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AIMING AND MISSING IN MULTIPLE DIMENSIONS

Douglas K. Howarth
MEE LLC
dhowarth@meevaluators.com

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Abstract

Aircraft manufacturers choose a variety of vehicle features in their new designs. Markets value these features in predictable ways, and adjust expenditures according to their demand curves. New methods described in this paper demonstrate how to aim for the desired attributes and how to plan for missed targets.

1 Feature Choice as Cost and Price Aiming

Designers select aircraft characteristics that buyers reward in predictable ways [1]. Failure to allow for missing targeted features through vehicle empty weight growth leads to overstated revenues projections. If designers know both how their products will tend to grow and how the market will reward their completed vehicles, they can take steps to maximize profits on aircraft sales during their design phases through optimized feature selection.

1.1 Consistently Unrealistic Expectations

Unwarranted optimism is the foe of optimization. All too often, under the guise of viewing previously missed cost goals as uncharacteristic anomalies, program managers attempt to force unattainable expenditure targets upon their teams. Overruns occur, and the programs suffers not only more expenses, but also possible losses in their vehicles' features. Since vehicle features support their sustainable prices, these programs may suffer lost profits.

Predicting and correcting for the outcomes of unjustified optimism alleviates these issues. In order to do this, we must understand how programs grow so that we can plan for that.

Consider Figure 1, in which we have initial, program launch, and final Manufacturing Empty Weights (MEWs) for 17 unnamed civil and military aircraft programs [2].

Pro-gram	Initial MEW	Launch MEW	Final MEW
1	70,310	69,000	81,390
2	55,846	54,733	61,842
3	10,981	10,875	13,384
4		10,524	11,500
5		85,250	91,400
6		54,000	59,338
7	18,412	18,343	21,455
8		118,350	130,971
9	65,875	65,875	67,486
10	341,579	313,500	342,158
11	26,271	26,344	26,864
12	47,210	38,783	41,437
13	823	783	998
14	24,800	23,200	24,765
15	27,600	25,500	29,444
16	26,950	24,600	27,123
17		597,447	610,240

Fig. 1. Initial, Launch and Final Empty Weights for 17 Aircraft Programs

Regression analysis on the changes from initial empty weights to those at program launch reveals that:

$$\textit{Launch MEW} = 1.01 * \textit{Initial MEW}^{0.994} \quad (1)$$

Where:

Launch MEW = MEW at program start
Initial MEW = First posted MEW

Equation 1 has a Pearson's^2 value of 99.9% and a P-value of 2.87E-15, adjusted by the Ping Factor [3], and is therefore highly significant.

When we take the same dataset and go from launch to final MEWs, we discover that:

$$Final\ MEW = 1.49 * Launch\ MEW^{0.973} \quad (2)$$

Where:

Final MEW = MEW at 1st production flight

Just as with Equation 1, Equation 2 (also adjusted by the Ping Factor) is highly significant. It has a Pearson's^2 value of 99.9% and a P-Value of 1.79E-23.

If we combine the effects of Equations 1 and 2 over time, we observe Figure 2.

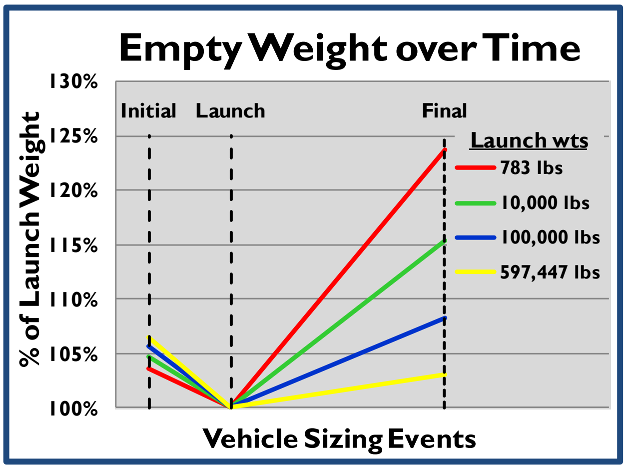

Fig. 2. Vehicle MEWs Change over Time

Since vehicle empty weight correlates well with cost, program leaders rightfully understand that lower mass means lower cost. Management may therefore push for impractical goals with respect to vehicle empty weights. Figure 2 reveals the impact of unrealistic targets. Mass property engineers assign initial weight estimates prior to program launch. In all weight ranges, these estimates fall at program launch, revealing more optimistic views of these programs. When vehicles attain their ultimate configurations (by this study's convention, at first production flight), however, their empty weights rise across the board, with smaller craft experiencing far greater weight changes, on a percentage basis, than larger ones. We call this change in forecasted versus actual size the Checkmark Function (as epitomized by the two red lines in Figure 2, which represent a vehicle targeted to have an empty weight of 783 pounds at program launch).

2 Value and Demand

2.1 Determining Value and Demand

Demand in any market is the relationship between quantities sold and price. In the case at hand, we will consider aggregate demand (total quantities purchased for models current in 2009 from their inception through 2015) for 144 fixed-wing civil aircraft models. This mix includes airliners, regional aircraft, business and general aviation aircraft, as shown in Figure 3.

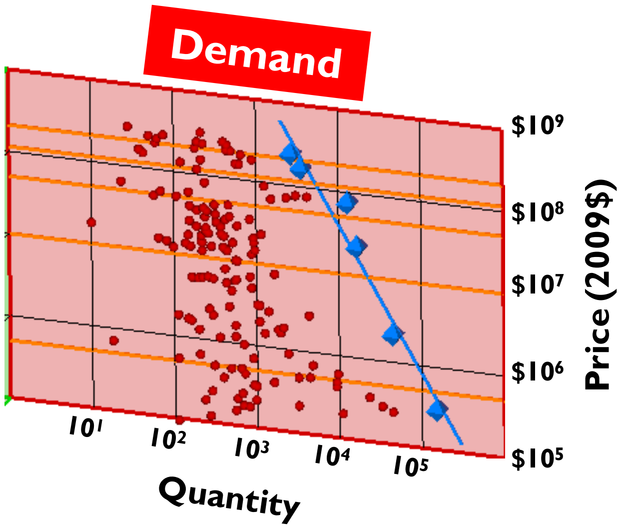

Fig. 3. Civil fixed wing aircraft Aggregate Demand for 2009 models through 2015

In Figure 3, we added up the total quantities and calculated the average price in each of six bins. In the lowest bin, for all aircraft priced less than or equal to \$500,000, we discovered that we had 151,386 vehicles at an average price of \$304,450. This ordered pair (151,386, \$304,450) forms the lowest blue octahedron in Figure 3. The next five bins, in order from low to high, consist of the following ordered pairs of total quantities and average prices: (41,968, \$2,213,000), (15,430, \$22,966,000), (12,883, \$74,973,000), (3,531, \$169,218,000) and (2,675, \$247,043,000), all represented by blue octahedrons. When we perform regression on these aggregated points, we obtain Equation 3.

$$Ave\ \$ = 2.86e{+}14 * Qty\ to\ 2015^{-1.72} \quad (3)$$

Where:

Ave \$ = Estimate Average 2009\$
Qty to 2015 = Projected vehicle quantities for then-current models from inception to 2015

Equation 3, which includes the Ping Factor, has a Pearson's^2 of 95.3% and a P-Value of 0.09%; thus it is statistically significant.

Previous work done by the author indicates that vehicle features support prices [4] [5] [6]. If we use regression analysis on the characteristics of these same 144 vehicles, we get Equation 4.

$$Ave\ \$ = 0.182 * 2ClsPass^{0.683} * Max\ Crs\ MPH^{2.66} \quad (4)$$

Where:

2ClsPass = Typical passenger capacity in two class arrangement (for airliners) or usual capacity in non-airliners
Max Crs MPH = Maximum cruise speed in miles per hour

Equation 4, adjusted by the Ping Factor, has a Pearson's^2 of 95.5%, with P-values for 2ClsPass and Max Crs MPH of 5.15e-48 and 5.03e-57, respectively, shown as the plane in Figure 4 (it should be cautioned, however, that there are more variables determining price than just the two shown above, the others removed for ease of analysis. Adding other variables will change the impact of those shown above, most notably that for cruise speed [7]).

Since Equation 4 has two independent variables and one dependent variable, in order to plot the results from it, we must use a three dimensional Value Space, as we do in Figure 4.

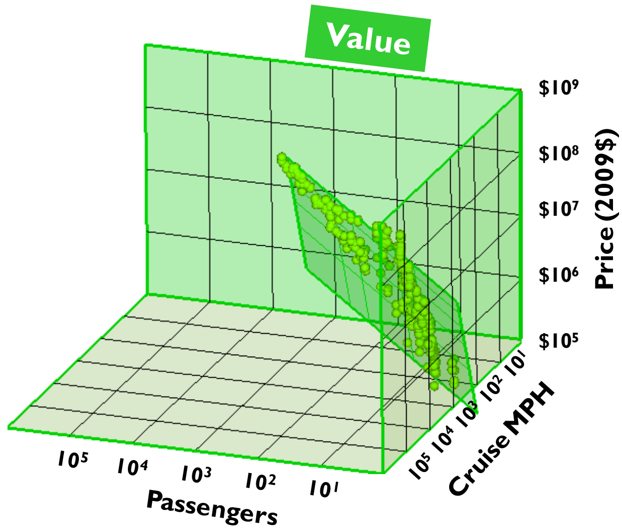

Fig. 4. Civil fixed wing aircraft Value for 2009 models projected through 2015

Figure 3 contains the quantity and price for the Boeing 747-8 [8] and the Cessna 172 [9], among 144 models it represents. With Figure 4, we have the passenger capacity, cruise miles per hour and price for those same two models. Jointly they form the dataset found in Figure 5.

Model	Pass-engers	Cruise MPH	Price (2009\$M)	Qty to 2015
172	4	145	\$0.246	44,241
747-8	588	562	\$303.0	28

Fig. 5. Specifications and prices for Boeing 747-8 and Cessna 172

Note that the Figure 4 Value Space shares the same vertical axis, Price (2009\$) as its companion Demand Plane, which we observed in Figure 3. This is a very useful observation, because with it, we have more options for data display. Since Figures 3 and 4 share the currency axis, this means that they abut one another, as shown in Figure 6, which is a four dimensional nonnegative coordinate system. Such coordinate systems have four color-coded axes, Valued Feature 1, Valued Feature 2, **Price,** and Quantity. Ordered quads populate these systems. The ordered quads that come from Figure 5 are (4, 145, **\$.0246M,** 44,241) for the Cessna 172 and (588, 562, **\$303.0M,** 28) for the Boeing 747-8.

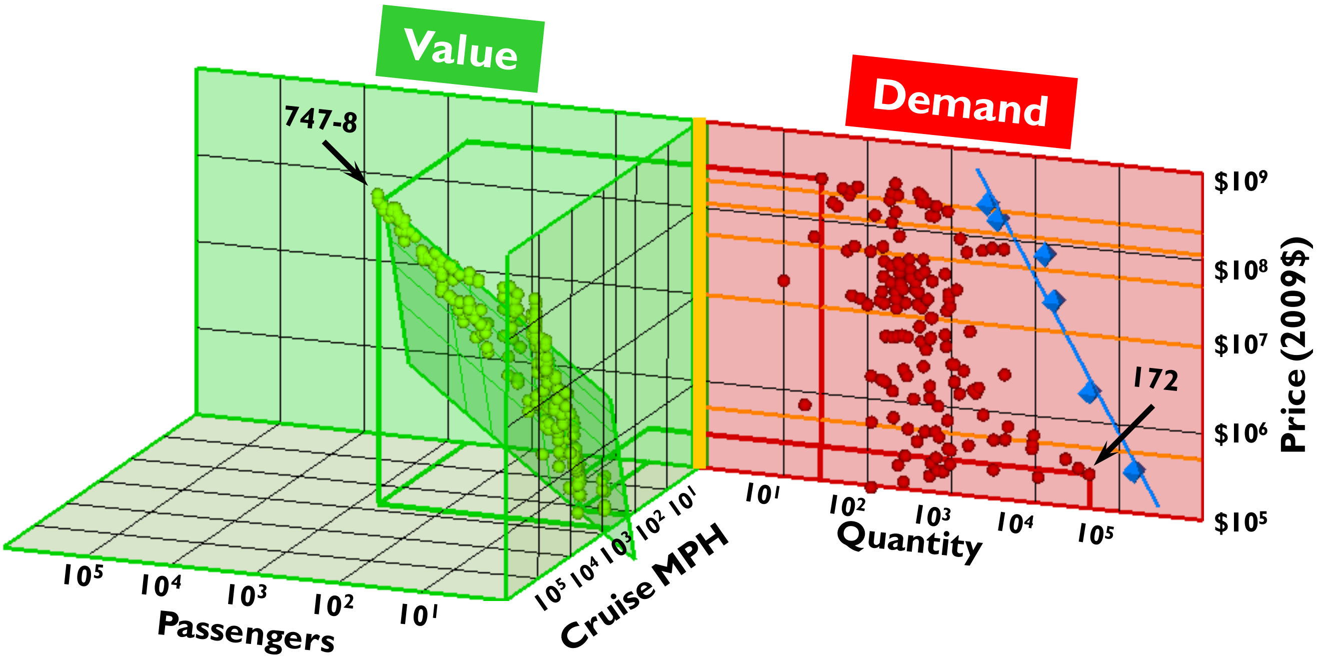

Fig. 6. A 4D model of the Civil Aircraft Market, highlighting the Boeing 747-8 and Cessna 172

3 Using Market Information to Aim

3.1 Business Aircraft Case Study

Given that markets provide information about what they like, it makes sense that we should study them before building new products.

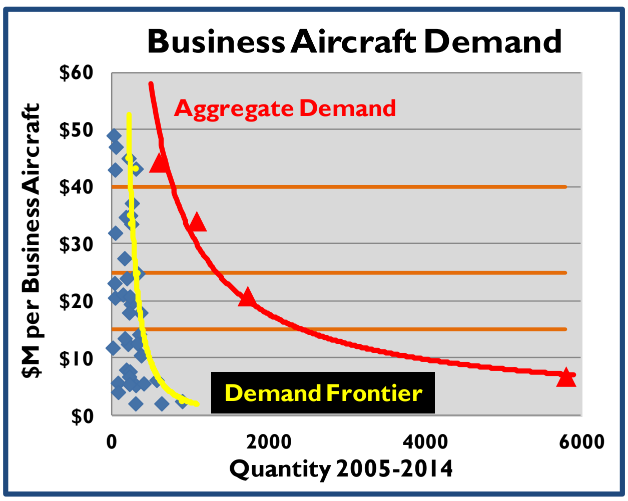

Fig. 7. Projected Business Aircraft Demand from the beginning of 2005 to the end of 2014

Suppose that a few years ago, we considered building a new business aircraft. If we had already derived the demand curve for the entire market, as we did in Figure 3, we might be convinced that we know how the market will respond to changes in price. However, if we decide to derive aggregate demand for the subset of 46 business aircraft instead, we would plot the data as Figure 7 (in the manner described for Figure 3, this time with bin lines drawn at \$15 million, \$25 million and \$40 million), and then we get Equation 5.

$$\textit{Aggregate Demand }\$ = 11870 \ {}^{*}Qty^{-0.856} \tag{5}$$

Where:

Aggregate Demand \$ = Estimated 2005\$
Qty = Estimated Quantity 2005-2014

Its leading term adjusted by the Ping Factor, Equation 5 has a Pearson's^2 of 95.8% and a P-value of 0.81%, indicating that it is statistically significant. Note the exponent for Quantity. At -0.856, the business aircraft demand slope is significantly different from the slope of -1.72 that we discovered for all aircraft as Equation 3. The highly negative slope from Equation 3 means that there is more money at the top of the market (as for airliners) than there is at the bottom (as for general aviation aircraft). By contrast, Equation 5's relatively flat slope means that for the business aircraft submarket, there are more dollars in the lower priced bins than there are at in the more expensive categories.

Additionally in Figure 7 we have a Demand Frontier curve, which we calculate by taking, in this case, the six outermost points with respect to the vertical axis (marked as yellow circles), run regression analysis upon them to find Equation 6.

$$\textit{Frontier \$} = 2.28e{+}06 \cdot \textit{Qty}^{-1.99} \qquad (6)$$

Where:

Frontier $ = Estimated Frontier 2005$
Qty = Estimated Quantity 2005-2014

This equation (like all other power form equations, adjusted by the Ping Factor) has a Pearson's^2 of just 69.8%, but works out to be statistically significant with a P-value of 0.17%. The very steep exponent means that the limiting quantities sold up and down the price line are very inelastic, and not as responsive as are revenues.

If we do some work to figure out business aircraft value, we derive Equation 7.

$$\textit{Ave \$} = 5.79e{-}07 \cdot \textit{Pass}^{0.621} \cdot \textit{Max MPH}^{1.17} \cdot \textit{Range}^{1.04} \qquad (7)$$

Where:

Ave $ = Estimated Average 2005$
Pass = Typical passenger capacity
Max MPH = Maximum cruise speed, in miles per hour
Range = Range in statute miles

Equation 7 (adjusted by the Ping Factor) has a Pearson's^2 of 91.4%, and P-values for passenger capacity, maximum cruise miles per hour and range in miles of 5.30E-06, 4.69E-07 and 1.64E-09, respectively. Therefore Equation 7 is statistically significant (however, with a Pearson's^2 of 91.4%, which is good but not as high as it might be, other statistically significant variables may figure into vehicle value).

Suppose that we decide to use Equation 7 to design a $25 million vehicle in Figure 8.

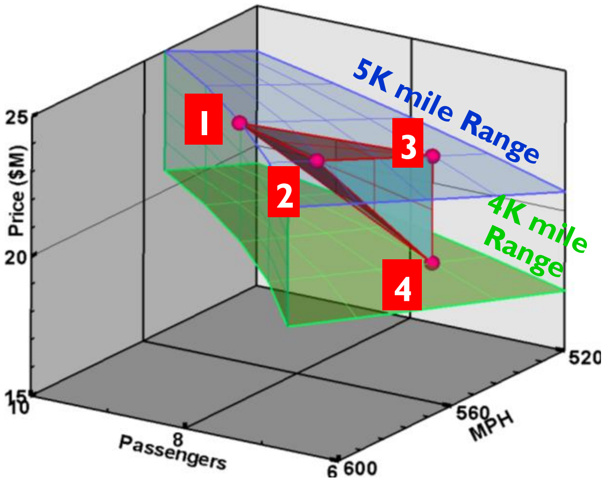

Fig. 8. Feature Loss Effect on Sustainable Price

We may have picked the $25 million target because we noticed that there few competitors in this region with respect to price, or perhaps we examined the features that our competitors offered and found some gaps there. In any event, we know from Equation 7 that we must populate it with its independent variables. We do that and get Equation 8.

$$\textit{Ave \$} = 5.79e{-}07 \cdot 8^{0.621} \cdot 575.5^{1.17} \cdot 5000^{1.04} \qquad (8)$$

Where:

Ave $ = $25.0 million
Pass = 8
Max MPH = 575.5
Range = 5000 statute miles

This is our starting point, shown in Figure 8 as Position 1. A competitive vehicle in this price range at this time was the Falcon 2000DX, which has an empty weight of 20,725 pounds [10]. If we take Equation 2 from above and solve for the Falcon 2000DX launch weight given its final weight, we get the following:

$$20{,}725 = 1.49 * \text{Launch MEW}^{0.973} \quad (9)$$
$$13{,}908 = \text{Launch MEW}^{0.973} \quad (10)$$
$$Ln\ (13{,}908) = 0.973 Ln(\text{Launch MEW}) \quad (11)$$
$$9.805 = Ln\ (\text{Launch MEW}) \quad (12)$$
$$Exp\ (9.805) = Exp(Ln(\text{Launch MEW})) \quad (13)$$
$$18{,}125 = \text{Launch MEW} \quad (14)$$
$$\text{Final MEW } (20{,}725) - \text{Launch MEW } (18{,}125) = 2{,}600 \text{ lbs} \quad (15)$$
$$\text{Final MEW/Launch MEW} = 20{,}725/18{,}125 = 114\% \quad (16)$$

Based on this analysis, vehicles in this size category grow significantly from their initial targeted empty weights to their final weights. In this range, we can expect their empty weights to grow by about 2,600 pounds or 14% from their launch projections to when they finally fly.

Suppose that in designing this hypothetical vehicle, we decide that will not let our maximum takeoff weight grow, so that given the engine thrust that we have chosen, we can make a balanced field length target that we have set for ourselves. Now assume that we have weight growth for which we have not planned. If we have to give up one seat on our passenger count, we encounter Equation 17.

$$\text{Ave } \$ = 5.79e\text{-}07 \ *7^{0.621} * 575.5^{1.17} *5000^{1.04} \quad (17)$$

Where:

Ave $ = $23.0 million
Pass = 7
Max MPH = 575.5
Range = 5000 statute miles

Losing one passenger has cost us $2 million per aircraft in its sustainable price, and moved us from Position 1 to Position 2 on Figure 8. Imagine that our problems spread into our ability to hold our top cruise speed, which falls to 560 miles per hour. At this point, we end up with Equation 18.

$$\text{Ave } \$ = 5.79e\text{-}07 \ *7^{0.621} * 560^{1.17} *5000^{1.04} \quad (18)$$

Where:
Ave $ = $22.3 million
Pass = 7
Max MPH = 560
Range = 5000 statute miles

That difference, 15.5 miles per hour at maximum cruise speed, has cost the vehicle $700,000 in the price that it will command, and shifted us to Position 3 on Figure 8. Finally, assume that with the empty growing, we have had to reduce our range, from 5000 to 4000 statute miles, which we depict with Equation 19.

$$\text{Ave } \$ = 5.79e\text{-}07 \ *7^{0.621} * 560^{1.17} *4000^{1.04} \quad (19)$$

Where:

Ave $ = $17.7 million
Pass = 7
Max MPH = 560
Range = 4000 statute miles

This final feature loss has pushed the price that the market will support for it to $17.7 million, downward from the $25.0 target with which we started, as we settle into Position 4 on Figure 8. Our first loss in value, from Position 1 to 2, gave us a Value Error Line. The second time we did not meet our specifications, when we moved from Position 2 to Position 3, we drew a Value Error Triangle. Finally, as we lost range in our transition from Position 3 to 4, we drew yet another line, which, when coupled with the others that came before it, forms a Value Error Tetrahedron, the shaded volume in Figure 8 (other errors in value targeting, beyond those described by a Value Error Tetrahedron, result in Value Error Tetrahedrons with tails).

Meanwhile, on the Demand Plane, loss of sustainable price has implications too. Our Aggregate Demand is slightly flat, at -0.855, indicating that there is slightly more money in the lower parts of the market (the lowest bin has a projected revenue of $39.2 billion for the period) than its upper regions (the uppermost bin contains $26.6 billion for the same phase). However, the business aircraft Demand Frontier constrains this market with a much steeper slope (-1.99). This means that there is less downward mobility for aircraft models in this submarket.

It also means that there are implications for revenue projections as well. Suppose our hypothetical new vehicle did the best that it could do in the market, and found itself having the limiting number of vehicles sold in the period, the limit for which is the Demand Frontier, as shown in Figure 9, where we show the transition from Positions 1 to 4 (P1 to P4).

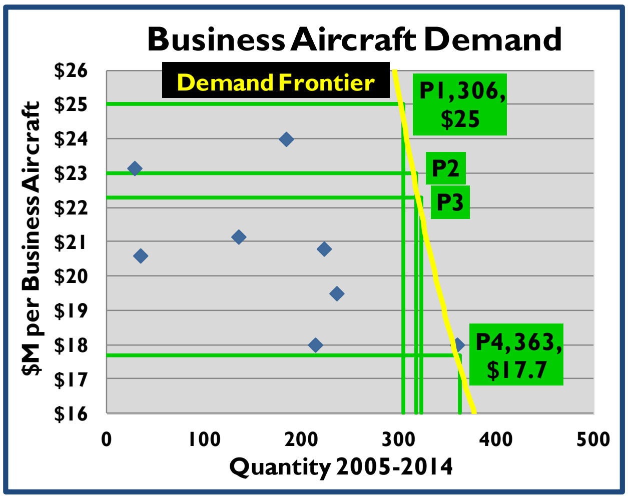

Fig. 9. Feature Loss Effect on Demand

We can compare our potential revenues relative to where we started, as Position 1 with Equation 20, to where we finished, in Position 4 with Equation 21.

$$\textit{Potential Launch Revenue Limit (P1) \$} = 306 * \$25M = \$7.65B \tag{20}$$

Where:
Demand Frontier Limit = 306
Launch Sustainable Price = $25M

$$\textit{Theoretically Realized Revenue (P4) \$} = 363 * \$17.7M = \$6.43B \tag{21}$$

Where:
Demand Frontier Limit = 363
Final Sustainable Price = $17.7M

In this market, with the steep demand frontier function, the market imposes penalties if we suffer steep drops in the sustainable value of our vehicle based on its features.

In order to round out our analysis, we will need to compare value to cost as well. While costs vary from manufacturer to manufacturer, the industry has a cost model, the Development and Procurement Cost of Aircraft (Version IV) that provides insight into recurring costs, including that for added cruise speed, as shown in Figure 10 [11]. Note that as we add more of the things that we like, features that add value, the cost to provide them goes up as well.

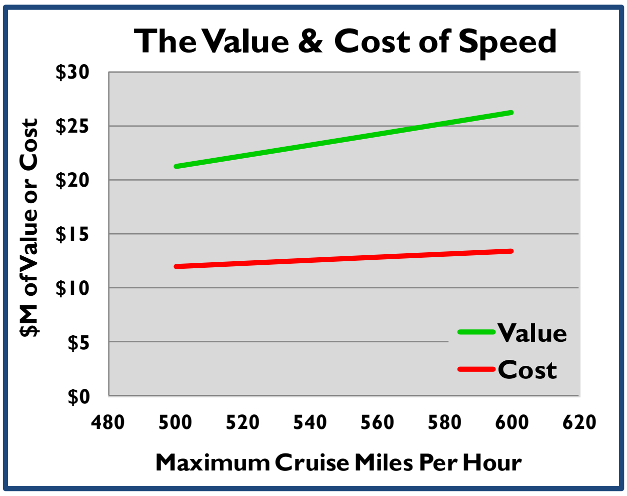

Fig. 10. Speed adds Value faster than Cost

From Equation 7, we know that as we add speed, as measured in miles per hour, value goes up to the 1.17 power, as shown in Figure 10 (where we have fixed passenger capacity to 8 and range to 5000 statute miles). However, across the same speed scale, the DAPCA IV cost model states that cost goes up to the 0.621 power (also shown in Figure 10, though the intercept here is notional). This means that our per unit profit margin (here, unit value – unit cost) will always increase as we add speed.

It becomes harder for us as we compare the value of added capacity, in the form of added passengers, however. We know that as maximum passenger capacity goes up, the cost and value for it go up at the same time, but likely at different rates. These variations will change from supplier to supplier, but we can broadly characterize them in Figure 11. In this figure, we know that the value for added capacity goes up to the 0.621 power as we add passengers. Cost likely goes up at a slower rate.

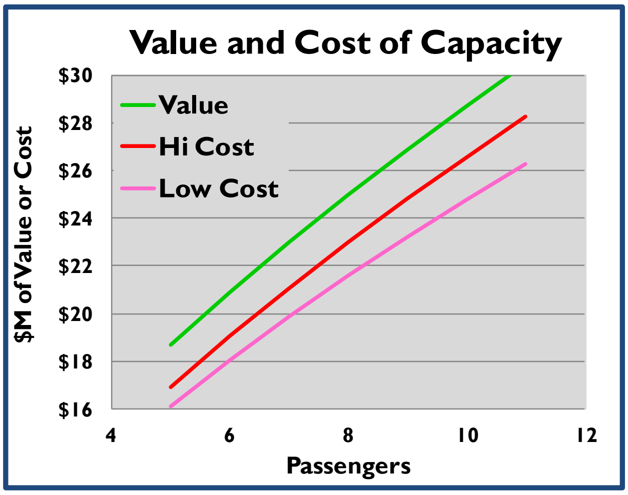

Fig. 11. Added capacity Value versus Cost

The same type of phenomenon happens with respect to range, as shown in Figure 12. There, we show the known value response to range that we obtained from Equation 7. As with all other features, the additional cost of adding range may closely mimic its value, or have an entirely different slope. We would need to have detailed manufacturers' data to perform analysis to make sure of their costs.

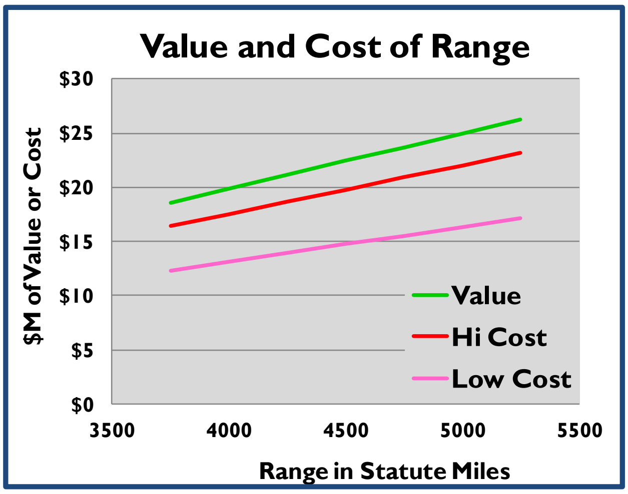

Fig. 12. Added range Value versus Cost

If we encounter unplanned weight growth, we will certainly find feature loss of one sort or another. Often, the attribute that manufacturers of fixed wing aircraft give up first is balanced field length, as they are willing to suffer longer takeoffs and landings in their desire to maintain their other features, such as their cruise speeds, ranges or passenger capacities. As the analysis above indicates, it is not intuitively obvious which features pay off the most relative to their costs. Rather than rely on their intuition, then, manufacturers should compare their costs to their buyers' values and demand curves, to optimize their products from the beginning.

3 Conclusions

3.1 Summary of Findings

A key parameter to any viable aircraft program is profitability, the prices of the vehicles minus their costs times the number of them sold. Bigger programs, in general, cost more than do smaller ones. Because of this, costs correlate well with vehicle empty weights, which are proxies for sizes. Importantly, empty weight predictions grow from program launch to first flight, taking costs with them. However, we can predict this growth with statistically sound models based on past behavior, and make allowances for changes in weight and their attendant implications for cost.

Changes in weight have implications for vehicles' features as well. Customers reward various features in different ways, while at the same time limiting their purchases in Value Space through their collective demand curves on the Demand Plane. We can display such interactions in 4D coordinate systems, which use ordered quads that depict Valued Feature 1, Valued Feature 2, Price, and Quantity. These 4D coordinate systems do not entertain negative numbers and have an origin of (0, 0, 0, 0). We can compare costs to value in Value Space, and verify that we are not adding cost faster than value. On a recurring basis, we can evaluate our recurring costs against demand. Flat Aggregate Demand curves (elastic curves with slopes > -1.0) indicate that there is more money at the bottom of the market, while steep Aggregate Demand curves (inelastic curves with slopes < -1.0) mean the opposite. In many cases, however, Demand Frontiers limit market movement due to their unique slopes, which are often higher than those for Aggregate Demand.

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5 Contact Author Email Address

You may contact the author at the following email address:

dhowarth@meevaluators.com

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