Aeronautical Engineering Design II

Sizing Matrix and Carpet Plots

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Empty weight estimation and refined sizing

- Empty weight of the airplane was calculated using statistical group weights method by a detailed estimation of the weight of each component of the aircraft.
- Empty weight thus calculated will usually not be equal to the empty weight previously calculated using approximate group weights method.
- It is possible to go back to the detailed weight equations and recalculate the empty weight using statistical group weights method $\Rightarrow$ too prohibitive in terms of time required.

Empty weight estimation and refined sizing

- An approximate non-computerized method relies on statistical data:

$$\frac{W_e}{W_o} \searrow \text{ as } W_o \nearrow$$

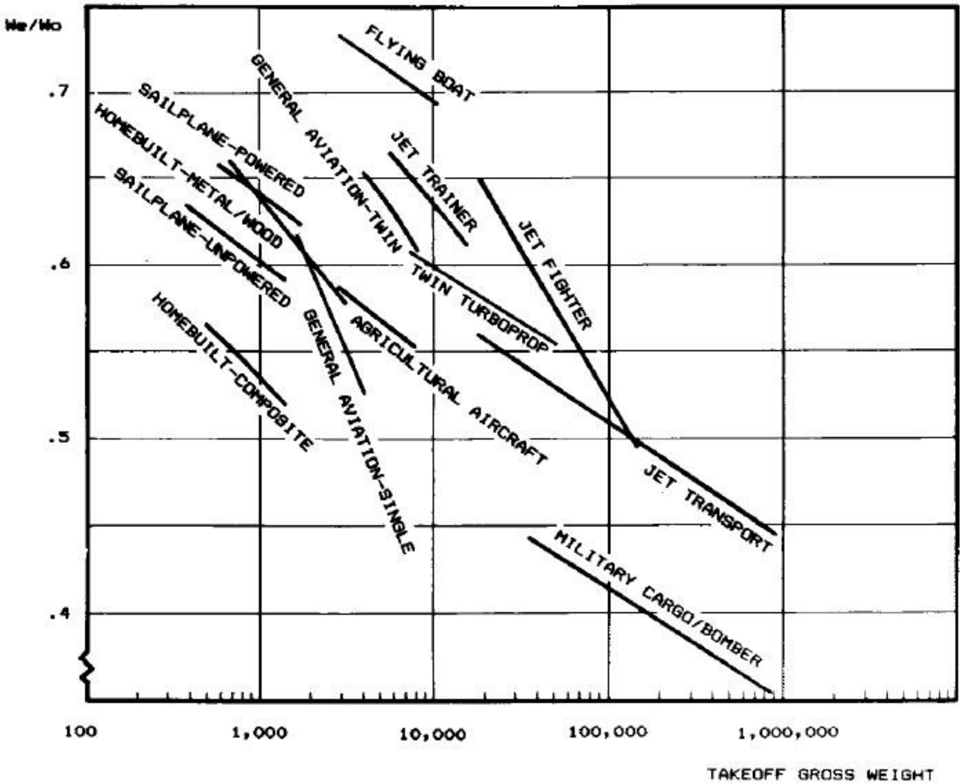

Fig. 3.1 Empty weight fraction trends.

Empty weight estimation and refined sizing

- Empty weight:

$$W_e = W_{e,as\ drawn}\left[\frac{W_o}{W_{o,as\ drawn}}\right]^{1+c},\ c \approx -0.1$$

- For c:
  - Either use a statistical value $(c \approx -0.1)$ or:
  - Calculate for a specific airplane. Make an arbitrary change (e.g. 10%) in W_o and recalculate W_e with all effects considered including changes in wing and tail areas, increased fuselage size, heavier landing gear and larger engine. With the new value of W_o and W_e, solve for c in the above equation.

Empty weight estimation and refined sizing

Methodology:

- With an initial estimate of W_o (as drawn) and W_e (as drawn), calculate the fuel weight W_f by using the refined sizing analysis.
- Using $W_o = W_{e,as\ drawn} + W_f + W_c + W_p$ obtain a new value of W_o.
- Using $W_e = W_{e,as\ drawn}\left[\dfrac{W_o}{W_{o,as\ drawn}}\right]^{1+c}$ obtain a new value of W_e.
- Iterate until convergence.

Sizing matrix method

- The sizing procedure described ensures that the as-drawn aircraft will meet the required mission range or other important performance criteria.
- The configuration geometry was initially selected to meet the requirements based on assumptions for lift, drag, thrust, etc.
- The aircraft sized using the method described will have different characteristics and may no longer meet all requirements or may exceed all of them $\Rightarrow$ the aircraft is overdesigned and is not the lighest possible design.

Sizing matrix method

- Thrust-to-weight ratio (T/W) and wing loading (W/S) are varied from the baseline values (typically $\pm$ 20 %).
- Each combination of T/W and W/S produce a different airplane with different aerodynamics, propulsion and weights. Size each of the airplanes separately to determine the takeoff weight of each to perform the <u>design mission</u>.
- Analyze each combination separately for performance.
- If the T/W and W/S variations are wide enough, at least one aircraft will meet the requirements.

Sizing matrix method

- What combination of T/W and W/S will meet the all the requirements at a minimum weight.

	$W/S = 50$	$W/S = 60$	$W/S = 70$
$T/W = 1.1$	1 W_0 = 56,000 lb P_s = 700 fps (M0.9, 30k ft, 5g's) S_{TO} = 340 ft a = 46 s	2 W_0 = 49,000 lb P_s = 330 fps S_{TO} = 430 ft a = 42 s	3 W_0 = 46,000 lb P_s = 30 fps S_{TO} = 660 ft a = 39 s
$T/W = 1.0$	4 W_0 = 48,500 lb P_s = 430 fps S_{TO} = 450 ft a = 50.5 s	5 RESIZED BASELINE W_0 = 43,700 lb P_s = 30 fps S_{TO} = 595 ft a = 47 s	6 W_0 = 42,000 lb P_s = −190 fps S_{TO} = 800 ft a = 45 s
$T/W = 0.9$	7 W_0 = 44,000 lb P_s = 140 fps S_{TO} = 670 ft a = 56 s	8 W_0 = 39,000 lb P_s = −230 fps S_{TO} = 810 ft a = 53 s	9 W_0 = 36,000 lb P_s = −320 fps S_{TO} = 1070 ft a = 51 s

Require: $P_S \geq 0$ at (M0.9, 30k ft, 5g's)
$S_{TO} \leq 500$ ft
$a \leq 50$ s from M0.9 to M1.5

Fig. 19.1 Sizing matrix.

Sizing matrix plot

- Start optimization of T/W and W/S by cross-plotting the sizing matrix data in terms of chosen performance characteristics and takeoff weights.
- From the takeoff weight graphs, wing loadings corresponding to regularly spaced arbitrary gross weights are determined.

Sizing matrix plot

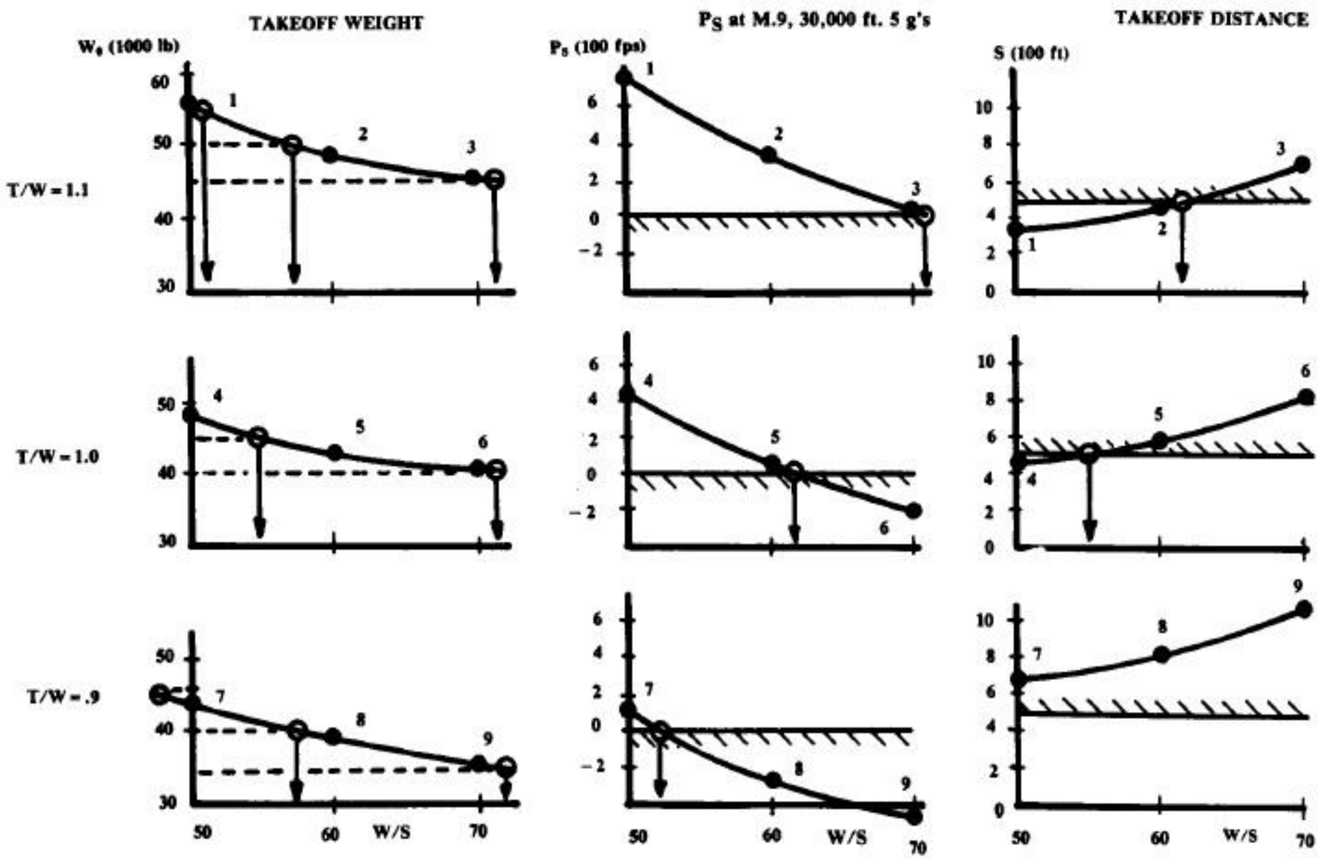

Fig. 19.2 Sizing matrix cross plots.

Sizing matrix plot

- T/W and W/S values for the arbitrary gross weights are transferred to a $W/S - T/W$ graph.
- Smooth curves are drawn connecting various points with identical gross weight to produce lines of constant takeoff gross weight.
- From these curves, it is possible to determine the sized takeoff weight for any combination of T/W and W/S.

Sizing matrix plot

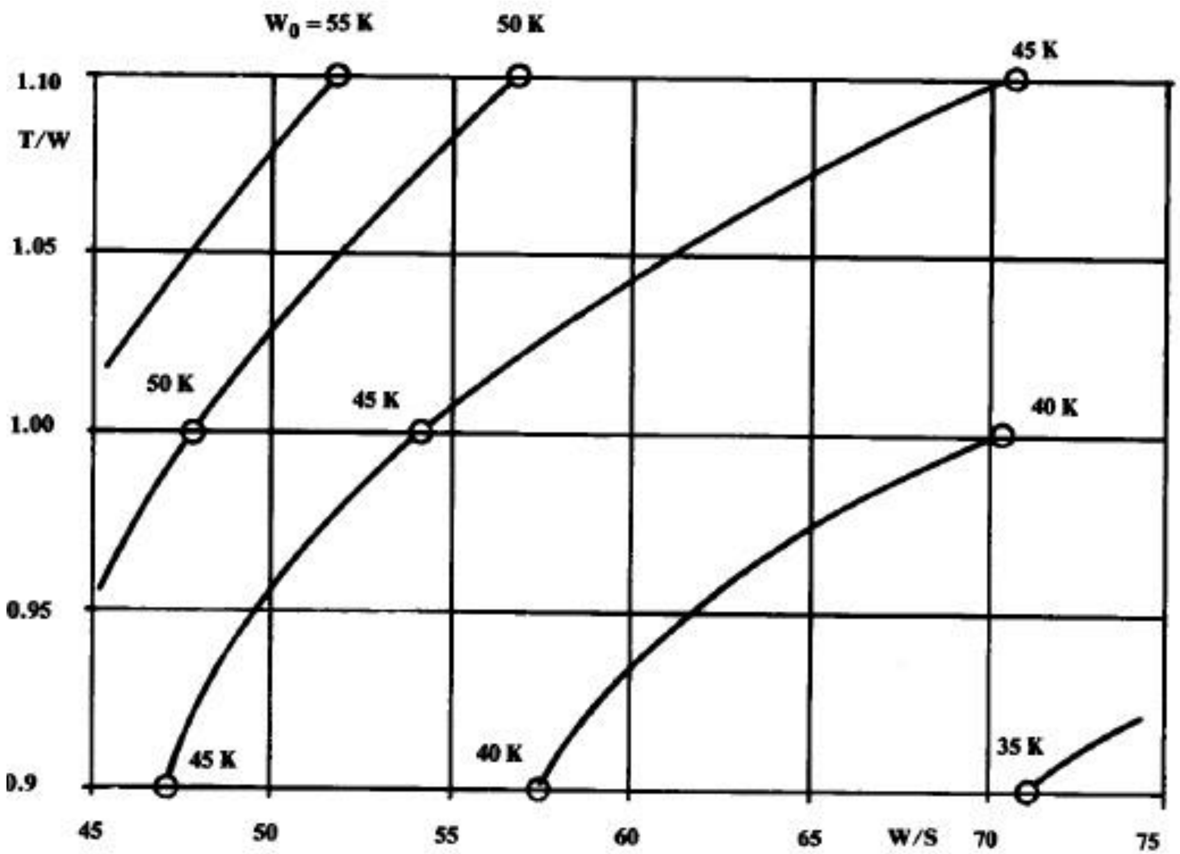

Fig. 19.3 Sizing matrix plot (continued).

Sizing matrix plot

- W/S values that exactly meet various performance requirements are obtained from the performance plots for different T/W values.
- The combinations of T/W and W/S that exactly meet a performance requirement are transferred to the W/S - T/W and connected by smooth curves.
- The desired solution is the lighest aircraft that meets all the requirements.
- It is usually a combination where two constraint lines meet.

Sizing matrix plot

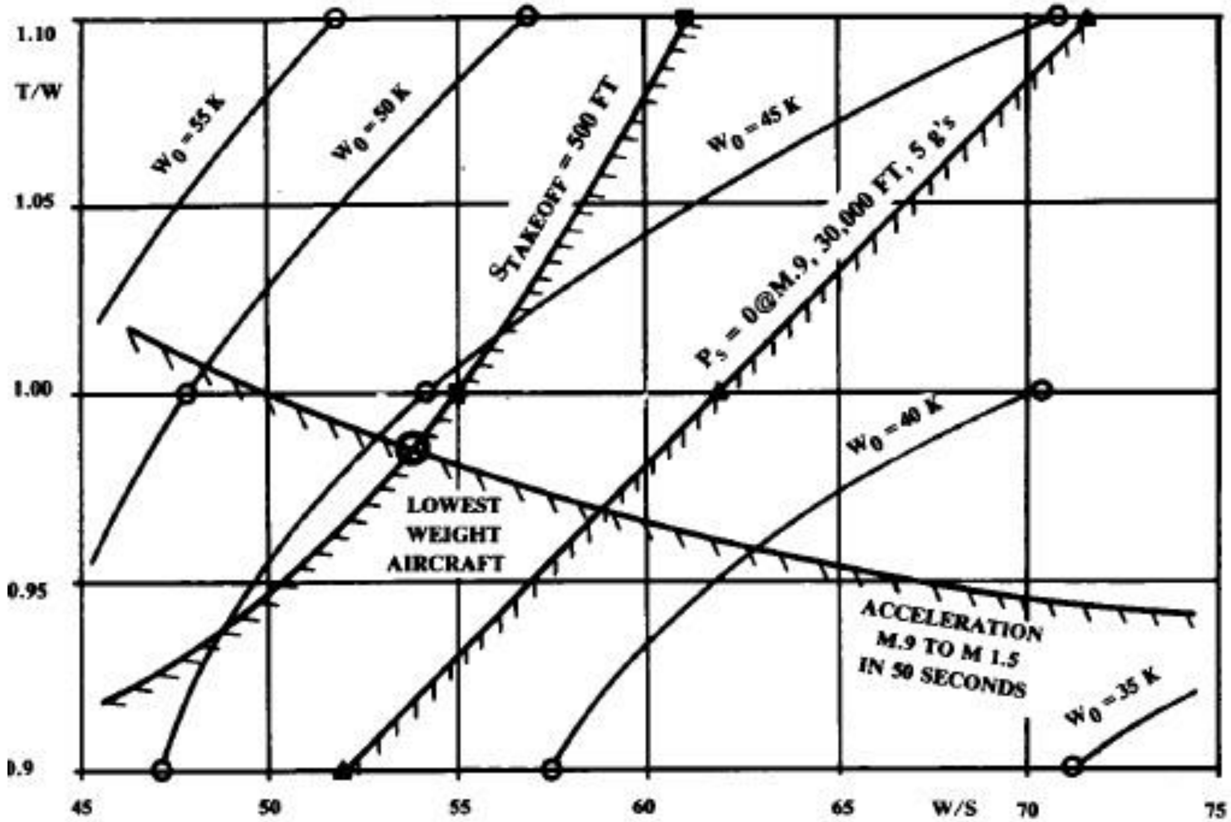

Fig. 19.4 Sizing matrix plot (concluded).

Carpet plots

- Carpet plot is based on superimposing the takeoff weight plots like in

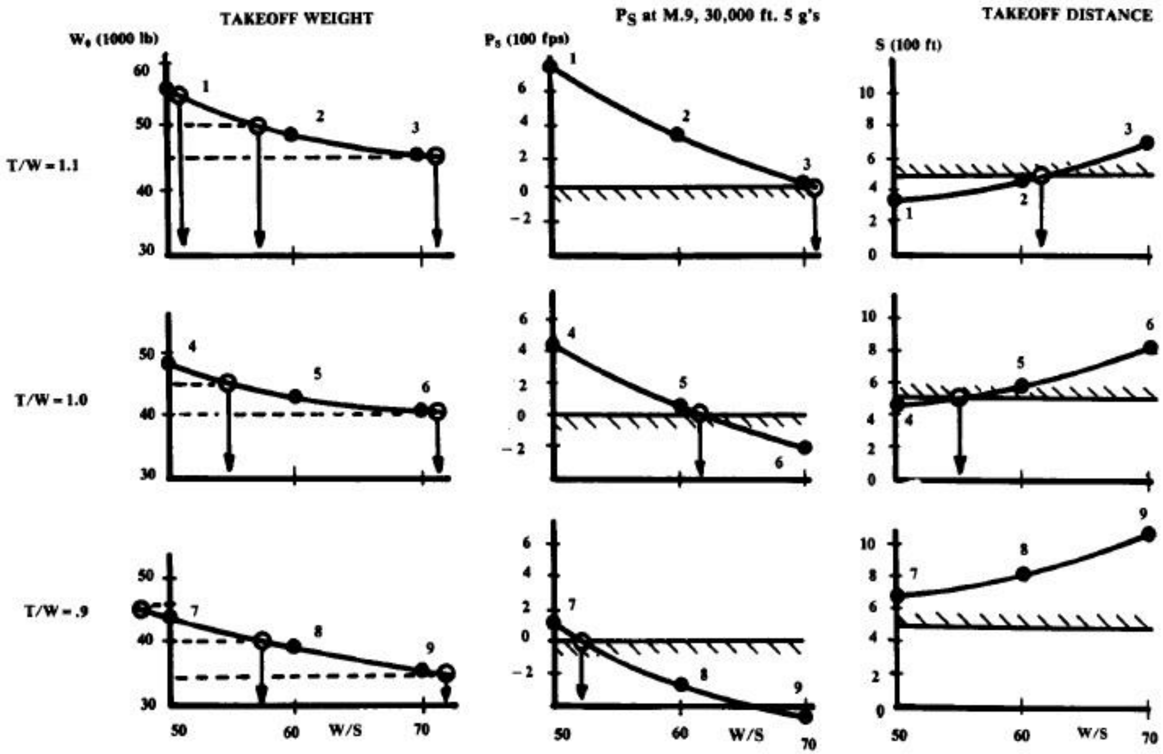

Fig. 19.2 Sizing matrix cross plots.

Carpet plots

- Plot W_o as a function of W/S for say $T/W = 1.1$,
- Plot W_o as a function of W/S for say $T/W = 1.0$. To avoid clutter, shift the horizontal axis to left by some arbitrary distance.
- Plot W_o as a function of W/S for say $T/W = 0.9$, again shifting the horizontal axis.

Carpet plots

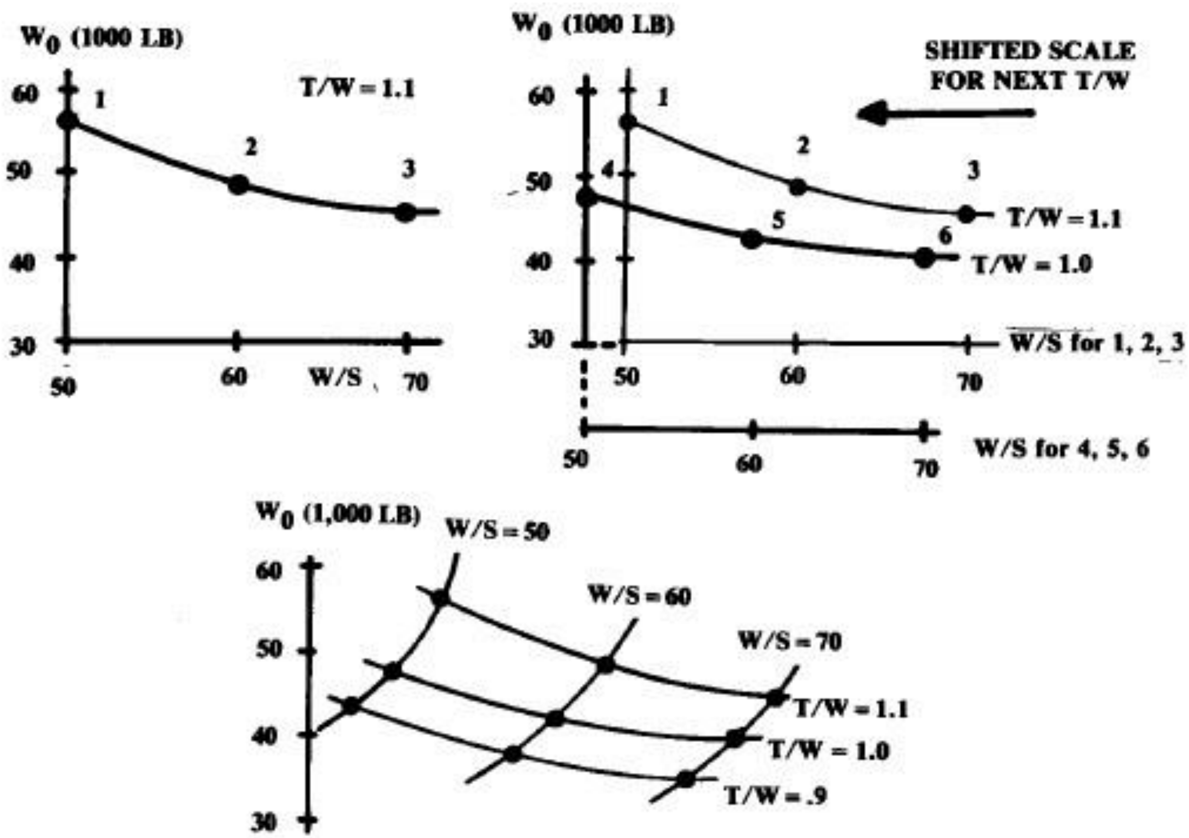

Fig. 19.5 Carpet plot format. (same results!)

Carpet plots

- Mark and connect with smooth constraint lines, the wing loadings that exactly meet requirements, say takeoff distance, P_s and accelaration time.
- The optimal airplane is the one corresponding to the lowest point on the curve that meets all the constraints.
- It is possible to create carpet plots in which the figure of merit is the cost rather than the weight.
- For most airplane types minimization of weight will also minimize the cost.

Carpet plots

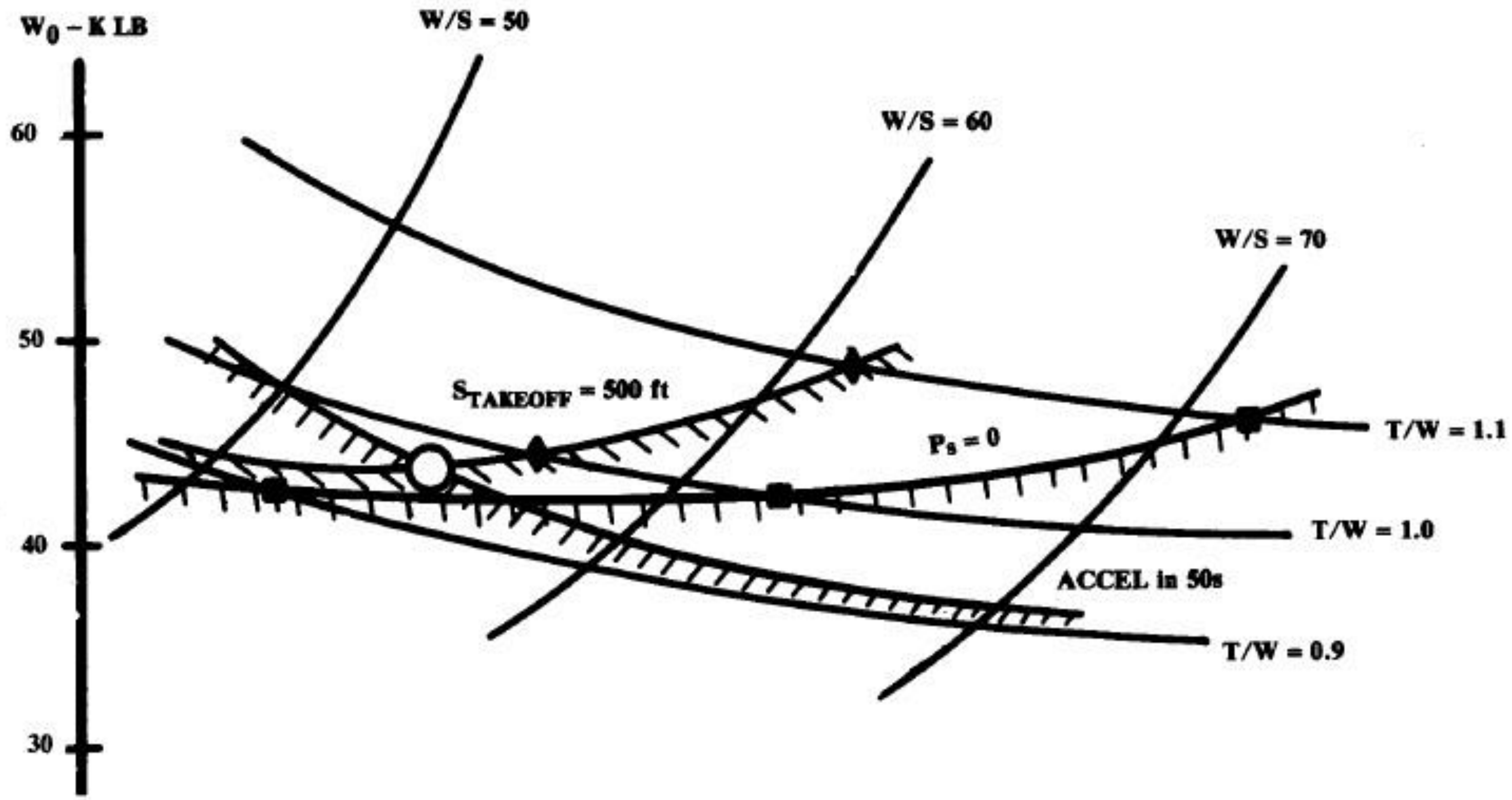

Fig. 19.6 Completed carpet plot.

Trade studies

- Trade studies allow the true optimum airplane emerge.
- The most basic trade study is the T/W and W/S carpet plot.
- Trade studies commonly undertaken in aircraft design:
  - Design trade: reduce the weight and cost of the airplane to meet a given set of mission and performance requirements.
  - Requirements trade: determine the sensitivity of the airplane to changes in the design requirements.
  - Growth sensitivity trade: determine how much the weight of the airplane will change if various parameters such as drag or specific fuel consumption should increase.

Trade studies

- Design trade studies must be calculated using a complete T/W and W/S carpet plot for each data point.
- For example, for an optimization of aspect ratio, sweep, T/W and W/S 3x3x3x3=81 parametric variations of the airplane are needed.

Sizing matrix data approximations

- Variation in T/W: variation in thrust and fuel flow $\Rightarrow$ wetted area and wave drag increase due to change in nacelle size.
- Variation in W/S: variation in wetted area and wave drag $\Rightarrow$ variation in K because the fuselage covers more or less of the wing span.

Sizing matrix data approximations

Approximations:

- $C_{Do} \sim S_{wet}$ due to wing area and nacelle size variations.
- $S_{wet,wing} \sim S$.
- $S_{wet,nacelle} \sim T$.
- $C_{D,wave}$ must be recalculated.
- $S_{wing,cross\ section} \sim S_{wing}$.
- Variation in K may be neglected but if the wing area changes, the airplane will fly at a different C_L, effecting K.

Sizing matrix data approximations

Approximations:

- $W_{wing} \sim S_{wing}^{0.7}$ (same holds for tail surfaces).
- $W_{engine} \sim T^{1.1}$.
- $T_{installed} \sim T_{uninstalled}$.