Statistical Time and Market Predictive Engineering Design (STAMPED) Techniques for Preliminary Aircraft Sizing

By

Dr. Ron Barrett
Director, Aircraft Design Laboratory and Professor of Aerospace Engineering
2120 Learned Hall
The University of Kansas, Lawrence, KS USA
adaptivebarrett@gmail.com

A new technique for preliminary sizing and design of certain aircraft categories will be presented. These Statistical Time and Market Predictive Engineering Design (STAMPED) methodologies can be applied to many different product lines with historical data bases (even outside of the aerospace industry). The generalized terminology and trend-tracking methods will be presented for a generic broad, established category of goods. The generalized terminology will then be refined and focused on aircraft, then one or more categories of aircraft including regional turboprops in particular will be used as an example. By using STAMPED techniques it will be shown that "classical" preliminary aircraft design techniques which call upon the use of "appropriate" numbers for certain engineering values can be replaced with far more exacting, historically based methods to determine certain aircraft characteristics in the preliminary aircraft design stage. By using historical market-driven data, it is also shown that STAMPED techniques provide a simple and powerful tool for engineering design education. An analysis of the regional turboprop market over the past 30 years shows particular trending of passenger seat-mile per pound of fuel numbers from 1981 through 2014. An extrapolation exercise using STAMPED techniques shows market direction projected into the future for projected IOC dates. The study concludes with a presentation of several STAMPED trends for a number of aircraft variables over the past 30 years.

1 INTRODUCTION

In October of 1974, a conference was organized by Prof. Jan Roskam on *The Future of Aeronautics* at the University of Kansas with proceedings being published the following summer.[1] This conference was centered on discussion of trends and opportunities in aeronautics in aeronautical education and featured 75 of the most noteworthy figures in aeronautics of the day from around the United States and other countries. Among the attendees were Presidents and Vice Presidents of Cessna, Douglas, Lockheed and NASA Administrator James Fletcher.

The results of the 1974 conference were both subtle and profound. As the Associate Director of NASA Langley was also in attendance, the drive to support the NASA-USAF-Boeing KC-135 winglet drag reduction program was reinforced and amplified. Indeed, that program would lay the foundations for much of what was known about winglets in the early days. At this conference came observations among some of the attendees that there were holes in US aeronautics education. Among the most profound deficiencies observed was the state of aircraft design education.

Throughout the 1970's Professor Roskam continued to collect and organize ever better and voluminous course notes on aircraft design. To help shore up aircraft design education, he constructed, then presented a large number of aircraft design seminars around the country. In 1983 he took a sabbatical with the express purpose of transposing the notes into a series of aircraft design books. These books would be centered on a structured process and targeted at educating inexperienced students in aircraft design by using a series of structured techniques. Over the following decade, a series of eight volumes covering various aspects of aircraft would come to be.[2-9] These texts have been used as the primary instructional tools of many thousands of aerospace engineers and are integrated into curricular instruction in institutions around the world. Arguably, these texts would "bring order to the chaos" and establish (according to many) the "Classical" approach to aircraft design education.

This Classical approach to aircraft design education would start with basic aircraft sizing techniques which were based on historical trends and statistical information of aircraft in active service. Roskam divided the fixed-wing endoatmospheric aircraft into twelve major categories as he threw his net around many of the most common aircraft which populated each category. Figure 1 shows the aircraft that he chose to include in the "Regional Turboprop" category (as an example) along with their ranges of first flight and first delivery.

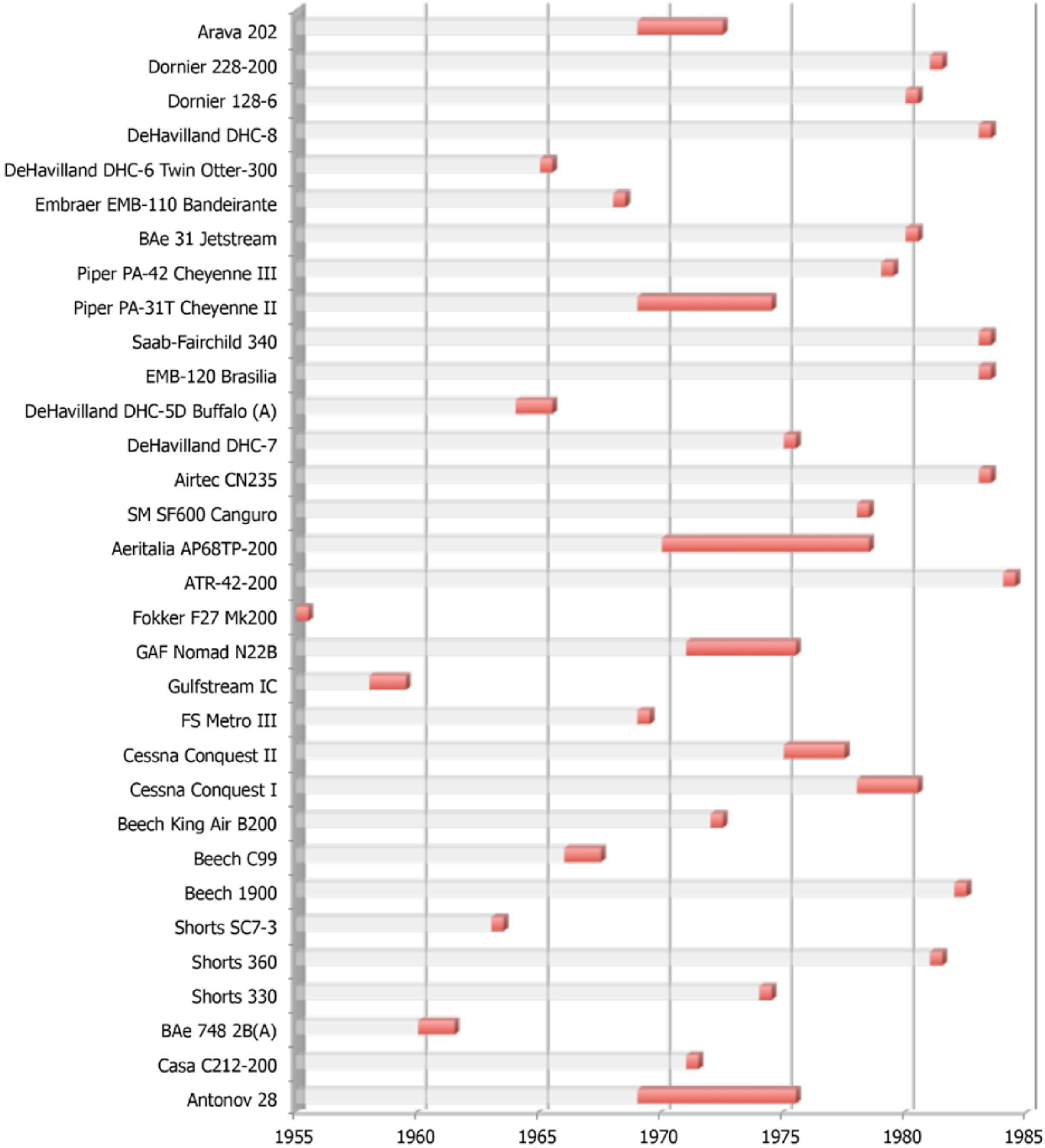

Figure 1 Regional Turboprop Aircraft Chosen by J. Roskam for Trending Analysis in Ref. 2

While the list was outstanding for 1983, the reader can immediately see the structural problem with the approach: It's frozen in 1983. The relevance of using data from aircraft which are now 60 years old is potentially questionable. What is more is that students of today are regularly designing aircraft for classes and competitions which are supposed to be delivered in 2020, 2030 and beyond.

Compounding this three-quarter century time lag between relevance of data used for statistical analysis and projected delivery date of hypothetical aircraft are several factors which have impeded the updating of these classical texts with modern data. The first is the consistent pirating of copyrighted materials as students at many universities and technologists in a number of countries with notoriously weak copyright law enforcement will simply find an electronic copy on line, then download illegal files of the texts.[10] This in turn suppresses legal textbook demand, which then retards revenues for existing books, and leaves would-be authors wondering if they would ever see reasonable financial return for their time. Further, because the total market for aircraft design texts is limited (with respect to, say introductory biology or physics books), the total potential revenue even under ideal circumstances is limited. If one adds the tremendous research burden and costs associated with proper and thorough data collection, it is no wonder that these Classical texts have gone three decades without a significant update and potentially run the risk of never being updated at all.

Of course, while the technical community may lament this lack of a modern update of these classical instructional texts, a new method may be added which can quite handily augment the texts to not only provide modern data, but also predict future design variables.

2 STATISTICAL TIME AND MARKET PREDICTIVE ENGINEERING DESIGN (STAMPED) MOTIVATION

Although this work is centered on aircraft design, the reader should note that STAMPED techniques are extremely general and can be applied to any product or product line with documented history and at least one characteristic variable describing it.

Procedures akin to STAMPED techniques have been in place in the marketing and business analysis groups and Design departments of major manufacturing and design companies for many decades in many industries. Because each company invests nontrivial amounts of time, resources and effort to generate large statistical databases of their own and competitors' products (aircraft in this case), they are typically loathe to share that information with the general public and others, including and especially their competitors, which is only natural. Unfortunately, this means that the collection of such information is repeated over and over by many groups and yet is still not available in an organized manner in the public domain. Given the dynamics of the business world and daunting costs for entry, this trend is likely to continue for some time to come.

For the purposes of this document, the STAMPED techniques will be applied to aircraft design as they are particularly useful for predictive analysis. The basic premise of STAMPED methods are centered on considering all of the variables, properties, performance metrics and market performance as time-dependent multi-component vectors. Even variables which appear to be static with time, are still counted as dynamic with the possibility of someday changing with time. These time-dependent, n-dimensional vectors describe zones in which a wide variety of metrics may be presented one or more at a time as they progress through time. By using time-related trends, educated predictions of future performance may be obtained.

References 11 and 12 were two of the first documents to air the basic structure of STAMPED techniques. Although these techniques have been firmly solidified within corporate entities (and are accordingly cloistered behind the above described walls of corporate secrecy), this document will describe what is perhaps the most important motivation for STAMPED techniques: technical education. The purpose of the public airing of the original STAMPED structure in February 2014 was specifically in support of the educational process of aerospace design students.

While the texts of Roskam (Ref. 2 – 9) are filled with historical data (typically predating 1983), the Classical aircraft design student is simply handed a plate of historical information as manna from heaven, requiring little to no thought as to what it means, where it came from or how important it is. By asking individual students to perform a STAMPED analysis on a given market sector in support of a well written specification and mission profile, the student not only learns about the relevant technology, but can see first hand what drives the design, what is important, how interconnected the aircraft is to market, societal and economic forces (like recessions and 9/11 etc.). Also importantly, the method can also predict where the overall design variables will logically move to in the future and therefore can be used to guide competitive design projects. In short, STAMPED analysis methods are ideal tools to force students not just to absorb temporary knowledge to be regurgitated for "the test," but to embrace, become intimately familiar with and truly understand the history of a given subset of the aerospace market and class of machines.

In a grand experiment, conducted in the 2013 – 2014 academic year, the first description of STAMPED techniques were aired in a public medium in a very obscure, open access journal.[10] The primary reason for presenting the techniques in this manner rather than going to one of the major conferences or journals was not to draw attention to the techniques, but to allow students to refer to an archival reference as they would compete in the annual American Institute of Aeronautics and Astronautics (AIAA) Aircraft Design Competition. The students faithfully applied the techniques, and in the process learned well about the market forces, trends and history of Regional Turboprop aircraft as they competed in the team undergraduate design category. In the end, the two teams which employed STAMPED techniques both won awards including first place. This turned out to be the first time that students from that institution would win awards in that competition in nearly twenty years.

3 APPLICATION OF STAMPED TECHNIQUES TO PRELIMINARY AIRCRAFT SIZING

If one examines the entire Aircraft Design sequence of References 2 – 9, one will see that Part I (Reference 2) covers preliminary aircraft sizing. This part, more so than the others, relies on nontrivial amounts of statistical data to enable its utility. Because this statistical data is decidedly dated (prior to the mid 1980's), the data presented may or may not be relevant to aircraft with a planned first flight date of 2030.

The fundamentals of STAMPED techniques as applied to basic wing and power loading was handily shown in Ref. 10. If one examines a well defined market like the Regional Turboprops (as listed in Fig. 1), then the relationship between Empty Weight (We) and Takeoff Weight (Wto) can be plotted in a Log-Log relationship as shown in Ref. 2:

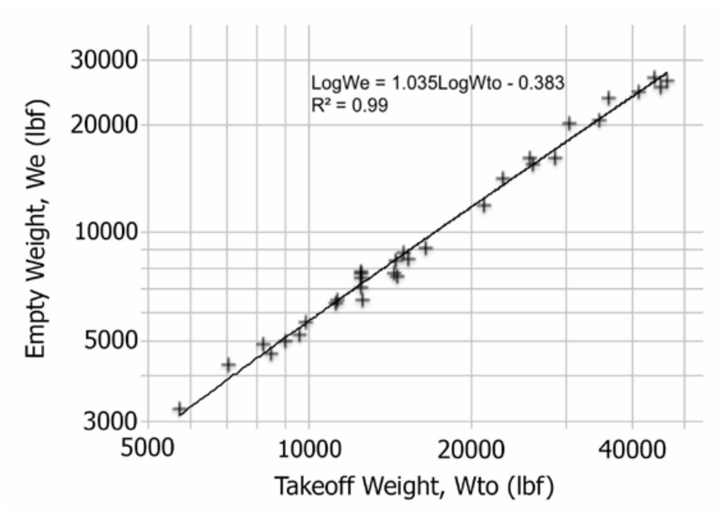

Figure 2 Regional Turboprop Aircraft Empty and Takeoff Weight Trends as Presented in Ref. 2

Often, a log-linear relationship often brings interesting trending between flying objects of widely disparate flying objects. Indeed, DARPA has developed log-linear trending from bumble bees through widebody aircraft in one chart. However, if a given market is well defined and narrow, then linear Cartesian trending often suffices quite well.

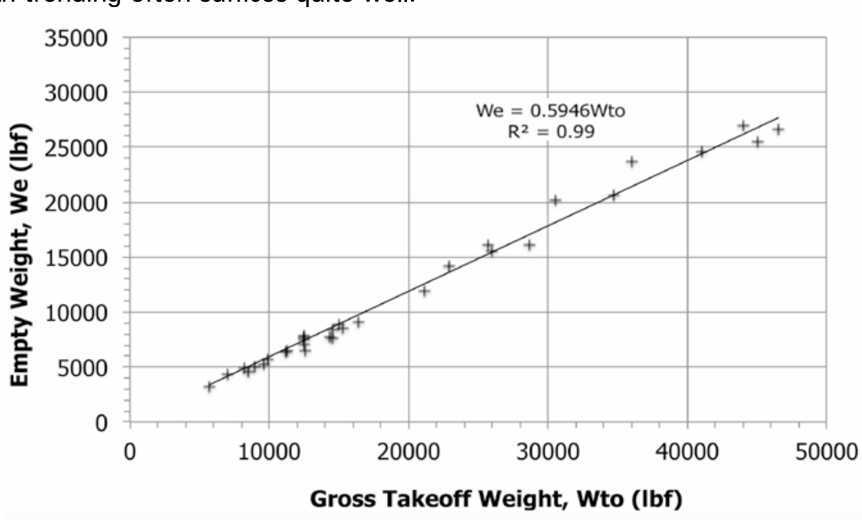

Figure 3 Regional Turboprop Aircraft Empty and Takeoff Weight Trends

Although the Classical techniques presented in Ref. 2 have been long accepted as the "gold standard" in aircraft design instruction, this examination shows very clearly that essentially identical levels of statistical correlation in empty-to-takeoff weight trending can be obtained by a very simple linear relationship passing through the origin.

While the analysis of the above linear relationship is good and illuminating, it smears the properties of aircraft which incorporate materials and manufacturing techniques that range from the late 1940's to the early 1980s with an equal weight applied to all of the aircraft regardless of how well they did in the marketplace or how long the various production lines ran.

If one examines the major weight relationships in the Regional Turboprop market from the early 1980's through 2014, then different trending may result. By using STAMPED techniques, a selection of Regional Turboprops can be examined to arrive at trends that are relevant today and beyond by using the data of Reference 13.

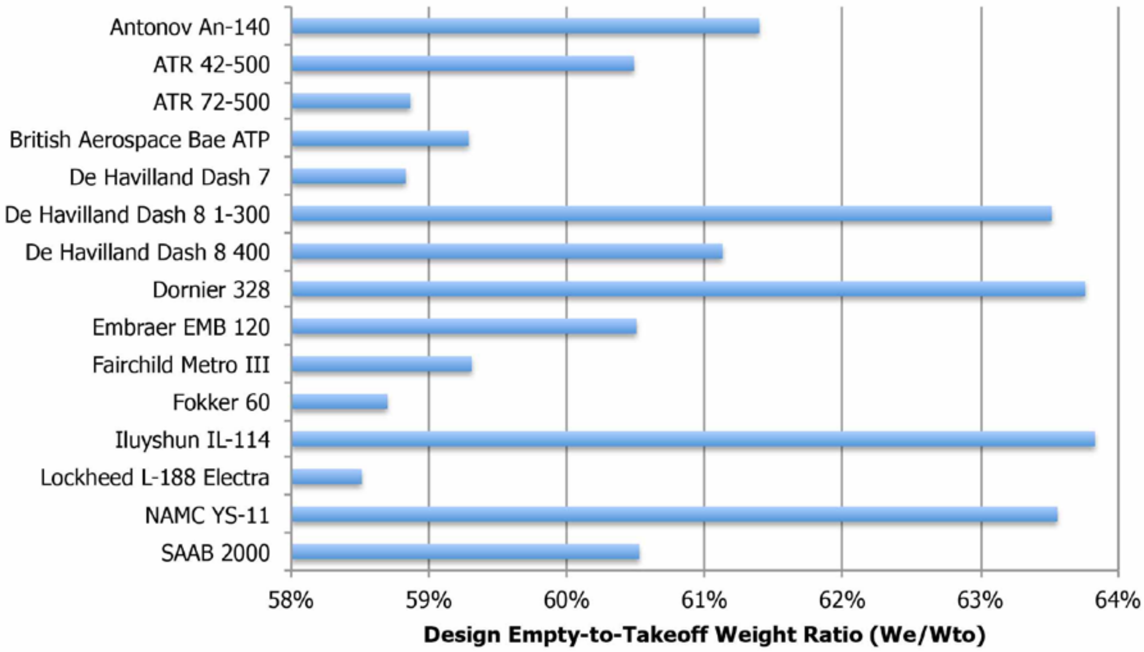

Figure 4 Representative Selection of Major Regional Turboprops in the Marketplace 1980-2014[13]

Clearly Fig. 4 shows that there is a comparatively tight distribution of We/Wto of modern regional turboprops. Indeed, if all are plotted together, then a chart mirroring Fig. 3 can be seen:

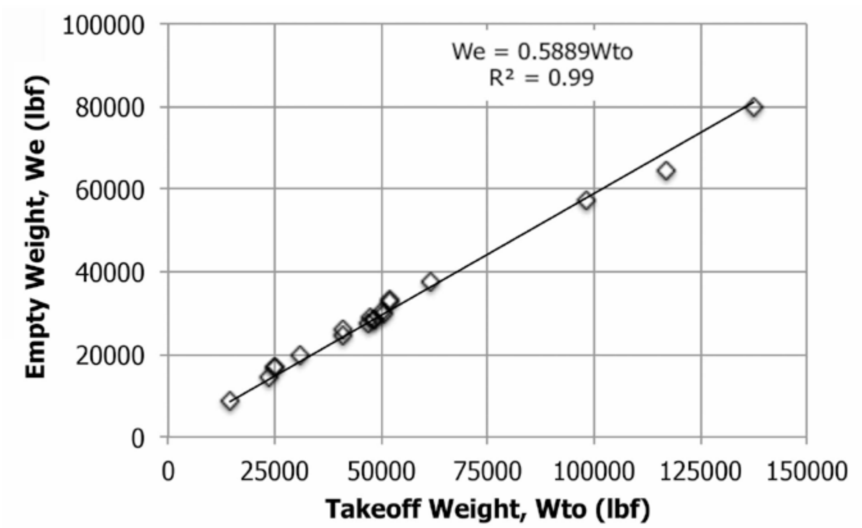

Figure 5 We/Wto Trends for Selection of Regional Turboprops in the Marketplace 1980-2014[13]

Interestingly, Figures 3 and 5 show regional turboprop We/Wto values from 1955 – 1983 and 1980 – 2014 respectively with excellent correlation. The reader will note that a general smearing of these aircraft properties demonstrates that roughly 30 years of evolution yields a reduction in We/Wto by only about 1%. If STAMPED principles are applied to the market, considering the properties that the market believes is important, then a more cyclical trend emerges:

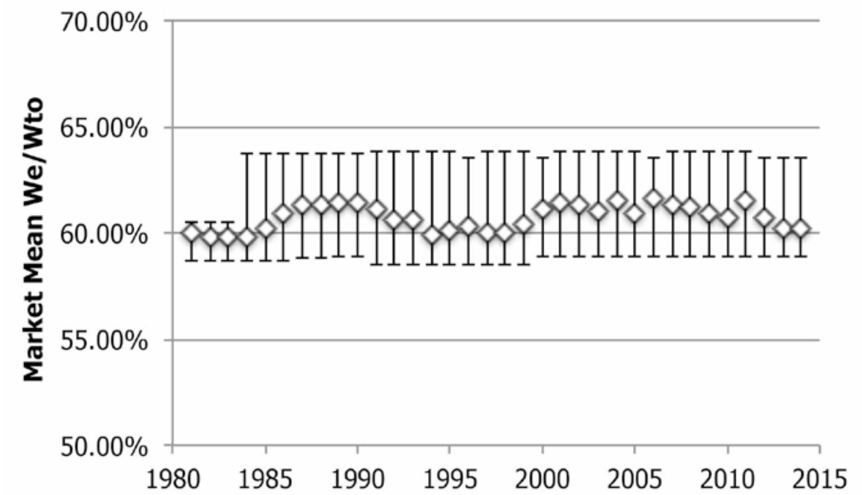

Figure 6 STAMPED Analysis Market Mean We / Wto Trends for Selection of Major Regional Turboprops in the Marketplace 1980-2014

Clearly the marketplace has settled on a narrow band of suitable We/Wto ratios. The error bars depict total ranges (not standard deviations) and demonstrate that the We/Wto ratio is close to constant with time with a mean value of the time-averaged means of 60.7% from 1981 through 2014. So for the purposes of preliminary design, rather than use the cumbersome log-iterative method of Reference 2 for preliminary sizing, it may be quite appropriate to allow students simply to select a well-established ratio of We/Wto in this very mature, well populated market.

Another important geometric variable which is directly related to aircraft design is aspect ratio, AR. If AR is tracked with time by using a STAMPED analysis, a far more profound trend can be observed:

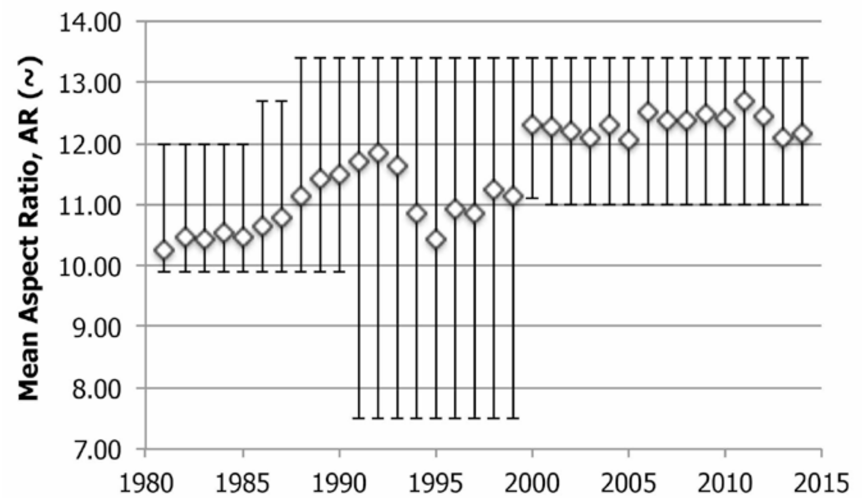

Figure 7 STAMPED Analysis Market Mean AR Trends for Selection of Major Regional Turboprops in the Marketplace 1980-2014

Clearly from Fig. 7 the presence of a “corrupting factor” is glaringly present from 1991 – 1999. If one looks closely at the market, then it becomes clear that sales of Lockheed Electras skew the numbers in the 1990’s severely. Because the design fix date of the Electras occurred decades before the rest of contemporary regional turboprops, it is doubtless quite appropriate to examine the market without the presence of the Electras. Accordingly, a steady trend in aspect ratios can be seen in Figure 8. While one may observe such a skewing factor in a given data set as an adverse characteristic the method, it clearly gives a complete perspective of the market. What is more important is that students who are observing the market must carefully observe and note the market trends and in doing so, they will (arguably) learn much more about the class of aircraft under study.

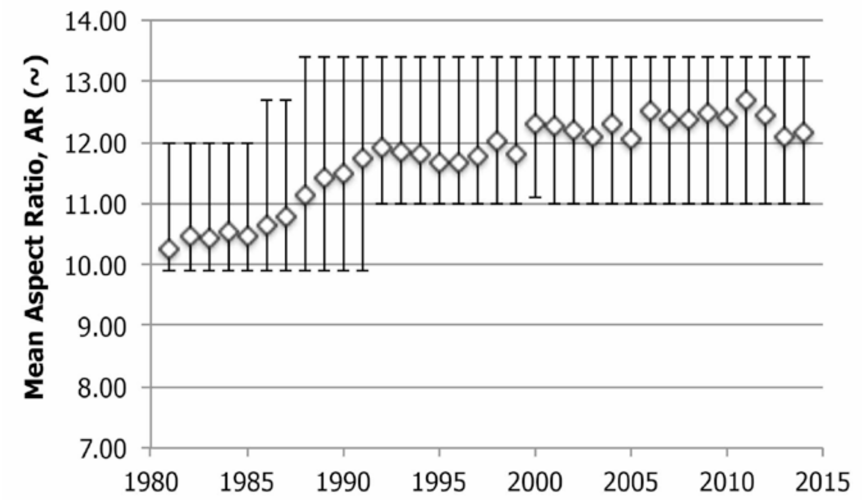

Figure 8 STAMPED Analysis Market Mean AR Trends for Selection of Major Regional Turboprops in the Marketplace Considering Design Fix Dates after 1970 Only (1980-2014)

Clearly, by observing the trends in modern regional turboprops, it can be seen that modern regional turboprop customers have settled on aircraft with aspect ratios just over 12:1. Accordingly, for preliminary sizing, it may be appropriate for students to start with aspect ratios in that range when laying out geometric characteristics for the first estimate of wing geometric characteristics. The interim goals of such an examination is, of course, to settle arrive at a drag polar, which allows for the students to arrive at representative cruise L/D ratios, which in turn, is needed to support Breguet Range and Endurance calculations in preliminary sizing.

If one examines Table 2.2 of Ref. 2, it can be seen that simple ranges of L/D are often suggested as well as values for propeller efficiency and specific fuel consumption. While these were reasonable values for the early 1980's, some of those numbers have changed rather significantly. Rather than rely upon individual tracking of variables, it is now possible to use market-related data to arrive at the hybrid of these variables to aid students in the preliminary sizing process. From manufacturers data, one can fairly easily calculate the Limit Passenger Seat-nmi/lbf of fuel as shown in Fig. 9.

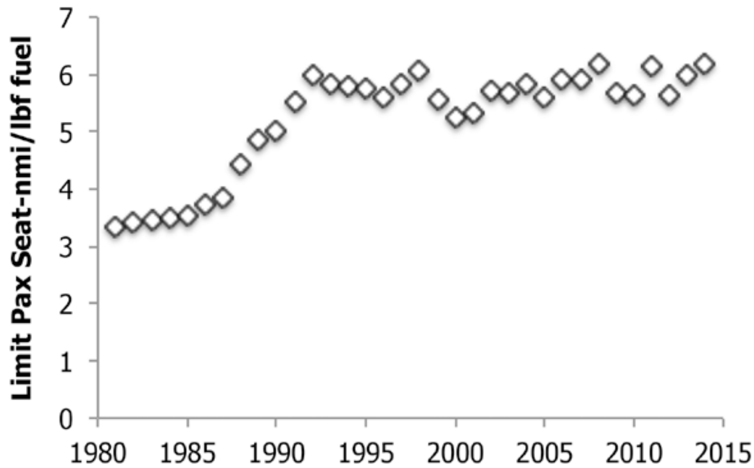

Figure 9 STAMPED Analysis Limit Passenger Seat-nmi/lbf of Fuel $\left(n_{pax}\frac{dR}{dW_f}\right)$ **Trends for Selection of Major Regional Turboprops in the Marketplace (1980-2014)**

Figure 9 represents a very important variable that is carefully tracked by the airlines as it gives to planners the ability to track fuel costs on a given route. For the purposes of preliminary sizing of aircraft, all a student needs to do to determine the amount of fuel burned in a given range segment is determine the limit seat-mile/lbf of fuel by extending the trending analysis out to the year desired, then determine: $\left(\frac{dW_f}{dR}\right) = \frac{n_{pax}}{\left(n_{pax}\frac{dR}{dW_f}\right)}$

For more versatility a student can calculate the Breguet constant considering a constant L/D cruise leg by applying: $\left(\frac{\eta_p}{C_p}\right)\left(\frac{L}{D}\right)_{cr} = \left(\frac{dW_f}{dR}\right)\left(\frac{1}{W}\right)$ to the traditional Breguet range equation considering a constant L/D: $R_{cr} = \left(\frac{\eta_p}{C_p}\right)\left(\frac{L}{D}\right)_{cr} Ln\left(\frac{W_i}{W_{i+1}}\right)$

If a student uses this number, advised by market trends then it can easily be argued that the initial weight sizing of the aircraft will not only be more accurate, but can also be adjusted to be more aggressive, less aggressive or exactly on historical trending. If rough estimates or valid ranges from decades old numbers are used, then they are bound to be substantially off target.

Following the initial weight sizing, rather than having a series of target numbers like Cp, L/D and η_p to match exactly to render their initial designs valid, they will have the product of $\left(\frac{\eta_p}{C_p}\right)\left(\frac{L}{D}\right)_{cr}$ which needs to be satisfied. Because three major variables come together to make this product, it gives the student much more leeway in the design process, thereby expanding the chances of achieving a successful design.

4 CONCLUSIONS

This document has presented several applications of Statistical Time and Market Engineering Design (STAMPED) techniques to improve the educational experience for aircraft design students. The method is shown first to enhance students' understanding of the deep and important history of their chosen field by demanding a thorough review of aircraft markets, aircraft types and time-dependent trends prior to the start of the design process. The second is to augment old aircraft design textbooks which contain good, highly relevant *procedures*, but are because they have not been updated in decades, their trending data is sometimes no longer valid. The third improvement comes in simplified methods for aircraft weight sizing which will allow students to use market data to arrive at market beating, relevant designs for aircraft that will not be produced for years to come.

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