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Concept Design Trade-Offs Considering Performance Margins

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Abstract

Multi-disciplinary optimization (MDO) methods have become mature as software applications have been developed and distributed in Nordic countries and elsewhere. Typically, engineers formulate concept design problems using multiple system-level responses to allow simultaneous optimization along a Pareto trade-off frontier. These tools make use of trade-off graphs depicting each design concept as a point in a scatter plot, to observe the frontier versus dominated solutions. Often lost is the practical design engineering considerations of the equipment components that compose the system. In particular, there are operational performance limits of the equipment components, usually expressed as safety margins. In an MDO formulation, these margins are often modelled with fixed constraint limits. With optimization, the MDO search can then often drive these constraints active in the considered Pareto optimal solutions. That is, MDO methods can potentially drive a designer toward aggressive risky concepts on equipment margins. Hence, our research questions may be formulated as follows: May margin constraints be mapped or converted to system level objective functions and effectively traded-off against system level requirements? If so, would this approach enable more robust design concepts? In this work, we formulate a MDO problem allowing design performance requirements to be traded off against component performance limits. This will facilitate feasible design configurations that are not only high performing at a systems level, but are also more robust to design margin considerations. We have shown that overall improved designs can be generated when trading off performance limits slightly but greatly increasing the constraint margin safety margins. We do this by considering a family of Pareto frontiers at several levels of constraint margin limits. This highlights the relative sensitivity of component limits with performance levels, by adjusting either the performance requirements or engineering margins.

Keywords: Optimization, safety margins, trade-offs

1 Introduction

Engineers can parametrically formulate concept design problems as multiple system-level responses to allow *multi-disciplinary optimization* (MDO) along a Pareto trade-off frontier. Multi-disciplinary optimization (MDO) methods have become a part of industrial practice as commercial and open-source toolboxes and applications have been developed and distributed in Nordic countries and internationally, such as Modelica simulation software (Modelica Association 2016) and DACE computer experiment software (Lophaven 2002). Multidisciplinary optimization (MDO) has become a methodology exemplified by the Nordic countries. Trade-off analysis is achieved by trading off the performance of one system requirement against others. Within this analysis, however, the design margin limits of component constraints are often not traded-off in this manner, and instead typically treated using fixed margin limits.

An MDO approach that does not adequately handle trade-offs and margins can lead to problems when a design with an optimized system performance is developed, but then fails during the deployment phase when less than ideal fabrication and operational conditions can erode the effectiveness compared to the assumed margin limits. One of the classical examples of MDO is the design of an aircraft wing, where structural weights have to be carefully traded off with the aerodynamic properties of the wing (e.g. airfoil) for the optimal range performance of the aircraft (Ferguson 2009 and Janson 2010). Every design has a limit to its performance subject to constraints of its components, these limits can be normalised for ease of comparison among each other.

The following industrial examples illustrate this problem and highlight the need to consider design margins early, to trade-off design margins with system level performance. Failures in several Unmanned Aerial Vehicles (UAV) projects in the United States Air Force (USAF) has been attributed to insufficient margins, one notable example failure was attributed to the battery life (Whitlock 2016 and Moon 2016), where the failure of the starter generator left an insufficient supply of electrical power to the UAVs. Also the inability to understand system requirements versus design margins in other UAV applications led to the selection of unsuitable valves (Whitlock, 2014). In other turnkey aerospace projects, the failure to understand margins with conceptual new-technology components led to performance requirements not being met and resulted in the cancellation of the programme, as in the design of the RAH-66 Comanche helicopters (Ward, 2012). This was also repeated in the Mk 3 upgrade programme of the Royal Air Force Chinook helicopters (Burr, 2008). In that programme, the constraints and limits of the software system was not adequately addressed, resulting in the inability to certify the aircraft for operational usage.

MDO has been used extensively in the aerospace industry (Giunta, 1996) to study the impact of performance variables against each other subjected to constraints. The use of visualisation (Simpson, 2008) to study this phenomenon. Otto and Jacobson (2012) discussion use to establish plans to decrease verification testing. Some authors (Levandowski, 2013, Becz, 2010) has also proposed the use of formalised design languages to assign hierarchy to the design of complex systems. Thus, the ability to understand the trade-offs between performance and margins can lead to optimal design solution. One such example for illustration is the development of the Volvo Aero (now GKN Aerospace) RM-12 Engine for the JAS-39 Gripen single engine fighter. The RM-12 is a derivative of the General Electric GE-F404-400 engine used most commonly in the US Navy's (USN) F/A-18 twin engine fighter. Design changes to optimise for single engine performance included (Larsson, 1988 Städje, 2008). A ten percent increase in airflow for higher turbine pressure (increase of 26 percent) and temperature (increase of 87 degrees Celsius) at the expense of hot section turbine life. For increased resistance against bird strikes, thicker fan blades resulted in the reduction of fan blades from thirty two to twenty eight, resulting in a ninety four percent thrust retention over the required seventy five percent as per US military propulsion certification standard JSSG-2007A.

Consideration of component design margins is important for design of new and novel concepts, as new technologies may have unknown behaviours that affects the operating conditions of the design. This paper will provide insights into providing margins to such constraints through MDO visualization methods combining the MDO performance characterisation and margins as objective functions. We will also illustrate the methods with an example on the design of a novel hybrid UAV engine, an electric motor propulsion system.

2 Multi-Disciplinary Optimization with Design Margins

For the purposes of context and a concrete case study, we consider the systems design of a UAV in this section. A hybrid engine – electric motor fixed wing UAV shown in Fig 1 is to be designed to carry out surveillance using an electro-optical payload with the performance variables as shown in Table 1.

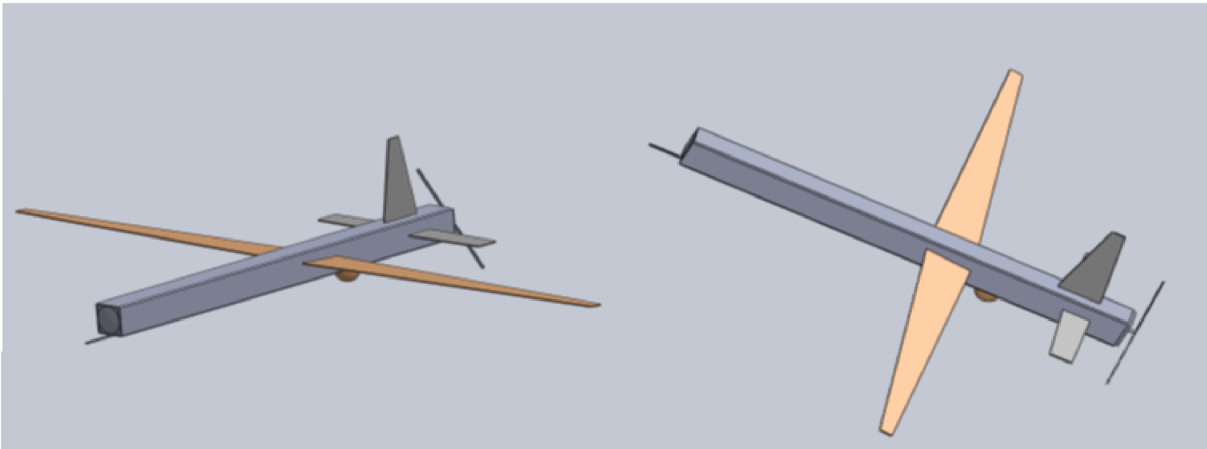

Fig 1. Conceptual design of hybrid engine – electric motor UAV

Table 1. Performance Variables

Performance	Quantity
Speed	40 m/s
Altitude	1524 m
Range	1000 km
Payload	7 kg

The design concept is defined using the variables as show in Table 2, with size limits;

Table 2. Design Variables

Design Variable	Unit	Nominal Design	Lower Limit	Upper Limit	Levels
Half Wingspan	m	2.27	0	2.5	9
Wing Root Chord	m	0.29	0.2	0.3	3
Wing Tip Chord	m	0.08	0.2	0.3	4
Fuselage length	m	2.75	1.8	3.5	5
Fuselage Radius	m	0.2	0.07	0.2	4
Wing angle of attack	deg	5	0	5	3
Fuel mass	kg	7.8	5	14.5	3

These design variables are related to the performance responses using derived equations of motion and physics, incorporating the flight stability, lift and propulsion physics, which thereby can be studied in a concept level MDO trade-off framework.

For early concept phase studies, performance variables include, amongst other (Anderson 2008 and Roskam 1997), the UAV range and payload which can be represented as MDO objective functions as

$$Range = \frac{L}{D}\frac{\eta o\ Q}{g}\ln\frac{m{,}b\_cruise}{m{,}a\_cruise} \qquad (1)$$

$$Payload = 0.7 * w\_fuse \qquad (2)$$

where

L is the lift generated from the wing
D is the drag of the UAV
g is the gravitational acceleration
η_o is the overall energy efficiency of the UAV
$_Q$ is the calorific value of the fuel
$m_{,\text{b\_cruise}}$ is the mass of the UAV before cruise
$m_{,\text{a\_cruise}}$ is the mass of the UAV after cruise
w_{fuse} is the mass of the fuselage

Engineering the system also requires the assignment of a margin (safety factor) on the performance limits of the components in the system. As an example, the lift margin of the wing can be expressed as

$$LM = \frac{MDTW - MTOW(x)}{MDTW}, \qquad (3)$$

where

LM is the lift margin
MDTW is the maximum design take-off weight
MTOW(x) is the maximum take-off weight

Lift Margin may be assigned an *a-priori* margin value and thereafter ignored in preliminary concept trade-off analyses, or as we will develop, can be made explicit in concept phase trade-off analyses.

The standard MDO optimization considers system level responses, and as such margins, are incorporated as constraints as defined. That is, there are bounds on the system level responses (or general objective functions) $\bar{f}$, and then MDO analysis is performed to determine the Pareto frontier amongst the *f*. There are also constraints g on elements of the system, on which bounds are placed. This leads to the optimization formulation in equation 4:

$$\min_{\bar{x}} \bar{f}(\bar{x}) \qquad (4)$$

subject to

$$\bar{f}_l \leq \bar{f}(\bar{x}) \leq \bar{f}_u$$
$$\bar{g}_l \leq \bar{g}(\bar{x}) \leq \bar{g}_u$$
$$\bar{x}_l \leq \bar{x} \leq \bar{x}_u$$

where minimising $\bar{f}$ implies a Pareto optimal search activity, allowing trade/offs among the f_i vs f_j objective functions.

The above formulation, Eqn (1), formulates component margin constraints at fixed *a-priori* levels. Here we now formulate the MDO to consider both performance and design margins. In essence, we consider the margins as objective functions, and so both the performance and margin variables are driven by the design variables, $\bar{x}$ in equation 5:

$$\min_{\bar{x}} \bar{p}(\bar{x}) \qquad (5)$$

subject to

$$\bar{p}_{lower} \leq \bar{p}(\bar{x}) \leq \bar{p}_{upper}$$

$$\bar{m}_{lower} \leq \bar{m}(\bar{x}) \leq \bar{m}_{upper}$$

where

$\bar{p}$ represents the system level performance variables,
$\bar{m}$ represents the component safety margin constraint variable,
x is the design configuration under consideration.

The UAV design is parameterised by its geometry and fuel mass to determine the range and payload as per Table 2. Within the bounds of the design variables, a total of 222 feasible designs exist, of which 50 were useful designs out of the 19,440 possible designs (factorial of the levels as shown in Table 2) were generated as shown in Fig 2. Feasible designs are designs that can be physically constructed but may not meet system requirements. Useful designs are designs that can both be constructed made and meet system requirements. Each dot on the scatter plot is a design configuration driven by the design variables.

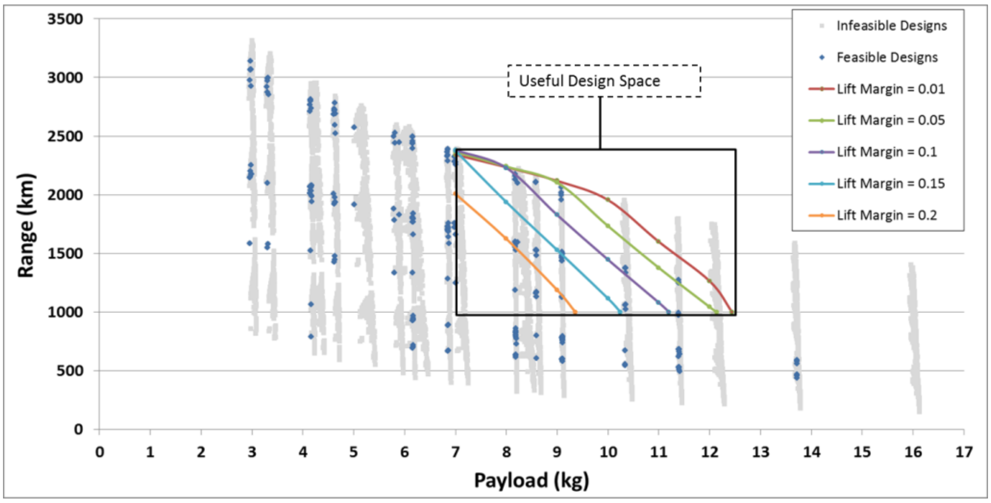

Fig 2. Location of useful design space with relation to the Iso-margin curves

The objective function is maximised to determine the point at the Pareto optimal for the particular range and payload. This is because as shown in equations (1) and (2), range is a trade-off function between lift and weight, which implies that the increase in payload increases the weight of the UAV, thereby reducing the range. The resulting Pareto curve(s) will be for different lift margin values as shown in Fig 3. From an optimality point of view, we would want to select the design with the least margin and the most payload carrying capacity. In this case, our nominal design derived from a single objective optimisation exercise (equations 4 and 5) fits the bill.

However, the nominal design would just meet the range requirement of 1000 km, and would greatly exceed the payload requirement of 7 kg. This would imply that any externalities such as modelling errors and adverse operating conditions (e.g high temperature and altitude, "hot and high") might cause the design to not meet requirements. A better design would be increasing the lift margin at the expense of payload, to introduce robustness to the design; i.e. moving away from the maximum lift capacity of the wing. In our case, we will choose a design with a range of 1447 km and a payload of 10 kg.

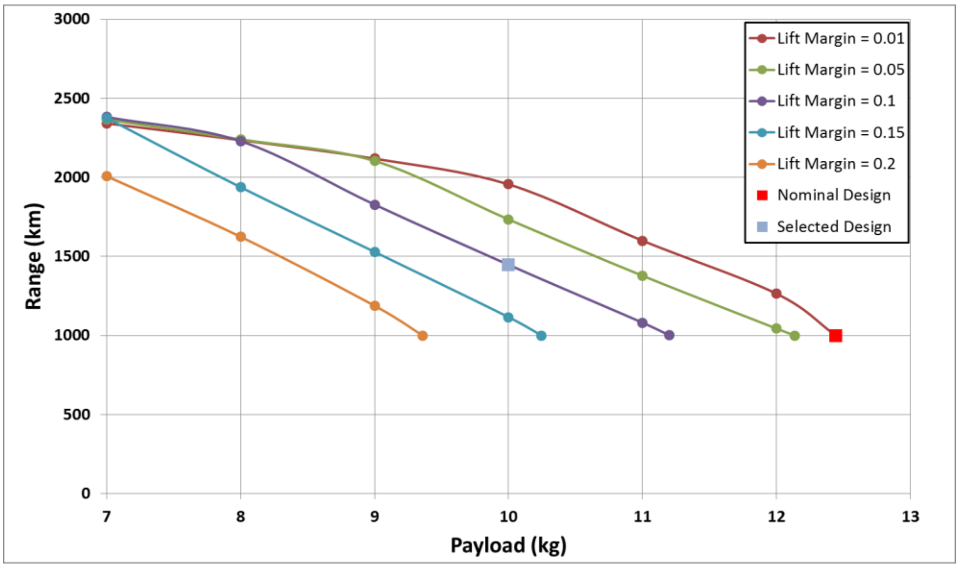

Fig 3. Effect of varying margins on Pareto Range-Payload Performance

Based on the information provided by the Iso-margin curve, the following design is selected over the nominal design. The difference between the nominal and selected design with reference to the nominal is shown in Table 3. The amount of payload reduction increases the margin substantially by more than two times. By adopting this approach, we can increase the buffers of a design to its limits, subjected to the system requirements. This is potentially useful in industry because, engineers can analyse the design limits and technical managers can address system requirements (which are usually derived from contractual deliverables) under the same metric.

Table 3. Design Variables

	Nominal Design	Selected Design	Change (%)
Payload (kg)	12.44	10	-19.6
Range (km)	1000	1447	44.7
Lift Margin	0.01	0.10	900

With an increase in lift margin by an order of magnitude, the payload decreases by 19.6%, and the range increases by 44.7%. The selected design allows range and payload requirements to be met, yet increasing the margins and hence robustness. By moving along the Iso-margin curves, we are able to explore the changes to the design configurations. Fig 4 shows an example of design exploration with the nominal and selected design along their Iso-margin curve. From the 2-D plots and 3-D illustrations, we can view the configuration changes (wing geometry and fuselage geometry) necessary to achieve designs with maximum lift margin at the expense of payload and vice-versa.

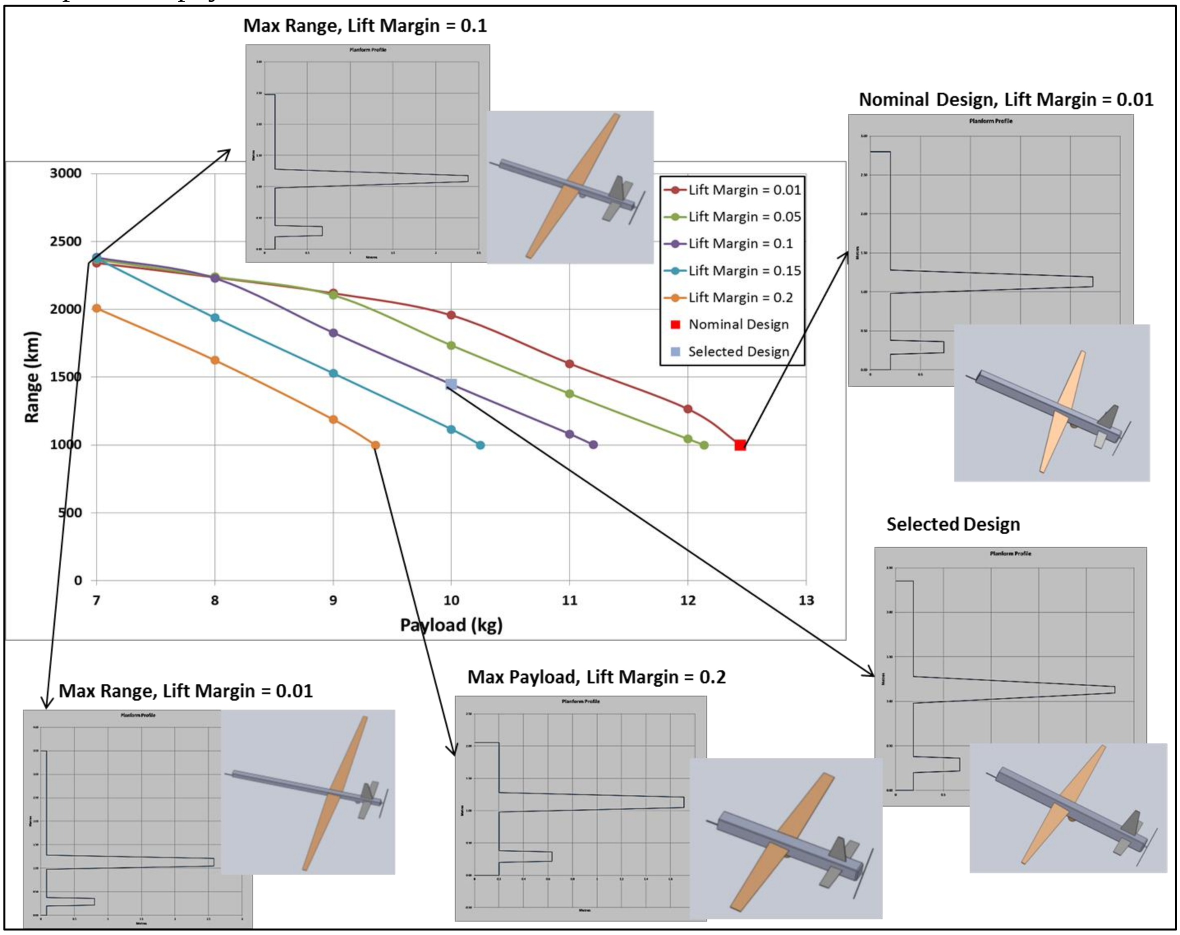

Fig 4. Effect on design configurations on the Pareto curves by varying margins

3 Discussion and Conclusion

With the performance margins made explicit, we have demonstrated that a small reduction of the targets on system level performance can greatly increase the design margin of components in the system in our study. This can thereby greatly increase the robustness of the design, and potential of success, but is subjected to further investigations. This is because we have only illustrated a single performance and margin variable of an entire complex system.

In the design of complex systems, the trade-off between performance and margins become apparent when they are viewed as variables instead of fixed values. This adds on another dimension to meeting design targets while considering the system performance and component limits. By modelling the performance behaviour as a relation to margins as a variable, engineers can plan ahead the product sustainment programmes (such as incremental upgrade programmes), customising existing designs for new customers (while still meeting system requirements) or spotting potential engineering problems early (by identifying components that are very close to their limits as result of system level optimisation). Potentially, a descriptive study on a company's design process could be implemented to determine which stage of design would the margin selection have the most impact.

Given that complex systems are typically non-linear and nested, future work will involve development of a method to include multiple performance and margins, variations in conditions, errors in engineering models and optimisation based on the level of abstraction.

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