

Surplus Value in Propulsion System Design Optimization

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ABSTRACT

An economic model is presented which relates engineering performance characteristics to product profitability for conceptual and preliminary design of propulsion systems and aircraft. The model represents the competitive marketplace rigorously, which sets it apart from the prevailing state of the art. The model is shown to produce significantly different design results than current approaches.

INTRODUCTION

Today the design, certification and tooling costs to introduce a new aircraft engine can exceed one billion dollars. To make such an investment responsibly, design engineers must be focused on creating a product that will succeed in the marketplace, providing a good value for prospective customers [Collopy, 1997]. However, today's design teams lack the economic tools to translate among engineering parameters, market needs, and costs. Therefore, new propulsion systems are based on goals such as "reduce aircraft total operating cost by 10%" [Aviation Week & Space Technology, 1996] that neglect airline revenue and engine manufacturing costs. Attempts to incorporate economic values, such as Altman [1994], although laudable, do not incorporate rigorous, complete representation of market operation and therefore do not generally lead to optimal designs.

This paper presents an economic model that relates aircraft performance and manufacturing cost to aircraft, airline, and engine profitability. The model incorporates a rigorous representation of the aircraft market. It is shown that the total profit of the airframer, engine manufacturer, and purchasing airline, referred to as the surplus value, is set by the aircraft and engine design; the market functions only to divide the profit among the parties. Furthermore, it will be shown that the optimal design for airframe and engine is that design which maximizes surplus value. This same design maximizes profit for the airline, the airframer and the engine manufacturer—a true win-win solution.

An example is provided in which the economic model is employed in a simplified design study to optimize bypass ratio. The results using the model are significantly different than with prior techniques.

WHY AIRLINES PURCHASE AIRCRAFT

Aircraft purchases are complex decisions. Salesmanship, maintenance agreements, manufacturing offsets and international politics all come into play. But virtually all purchases rest on a fundamentally rational financial base: the intent of the airline to make money by operating the aircraft. A simple economic model of the aircraft purchase decision can be made by assuming that operating profit is the airline's only objective in purchasing an aircraft. The influence of this model on propulsion system design is instructive.

Revenue and Operating Cost

Airline operating profit is the difference between revenue and operating cost. The revenue that an aircraft can earn for an airline depends on the payload and range capability of the aircraft, in conjunction with airline's route structure and the passenger and freight demand on those routes. Note in Figure 1 that payload and range are not separate attributes—the usual measure is in fact a function of maximum payload which depends on range. Economic probabilistic models can be used to estimate the

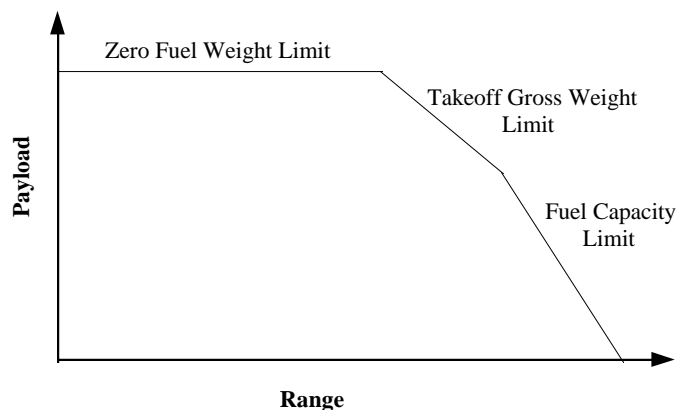


Figure 1: A Typical Payload / Range Curve

revenue impact of payload / range capabilities on particular routes where the transportation market demand has been characterized.

Revenue can also be influenced by block times, insofar as significantly reduced block times may allow an airline to increase the number of flights per aircraft per day. Delays and cancellations impact revenue, directly via passengers and freight that switch to other carriers to avoid a delayed or canceled flight, and less directly through the loss of customer goodwill entailed by D & C's.

Direct Operating Cost, which includes fuel, maintenance, crew, and landing fees, is a well established metric for aircraft and propulsion system design. Alone, however, it is not a reliable indicator of the desirability of an aircraft or propulsion system [Altman, 1994].

Design features generally affect both the revenue and cost sides of an airline's profit equation. For example, efficiency, whether in the engine's turbine or the aircraft's wing, improves fuel consumption. This reduces fuel cost and simultaneously increases aircraft range (that is, it increases payload capability at Takeoff-Gross-Weight-Limited ranges). Lighter weight structures increase payload capability and, by reducing lift, induced drag, and ultimately thrust, improve fuel consumption and cost.

Discount Factors

Revenue and operating cost analyses can be used to estimate the annual operating profit which the airline can earn by purchasing an aircraft. Note that operating profits, as defined here, do not include the cost of purchasing or leasing the aircraft. To properly aggregate operating profits across the many years of the aircraft's life, a present value calculation should be done on the annual operating profits, as follows:

$$present\ value = \sum_{i=1}^{aircraft\ life} operating\ profit \cdot (1 + r)^{-i} \quad (1)$$

where r is the airline's discount factor, a measure of the relative value that the airline places on money over time. Specifically, 1 + r equals the ratio of the value of a dollar earned today to a dollar earned one year from now.

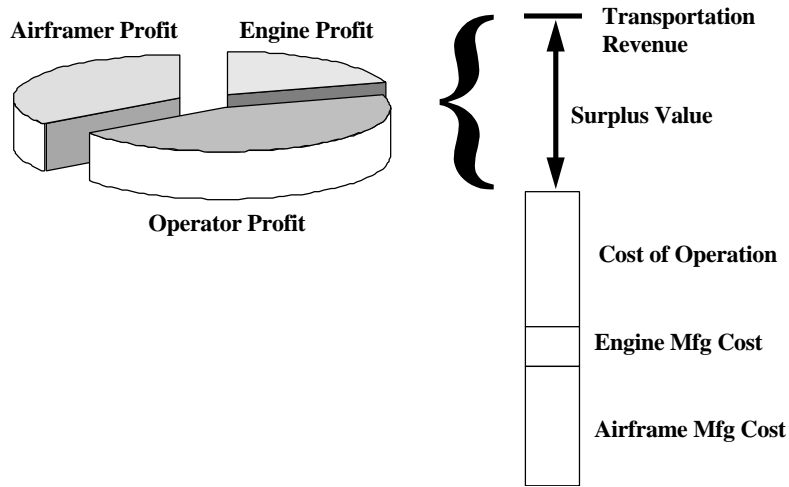


Figure 2: The Profit Pie

Purchase Equivalence

The aircraft purchase decision can be quantified as follows: a rational airline will purchase an aircraft (and propulsion system) if and only if the present value of the profits to be earned from operating the aircraft exceed the purchase price. To properly compute this, the tax impact of owning the aircraft on cash flow (depreciation impact plus any applicable investment tax credits) must be included in the present value calculation. The present value of the profits from aircraft operation, adjusted for taxes, is then the **Reservation Price**: the upper limit on the price the airline will pay in the absence of competition.

The **net value** to the airline is the reservation price less the actual price. Since the reservation price is the present value of operating profit, net value is the present value of net profit, where net profit is defined to account for ownership cost (the aircraft price). If more than one aircraft are available for purchase, the rational airline will select the aircraft with the greatest net value. If more than one aircraft share the market, it is because they are priced to offer airlines approximately equal net values.

THE PROFIT PIE

The next step in understanding the relationship of design features to aircraft and engine profitability is to relate the airline's reservation price and the manufacturer's costs to each party's profit. Markets have a powerful effect on the allocation of profit among the airline, the airframer, and the engine

maker; however the total profit is fixed by the aircraft design (given the model of aircraft operation discussed above):

$$\text{Surplus Value} = \text{Total Profit} = \text{Reservation Price} - \text{Airframe Mfg Cost} - \text{Engine Mfg Cost} \quad (2)$$

As indicated in Equation 2, and illustrated in Figure 2, the term **Surplus Value** will be used to refer to the total profit of the airline, airframer, and engine manufacturer. An easy way to think about surplus value and profit is to consider the operation of the United Aircraft Company.

The United Aircraft Company

In the early 1930's, the dominant aviation company in the United States was the United Aircraft Company, a vertical conglomerate that was divided by court order into Boeing, United Technologies and United Airlines. Prior to the breakup, there was a single company which manufactured aircraft and propulsion systems, and flew commercial routes.

Profitability was straightforward for United: Revenue from operation minus direct operating costs minus engine and airframe manufacturing costs. When adjusted for cash flows over time, this is exactly the surplus value in Equation (2). The difference is that, whereas the United Aircraft Company retained the surplus value as gross profit, today it is distributed among the airline, airframer, and engine manufacturer. The mechanism for distributing surplus value is the aircraft marketplace. The driving force for distributing profit is competition.

A MODEL OF COMPETITION

A basic economic model can provide a great deal of insight into the behavior of the competitive marketplace in allocating profit. In this section, a rational competition between three aircraft will be described. Key characteristics of the competition will be noted, and a simple model of the steady-state outcome will be constructed from these characteristics. The model will then be extended to include the separate purchase of airframes and propulsion systems.

Reservation Price	\$120M
Manufacturing Cost	\$80M
Surplus Value	\$40M
Eventual Selling Price	\$120M
Unit Gross Profit	\$40M

Figure 3: Monopoly Aircraft Market

A Monopoly Market

Imagine that a single aircraft vendor is selling to a market of similar airlines (that is, they have the same reservation price for each aircraft). The aircraft is described in Figure 3. Since there is no competition, the airframer can raise its price up to the reservation price and still make sales.

Surplus value, the difference between Reservation price and manufacturing cost, is key to this market model. In the case of a monopoly, the unit profit is equal to the surplus value.

A simple competition between three aircraft

Next, consider the competitive market, illustrated in Figure 4. This example is central to understanding competition in the commercial aircraft market. The results of each round are determined by the difference between the price offered and the reservation price. Recall:

Aircraft	A	B	C
Reservation Price	\$120M	\$110M	\$125M
Manufacturing Cost	\$80M	\$85M	\$90M
Surplus Value	\$40M	\$25M	\$35M

Round	Price Offered			Result
1	\$120M	\$120M	\$120M	Market prefers C
2	\$110M	\$100M	\$120M	A & B split market
3	\$100M	\$100M	\$110M	Market prefers A
4	\$100M	\$90M	\$100M	Market prefers C
5	\$90M	\$85M	\$100M	Market prefers A
6	\$90M	\$80M	\$90M	Market prefers C
Equilibrium	\$85M	\$75M	\$90M	All share market

Figure 4: The Competitive Market

$$\text{Net Value} = \text{Present Value (Airline Net Profit)} = \text{Reservation Price} - \text{Purchase Price} \quad (3)$$

The reservation price less the purchase price is the airline's slice of the profit pie. Airlines buy the aircraft with the largest difference between reservation price and purchase price so as to maximize profit. Maximizing profit is the same as maximizing net value.

Airframers who are dissatisfied with their market share (either because they are shut out of the market entirely or because they can increase their profit by trading unit profit for market share) reduce their price, increasing their net value and making their product more attractive to airline customers. The significant round in Figure 4 is the last round: equilibrium. Although it may take a couple of years for an aircraft market segment to reach equilibrium, most of the sales during the life of the product take place near equilibrium price, so the equilibrium prices largely determine product profitability.

Characteristics of Competition

Aircraft	A	B	C
Surplus Value	\$40M	\$25M	\$35M
Unit Profit	\$5M	-\$10M	0

Figure 5: Airframer Profit at Market Equilibrium

Figure 4 is just an example of how market dynamics may play out following the introduction of new products, but the equilibrium prices shown in Figure 4 will be reached eventually regardless of the path the market takes. Figure 5 shows the relationship of unit profit at equilibrium to surplus value and helps explain why the equilibrium falls where it does. There are two fundamental characteristics that determine equilibrium:

1. The difference between reservation price and purchase price is the same for all aircraft.
2. The aircraft with the second largest surplus value earns zero unit profit.

Characteristic One is true, otherwise all three aircraft cannot participate in the market. The desirability of each aircraft to customers is measured by the amount its reservation price exceeds its selling

price. Unless all three aircraft are equally desirable, they will not all sell. Indeed, Aircraft B may choose to drop out, rather than lose money on each sale.

Characteristic Two is true because the second place airframer can always improve its profitability by moving its price toward its manufacturing cost. If its price is below manufacturing cost, increasing price reduces unit losses and improves profitability. If its price is above manufacturing cost, it can increase market share with a small price cut, such that the additional volume will compensate for the loss in unit profit, yielding greater total profit. Unfortunately, by the same logic, the airframer with the largest surplus value will always take back the market share by cutting its price.

A Competition Model

Given these two characteristics, it follows that the unit profit for each aircraft is its surplus value minus the surplus value of the aircraft with the second largest surplus value. In Figure 5, Aircraft C has the second largest surplus value, \$35M. The unit profit of Aircraft A is its surplus value, \$40M, less \$35M. The unit profit of Aircraft B is \$25M minus \$35M, -\$10M, a unit loss of ten million dollars. The third place player tends to lose money. Finally, the unit profit for C, the second place player, is \$35M minus \$35M, or zero as stated above in Characteristic Two. This model can be derived from the two characteristics noted above. First, since net value, the difference between reservation price and equilibrium price, is constant across all aircraft (characteristic one), and surplus value is reservation price less manufacturing cost, and unit profit is equilibrium price less manufacturing cost, then the difference between surplus value and unit profit is constant across all aircraft. Since the unit profit of the second place aircraft is zero (characteristic two), the difference between surplus value and unit profit is the surplus value of the second place aircraft (both for the second place aircraft, and, by extension, for all the aircraft).

Note that the model neglects many of the complexities of actual markets and assumes pure, non-collusive competition, but nevertheless provides a simple and coherent base for relating airline revenue, direct operating cost, and manufacturing cost to manufacturer's profit, as follows:

$$\pi = \sum_{i=1}^{\text{aircraft life}} \left[(R - \text{DOC}) \cdot (1 + r)^{-i} \right] - \text{MC} - \text{SV}_2 \quad (4)$$

π is profit, R is revenue, DOC is Direct Operating Cost, MC is Manufacturing Cost, and SV_2 is the second largest surplus value among the competing aircraft. In a monopoly, $\text{SV}_2 = 0$.

Two refinements to the model, which go beyond the scope of this paper, are to make adjustments for the tax benefits of depreciating the aircraft and to increase the manufacturing cost to include other variable costs, such as sales and technical support, which determine the break-even point for profitable production. Even with these refinements, however, the model is straightforward.

Extending the model to include propulsion systems

The model just presented presumes that the complete aircraft, including propulsion systems, is purchased from the airframer. In fact, propulsion systems are often purchased separately. Many market configurations can result.

- The Boeing 747 currently monopolizes a market segment, but supports three competing engine models.
- In the early 1960's, the Boeing 737 and Douglas DC-9 competed for the 100 passenger market, but Pratt & Whitney monopolized propulsion for both planes with the JT8.
- The long range 300 passenger market is currently shared by the Boeing 777, the MDA MD-11 and the Airbus A340. The 777 supports 3 engines, the MD-11 supports two, and the CFMI CFM56-5C holds a monopoly position on the A340.

In these cases profit can be modeled by an extension to the original model through the same competition dynamic discussed above:

1. Determine the reservation price for each aircraft / propulsion combination as above.
2. Determine the surplus value of each combination: $SV = \text{Reservation Price} - \text{MC}_{\text{Aircraft}} - \text{MC}_{\text{Propulsion}}$

3. Since an aircraft or engine will not price-compete among its own models, SV_2 is largest surplus value of any combination that does not include the aircraft or engine that, in combination, have the largest surplus value. That is, if Aircraft A and Engine 1 make up the combination with the greatest surplus value, then SV_2 is the largest surplus value among all the combinations that do not include Aircraft A or Engine 1. If all combinations include either Aircraft A or Engine 1, then $\text{SV}_2 = 0$.
4. If an Aircraft supports more than one engine, and at least two combinations have surplus values greater than SV_2 , then call the second largest surplus value SV_b . The Aircraft unit profit will be $\text{SV}_b - \text{SV}_2$, and the Propulsion System unit profit will be the surplus value of the combination minus SV_b .
5. If an Aircraft has only one combination with a surplus value greater than SV_2 , then the unit profit for the aircraft is 0, and the unit profit for each Propulsion System is the surplus value of the combination minus SV_2 .
6. If the Aircraft has no combinations with surplus value greater than SV_2 , then let SV_a be the greatest surplus value among all the combinations. The unit *loss* for the Aircraft is $\text{SV}_2 - \text{SV}_a$, and the unit loss for each Propulsion System is SV_a minus the surplus value of the combination using that propulsion system.

Results of applying the competition model

The most important insight provided by the competition model is that, in all cases, unit profit increases monotonically with surplus value. Figure 6 provides an illustrative example for the simple single manufacturer case, but the result is also true for the extended model where the aircraft and propulsion system manufacturers are separate. The unit profit of each party increases monotonically with the surplus value of the combination. Thus, optimizing surplus value will automatically optimize unit profit. Since market share increases with surplus value, optimizing surplus value also optimizes the total profit of the product line. Regardless of the competitive environment, a design that optimizes surplus value can be assured of producing the most profitable product within the capabilities of the manufacturer.

The second important insight is that decreasing the manufacturing cost of either the aircraft or the engine causes the surplus value to increase dollar for dollar. Thus, the optimal propulsion system, from the point of view of the airframer, is the one which maximizes the difference between the reservation price of the combination and the manufacturing cost of the engine (for a constant aircraft).

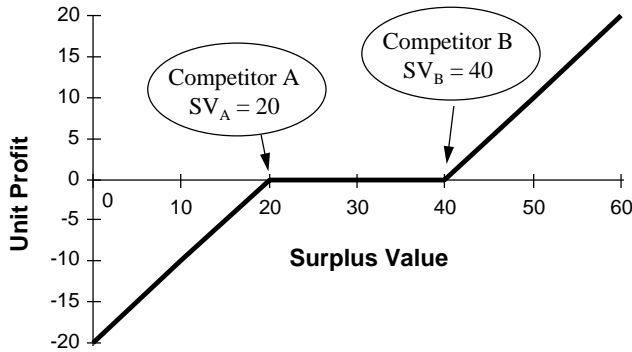


Figure 6: Profit versus Surplus Value

It is in the airframer's interest for the engine manufacturer to maximize surplus value, just as it is in the engine manufacturer's interest for the airframer to maximize surplus value.

This suggests a fundamentally different metric than has been used traditionally for propulsion system design (cf. Altman [1994] and AW&ST [1996]). The results of using this metric will now be explored.

THE EFFECT OF VALUE METRIC ON BYPASS RATIO

To illustrate the impact of surplus value optimization on propulsion system design, a very simple engine conceptual design model will be presented. Using the model, bypass ratio will be optimized using traditional metrics and using surplus value.

A simple conceptual propulsion system model

The following model describes a long-range 200 ton max takeoff gross weight generic transport with state of the art propulsion systems. It is deliberately not representative of any particular engine or engine family—it is simply an illustration, with the hope that aircraft and engine manufacturers will be encouraged

to examine this phenomenon using their own proprietary data.

$$DOC = 0.0125 \cdot \beta^2 - 0.4 \cdot \beta + 30 \quad (5)$$

DOC is the airline's annual direct operating cost for the aircraft in millions of dollars. Here the only impact being considered is the influence of bypass ratio (β) on fuel burn. The negative linear term reflects the improvement in propulsive efficiency with increasing bypass ratio. The positive quadratic term captures the effects of nacelle drag from larger nacelles and ram drag that eventually limit the improvement possible from high bypass ratio. The constant term includes all the other elements of direct operating cost.

$$W = \beta + 4 \quad (6)$$

W is the propulsion system weight (all engines) in tons. The weight increases with bypass ratio primarily because the fan and nacelle grow in size.

$$R = 45 - 0.22 \cdot W \quad (7)$$

R is the annual revenue generated by the aircraft in millions of dollars. The revenue decreases as the propulsion weight increases, because the propulsion system displaces cargo on gross weight limited departures. This effect has been deliberately understated because it is partially offset by the increase in bypass ratio and fuel efficiency, which reduces the amount of fuel that must be carried.

$$OP = R - DOC \quad (8)$$

$$RP = 6.5 \cdot OP$$

The airline's annual operating profit, *OP*, is simply revenue less cost in millions of dollars. The reservation price has been determined by discounting the operator's profit over the life of the aircraft and adjusting for depreciation.

$$MC = 0.3 \cdot W + 5 \quad (9)$$

$$SV = RP - MC - 75$$

MC is the manufacturing cost of the propulsion system (aircraft ship set) in millions of dollars. *SV* is the surplus value, using 75 million dollars as the manufacturing cost of the aircraft.

The results of this model are plotted in Figure 7. Notice the impact of choice of metric on the fundamental design of the propulsion system. An engine designed to minimize direct operating cost would have a bypass ratio of 16. However, it would have a surplus value of near zero and be non-

competitive, because the weight of the engine would limit the operator's revenue, and the manufacturing cost of the engine would drive the price too high. Better would be to design to maximize the operator's profit, at a bypass ratio of 7. This engine commands the highest price of any option (reservation price is proportional to operator's profit). However, it is expensive to manufacture compared with lower bypass ratio engines. The best design for all parties

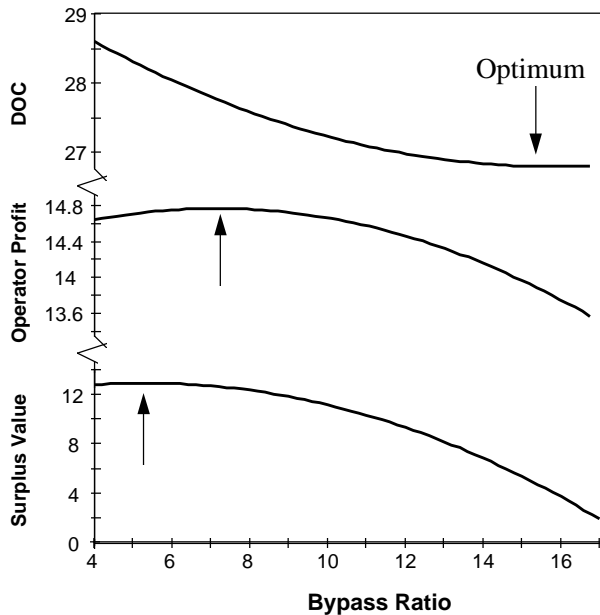


Figure 7: Impact of Designing to Maximize SV

is the one that creates the largest profit pie, the engine with the maximum surplus value. At a bypass ratio of about 5, it is significantly smaller, lighter and less expensive than the other designs. As a result, it will be more profitable.

CONCLUSIONS

Conceptual design of commercial transport aircraft engines has largely ignored the impact of the design on price and manufacturing cost because of the lack of proper tools to model economic issues. A model of competition has been presented which begins to remedy this need. It is based on a metric, surplus value, which is shown to be superior to other metrics in providing a profit to airframers, engine manufacturers, and airlines alike. The reason is that surplus value is in fact the net present value of the total profit of all three parties.

Although this economic model is simplistic, it provides a more rigorous and realistic characterization of market interactions than any prior approaches.

Still the model will benefit from future enhancements. As a profit-focused model, it ignores economic externalities, such as noise and atmospheric emissions, except insofar as these are captured in taxes, fees, and revenue attributable to full time access to noise-restricted airports. These externalities can be incorporated in the model by a pricing analysis, as is done in economic policy analysis. Optimization will yield the best design only when all significant design consequences are incorporated in the value function.

This model represents an important step on the way to quantifying market needs to drive design decisions. Optimizing engine designs to maximize surplus value will dramatically change future configurations, with the end result of more affordable air travel for consumers.

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