Homework 7: Sizing Project

Ari Jain
arihant2@illinois.edu
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Similarity Analysis [1]

A similarity analysis is important in selecting a seed aircraft for the design of the aircraft outlined by the RFP. Rather than starting from a blank slate, there are existing aircraft that are used to take educated guesses on some design parameters that may otherwise have been completely off the mark. For an austere field light attack aircraft, there have been numerous aircraft made since World War II that fit the requirements of providing close air support to ground forces. Due to the versatility of a close air support aircraft, manufacturers have used a variety of engine types including turboprop, reciprocating, turbojet, and turbofan engines. Each of course comes with its advantages and disadvantages. To obtain a complete image of potential seed aircraft, one aircraft that has each of the four engine types is analyzed. An A-10 Thunderbolt II is the examined turbofan, A1 Douglas Skyraider the reciprocating, SU-25 Frogfoot the turbo jet, and finally the Embraer Super Tucano as the turboprop. The submitted spreadsheet contains the collection of all the important data that could be found or estimated for these aircraft from various sources.

Looking at key parameters such as maximum ramp weight, wing area, geometric dimensions, one notices there is a large variance amongst the aircraft that in general all adequately serve the same purpose. On the larger end, the A10 has a maximum ramp weight of 50000 lbs and a wing area of 506 square feet. It is capable of carrying a payload over five times that of that required in the RFP. The SU-25 is similar in that it has a ramp weight of 42549 pounds and carries three times the desired payroll. In comparison, the A1 and Super Tucano, which only have one engine that are not jet powered, weigh far less. Out of the all of the aircraft analyzed, the Super Tucano most closely resembles the parameters outlined by the RFP. It carries at 3300 pound payload with a ferry range of 847 nautical miles. Although the Super Tucano is most similar, doing the initial sizing process is slightly more involved because it uses a turboprop engine. Therefore, in the sizing spreadsheet, the A10 is initially used to verify that the spreadsheet works, but the parameters estimated for the sizing of our aircraft are largely taken from the Super Tucano. This will be explained in detail later on.

Constraint Analysis

A constraint analysis is important in the design process as it establishes bounds for the thrust to weight ratio and wing loading, which are the two most important parameters in initial sizing. Some of the constraints are defined by the RFP given by AIAA. For example, the aircraft must have a take-off field length (TOFL) and landing field length (LFL) of less than 4000 ft. As briefly alluded to earlier, the aircraft should be able to carry 3000 pounds of payload. The RFP outlines both a design mission and a ferry mission that the aircraft must both satisfy. The design mission accounts for the aircraft loitering for four hours, which is difficult to incorporate into the current sizing analysis in its current scope. Therefore, the ferry mission is used as the outline. It still requires a TOFL and LFL of 4000 ft while being able to cruise for 900 nautical miles after climbing. It also prescribes that there be enough reserves to climb to 3000 ft and loiter for 45 minutes in case of any unforeseen emergencies.

Chapter 5 of Raymer outlines the process for finding the wing loading and thrust to weight ratio that is shown by the given constraint diagram in Figure 1 [2]. It is assumed that the plane takes the full 4000 feet to land and take off. Since both of these occur at sea level, $\sigma = 1$. Figure 5.4 in Raymer gives a method for estimated a slope of the balanced field length line. For a jet aircraft with two engines, this slope is approximately 38. Note that Figure 5.4 is based on FARs and takeoff distnace includes clearance of a 50 foot obstacle, which is identical to the RFP requirements. The remaining parameter to be estimated is the $C_{L,\max}$ at takeoff. This is traditionally a difficult parameter to estimate without having more information about the aerodynamics of the aircraft. Roskam gives an estimation for $C_{L,\max}$ at takeoff for fighters as a range between 1.4-2.0 and at landing between 1.6-2.6 [3]. For the sake of our calculations, $C_{L,\max}$ at takeoff will be taken as 1.6 and landing will be taken as 2.1, which is the average of both ranges.

It is important to note that in order to produce a correct constraint diagram, the thrust to weight ratio and wing loading values obtained must be obtained for the same point in flight. Therefore, although the max landing coefficient will be used in the initial calculation, Raymer gives the weight ratio between takeoff and landing, $\frac{W_{TO}}{W_{Land}}$, as 0.835. Therefore, per the takeoff parameter expression given on the x-axis of Raymer Figure 5.4, the wing loading obtained using the landing numbers must be divided by 0.835 to give the value of 73.92 lb/square feet that is shown plotted by the gray vertical line. From Raymer Equation 5.2, one also knows that

$$(\frac{T}{W})_{\text{cruise}} = (\frac{L}{D})^{-1}_{\text{cruise}} \tag{1}$$

The lift to drag ratio can be estimated following the process from Homework 4. Once cruise altitude and Mach number are determined, which in this case are defined by the RFP, estimations for wing area taken from the similarity analysis and top of climb weight, which is a fraction of the ramp weight given by Raymer, are used to find the coefficient of lift. The coefficient of drag requires parasitic drag to be known, which is given by Raymer Equation 12.23. A more detailed outlined of this estimation is given later. However, one finds the L/D to be 14.92. Correcting between cruise and takeoff as was done in landing, a cruise T/W adjusted for takeoff was found to be 0.36. Finally, the orange line in Figure is determined by calculating the T/W for a range of wing loadings. In this case, the wing loadings were ranged from 40 to 100 lb/square foot and the formula used was again from the x-axis of Raymer Figure 5.4 [4, 5]. The valid design region is highlighted by red.

Sizing Analysis

The sizing spreadsheet takes 35 inputs from the user in order to initially size the airplane. The four most important are at the very beginning and are the required range, required balanced field length, wing area, and aspect ratio (AR). Some of the inputs are defined from the RFP. For example, the payload for the ferry mission is 60% of the maximum payload, which is equal to 1800 pounds. Some of the inputs are estimated from the Super Tucano as it is the most similar to the desired design. This mainly applies to geometric sizing of the aircraft. The length of the fuselage, wing sweep, and wing taper were all estimated as being relatively close to the Super Tucano. It was intended that the sized aircraft would operate with jet engines. Since the Tucano uses a turboprop, those parameters could not be used to size the engine and nacelle. Therefore, SU-25 Frogfoot data was used for those estimations.

Other parts of the inputs are taken from Raymer estimations. For example, Raymer describes the limit load factor for a fighter to be 6.5. Incorporating a 1.5x safety factor, we arrive at 9.75 ultimate limit load factor that was used in calculations. Table 15.2 was used to estimate weight trades for the fuselage, horizontal tail, and vertical tail. Breguet range constants, weight fractions, and wetted area formulas were also taken from Raymer estimations. One of the more important calculated parameters in the spreadsheet is the stuffed wing weight area. This is composed of the structural weight of the wing plus additions for the systems within the wing itself. There are numerous textbooks that have empirical equations for the weight of a wing. Raymer and Roskam both offer independent equations that take a variety of inputs. Using both of these equations, it was found that the wing weights estimated by the independent equations were 1000 pounds apart. Raymer estimated the wing weight to be 4250 pounds and Roskam as 5250 pounds for the seed A10. As such, an average of the two formulas were used in the actual sizing calculations.

To optimize the aircraft, the dimensional variables of wing area and aspect ratio were varied to create contour plots that showed trends in maximum ramp weight and empty weight of the aircraft. Additionally, T/W IPPS of the engine and SFC of the engine are also varied to analyze the effect on the wing area and aspect ratio. From the similarity analysis, a range of wing areas and aspect ratios were determined to be examined. Wing areas of 375:25:625 square feet and aspect ratios of 3.5:0.5:7.5 were plotted. T/W IPPS was varied 3:0.5:6.5 and SFC was varied 0.3:0.05:0.65 lb/lb-hour. The contour plots for these are given by Figures 2-5. Note that T/W IPPS and SFC were varied independently of each other and that all other inputs were kept constant during the calculations. Also, for the varying SFC, the T/W IPPS of the Super Tucano was taken as an estimate and for T/W IPPS, the SFC of the Super Tucano was taken for calculations. Although these numbers may not exactly be accurate, they are able to show the general trends that one can expect from sizing and allow some preliminary design decisions to be made.

Figure 2 shows that as one increases the T/W IPPS of the engine, the max ramp weight and empty weight of the aircraft decrease. Intuitively, this is relatively easy to understand as the engine is producing more thrust compared to its weight. Since the rest of the aircraft parameters are staying constant, more thrust means the aircraft can reach its destination in a shorter amount of time and use less fuel. Therefore, the aircraft overall weighs less. There is little to no effect that can be seen along the axis of the wing area as we are not looking at the T/W of the whole plane, but rather just the engine. Figure 3 in general shows the same trends as Figure 2 for the same reason. As such, one would aim to find a engine that maximizes T/W IPPS in order to decrease weight, which will in turn reduce operating costs and save money. Although this can intuitively be concluded, it is helpful to have data to solidify these findings and quantify the trend. In order to maintain realistic parameters for aspect ratio and wing area, one could conclude that a T/W IPPS of at least 5.5 should be considered, which helps narrow down the choices of engines should a fixed engine design be used.

Figures 4 and 5 analyze the effects of changing the SFC of the engine. Figure 5 shows that once again wing area has relatively little effect on the SFC. However, as aspect ratio is increased, the empty weight for any given SFC rises. Further, for any given aspect ratio, the empty weight rises when the SFC rises. As the aspect ratio increases, while keeping the wing area constant, the span of the wing also increases. Since the span is larger, both the empty weight and the maximum ramp weight see increases. The initial trend of increasing weight can be seen in Figure 4, however, at higher SFCs, one notices a bottom half of a circular trend come into the picture for our analyzed parameters. This means that of course there is some center of the contour, which by the shading seems to be the minimum, and one either decreases both aspect ratio and wing area or increases both aspect ratio and wing area, the maximum ramp weight increases. This circular trend can also be seen at low T/W IPPS in Figure 2. Based on the plots, an SFC between 0.35 and 0.45 lb/lb-hour would be ideal for this application. Between the thrust to weight and SFC optimizations, it will be much easier to select engines that are suitable for this aircraft.

References

[1] Taylor, J. W. R., *Jane's all the world's aircraft, 1982-83: Seventy-third year of issue: The annual record of aviation development and progress*, Jane's Publishing Company, 1987.

[2] Raymer, D. P., *Aircraft design: a conceptual approach*, AIAA education series, American Institute of Aeronautics and Astronautics, Inc, 2018.

[3] Roskam, J., *Airplane design*, DARcorporation, 2002.

[4] Perkins, C. D., and Hage, R. E., *Airplane performance stability and control*, Wiley, 1949.

[5] Loftin, L., *Subsonic Aircraft: Evolution and the Matching of Size to Performance*, NASA reference publication, NASA, 1980. URL `https://books.google.com/books?id=aIM4AQAAIAAJ`.

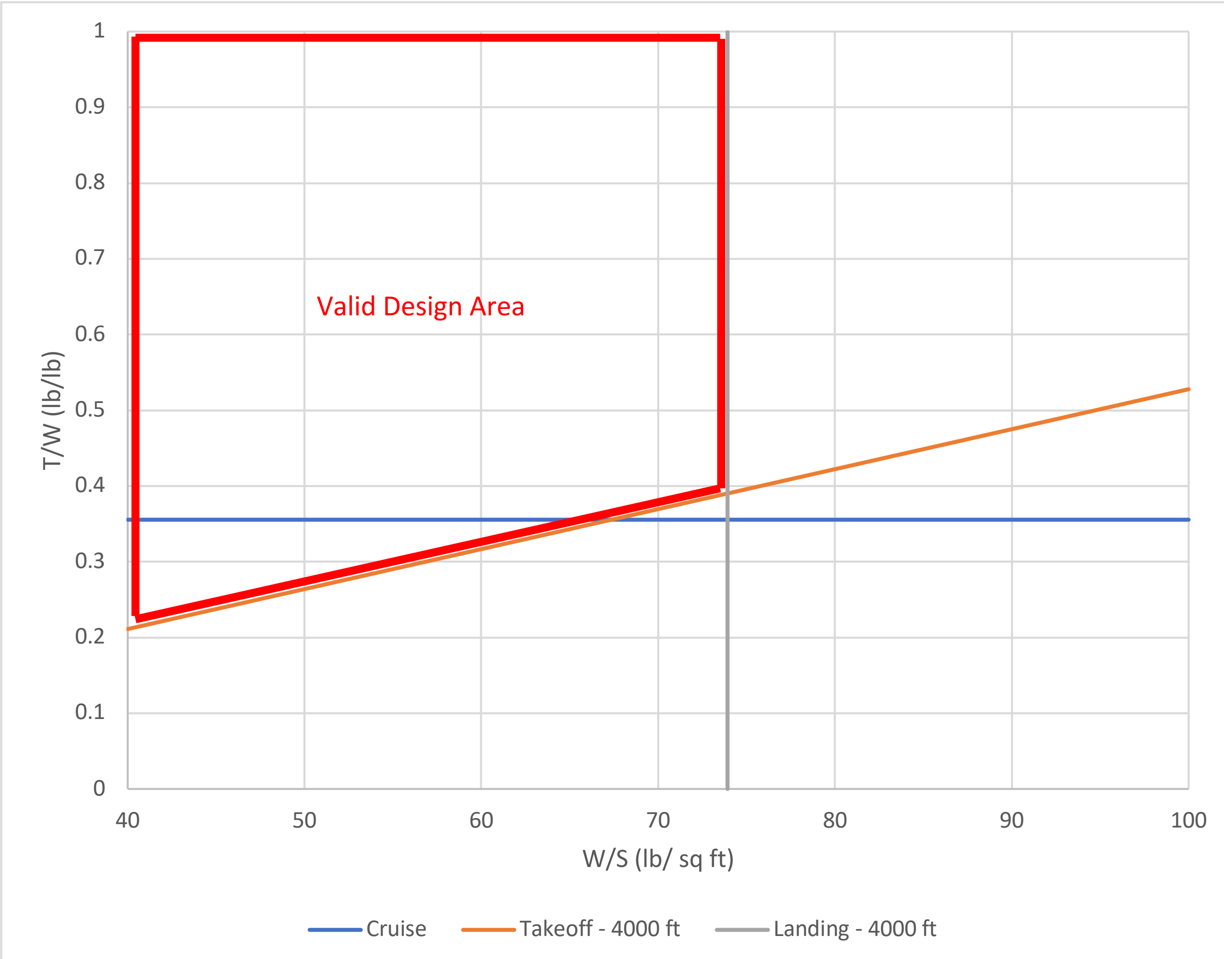

Figure 1: Constraint Diagram

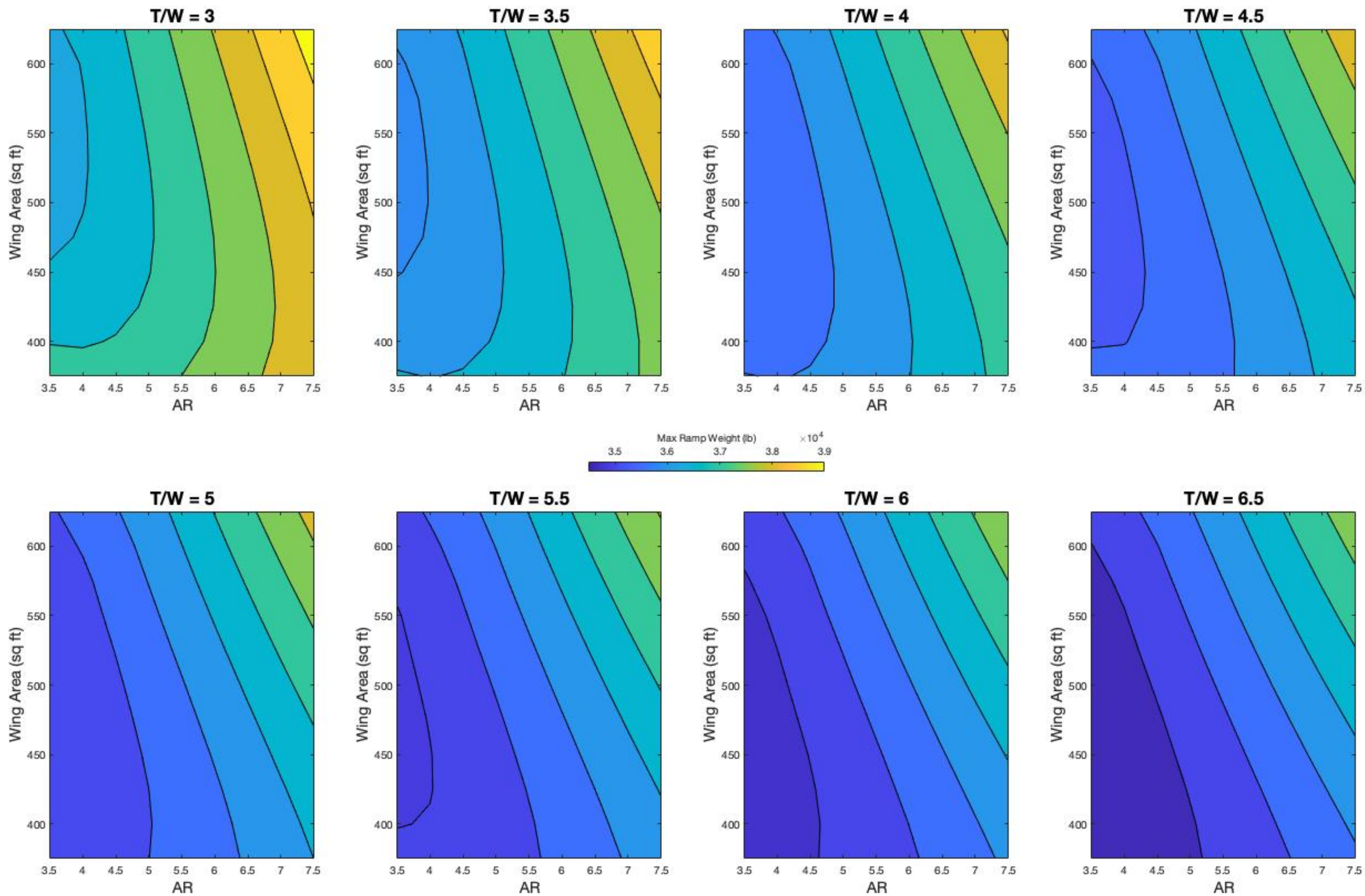

Figure 2: Dimensional Diagrams for Max Ramp Weight with varying T/W IPPS

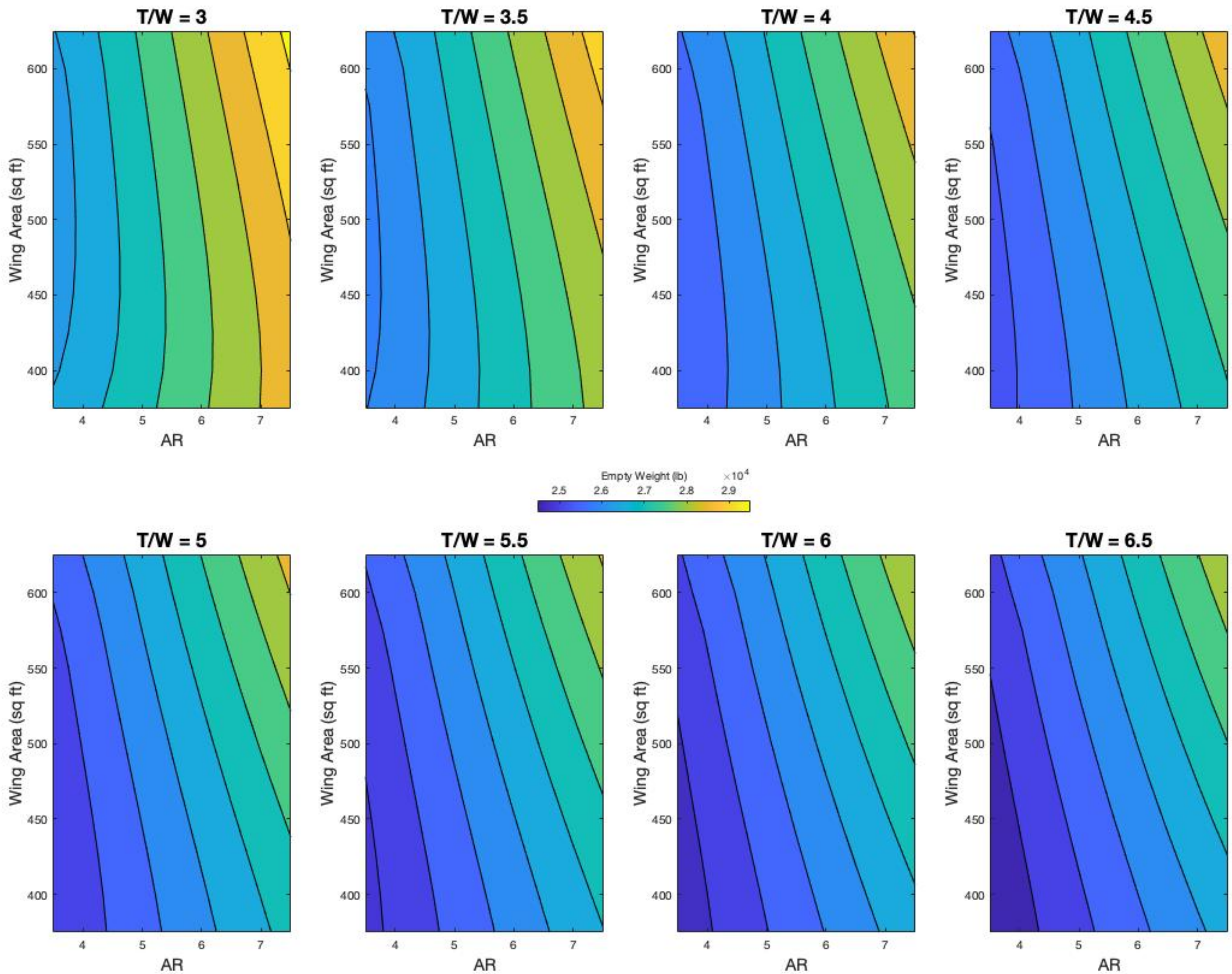

Figure 3: Dimensional Diagrams for Empty Weight with varying T/W IPPS

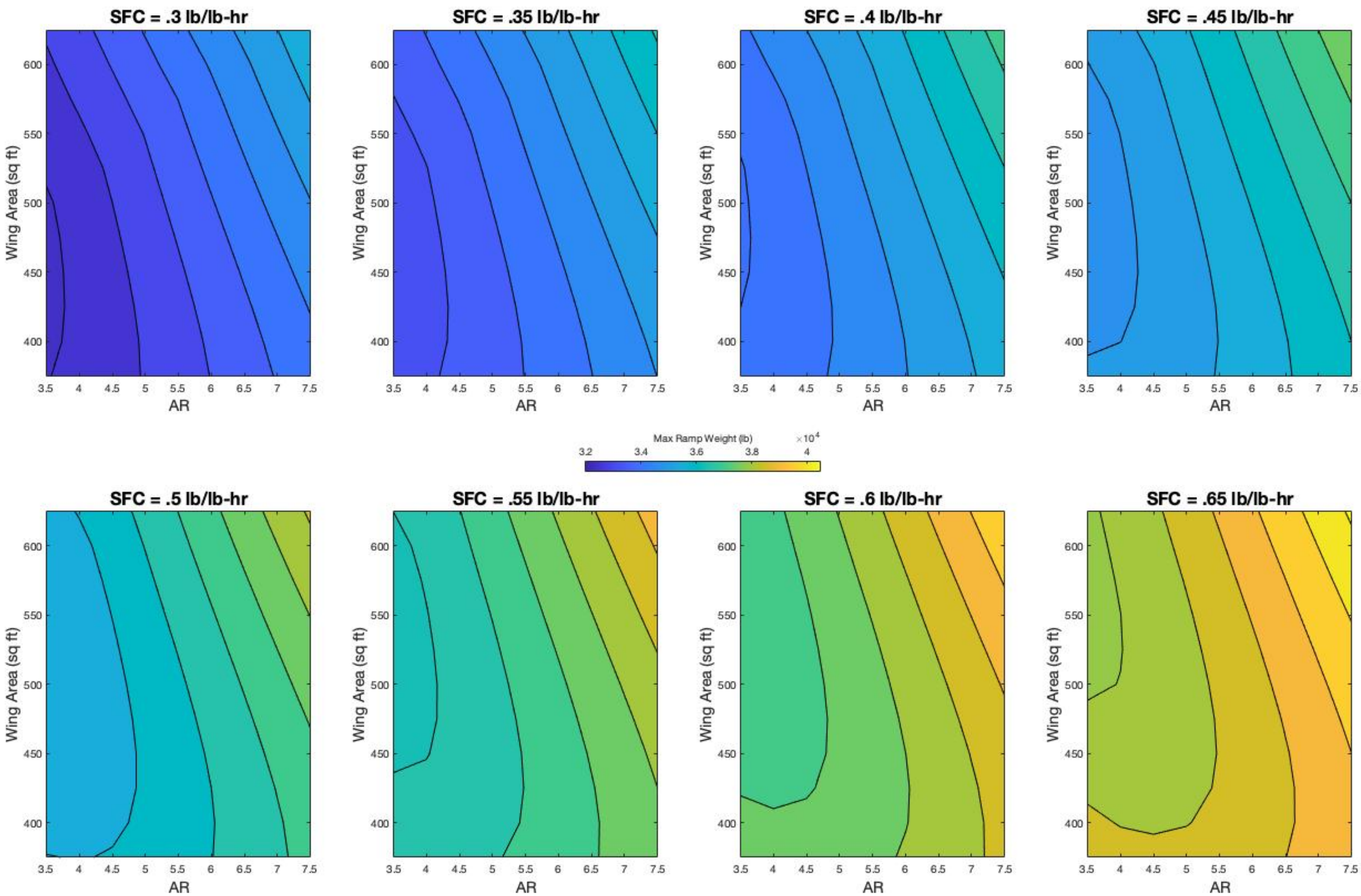

Figure 4: Dimensional Diagrams for Max Ramp Weight with varying SFC

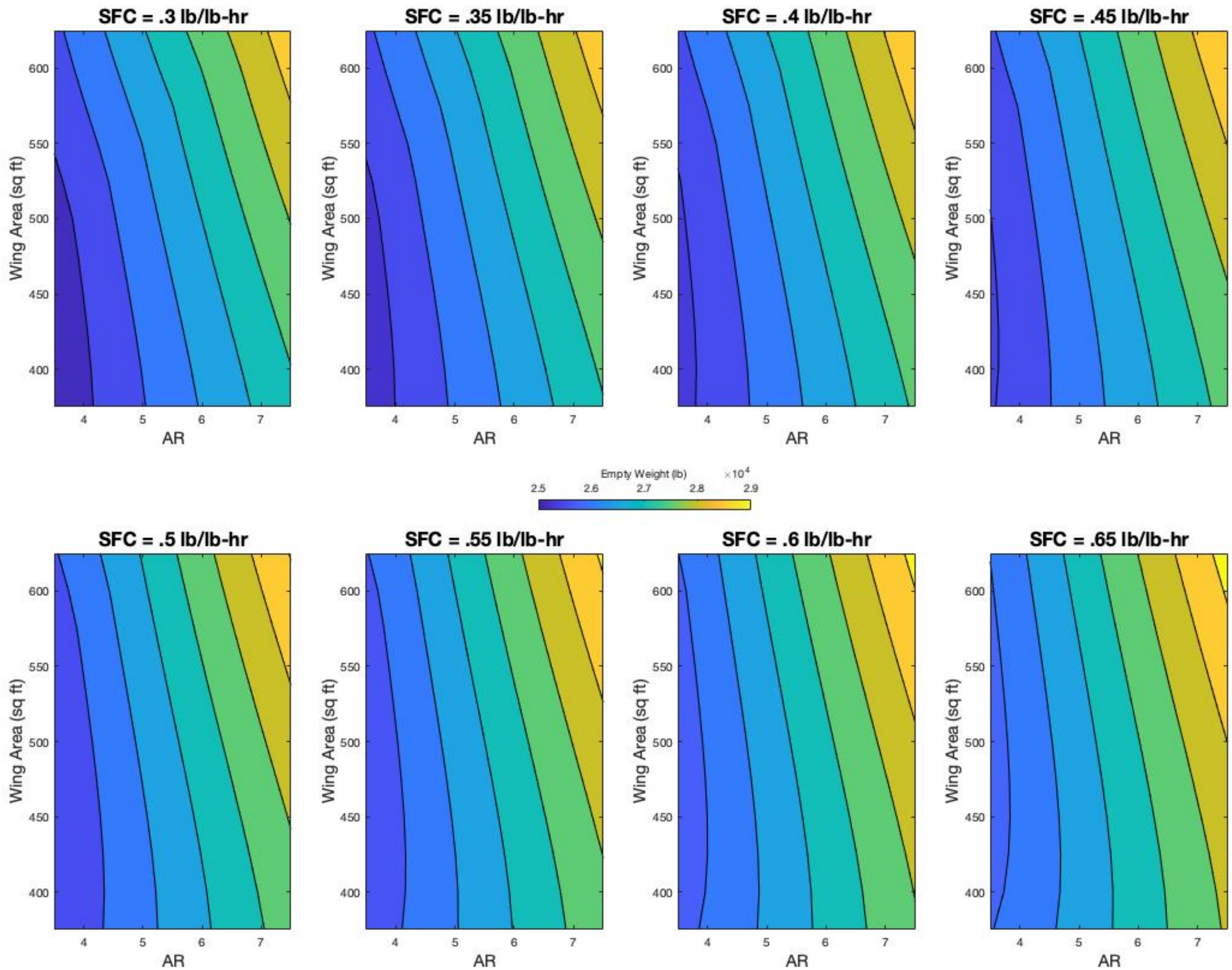

Figure 5: Dimensional Digrams for Empty Weight with varying SFC