

Starting in year 4 and working backwards to calculate the ENPV with flexibility results in the following lattice and shows that the ENPV of the project is $609,870. The option is exercised in the lowest observation in year 4 and in the two lowest observations in year 5.

	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5
ENPV(Net Revenue)	609,870	846,377	749,431	595,474	415,572	217,681
WITH OPTION TO SWITCH		502,220	635,969	574,791	415,572	217,681
Dynamic programming			210,212	349,940	370,962	217,681
approach				33,800	136,380	121,463
(check next year)					(83,737)	(32,601)
						(146,701)

	t = 0	t = 1	t = 2	t = 3	t = 4
Switch to 3LY Purchase?	4LY	4LY	4LY	4LY	4LY
WITH OPTION		4LY	4LY	4LY	4LY
Dynamic programming			4LY	4LY	4LY
approach				3LY	3LY
(check next year)					3LY

The difference between the ENPV of the inflexible case (always buy 4 line-years of tools) and the ENPV of the flexible case (able to switch to purchase only 3 line-years of tools) is the value of the option, $19,146 in this case. This represents the maximum price that the plant would be willing to pay to alter the contract and buy only 3 line-years of tools.

ENPV (flexible)	609,870
ENPV (inflexible) -	590,724
Value of option to purchase only 3 line-yrs of tools	**19,146**

An important caveat is needed to interpret these results. Binomial lattice models assume path independence, which means that it shouldn't matter if you travel up, then down—or down, then up—through the tree. Yet RTM tool investments are necessarily path dependent because the number of tools that a plant will purchase in a given period depends on how many tools the plant purchased last period and how many tools it used.

Conclusions

Composite materials are usually valued in design applications because they offer weight saving advantages. However, the tool investment flexibility inherent in certain composite manufacturing techniques like RTM presents a viable real option that can add value and reduce the risk of projects. As shown in this paper, this flexibility can significantly limit downside risks by facilitating smaller-stage tool investments in future years given low observed market demand for a product. Binomial lattice models are a promising way of analyzing this flexibility, though they are probably not fully appropriate due to path-dependence limitations.

As a learning exercise, this project succeeded in applying real options valuation methods to a simple composite manufacturing case. Moreover, it helped me think about the relative competitiveness of modern composite manufacturing techniques in comparison to incumbent technologies like steel stamping. If alternative materials technologies like RTM are ever to overtake traditional metal solutions as the preferred design for mass-produced products like car body panels, more work will surely need to be done along the lines of this paper, investigating the value inherent in the system's flexibility.