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A SYSTEMS APPROACH TO MASS BUDGET MANAGEMENT

Olivier L. de Weck.*
Massachusetts Institute of Technology, Cambridge, MA 02139

This paper presents a system approach to mass budget management during early design of new complex vehicles and products. The traditional approach to mass budget management is that of hierarchical decomposition of the system, followed by top-down allocation of mass budgets to subsystems and components. We argue that subsystem level interactions must be taken into account when allocating mass budgets within a constrained mass target. Mass savings in one part of the system can have costly consequences in other parts. Isoperformance is presented as a potential method for keeping the total mass of a system constrained, while trading off other objectives such as technical performance, risk, modularity and cost. The F/A-18 aircraft and an automotive example will be utilized to illustrate the method. The discussion also includes principles of how NASA has traditionally managed manned space vehicle mass estimates.

Nomenclature

g	=	gravitational acceleration on Earth, 9.81 m/s^2
m	=	mass, kg
m_{dry}	=	vehicle dry mass
L/D	=	lift over drag ratio
R	=	range, m
SFC	=	specific fuel consumption, kg/sN
V	=	cruise velocity, m/s
W	=	weight, N
CDR	=	Critical Design Review
PDR	=	Preliminary Design Review
SRR	=	System Requirements Review

I. Introduction

Weight is a critical quantity in engineering design of complex vehicles such as aircraft, spacecraft and automobiles, as well as mobile hand-held products. While many sources refer to "weight" management, since

$$W = m \cdot g \tag{1}$$

it is more accurate and general to speak of "mass management". Weight is the force exerted by a physical body with non-zero mass due to gravitational acceleration in a non-relativistic context. Mass is a more generic term, since it is independent of the central body (like Earth, Moon, Mars …). During vehicle design it is especially critical to manage vehicle mass, since vehicle mass is a main factor influencing vehicle performance. Some systems are critically depended on delivering functional performance at minimal mass:

- aerospace vehicles: aircraft, spacecraft, satellites,…
- ground vehicles: cars, trucks,…
- watercraft: ships, submarines
- mobile electronic products: laptop, PDA,…

* Associate Professor, Dept. of Aeronautics & Astronautics, Engineering Systems Division, 33-410, AIAA Senior Member, deweck@mit.edu

Typically mass management is not as critical for the design of industrial equipment (machinery) and civil infrastructure. A classical example to illustrate the impact on vehicle dry or empty mass on flight performance is the Breguet Range Equation:

$$R = \frac{V(L/D)}{g \cdot SFC} \cdot \ln \frac{W_{initial}}{W_{final}} \tag{2}$$

whereby the assumption is that the total fuel mass is

$$W_{fuel} = W_{final} - W_{initial} \tag{3}$$

and that this fuel mass is entirely consumed during flight. Changing the vehicle dry mass will change $W_{initial}$, and this in turn will impact range, R, all else being equal. Figure 1 shows how range scales as a function of fuel mass and vehicle dry mass. The baseline is a B737-300 class commercial aircraft with a total gross mass of 57 metric tons.

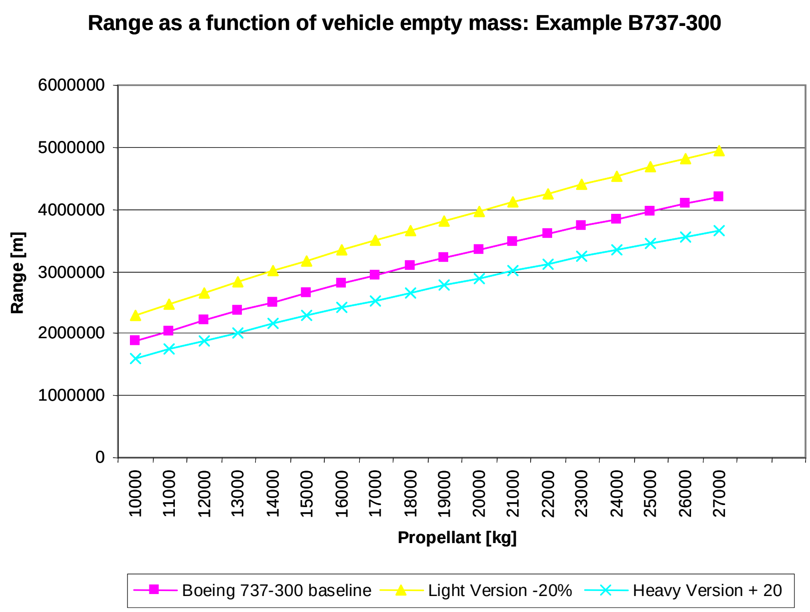

Fig.1: Range as a function of vehicle empty mass: mo= 30,000 kg, V=200 m/s, SFC=4.67 mg/Ns, L/D=15

While the nominal range of the aircraft is 4,200 km, a 20% increase in vehicle dry mass leads to a 539 km decrease in range. Conversely a 20% decrease in vehicle dry mass would lead to a 733 km increase in range. The raw and normalized sensitivities are shown in Table 1. A 1kg increase in dry mass of the baseline configuration leads to roughly a 106 meter decrease in total range. In other words a 1% increase in dry mass leads to a 0.76% decrease in range.

Table 1: Sensitivity of range performance w.r.t. vehicle emplty mass (example)

Raw Sensitivity	ΔR/ΔW	(-20%) -122.147 m/kg	(+20%) -89.7547 m/kg
Normalized Sensitivity	%R/%W	-0.87183	-0.64063
Central Difference			
Raw	-105.951 m/kg	Normalized	-0.75623

One of the major difficulties in the management of mass in complex systems development is that the mass is the aggregate of the masses of individual subsystems, which interact to create overall system performance. Figure 2 illustrates a cross section through the F/A-18 aircraft. The Figure shows the airframe, engines, crew, avionics and various subsystems which all contribute to overall system mass. How should the mass be decomposed and properly allocated to subsystems? How can one ensure that mass savings in one subsystem do not lead to disproportionate increases in another subsystem?

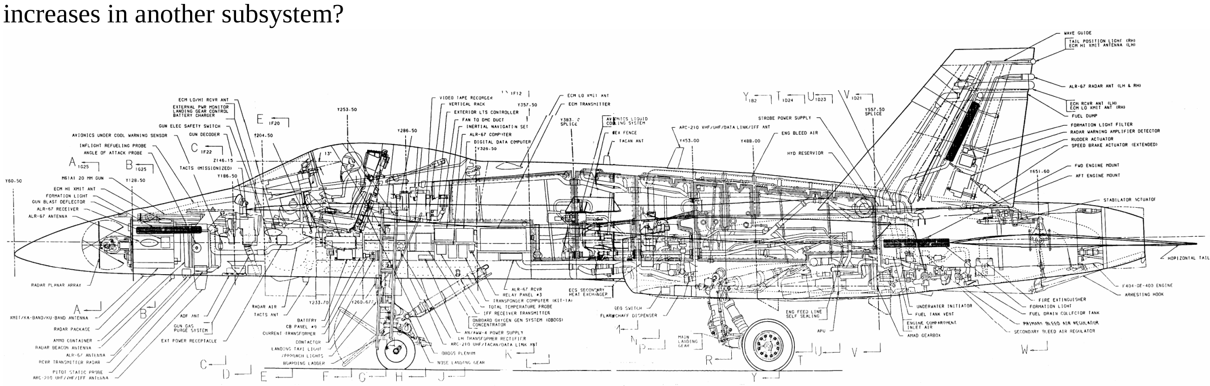

Fig. 2: Cross section of F/A-18 aircraft (C/D configuration)

Definitions

In order to clarify the usage of the term "mass" or "weight" and facilitate design, management and regulations, various fields have introduced standardized definitions for weights. Examples are provided below:

Aircraft - Maximum Takeoff Weight [kg or lbs]
Maximum Take-Off Weight (or MTOW) is the maximum weight with which an aircraft can achieve flight. MTOW is affected by the design of the airframe, engine type and power, drive type and air density. This is typically the same or similar to GTOW – gross takeoff weight

Automobiles - Curb Weight [kg or lbs]
Curb weight is the total weight of an automobile with standard equipment, oil, lubricants, coolant, a full tank of fuel and not loaded with either passengers or cargo.

General Vehicles - Gross Weight [kg or lbs]
Gross Weight is the total weight of a vehicle when fully loaded with passengers and/or cargo. It usually refers to the fully loaded weight of trucks, automobiles. A gross vehicle weight rating (GVWR) is often required for certification. In the United States, two important GVWR numbers are 6,000 pounds (2,721 kg) and 8,500 pounds (3,856 kg). Vehicles over 6,000 pounds are restricted from many city roadways.

NASA has collected the mass history of past manned spacecraft programs and derived rules for mass estimation and forecasting.[1] Many problems in mass budget management during vehicle design are due to ambiguous definitions, incomplete accounting by various teams and resulting double counting or neglecting of system mass contributors. What is needed is a straightforward framework that addresses the most important issues in mass budget management.

II. A Systems Framework for Mass Budget Management

The author proposes that the following five are among the most important and most difficult issues in mass management during vehicle design:

- ❑ 1: How does system mass scale as a function of key performance requirements of the system?
- ❑ 2: How do we account for uncertainty in required mass during early system design? What should the margins be?
- ❑ 3: How should the total system dry mass be decomposed and assigned to individual subsystems?
- ❑ 4: How do we manage creep in system mass during project management?

- ❑ 5: How do we trade off mass (light-weighting) against manufacturing cost?

Some of these questions dominate early conceptual design, while others are more relevant later in the product lifecycle. Fig. 3 puts these issues in context of a generic system lifecycle consisting of the following lifecycle phases: Conceive – Design – Implement – Operate.[2]

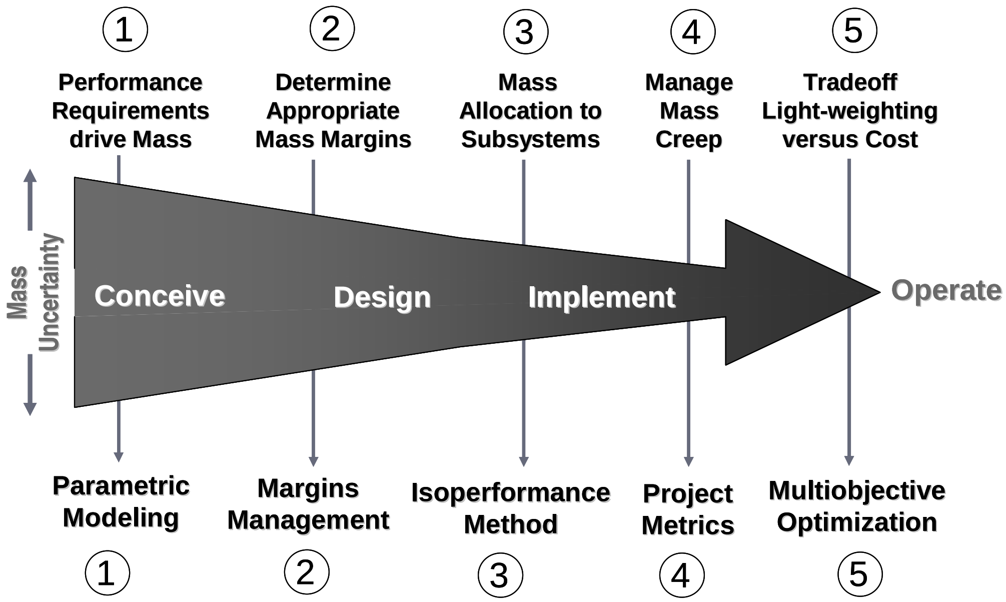

Fig. 3: A systems framework for system mass management

During conceptual design system requirements are set (range, payload capability, endurance,…) and it must be determined what the system mass drivers are and an estimate of system mass typically within +/- 5% should be provided (1). Because of the uncertainty in these estimates it is critical that appropriate mass margins are maintained and managed throughout the program (2). A part of this management process is the allocation of mass and available margins to subsystems (3). This should be done based on integrated modeling and simulation (IM&S) to ensure that mass savings in one subsystem don't lead to mass increases in another.

It is well known that mass budgets tend to grow as development projects mature. This growth must be carefully managed, by treating mass as a project metric (4) and reviewing factors that contribute to mass growth or losses carefully during design reviews. Finally, from a manufacturing perspective it is often true that light-weighting of structural components can often be achieved without compromising structural performance. This, however, often comes at an increase in manufacturing cost. Multiobjective optimization can help in identifying "knees" in the curve of mass versus manufacturing cost. The next section gives an overview of Methods to address the five issues of mass management shown in Fig. 3. There is no claim that this a complete list of issues.

III Methods and Issues in Mass Management

III.1 Parametric Modeling

Parametric mass modeling is a method to obtain a fast rough estimate of total system mass based on few (typically 1, 2 or 3) key system variables. The first step is to determine key performance requirements and to map these against key system variables. This mapping can be used to establish parametric scaling relationships. These can be:

- First order physics based models – OR -
- Empirical models based on historical data

The accuracy of the models depends on the size and quality of data sets in the case of empirical modeling. Increasing the number of parameters can increase model fidelity, but noise will always remain. This step only gives and aggregate estimate of system mass within ~ +/- 5%. This is typically sufficient for early trade studies and relative comparison of competing concepts.

Figure 4 gives an example of parametric modeling of the wet mass of non-geosynchronous orbiting (NGSO) communications satellites.[3] This model obeys the following power law:

$$M_{wet} = 38(0.14P_{PL} + M_{prop})^{0.51} \tag{4}$$

The model was obtained by first assembling a database of actual deployed spacecraft and of some for which detailed designs were available. When building such models using Response Surface Modeling[4] first a model of the form

$$y = f(\underline{x}, \underline{\theta}) + \varepsilon \tag{5}$$

must be established, whereby x are the design variables of the system, θ are parameters of the model and ε is the remaining modeling error. An estimate of the model parameters is obtained by minimizing the least squares error:

$$S(\underline{\theta}) = \sum (f(\underline{x}, \underline{\theta}) - \hat{y}_u)^2 \tag{6}$$

The quantities $\hat{y}_u$ represent the truth data from the database.

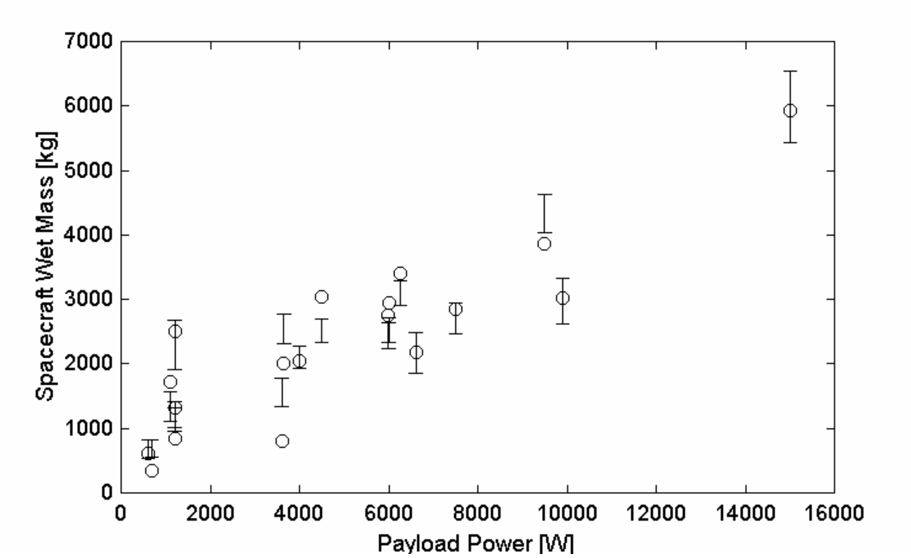

Fig. 4: Parametric model of wet mass of NGSO satellites as a function of payload power [W] and propellant mass

In the case of Fig. 4 the vertical bars indicate 95% confidence intervals and the model predicts satellite wet mass with an RMS accuracy of 301 kg. Thus, the estimate turns out to be more accurate for large satellites than for smaller satellites below 2000 W of payload power. Other examples of mass scaling relationships are available for automobiles[5], spacecraft[1] and other systems. These models are useful for early trade studies and to establish first order estimates.

III.2 Mass Margins

Due to uncertainty during early design, we must use appropriate mass margins. Margins are *reserves*, that are not allocated to subsystems but are controlled by project managers. Mass Growth has been experienced in almost of vehicle development programs (see Fig. 5). Mass growth can range from 10-60%. The amount of mass growth depends primarily on the novelty of the project and the complexity of the system that is to be produced.

Typical guidelines for maintaining margins are as follows:

- Establish SRR Mass + 30% margin
- pre-PDR keep 20% mass margin
- pre-CDR keep 10% mass margin
- pre-IOC keep 5% mass margin

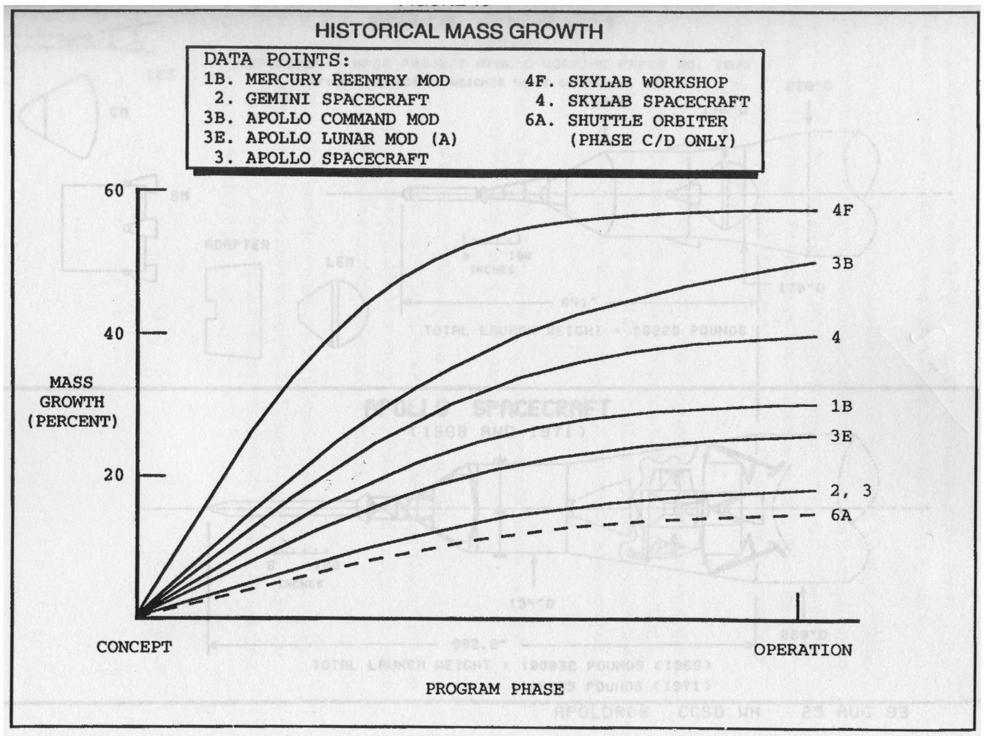

Fig. 5: Historical Mass growth in manned spaceflight programs. Source[1]: JSC-26098

III.3 Mass Allocation to Subsystems

Another critical issue is how mass is allocated to subsystems. Typically, masses are allocated according to the "tree decomposition" of the system based on historical percentages. An example is given in Table 2. One of the difficulties is that such an allocation does not take into account system level interactions or the effect of new technologies.

Systems Engineering will typically perform the following tasks:

- track total mass
- allocate masses to subsystems
- negotiate between groups, which group has the highest mass sensitivity?
- But how should this be done systematically?

One approach is to create an integrated model of the system that captures both the key performance metrics as well as total system mass as a function of system level design variables. Then, to constrain mass to a desired target level and one could also constrain certain target performance levels. Finally, work backwards by adjusting the design variables in a way that leads to satisfaction of both the performance as well as the mass targets. Typically the design variables can be grouped such that they are assigned to individual subsystems.

Table 2 Typical Subsystem Masses as Percentages of Spacecraft Dry Mass (adapted from Ref. 8)

Subsystem	% M_{dry} (Std. Dev.)
Payload	27 (4)
Attitude Control	7 (2)
Electrical Power	32 (5)
Propulsion	4 (1)
Structure	21 (3)
Thermal	4 (2)
Tracking and Command	5 (2)
TOTAL	100

The Jacobian matrix is a key piece of information in this process:

$$\nabla J_z = \begin{bmatrix} \frac{\partial J_{z,1}}{\partial x_1} & & \frac{\partial m_{tot}}{\partial x_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial J_{z,1}}{\partial x_n} & & \frac{\partial m_{tot}}{\partial x_n} \end{bmatrix} \quad (7)$$

This matrix contains the sensitivity of the system performance metrics $J_{z,i}$ and the total mass with respect to the design variable. Isoperformance[6] is a technique that can find solutions that meet both the performance and mass targets (if such feasible solutions exist) by following performance- and mass-invariant contours in an n-dimensional design space.

III.4 Managing Mass Creep

Even once a sound design is found, mass growth (creep) will occur during project development (see Fig. 6). This is due to non-conservative assumptions during early design, complexity increases, often forgotten items (e.g. wire harnesses) during more mature stages of design. Successful programs carefully track mass as a project technical performance metric (TPM) throughout the program. Figure 6 shows the typical evolution of mass creep for three hypothetical projects labeled “Ideal”, “Typical” and “Crisis”.

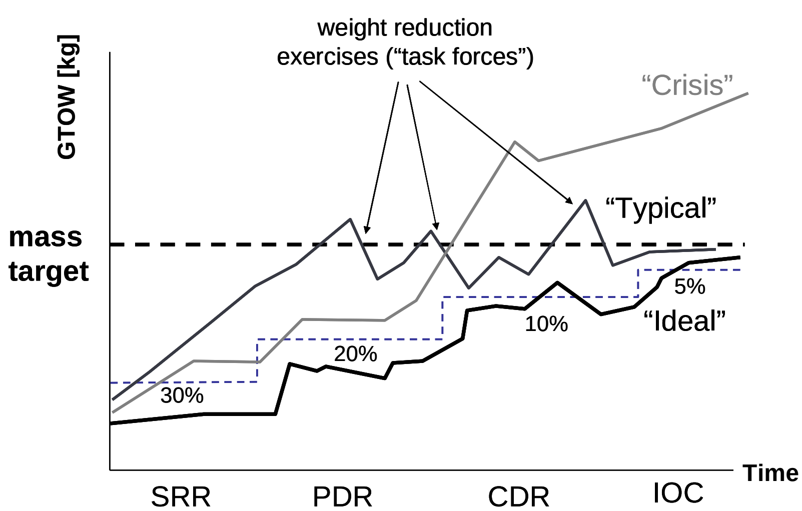

Fig. 6: Typical evolution of system mass estimate during complex product/vehicle development

An ideal project is one that always remains under or near the 30-20-10-5% mass margins in each project phase. More typical is that the mass target is exceeded occasionally and that the design has to be brought back in line with costly and time-consuming weight reduction exercises. A project in crisis will overshoot its mass target early and never achieve the target in the end.

III.5 Tradeoff Mass versus Manufacturing Cost

It is generally established in the context of structural design and topology optimization that there is a tradeoff between system mass and manufacturing cost. Multiobjective Optimization is a technique that can quantify and visualize this tradeoff.[7] Light-weighting of components often requires intricate cutouts and adds details to structural parts that save mass, but add cost. For high value, low volume applications (aerospace) this is often easier to accept than in high volume, low margin situations (automotive design).

Figure 7 shows the tradeoff between total manufacturing cost ($) and mass (kg) for a relative simple structural component.

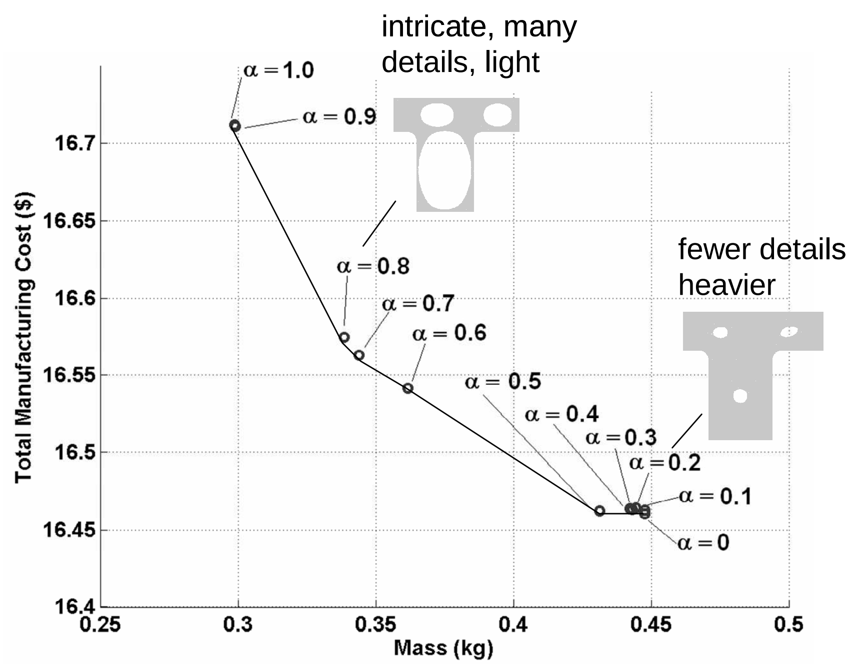

Fig. 7: Tradeoff between manufacturing cost and mass for a metallic component. Source: reference 7

IV. Conclusions

Open Issues

- Important *ongoing* research topics in the area of mass management are:
  - How does <u>modularity</u> impact system mass? More modular designs are typically heavier than integral designs (inefficiency, extra interfaces)
  - Impact of <u>mass savings on lifecycle cost</u> (e.g. cumulative aircraft fuel consumption savings vs. upfront manufacturing impact)
  - Managing mass increases during <u>operations</u>:
    - upgrades, retrofits etc…

Conclusions

Mass management is critical for vehicle design, because vehicle performance depends strongly on dry mass (see Fig. 1). This is typically only a secondary issue in the design of industrial equipment. This paper posits that the key issues in mass management are as follows:

- ❑ 1: How does system mass scale as a function of key performance requirements of the system?
- ❑ 2: How do we account for uncertainty in required mass during early system design? What should the margins be?
- ❑ 3: How should the total system dry mass be decomposed and assigned to individual subsystems?
- ❑ 4: How do we manage creep in system mass during project management?

Individual methods to address these questions exist, but they need to be integrated into a system framework. Such a framework has been proposed in this paper at a conceptual level (see Fig. 3). The key aspect of the framework is that the 5 issues and methods need to be addressed across the C-D-I-O lifecycle. Some firms are more advanced than others in this respect.

While some of the methods may be generic, there are many specific differences in how to apply them depending on the specific context. For example, even within vehicle design there are major differences between automobiles, aircraft and spacecraft, e.g. due to their vastly different propellant mass fractions:

Typical propellant mass fractions:

- cars: example: 20 gallons in a 4000 lbs car: 3%
- aircraft: example: 27,000 kg of fuel in a 60 ton aircraft: 45%
- spacecraft: example: propellant mass fraction up to 90%

The typically "value of 1 kg of mass" in mass management depends on the application. Even though mass management is often viewed as mundane and tedious, it is an activity of great importance and impact in complex system design. Methods that link system mass, performance and cost together in an end-to-end fashion are still evolving.

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[1] *NASA Report* T94-11099/JSC-26098, Design Mass Properties II, Mass Estimating And Forecasting for Aerospace Vehicles Based on Historical Data, November 1994

[2] See also: http://www.cdio.org

[3] Springmann P.N., and de Weck, O.L. "A Parametric Scaling Model for Non-Geosynchronous Communications Satellites", *Journal of Spacecraft and Rockets*, 41, No.3, pp.472-477, May-June 2004.

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