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AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Wing Design Regarding Mass and Drag

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Based on the Master Thesis of Houssein Mahfouz

Society of Allied Weight Engineers
Aerospace • Marine • Offshore • Land Vehicle • Allied Industries
83rd International Conference

SAWE 83rd International Conference on Mass Properties Engineering
Online, 20-22 May 2024
Paper 3801
https://doi.org/10.48441/4427.1587

Abstract

Purpose – To optimize the parameters of the wing of a jet transport aircraft with equations from the aircraft design on wing mass and drag in a spreadsheet (Excel) and with its optimizer (Solver).

Methodology – The wing mass is calculated using Torenbeek's equation (with and without wing strut) and alternatively using an equation from the Luftfahrttechnischen Handbuch (LTH). Drag is divided into zero-lift drag, induced drag, and wave drag. The respective methods for calculating these drag elements are taken from Scholz's lecture notes. The aircraft design is mapped in a simplified way without the many hierarchically structured iterations. Instead, this simple wing design uses only one iteration. Procedures with snowball effect (Mass Growth Factor), with the 1st law of aircraft design and with both procedures combined are examined. On the one hand, the drag (fuel consumption) is minimized and, on the other hand, the take-off mass, which can be seen as a proxy for Direct Operating Costs (DOC).

Findings – The simple approach to Multidisciplinary Design Optimization (MDO) is provided as a spreadsheet "Wing-MDO". In comparison with the complete aircraft design and optimization program "Optimization in Preliminary Aircraft Design" (OPerA), the results from the simpler "Wing-MDO" could be confirmed or calibrated to it. A further comparison resulted from the literature review. For an aircraft with parameters like the Airbus A320, an optimal wingspan is obtained by minimizing the drag of 42.52 m (-23.94 %) without a wing brace and 53.09 m (-24.50 %) using a wing brace and minimizing the take-off mass an optimal wingspan of 36.65 m (-8.76 %) or 44.20 m (-13.31 %). The resulting changes in drag or take-off mass are given in parentheses.

Abstract

Practical Implications – "Wing-MDO" is offered to the community as a simple and user-friendly tool in Excel for optimizing basic wing parameters.

Social Implications – The optimization of an aircraft traditionally starts with the wing. This can currently also be seen in the new Boeing X-66A project. The present thesis serves to classify such proposals and shows that wings with a high span (and aspect ratio) can significantly reduce fuel consumption and thus CO_2 emissions and environmental impact. Presented simple calculations make public discourse possible.

Originality – Disciplines have presented the impact of their investigations at aircraft level, without considering the iterations (snowball effects) of aircraft design. Using the example of the wing, it could be shown how individual effects on mass and drag can be transferred simply but correctly to the aircraft level.

Acknowledgment

Houssein Mahfouz prepared a Master Thesis:

"Einfacher Flügelentwurf optimiert hinsichtlich Masse und Widerstand"

(Simple Wing Design Optimized for Mass and Drag)

at

Hamburg University of Applied Sciences,

Aircraft Design and Systems Group (AERO).

http://library.ProfScholz.de

https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2023-10-16.018


HAW HAMBURG

Masterarbeit

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Einfacher Flügelentwurf optimiert hinsichtlich Masse und Widerstand

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Motivation

- **Wing optimization** is the classic first choice for optimization in classic aircraft design.
- Wing optimization has two closely related disciplines: **aerodynamics** and **structures.**
- The economics are always of most importance in commercial aviation
  => integration of **economics** as a third discipline.
- In order to integrate these disciplines, the method of **Multidisciplinary Design Optimization (MDO)** is used. Traditionally, numerical methods such as Computational Fluid Dynamics (**CFD**) and Finite Element Method (**FEM**) have been used for this purpose.
- This thesis investigates a simpler approach:
  => **handbook equations** are used for wing drag and wing mass
  => **objective function is the take-off mass**, which can be used as a proxy for the Direct Operating Costs (DOC).
- **How to integrate take-off mass into the optimization** without the whole Aircraft Design loop, but instead using – much simpler – the mass growth factor**?**

Table of Contents

Introduction

Objectives and Research Questions

- Development of a sound understanding of **simple** **Multidisciplinary Design Optimization (MDO)** in aircraft design.
- Consideration of **equations from aircraft design** (zero lift drag, wave drag, induced drag and wing mass) to model wing MDO in Excel.
- Research questions:
    - Is it possible to obtain **practical, optimized wing parameters if**, instead of the numerical methods (CFD and FEM), only equations from the aircraft design are used and aircraft design iterations are **only** taken into account by a **Mass Growth Factor**?
    - Optimization only with **Excel's Solver** and determination of relevant **objective function** for results (**maximum take-off mass**).
- Comparison of the Wing-MDO tool to be created with the existing aircraft design optimizer **OPerA** (from PhD program).
- Performing a **literature review** to support the comparison!

Wing Design Optimized with Wing-MDO

Description of Wing-MDO

- **Multidisciplinary Design Optimization (MDO)** Program
- **User-friendly Excel file**
- **Calculation** of wing mass, drag coefficients (zero-lift drag, wave drag, induced drag), and drag
- Two separate mass estimation methods:
  =>**Torenbeek Method**
  => **LTH Method**
- Set up with **20 Iteration Steps for Wing Mass** Determination
- Using the **Excel Solver** as a powerful optimization tool

Description of Wing-MDO

- Parameter variation:
  - Investigation of **classic compromises in wing design**,
  - **Variation of parameters**: wingspan, relative thickness, taper, sweep, wing loading, Mach number and flight altitude,
  - The user sets the range in which parameters are changed.

- Two program versions:
  - Wing-MDO-1: Focus on **minimization of drag**,
  - Wing-MDO-2: Overcoming the challenges of **minimizing take-off mass**.

Wing Design Optimized with Wing-MDO

Description of Wing-MDO

- Wing-MDO-1 Layout (Screenshot):

Wing-Multidisciplinary Design Optimization-1

Parameter	Symbol	Value	Unit	Source
Constant Parameters				
temperature at sea level	T_0	288,15	K	
density at sea level	ρ_0	1,225	kg/m^3	
earth acceleration	g	9,81	m/s^2	
Input Parameters				**Source:**
aircraft name		A320-200		Aircraft is given, then: "Which Airfoil on which Aircraft?" check at http://links.ProfScholz.de => Airfoil
airfoil name		nach OPerA		
Wing mass calculation method		Torenbeek method		
How are aspect ratio, A and span, b calculated?		Given: b, calculated: A		
give span to calculate aspect ratio	b_{given}	34,1	m	Excel-Table for OPerA, tab: Airbus sources
give aspect ratio to calculate span	A_{given}	9,5		Excel-Table for OPerA, tab: Airbus sources
thickness ratio	t/c	0,12		Excel-Table for OPerA, tab: Estimation of General Parameter
position of maximum thickness	x_t	0,45		Excel-Table for OPerA, tab: Estimation of General Parameter
ratio of relative wing thickness, root over tip	$k_{t/c}$	1,3		Lecture Notes "Aircraft Design"
taper ratio	λ	0,213		Excel-Table for OPerA, tab: Estimation of General Parameter
sweep angle of the 25% line	φ_{25}	25	°	Excel-Table for OPerA, tab: Estimation of General Parameter
equivalent fuselage diameter	d_F	4,04	m	Excel-Table for OPerA, tab: Airbus sources
maximum take-off mass	m_{MTO}	73500	kg	Excel-Table for OPerA, tab: Airbus sources
operating empty mass	m_{OE}	41244	kg	Excel-Table for OPerA, tab: Airbus sources
maximum zero-fuel mass	m_{MZF}	60500	kg	Excel-Table for OPerA, tab: Airbus sources
wing loading	m_{MTO}/S_W	600,49	kg/m^2	Excel-Table for OPerA, tab: Airbus sources
wing mass	m_W	5902	kg	
critical Mach number, fix	$M_{crit,fix}$	0,6		
A_wave	A_wave	0,000885		
B_wave	B_wave	3,734		
Mach number	M	0,76		Excel-Table for OPerA, tab: Max. glide Ratio in Cruise
cruise altitude	H	39000	ft	Semicircular flight rules for IFR: e.g. 35000 ft, 36000 ft, 37000 ft ...
		11887	m	
proportion of laminar flow	$k_{laminar}$	0,2		
interference factor	Q	1		
wing with spoilers?		yes		
number of engines on the wing?		2		
is the landing gear mounted on the wing?		no		

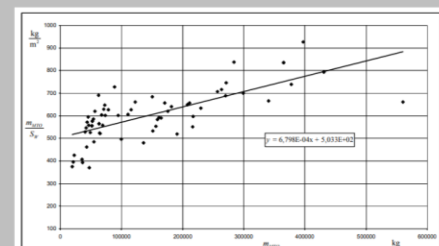


Fig. 5.11 Wing loading as a function of maximum take-off mass (data from **Jenkinson 1999**)

M_{crit} for different aircraft models to approximate wave drag

	A320-200	B727-200	B737-800	C-130H	BAe 146
M_{crit}	0,60	0,70	0,60	0,49	0,53

Table 1 Values of A_wave and B_wave for different airplane models to approximate the wave drag

	A320-200	B727-200	B737-800	C-130H	BAe 146
A_wave	0,000885	0,000766	0,001171	0,001201	0,001765
B_wave	3,734	5,257	3,543	3,126	3,457

Symbol | **Calculations** | Iteration of the wing mass | Results Graphs | Drag Optimization | (c)

- Similarity in user interface and table structure of Wing-MDO-1 and Wing-MDO-2

Wing-MDO-1

- Use of the **Snowball Factor** $k_{MG,i}$ to calculate the change in wing mass between iteration steps:

$$k_{MG,i} = \frac{m_{MTO,i}}{m_{MPL}} \tag{1}$$

- **Calculation of the new take-off mass from one iteration steps to the other**:

$$m_{MTO,i+1} = m_{MTO,i} + k_{MG,i} \cdot (-m_W + m_{W,i}) \tag{2}$$

Wing-MDO-2

- **Main goal: Solving the problem** of **take-off mass minimization** experienced **in Wing-MDO-1**
  - Identified problems with Wing-MDO-1:
    - Wingspan tends towards zero
    - Significant increase in relative thickness
  - Cause: **Failure to take fuel mass into account** in the take-off mass calculation equation of Wing-MDO-1
- Calculation of the take-off mass in Wing-MDO-2 using the "**1st law of the aircraft design**":

$$m_{MTO} = m_{MPL} / (1 - m_F / m_{MTO} - m_{OE} / m_{MTO}) \quad (3)$$

- Calculation of the **new operating empty mass**:

$$m_{OE,i+1} = m_{OE,i} + k_{MG,i} \cdot (-m_W + m_{W,i}) \quad (4)$$

- Results show that both k_{MG} in (4) together with (3) overestimate the change in wing mass.

  => **Introduction of a reduction factor $k_{k,MG}$** in (4):

$$m_{OE,i+1} = m_{OE,i} + k_{k,MG} \cdot k_{MG,i} \cdot (-m_W + m_{W,i}) \quad (5)$$

Wing-MDO-2

- **Identification of $k_{k,MG}$**, so that Wing-MDO-2 and OPerA achieve the same wingspan for a cantilever wing while minimizing take-off mass

  => $k_{k,MG} = 0.855$

- **Introduction of a damping factor $k_{damping}$** in (3) to cope with diverging iteration:

$$m_{MTO,i+1} = m_{MTO,i} + \left(\frac{m_{MPL}}{1 - \left(\frac{m_F}{m_{MTO}}\right)_i - \left(\frac{m_{OE}}{m_{MTO}}\right)_i} - m_{MTO,i} \right) \cdot k_{damping} \quad (6)$$

  => $k_{damping}$ **= 0.69** is a good value.

Optimization Results

- Concrete example:
  - **Optimization for cantilever and braced wing** based on the standard configuration of the A320-200
- Application of the LTH method:
  - **Aspect ratio out of range** in this example
    => no meaningful results
    => **LTH method not anymore taken into account**
- **Torenbeek method chosen to continue optimization**

Optimization Results (Wing-MDO-1)

- Results of drag minimization of a cantilever wing

	b_{given} [m]	t/c [-]	λ [-]	ϕ_{25} [°]	M [-]	H [m]	A [-]	m_{MTO} [kg]	S_W [m²]	m_W [kg]	D_{min} [N]	% difference in drag after optimization
f (b)	50,20	-	-	-	-	-	15,57	97214	161,89	11903	**28702**	**-11,54**
f (t/c)	-	0,190	-	-	-	-	9,51	73400	122,23	5876	31236	-3,73
f (λ)	-	-	0	-	-	-	9,30	75110	125,08	6323	31317	-3,48
f (ϕ_{25})	-	-	-	12,50	-	-	9,26	75385	125,54	6395	31731	-2,20
f (M)	-	-	-	-	0,73	-	9,07	77008	128,24	6818	31392	-3,25
f (H)	-	-	-	-	-	6858	9,07	77008	128,24	6818	25224	-22,26
f (b, t/c)	51,11	0,186	-	-	-	-	17,13	91545	152,45	10516	**27320**	**-15,80**
f (b, λ)	50,70	-	0	-	-	-	16,34	94457	157,30	11233	27399	-15,55
f (b, ϕ_{25})	51,17	-	-	9,92	-	-	16,64	94522	157,41	11249	27603	-14,93
f (b, M)	50,85	-	-	-	0,71	-	15,82	98170	163,48	12134	27316	-15,81
f (b, H)	38,98	-	-	-	-	7571	11,06	82537	137,45	8245	25022	-22,88
f (t/c, ϕ_{25})	-	0,186	-	12,09	-	-	9,68	72134	120,12	5544	30720	-5,32
f (b, t/c, ϕ_{25})	52,38	0,180	-	10,66	-	-	18,29	90090	150,03	10155	**26515**	**-18,28**
f (b, ϕ_{25}, M)	52,91	-	-	9,26	0,71	-	17,38	96738	161,09	11788	26005	-19,85
f (t/c, ϕ_{25}, M)	-	0,189	-	11,33	0,72	-	9,70	71980	119,87	5503	29502	-9,07
f (t/c, ϕ_{25}, H)	-	0,138	-	21,54	-	7076	9,28	75240	125,30	6357	25130	-22,55
f (b, t/c, ϕ_{25}, M)	54,74	0,185	-	9,84	0,70	-	19,50	92255	153,63	10691	24789	-23,60
f (b, t/c, ϕ_{25}, H)	42,52	0,149	-	14,45	-	8570	13,22	82157	136,82	8148	**24677**	**-23,94**

Optimization Results (Wing-MDO-2)

- Results for minimizing the take-off mass of a cantilever wing

	b_{given} [m]	ϕ_{25} [°]	M [-]	A [-]	S_W [m²]	m_W [kg]	$m_{MTO,min}$ [kg]	% difference in take-off mass after optimization
f (b)	35,20	-	-	10,90	113,63	7130	68236	-7,16
f (ϕ_{25})	-	27,50	-	10,16	114,38	6957	68687	-6,55
f (M)	-	-	0,74	10,21	113,82	6817	68353	-7,00
f (b, ϕ_{25}, M)	36,65	6,95	0,73	12,03	111,68	6986	**67065**	**-8,76**

Wing Design Optimized in Aircraft Design with OPerA

Description of OPerA

- Development of **OPerA** (Optimization in Preliminary Aircraft Design) as part of Mihaela Nita's **PhD Thesis**, supervision: Prof. Scholz (Nita 2013).
- Main objective: Set up **optimization for preliminary and conceptual aircraft design**.
- OPerA includes various modules such as Parameter Estimation, Preliminary Sizing, Area Estimation, Interference Factors, Resistance Estimation, Mass Calculation, Fuel Consumption Calculation, Direct Operating Cost Calculation and more.
- Two types of optimization with **genetic algorithm** (differential evolution):

  a) Built-in VBA algorithms or

  b) Interface with Optimus.
- **User** can set **control** parameters, free parameters, and objective functions (e.g., cost minimization or fuel mass reduction) to determine optimal aircraft parameters according to mission requirements.

Optimization of a Cantilever Wing Based on the A320-200

- Results to minimize fuel mass

	A [-]	ϕ_{25} [°]	M [-]	b [m]	m_{MTO} [kg]	S_W [m²]	m_W [kg]	$m_{F, min}$ [kg]	% difference in fuel mass after optimization
f(A)	18,56	-	-	50,24	81669	136,01	11417	13466	-16,18
f(ϕ_{25})	-	21,23	-	34,48	77296	125,15	6659	16045	-0,13
f(M)	-	-	0,72	34,68	76025	126,60	6238	15774	-1,82
f (A, ϕ_{25}, M)	19,88	20,09	0,68	**49,62**	77056	123,83	9920	12674	-21,12

- Results to minimize take-off mass

	A [-]	ϕ_{25} [°]	M [-]	b [m]	S_W [m²]	m_W [kg]	$m_{MTO, min}$ [kg]	% difference in take-off mass after optimization
f (A, ϕ_{25}, M)	12,01	7,04	0,65	**36,65**	111,92	6077	73594	-5,29

- Results to minimize DOC

	A [-]	ϕ_{25} [°]	M [-]	b [m]	m_{MTO} [kg]	S_W [m²]	m_W [kg]	$C_{DOC,min}$ [€/NM/t]	% difference in DOC after optimization
f (A, ϕ_{25}, M)	13,22	13,22	0,69	**39,35**	75507	117,06	7650	1,16	-1,98

Comparison of

the Results of

Wing-MDO and OPerA

Wing-MDO vs. OPerA

- Results to minimize drag, fuel mass, take-off mass, and DOC of a cantilever wing based on the A320-200

	Objective functions with % difference after optimization		b [m]	ϕ_{25} [°]	M [-]	A [-]	m_{MTO} [kg]	S_W [m²]	m_W [kg]
f (b, ϕ_{25}, M),$_{Wing\text{-}MDO\text{-}1}$	D_{min}	(-19,85)	52,91	9,26	0,71	17,38	96738	161,10	11788
f (A, ϕ_{25}, M),$_{OPerA}$	$m_{F,min}$	(-21,12)	49,62	20,09	0,68	19,88	77056	123,83	9920
f (b, ϕ_{25}, M),$_{Wing\text{-}MDO\text{-}2}$	$m_{MTO,min}$	(-8,76)	36,65	6,95	0,73	12,03	67065	111,68	6986
f (A, ϕ_{25}, M),$_{OPerA}$	$m_{MTO,min}$	(-5,29)	36,65	7,04	0,65	12,01	73594	111,92	6077
f (A, ϕ_{25}, M),$_{OPerA}$	$C_{DOC,min}$	(-1,98)	39,35	13,22	0,69	13,22	75507	117,06	7650

- Comparable results of Wing-MDO and OPerA
- Selection of tool depending on the specific objective function:
  - Drag minimization: Wing-MDO-1 due to faster calculation.
  - Minimization of take-off mass (proxy for DOC): Wing-MDO-2 is suitable (not Wing-MDO-1).
  - Complete aircraft design with many parameters and DOC calculation: Use OPerA.

Comparison of

the Results of

Wing-MDO and a Literature Review

Master Thesis of Hoogervorst 2015 (TU Delft)

- Titel:
  Wing Aerostructural Optimization Using the Individual Discipline Feasible Architecture.
- Objective: Minimizing drag by **optimizing the wing geometry of the Airbus A320**.
- Approach used: Applying the Individual Discipline Feasible (IDF) architecture to solve a gradient-based multidisciplinary design optimization problem.
- Advantage of IDF architecture: Does not require coupled sensitivity analysis for gradient-based optimization, allowing for greater flexibility in choosing software for disciplinary analysis and reducing overall computational costs.
- Software tools used:
  - Aerodynamics: **SU2 software** for deformation of surface and volume lattices, calculation of flow properties and derivation of sensitivities.
  - Structure: **FEMWET software** to model the static aeroelastic deformation and aeroelastic axis of the wing.

Wing-MDO-1 Compared to Hoogervorst 2015

- Results of drag minimization of a cantilever wing achieved by Wing-MDO-1 and Hoogervorst 2015

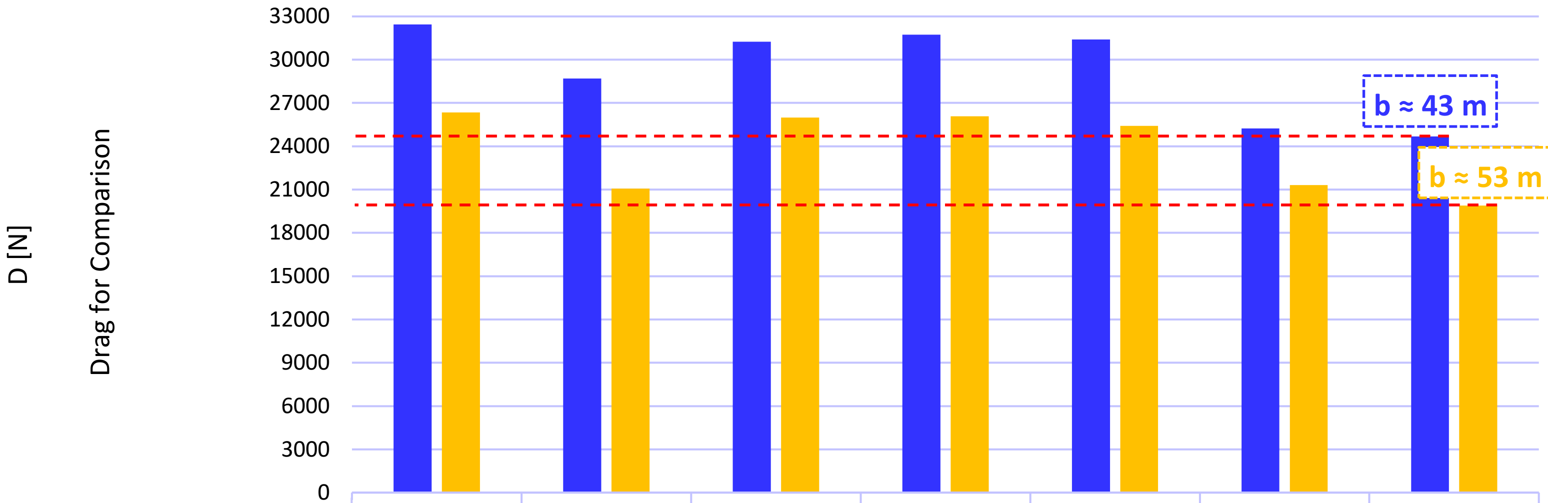
	$b/2$ [m]	ϕ_{25} [°]	A [-]	m_{MTO} [kg]	S_W [m²]	m_W [kg]	C_D [-]
Wing-MDO-1	**21,26**	14,4	13,22	82157	68,40	8148	**0,0136**
Hoogervorst 2015	**19,57**	20,2	11,55	70948	66,32	8270	**0,0142**
% Difference	8,64	28,71	14,46	15,80	3,14	1,48	4,23

- Comparable results despite different optimization approaches.
- Optimization with Wing-MDO-1 is faster than the optimization carried out in the study by Hoogervorst 2015.

Efficient Large Span Wing for the Next Generation of Aircraft

Efficient Wing

- Drag: Optimization vs. Standard A320-200 for Cantilevered and Braced Wing



	Standard Config A320-200	f(b)	f(t/c)	f(ϕ25)	f(M)	f(H)	f(b, t/c, ϕ25, H)
Drag of cantilever wing	32446	28702	31236	31731	31392	25224	24677
Drag of braced wing	26347	21067	25996	26079	25410	21305	19890

- A braced wing is more efficient than a cantilever wing.
- Recommended span: 36 m to 52 m (ICAO code D).

Boeing's Innovative Aircraft Project (Boeing X-66A)

- Boeing is working on a successor for the B737 Max in cooperation with NASA. This project, called the "Sustainable Flight Demonstrator", uses the innovative "**Transonic Truss-Braced Wing**" concept, known as the X-66A. (Bardan 2023, Ebner 2023, Sebayang 2023).
- Boeing X-66A is to be equipped with a **folding** braced wing with a **high aspect ratio** and **wingspan of approximately 52 m**. (Boeing 2019)
- Goal: Reduction of drag and integration of more efficient components (e.g. propulsion systems)

Boeing X-66A (Boeing 2019)

Conclusions
and
Outlook

Conclusions and Outlook

- The master thesis helps to understand **wing optimization in aircraft design** and shows that practical and optimum wing parameters can be found by using only **handbook equations** from aircraft design instead of numerical methods. The aircraft design iteration is taken into account by a **snowball factor** (mass growth factor) and optimization with the Solver in Excel.

- Ideas for future research:
  - Identifying different **values for the reduction factor $k_{k,MG}$** to achieve specific objectives:
    1. To achieve comparable results in drag minimization between Wing-MDO-1 and Wing-MDO-2 (instead of Wing-MDO-2 and OPerA).
    2. Ensuring comparable results between Wing-MDO-2 and OPerA for different aircraft types and a wide range of parameters, not only for taking into account wingspan.
  - Investigation of **efficient engines integrated into braced wings** using OPerA and its practical aircraft design approach.

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SCHOLZ, Dieter, 2024. Wing Design Regarding Mass and Drag. In: *Society of Allied Weight Engineers (SAWE), 83rd International Conference on Mass Properties Engineering*. Online, 20-22 May 2024.
Available from: https://doi.org/10.48441/4427.1587

Quote the thesis:

MAHFOUZ, Houssein, 2023. *Einfacher Flügelentwurf optimiert hinsichtlich Masse und Widerstand.* Masterarbeit. Aircraft Design and Systems Group (AERO), HAW Hamburg, 2023-10-30.
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