C19. Use of empirical/semi-empirical methods in computational design

W.H. Mason, June 2017

These comments are based on my own experience, although mostly vicariously through students.

First, I'm a fan of empirical and semi-empirical methods. They definitely have a place in design. That said, these comments address the use of empirical methods in computational design, and especially when doing numerical optimization and MDO.

Numerical optimization, and gradient based methods in particular, has some characteristics that cause a surprising amount of trouble when coupled with empirical methods.

1. Gradient based methods are very sensitive to the accuracy of the gradients *wrt* design variables. Even somewhat high level models can produce "wiggles" that drive the optimization crazy. An example would be shocks that jump between grid lines during design. Response surface models are required to solve the problem of artificial noise.
2. Numerical optimization will find any weakness in your model and exploit it. An example would be vacuum *Cp* in small disturbance theories (they can go past vacuum *Cp* unless special limits are included). Rafi Haftka has used optimization methods in a scheme dubbed antioptimization specifically to locate weaknesses in models.
3. Many of the advanced concepts of interest these days are significantly out of any experience-based data used to develop the models. That's where the idea of physics-based models comes from.
4. A side note: Classic optimization texts/classes can be misleading. It's great to understand the various optimization methods, but for a user it's amazingly tricky to formulate the problem, and especially getting the constraints formed so that the optimizer doesn't "fight" them. Our students could attest to the fact that it's harder than it appears.

Back around 1990 we were trying to do "variable-complexity" MDO, where we combined approximate and more accurate models in our optimization. Today this is called variable fidelity. Our initial efforts didn't work as well as we'd expected. We eventually found out how to do this, and this experience ended up giving me respect for statistics I hadn't had before.

I will illustrate with examples from aerodynamics and some weights experience.

Aerodynamics

Low speed lift models for HSCT Design

In doing MDO for the HSCT we needed a model to use to limit the angle of attack to avoid tail scrape at landing. We were using fairly high-fidelity aero at supersonic speeds (eventually Euler and parabolized NS), but wanted a "simple" model for the landing constraint. Figure 1 shows what happened. We tried three different algebraic models, but a single example makes the point. This figure is from Matt Hutchison's PhD thesis, but we also put the examples in AIAA Paper 92-4695. This is what semi-empirical models may produce in numerical optimization design. Wow!

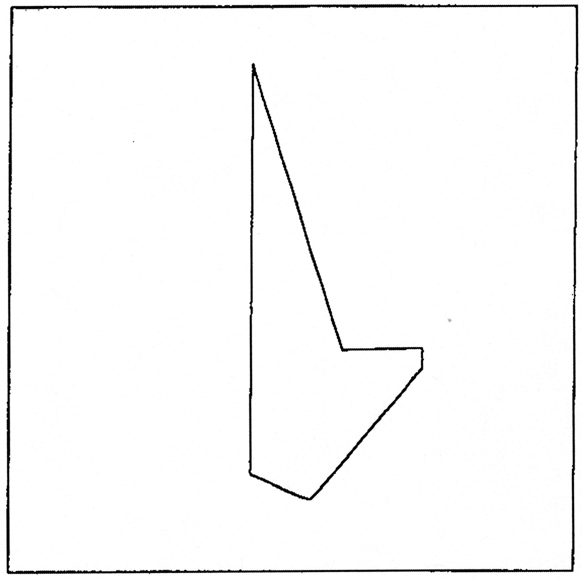

Fig. 5.26 — Wing Planform Obtained using Diederich Landing Model

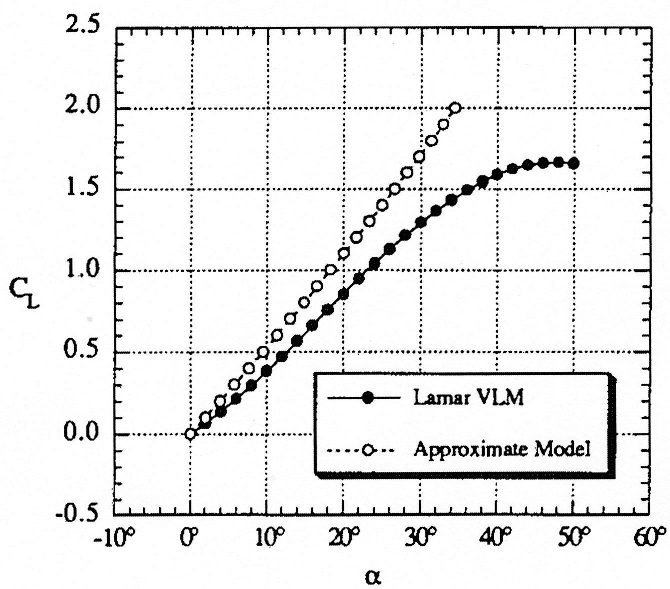

Fig. 5.27 — Final Design, Subsonic Lift Curve using Diederich Model Compared to Lamar VLM

Figure 1. The HSCT planform using a simple lift model for the landing tailscrape constraint. (Hutchison's PhD Thesis and AIAA Paper 92-4695)

Just to close the story, Figure 2 shows what Matt ended up with. We worked on this problem for about ten years, and many, many more students added higher fidelity analysis, advanced optimization schemes and a bunch of realistic constraints. It was an interesting problem, and we had a great collaborative team. We learned a lot about the problems of trying to use empirical models for various parts of the problem.

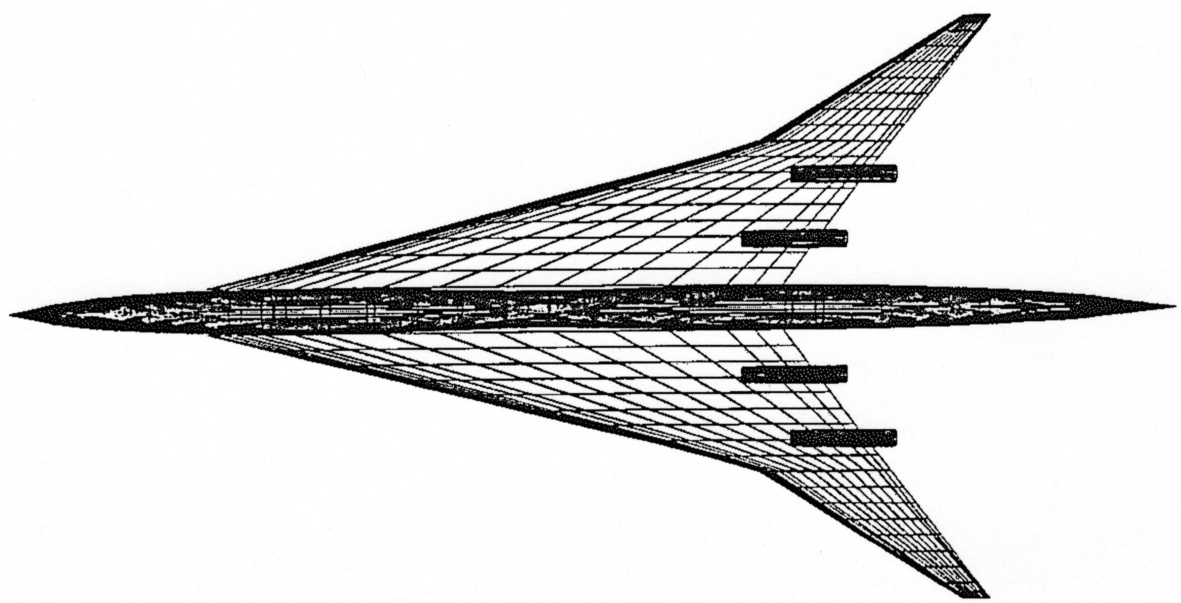

Fig. 6.18 — Composite-Wing Wing-Fuselage-Nacelle Design (WFN_{c12})

Figure 2. Hutchison's eventual HSCT final configuration planform
(Hutchison's PhD Thesis and AIAA Paper 92-4695).

Wave drag

This example shows results from the famous Harris wave drag program for an HSCT candidate wing. In this study we held everything constant except the wingspan. Normally an engineer would run a couple of cases, say semi-span values of 5, 7.5 and 10, and then use his ship's curve to fair the results. It looks pretty smooth. In this case I think we (actually Tony Giunta) ran 300 different values of semispan. Figure 3 shows the results plotted at a typical engineering scale. It generally looks OK, but not as smooth as you might expect. Figure 4 shows the results plotted at optimization scale. Now, you can see the small effects of discrete model numerics on the results. We were using the Harris at its maximum number of "cuts". Remember that this is what the optimizer would see and if we were using finite differences to find the wave drag gradient *wrt* to semispan we would get wildly different gradients and the optimizer would have big problems. The solution here was to fit a smooth curve through the results. I have that figure somewhere, but this is enough to make the point. We used second order polynomials, but a wide variety of other schemes have been used.

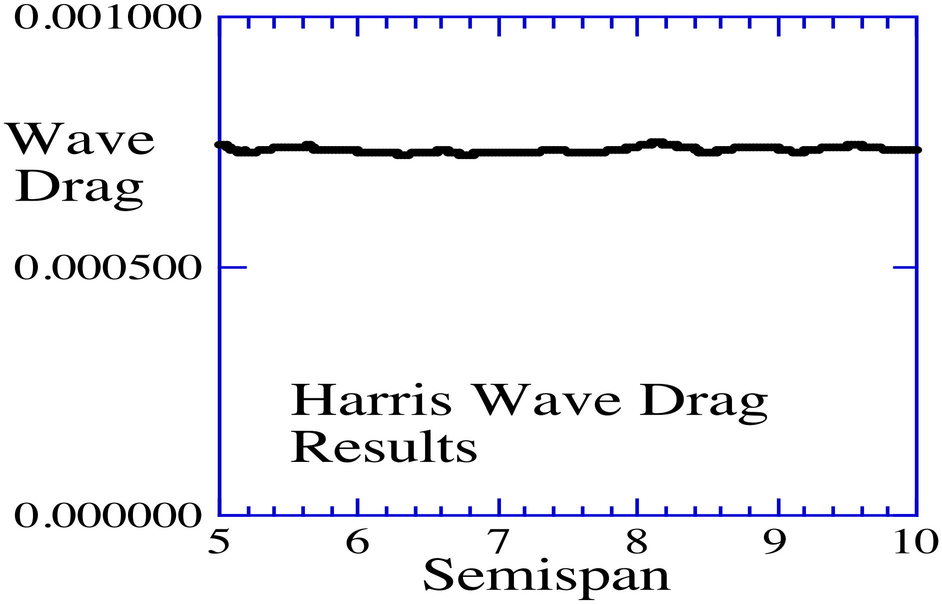

Figure 3. Wave drag results plotted on an engineering scale.

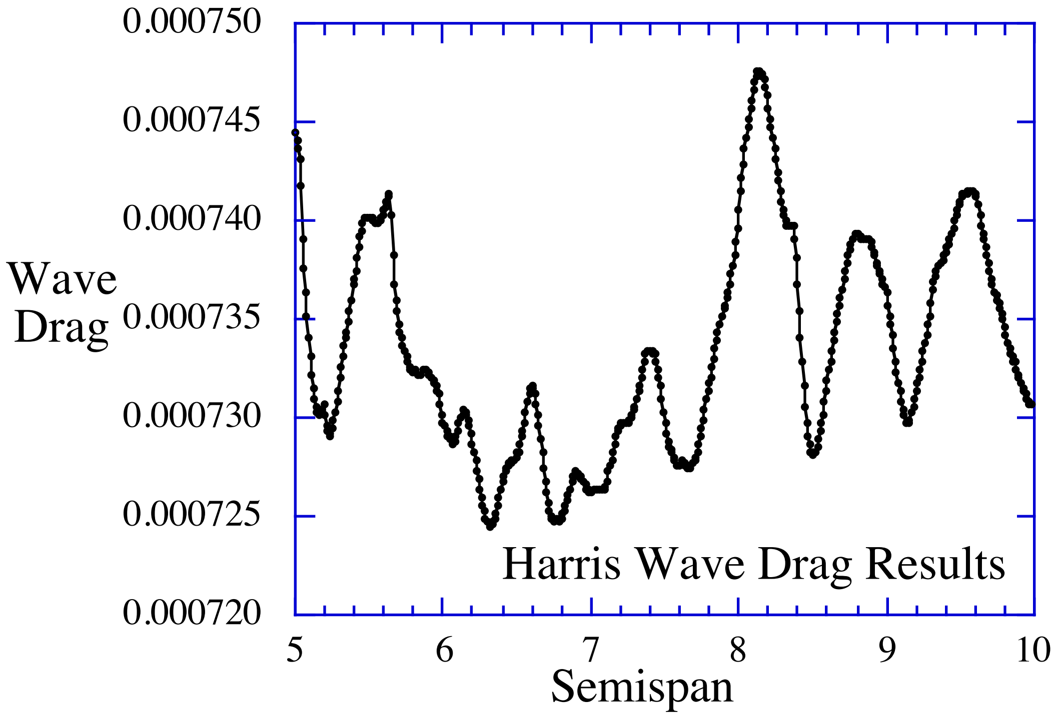

Figure 4. Wave drag results plotted on the optimizer scale.

Weights

Wing Weights

There are lots of approximate wing weight equations. For analysis they might all be useful. However, when the optimizer takes over the differences are magnified. Jarek Sobieski wanted us to put together an MDO code using approximate models and his global sensitivity analysis method. This became Brett Malone's MS Thesis (1991). We picked a C-17-like mission and Brett built the code. After it worked we could play with it to study lots of different effects. The example shown in Figure 4 from VPI-Aero-184, 1991, illustrates what happened when we used different wing weight equations.

Figure 5 shows the different TOGWs, Aspect Ratios, Wing Areas and Cruise Altitudes resulting from the use of wing weight equations from Raymer, Nicolai and McCullers (FLOPS). Note that the results are presented for a range of cruise Mach numbers. We were primarily interested in a cruise Mach number of 0.78. We found Mach sweeps to be extremely useful both for insight and see any hiccups in the optimization. We can see a few places where the results aren't smooth. Not included here, we also looked at wing sweep, *t/c*, taper ratio and span in a second page of the figure in the report.

Looking at the results in this figure we see how different wing weight model affect the optimization results. At low speed it's clear that two of the models bump up against the constraint of $AR = 25$ that we imposed. The TOGW result is plotted on a somewhat expanded scale, nevertheless, each model produces a different TOGW at $M = 0.8$. Curiously, each model predicts the minimum weight at about $M = 0.61$. For that case the wing for each model is found to be unswept.

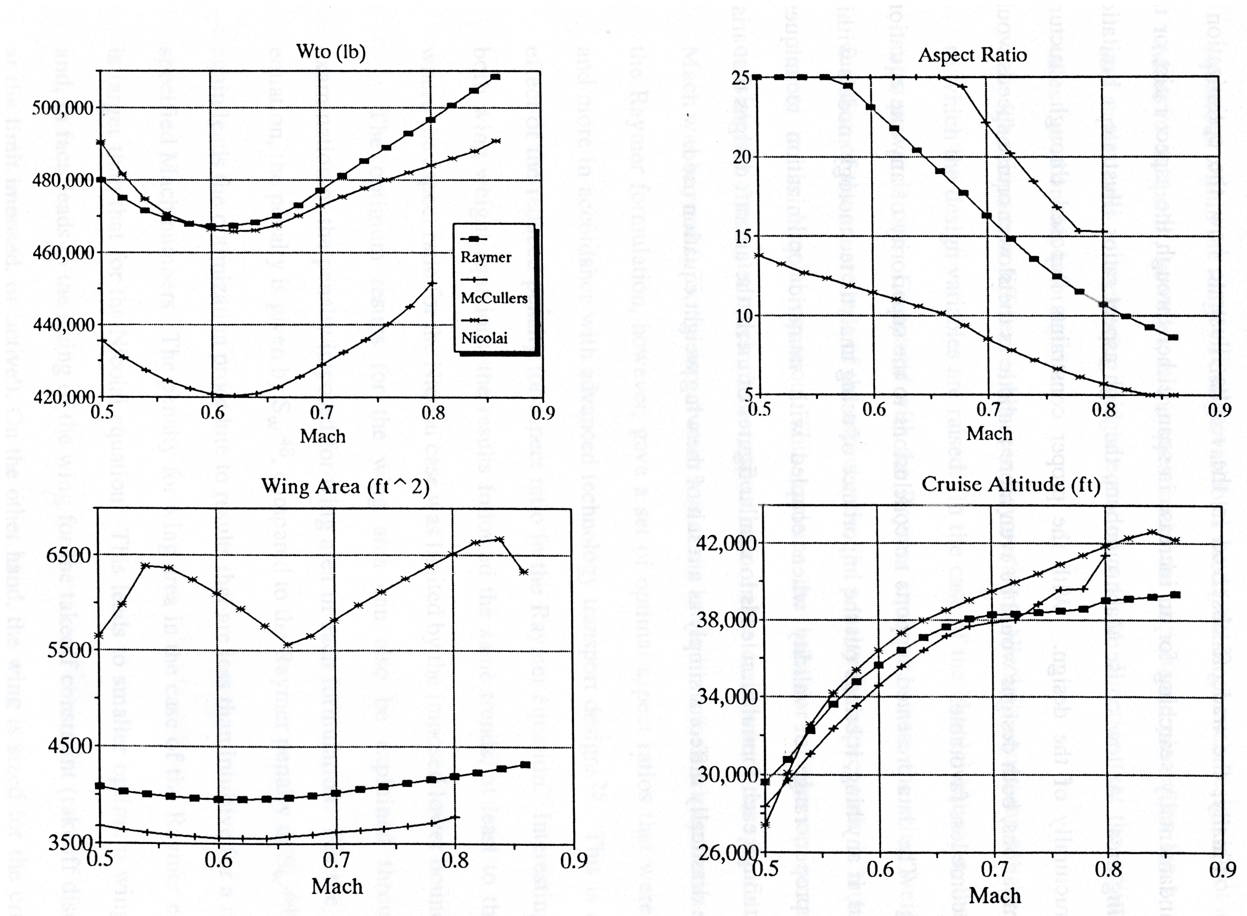

Figure 13. Effect of Increased Complexity (Wing Weight Models) on Optimum.

Figure 5. Design results using different wing weight equations, VPI-Aero-184, 1991 and AIAA Paper 91-3187.

For the HSCT work we ended up using a full-blown finite element code to get the wing weight (Gary Vanderplaats structural optimization code Genesis). For the strut-braced wing work we had a student develop a first principles beam model with a strut (Amir Naghshineh-Pour's MS Thesis, 1998). Initially for the strut model we focused on bending material weight, but over the years we added a lot of other constraints. One was inner wing buckling because the strut "pulls" on the wing under load.

Landing Gear Weight

This might be my favorite because of a comic development after we'd been working on this for a while. Paul Gelhausen was paying us to do landing gear for early design, http://www.dept.aoe.vt.edu/%7Emason/Mason_f/M96SC.html, see also AIAA Paper 1996-4038.

One part of the work had to do with the landing gear weight. We evaluated various landing gear weight formulas in the literature. Figure 6 is from the final briefing at NASA Ames in July of 1996. The question: what is the landing gear weight as a fraction of the TOGW? In particular, we were interested in the forthcoming new large aircraft. Toward the end of the job as we were putting the work together, *Av Wk* quoted the weight of a new plane from Airbus. That's the bold vertical line at a little less than a million pounds. The ACSYNT estimate and the Torenbeek estimate predicted the same value for the landing gear weight, but the trends with weight for the two models were exactly opposite! I about fell off my chair. Who would have thought? This is a great example of the problem of using empirical models outside of the data set used to construct them.

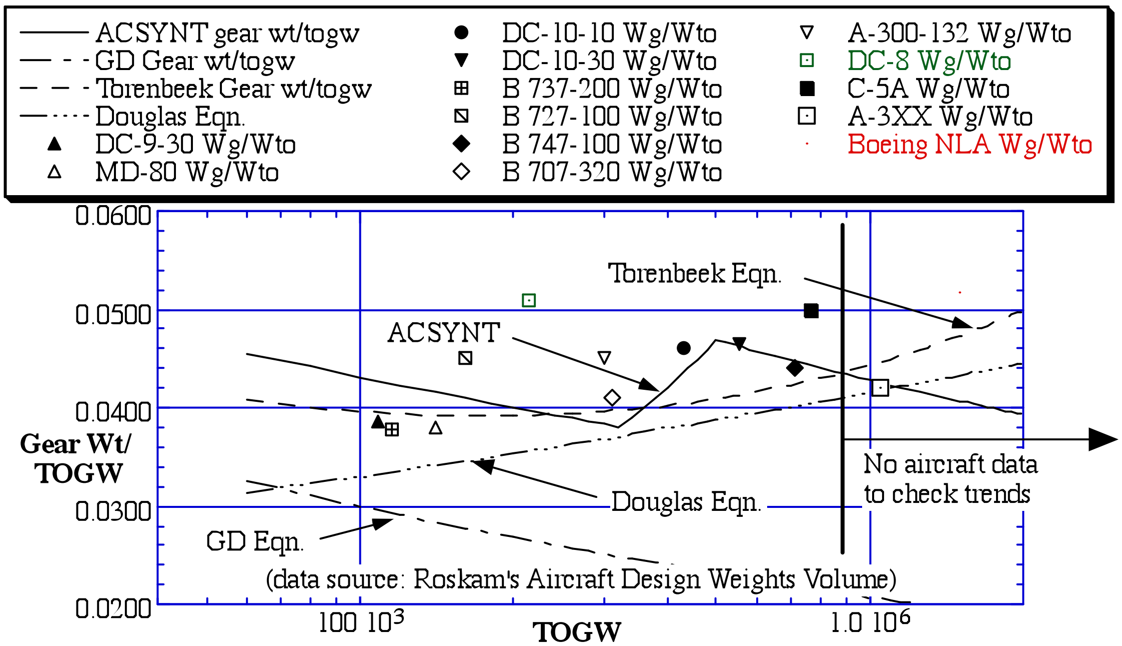

Figure 6. A chart from the final briefing at NASA Ames, July 1996.

In summary:

• You have to be very sure that the approximate model is working well in the design domain. Empirical models have trouble for novel concepts.

• Often you need to resort to a first principles physics-based model when you are outside of the data base of available designs.

• Mainly, optimization will focus your thinking.