CONCEPTUAL DESIGN OPTIMISATION OF A "MALE" CONFIGURATION USING A FLEXIBLE SCALING TOOL

Florian Schieck
Chair of Aeronautical Engineering
Technische Universität München
85747 Garching

Nikolaos Deligiannidis
Conceptual Design Department
EADS Military Aircraft
81663 München

Thomas Gottmann
Conceptual Design Department
EADS Military Aircraft
81663 München

Jan van Toor
Head of Conceptual Design Department
EADS Military Aircraft
81663 München

Keywords:
Aircraft Conceptual Design, Aircraft Scaling, Mass Growth Factor,
Aircraft Multidisciplinary Design Optimisation

Abstract

In the early design stages of a new aircraft, there is a strong need to broaden the knowledge base about the evolving aircraft project, allowing a profound analysis of the presented solutions and of the design driving requirements.

With the presented methodology, a tool is provided to help increase and improve that needed information, exemplified for a new unmanned Medium-Altitude Long Endurance (MALE) aircraft configuration. The developed program system is open-structured, allowing the design engineer maximum flexibility in a first step-by-step analysis, before switching to the automated scaling and optimisation modes.

In an extended requirement model, performance requirements are represented along with other operational requirements. An aircraft model is introduced in sufficient detail for conceptual design considerations. The step-by-step analysis functions are presented. The computer-aided scaling methodology is explained, which, controlled by an optimisation module, automatically resizes the aircraft model until it satisfies the requirements in an optimum solution regarding a selectable figure of merit. Typical results obtained at the end of the scaling are discussed together with knowledge gained along the process, and example results are given.

1 Introduction

The design of a new aircraft is driven by partly adverse requirements which have to be fulfilled simultaneously, like e.g. design to low cost, high mission efficiency concerning endurance and certain point performances, low detectability, furthermore unmanned operations, and interoperability. Additionally, system aspects are gaining importance in terms of FCS, avionics, C3, C4I, etc. In conclusion, the design engineer has to deal with extended operability envelopes, a rapidly growing degree of aircraft complexity, and complex design sensitivities. This is especially the case in a MALE configuration for use as a flying sensor platform.

In the consecutive design phases of an aircraft (Figure 1), the conceptual design phase of a new aircraft project is characterised by a large degree of design freedom and a lack of information about the aircraft. Simultaneously, there is a strong need to broaden the knowledge base in early conceptual design stages, enabling better substantiated decisions in order to minimise overall development cost and risk, as may be indicated by the arrows in Figure 1. This in turn requires faster, more flexible and more accurate tools to support the classical approach in conceptual design work. In order to close this gap, a computer-based automatic scaling process was developed in a joint Academia-Industry research

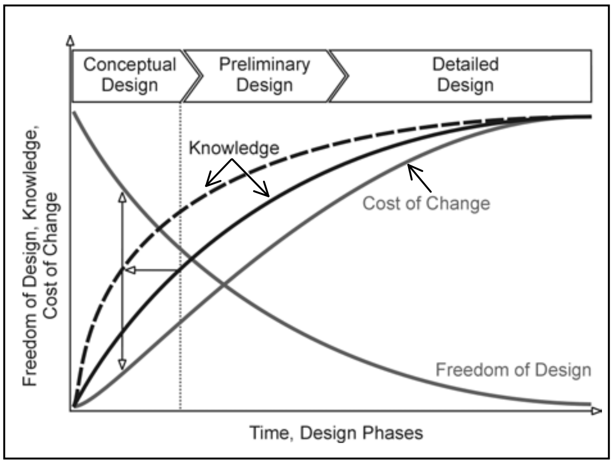

Fig. 1: Improvement chances during the conceptual design phase through faster increase of design knowledge

project [1]. In this approach, aircraft requirements, which have been integrated into a requirement model, are introduced as design objectives in Section 2. Complementing the requirement model, a MALE aircraft model is presented in sufficient grade of detail for conceptual design considerations in Section 3. Subsequently, the step-by-step analysis functionality and an automated scaling algorithm are described in Sections 4 and 5. The results of this scaling process are discussed in Section 6, and selected MALE scaling results are discussed in Section 7.

2 Extended MALE Requirement Model

The engineering design process of a new aircraft begins with the specification, which has to be reached in the end with a certain technical solution. These demanded performances can be divided basically into point performance requirements (Table 1) and mission performance requirements (Table 2). The former describe singular performance requirements which have to be satisfied at a single point in time with a fixed aircraft setup. The latter relate to performance requirements which have to be met in a specific mission context, along a flight profile, with a steadily changing fuel mass. Both requirement classes are integrated via various handbook methods and formula systems [2][3].

However, a specification for a flying sensor platform like a MALE aircraft is not restricted to performance requirements alone. Several operational requirements must be satisfied as well (Table 3).

Table 1 Point Performance Requirements
At any Fuel and Payload Percentage

- Stall speed	- Specific excess power
- Take-off distance	- Landing distance

Table 2 Mission Performance Requirements

- Payload mass	- Climb rate	In a mission context
- Range	- Acceleration	
- Cruise altitude	- Loiter altitude	
- Cruise speed	- Loiter speed	

Table 3 Operational Requirements
MALE Aircraft Characteristics

- Low radar and IR signatures
- Integration of pre-defined avionics/sensors suite
- Engine power-offtakes for sensor operation

However, most of these operational requirements are not immediately reflected in the above mentioned formula systems and performance models. So the presented scaling approach includes an extended requirement model, enabling the automated expansion of the above operational requirements into technical solutions with quantifiable effects on mass and drag, as well as further technical boundary conditions. These requirements are thus made compatible with the implemented core formula system, which mostly relies on the above mentioned formulas and equations. The specified low IR signature, e.g., will be translated into the integration of a nozzle exhaust stream cooling/mixing device, with certain individual mass and drag properties, and/or into the restriction of the engine's nozzle exhaust temperature. The integration of a pre-defined avionics/sensors suite will dominate parts of the internal configuration and come along with a clearly defined payload mass. Additionally, engine power-offtakes will influence the engine design parameters. With this, an extensive requirement model as guide for the scaling has been defined.

3 MALE Aircraft Model

For conceptual design considerations, the aircraft model is described in sufficient detail by a set of variables (Figure 2). In the presented approach, some 80 variables are currently used, describing a particular aircraft in terms of geometric key figures, propulsion data, aerodynamics, and mass properties.

This variable model is complemented in a second part by several methods for the parameter value determination in order to provide a parametric aircraft model for the scaling process. In this methods-part, the propulsion device is calculated according to a generic engine model [4]. The prediction and/or scaling of a longitudinal aerodynamic dataset, including trim losses, relies on adapted handbook methods [5][6][7]. Mass determination is realised using handbook methods and documented specific knowledge of experienced design engineers [8][9].

Additionally, the methods part includes an automated rule-finding/rule-applying functionality (a highly detailed input is possible, but not mandatory in the presented approach) around an extensively referenced MALE baseline aircraft, enabling a better model accuracy in parameter variations closely around that well-defined reference.

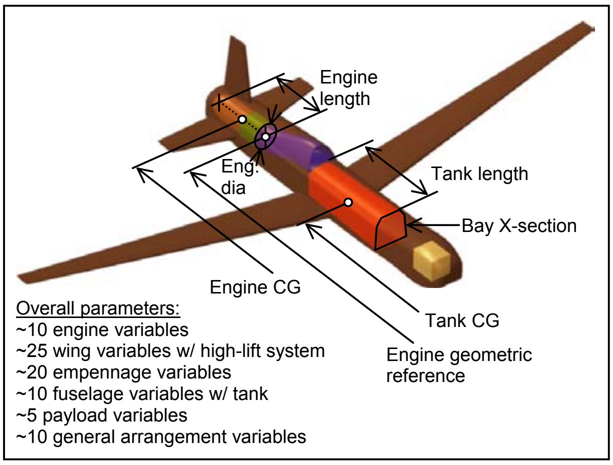

Fig. 2: MALE aircraft model in sufficient detail for conceptual design considerations (example variables)

4 Step-By-Step Analysis

In a step-by-step analysis, the point performance figures of the MALE aircraft (Table 1) can be investigated manually prior to the automatic scaling. Here, the design engineer can quickly investigate how the different performances change due to a single parameter value alteration: a wing area increase, e.g., bringing about a certain mass increase, will have different effects on stall speed and climb rate. Operational requirements (Table 3) and stability/control properties can be analysed as well. With the help of this functionality, the first-shot baseline design can be thoroughly tested and quickly improved with traceable changes, before a more complex scaling run appears sensible.

5 Automatic Scaling Process

The MALE aircraft model, as a whole or in part, is then sized in a scaling process in order to meet the initially specified requirements, as illustrated in Figure 3. At the beginning of this automated scaling process, a number of scaling rules, e.g. parameter value minimum/maximum envelopes, a master mission profile, key figures like wing loading or thrust/power loading to be kept constant, or scaling boundary conditions used by the optimisation module (see below) can be set individually.

5. 1 Scaling Core

The core sizing process starts using initially the data of the MALE baseline. That baseline design, however, does not need to meet the required performance, and does not necessarily represent an optimum design with respect to any objective. During the iterative scaling process, the current aircraft dataset is analysed in several modules in order to ascertain whether the given requirements can be satisfied. First, several required point performances listed in the aircraft specification are investigated. Performance figures of the current aircraft dataset are computed and checked against the requirements. If the current aircraft dataset over-qualifies or fails in this comparison by a definable margin, the responsible aircraft parameters are correspondingly marked for change.

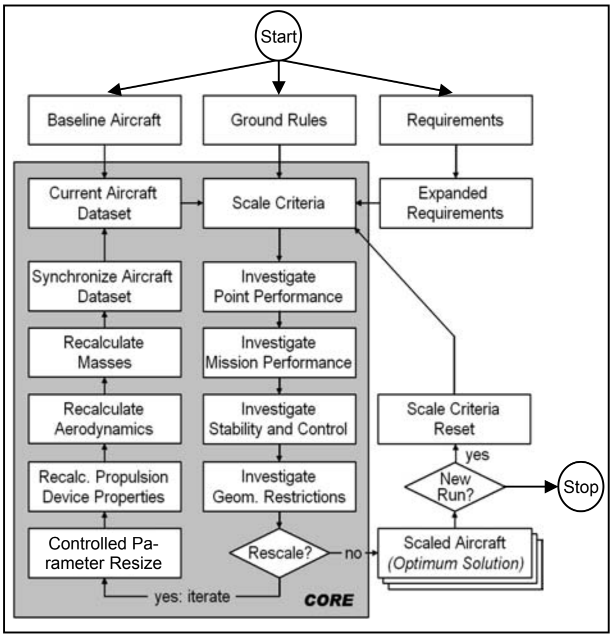

Fig. 3: Sizing procedure flowchart (simplified)

In the next step, required mission performances are investigated as well. The computer program allows the flexible definition of a master mission (Figure 4). Single mission segments, each defined separately, can be combined without any restriction, generating a mission which the current aircraft dataset "flies along".

In addition, a stability and control module is included to ensure certain aircraft handling qualities according to the requirements, and finally the compliance of the overall design with geometric restrictions is tested.

At the end of this "down-loop" a rescale decision is made: if the current MALE aircraft design satisfies all required criteria investigated earlier, the algorithm terminates with a solution satisfying the specification of the desired aircraft. If, on the other hand, there is still need for rescaling, and the parameters in question are still within their value envelopes, a parameter resize is initiated.

A "back-loop" then allows scaling of the current aircraft design, according to the parameters marked before, in terms of engine size, wing, empennage, and fuselage dimensions. Currently, about 25 variables used in the aircraft model are subject to direct manipulation, e.g. wing area or engine static thrust.

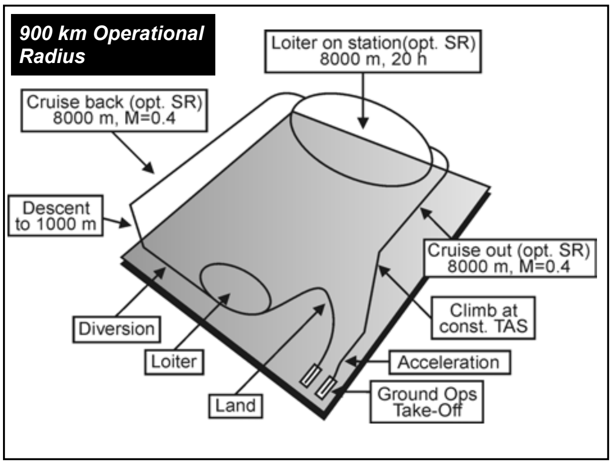

Fig. 4: Flexible definition of mission profile using an extensive mission model

This iterative process automatically resizes the baseline design towards the target design, aiming at e.g. the favoured minimum-mass solution. This scaled design is represented by an output list of aircraft properties according to the MALE aircraft model, including geometry, propulsion data, aerodynamics and mass. In addition, calculated point performance data, mission performance results, and stability/control properties complete the scaling result.

5. 2 Optimisation Module

An optimisation module finally evaluates the resulting scaled design regarding a selectable figure of merit, e.g. aircraft total mass, and decides on a new scaling run with slightly changed scale criteria. Thereby, several technical possibilities to solve the same problem are investigated – e.g. a required low stall speed, which could be reached by means of either a huge wing, or a sophisticated high-lift system, or a combination of both – and the best solution concerning this figure of merit is isolated, as an example will demonstrate in Section 7.

6 Results of the Scaling Process

With a number of optimisation module-controlled scaling processes, various scaled designs are available – each matching the requirements, but differing along a parameter list according to the individual ground rule-setting. Every single solution is plotted in a design diagram, thrust loading versus wing loading (Figure 5). Since each plotted point represents the multidimensional vector of a complete design, various trends, e.g. as defined by the aircraft total mass as a rough figure of merit, are determined, and the single solutions are evaluated individually. As additional guidelines, various boundaries are mapped which result from individual requirements: in the shaded areas those combinations of the design variables are located which fail to satisfy certain requirements. If a 850 m take-off run length is required, point ***A*** would mark the minimum mass design. If this requirement is withdrawn, point ***B*** would mark the favoured minimum-mass design. The baseline design not yet meeting all requirements is also plotted at point ***B/L***.

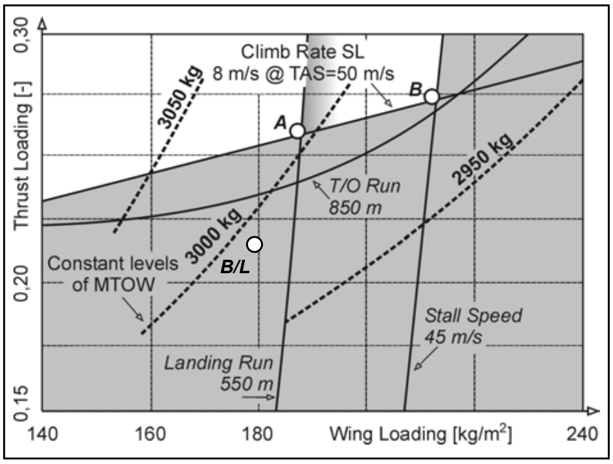

Fig. 5: MALE design diagram with plottings of evaluable solutions

The data obtained implicate even more than a variety of solutions that can be visualised in the above diagram. For once, mass growth factors – i.e. values for the partial differentiations of the aircraft total mass relative to a certain required aircraft quality [10] – are available through dedicated scaling runs. Thus the sensitivity of the baseline design concerning a certain requirement in terms of a total mass change becomes apparent. Specifically, this requirement may be any point performance requirement (see Table 1), or mission performance requirement (see Table 2), or additional operational requirement (see Table 3). Aircraft total mass as a figure of merit is currently used because of its implications, as there are methods available to easily derive rough cost and time schedule estimations from mass data [11]. Another parameter, e.g. aircraft total drag, can be investigated as well. With these results, the penalties – in terms of additional mass or drag – become clearly evident, which have to be accepted in order to satisfy a certain requirement. So it is possible to critically review the basic set of requirements, maybe weakening the one or other desired parameter value slightly, while focusing on a better overall performance in the end with respect to a definable figure of merit.

Moreover, as the scaling algorithm with its optimisation module can be used to investigate several technical possibilities to meet the same requirement, a discussion of favoured basic technical approaches can be provided as well, including the minimum mass and minimum drag solutions.

So the resulting data adds to the available knowledge about the MALE aircraft project in an early design phase. Moreover, it can be considered a valuable aid in the trade-off decision-making processes concerning certain requirement's parameter values or detail solution versus detail solution, as will be demonstrated below.

7 Example

In the example below, the search histories of two scaling runs are shown for selected key parameters. In Figure 6, the automated scaling process resizes the MALE aircraft towards a certain take-off field length performance by changing engine static thrust, wing area and lift coefficient respectively flap system, thus implicating a change in aircraft total mass. Interactions between lift coefficient, wing geometry and flap system properties are reflected in the calculations. Any of the vertically arranged parameter combinations in Figure 6 can be regarded as a possible solution, a result of a scaling core run (with the exception of iteration 0, which represents the baseline design not yet meeting the changed requirement). It becomes apparent that the minimum-mass technical approach to improve field performance is to revise the high-lift system, thus allowing a decrease of

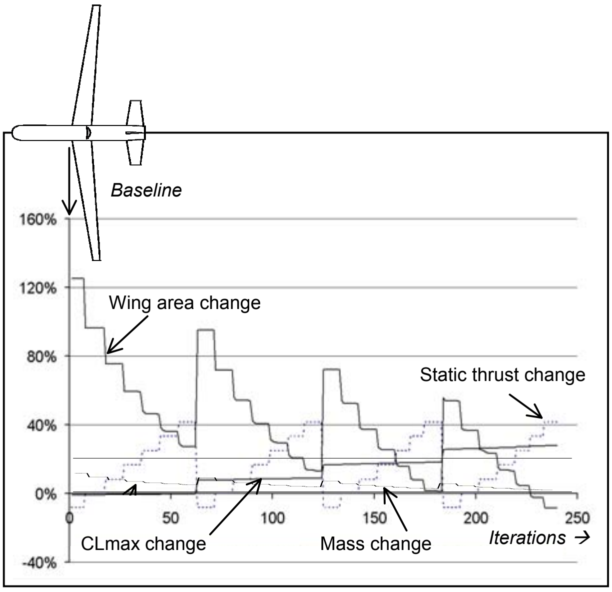

Fig. 6: Search history for a take-off field length improvement

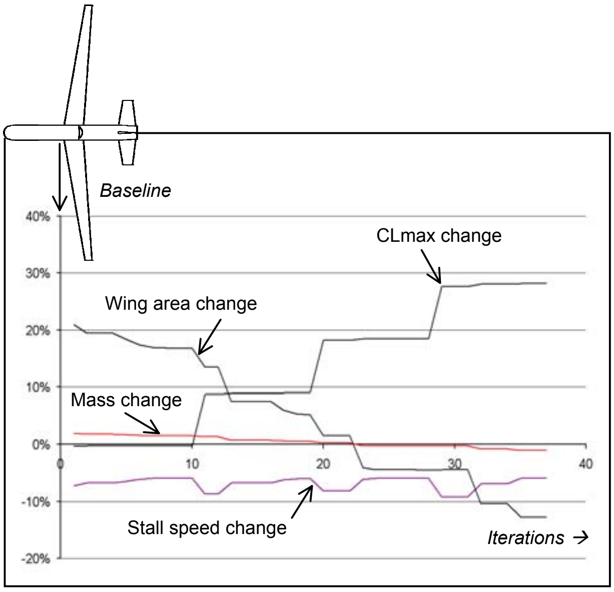

Fig. 7: Search history for a stall speed reduction

wing size and engine static thrust.

Relying on this result, the minimum mass solution for an e.g. 10 % take-off field length reduction and the corresponding mass penalties can be calculated (Table 4). Effects of a 10 % take-off field length increase can be determined as well (Table 5). With this data the mass penalties or benefits of the realisation of a certain field performance requirement are made obvious.

Table 4 T/O Field Length Reduction of 10 %

Changes relative to Baseline	
Static thrust change	+41.67 %
Wing area change	–8.51 %
Max lift coefficient change	+27.90 %
Overall mass change	+1.23 %

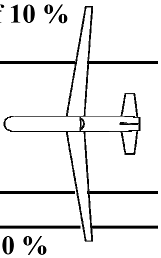

Table 5 T/O Field Length Increase of 10 %

Changes relative to Baseline	
Static thrust change	+41.67 %
Wing area change	–31.18 %
Max lift coefficient change	+29.76 %
Overall mass change	–0.97 %

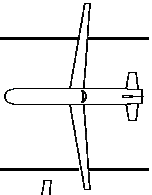

Table 6 Stall Speed Reduction of 10 %

Changes relative to Baseline	
Wing area change	–12.78 %
Max lift coefficient change	+28.16 %
Overall mass change	–1.00 %

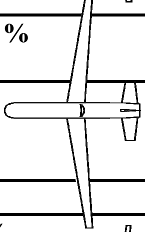

Table 7 Stall Speed Increase of 10 %

Changes relative to Baseline	
Wing area change	–45.36 %
Max lift coefficient change	+31.69 %
Overall mass change	–4.10 %

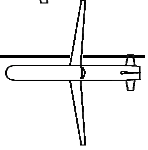

Figure 7 shows the search history for reduced stall speed through wing area and lift coefficient/flap system variation. Again, the overall mass change is determined along these variations, and the minimum mass approach is isolated. Finally, the solutions for a given required stall speed value, again improved as well as degraded by e.g. 10 % relative to the basic requirement, can be determined (Tables 6, 7).

Note that the example diagrams refer only to the mentioned take-off field length and stall speed variations. Additional constraints, e.g. a certain climb rate or a changed mission range performance, would lead to different results.

In addition to point performances, different technical approaches to satisfy a certain mission range requirement can be investigated as well.

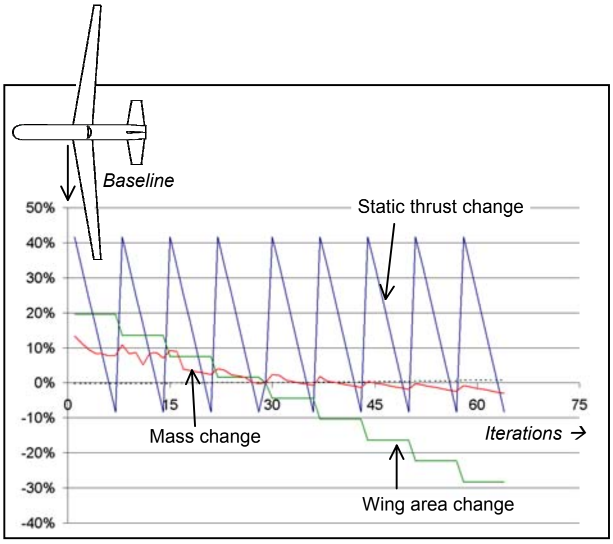

Fig. 8: Search history for increased time on station

In Figure 8, the example baseline design is scaled in order to accommodate enough fuel for a given increased *time on station* segment within a complex reconnaissance mission profile (Figure 4): fuselage tank length is varied, and the overall changes in mass and other key figures are determined. A general fuselage resize does not take place in this example, since the pre-defined antennae and sensor distances enforce a certain minimum fuselage length with enough volume for necessary tank integration. Note that both wing reference area and static thrust remain at fixed values which turned out to describe a minimum-mass design for the given master mission.

Relying on this recommended configuration, the mass and drag penalties for a *time on station* variation of e.g. 10 % can be investigated, and required key basic parameters are provided by scaling runs (Table 8). Implications of station altitude and range variations are also investigated. In the last column of this example, the benefits of a conceivable modern sophisticated engine a with a more optimistic specific fuel consumption (SFC) are computed as well.

These examples illustrate how trade-off decisions of the MALE design can be prepared with the presented scaling methodology.

8 Conclusion

A computer-based automatic scaling process, which has been developed in a joint Academia-Industry research project, is described. An extended requirement model reflecting point, mission and operational performances has been introduced. A MALE aircraft configuration is represented in sufficient detail for conceptual design considerations by a set of variables and methods to enable their parameter value's determination. With the described open-structured tool, this aircraft model can then be analysed flexibly in a step-by-step manner. Moreover, an automatic resize can be initiated, aiming at the satisfaction of a characteristic set of requirements in an optimum solution with respect to a selectable figure of merit. Results available at the end of, as well as information gained along the scaling process include growth factors and design sensitivities of the baseline design. Relying on this data, important trade-off decision-making processes during the MALE aircraft conceptual design are enabled and backed up with extended knowledge about the evolving aircraft.

Table 8 Mission Range Calculation
Changes relative to Baseline scaled to Master Mission

	Time on Station		Station Altitude		Operational Radius		SFC
	+10 %	–10 %	+10 %	–10 %	+10 %	–10 %	–5 %
Δ Fuel mass	+6.47 %	–15.98 %	–6.32 %	–3.87 %	–2.58 %	–7.17 %	–10.11 %
Δ Structure mass	–9.75 %	–14.39 %	–12.49 %	–11.96 %	–11.50 %	–12.07 %	–13.30 %
Δ Overall mass	0.89 %	–13.48 %	–7.32 %	–5.75 %	–4.87 %	–7.71 %	–9.75 %
Δ Wing area	–28.32 %	–28.32 %	–28.32 %	–28.32 %	–28.32 %	–28.32 %	–28.32 %
Δ Static thrust	–8.33 %	–8.33 %	–8.33 %	–8.33 %	–8.33 %	–8.33 %	–8.33 %
Δ Wetted area	–13.97 %	–13.97 %	–13.97 %	–13.97 %	–13.97 %	–13.97 %	–13.97 %
Δ Zero drag (individual ref. area)	+14.93 %	+14.93 %	+14.93 %	+14.93 %	+14.93 %	+14.93 %	+14.93 %
Δ Wing loading	+35.29 %	+16.01 %	+24.27 %	+26.39 %	+27.56 %	+23.75 %	+21.01 %
Δ Thrust Loading	–5.48 %	+10.22 %	+2.90 %	+1.18 %	+0.25 %	+3.33 %	+5.67 %

References

[1] Schieck, F., Deligiannidis, N., Gottmann, T.,
A flexible, open-structured computer based approach for aircraft conceptual design optimisation,
AIAA 40th Aerospace Sciences Meeting,
AIAA-Paper 2002-0593, Reno 2002

[2] Roskam, J.,
Airplane design, Part I-VII,
DARcorporation, Kansas 1988

[3] Torenbeek. E.,
Synthesis of subsonic airplane design,
Delft University Press, Delft 1982

[4] Wittmann, R.,
Generisches Modell für propeller- und strahlbasierte Flugzeugantriebe,
Internal Report LT-SA 01/6, Technische Universität München, Munich 2001

[5] Schemensky, R. T.,
Development of an empirical based computer program to predict the aerodynamic characteristic of aircraft,
Technical Report AFFDL-TR-73-144,
Volume 1, Wright-Patterson AFB, Ohio 1973

[6] Polhamus, E. C.,
Prediction of vortex-lift characteristics based on a leading-edge suction analogy,
AIAA Paper 69-1133, Washington D.C. 1969

[7] Hoak, D. E., Ellison, D.,
USAF stability and control DATCOM,
Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, (Revised) 1978

[8] N. N.,
Luftfahrttechnische Handbücher,
LTH-Band Masseanalyse,
IABG, Munich, February 1992

[9] N. N.,
ESDU International Structures Series,
ISSN 0141-4097, London 2000

[10] Ballhaus, W. F.,
Clear design thinking using the aircraft growth factor,
Presentation, SAE Los Angeles Aeronautic Meeting, October 5-9, 1954

[11] Burns, J. W.,
Aircraft cost estimation methodology for preliminary design development applications,
Presentation, SAWE Conference, 23-25 May 1994
(SAWE Paper No. 2228, Attachment E)