Multi-role Helicopter Life Cycle Cost (LCC) Optimisation: The Pre-Design Strategy

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Abstract

This paper presents a Life Cycle Cost (LCC) optimisation methodology for a helicopter which has to perform multiple missions. The helicopter design is being optimised for minimum LCC instead of the normally followed goal of minimum mass. This work has been partly performed within the Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE) programme. The NLR analysis tool SPEAR "SPEcification Analysis of Rotorcraft", and the Eurocopter Life Cycle Cost model have been integrated to develop the optimisation methodologies. Program objectives, tools, models, developed methodologies and sample calculation results are described.

Abbreviations

DMC	Direct Maintenance Cost
EC	Eurocopter
EMPRESS	Energy Method for Power Required EStimateS
FBW	Fly By Wire
FCS	Flight Control System
GB	Gear Box
LCC	Life Cycle Cost
MDO	Multidisciplinary Design and Optimisation
NLR	National Aerospace Laboratory
SPEAR	SPEcification Analysis of Rotorcraft
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative Enterprise

Introduction

The pre-design is normally driven by performance requirements. Other important requirements, such as maintenance cost, non-recurring cost, mass and specific customer requirements are not treated in the same manner. Also a formalised decision process for the assessment of different design solutions by trade-off analyses is often missing.

However, the ultimate goal would be to find the optimum helicopter design which not only reaches the required performance requirements, but also satisfies the customer's requirements at lowest possible costs. Several customers will use the helicopter, and they are likely to perform missions, both different in type and characteristics. In contrast to fixed wing operators, helicopter operators will often use the same helicopter for a diversity of missions. So, the helicopter should not only be optimised for the performance requirements matching the most demanding mission, but also to operate in a cost effective way, while performing a diverse mix of missions. The costs are influenced by the different mission characteristics (flight hours, flight profile, payload, etc.), but also by the maintenance policies applied, which can be effected by design choices (i.e. configuration, drive train architecture, chosen materials). To optimise cost, a multidisciplinary optimisation approach is required at the preliminary design phase.

Currently, the most demanding missions are identified by market analysis and the design choices are based on the cost estimates involved with those missions. So, the market as a whole is taken into account, but not the specific mission diversity of the various customers in the market.

In order to find an optimal technical solution for these multidisciplinary customer requirements a methodology had to be developed to find an optimal compromise between the “driving” design parameters. This requires the identification and evaluation of those driving parameters through the assessment of the sensitivity of the design to each of these parameters by means of trade-off analyses. Such a methodology can also improve the efficiency of the helicopter design process by reducing the number of iterations during the design process.

VIVACE

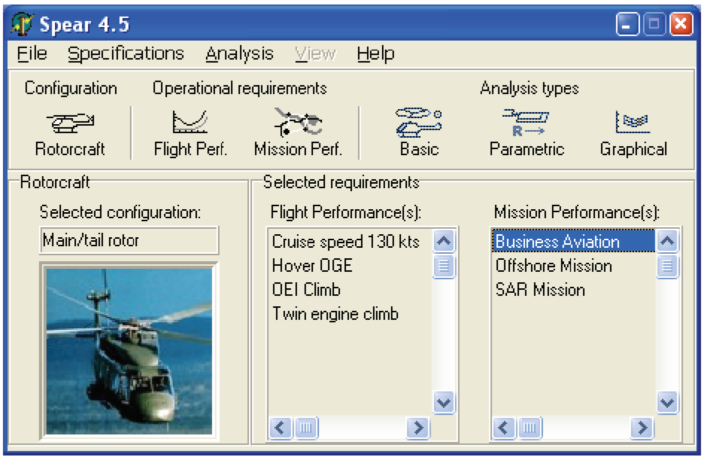
The Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE) project is an Integrated Project in the European 6th Framework Programme, and aims to define the future European Aeronautical Collaborative Design Environment (Ref 1).
The outputs will include enabling processes, models and tools available for use in this environment in the second half of this decade. The main result of VIVACE will be an Aeronautical Collaborative Design Environment and associated processes, models and methods. This environment will support the design of a complete aircraft and its engines by providing virtual products for each phase of the product engineering life cycle.

In the VIVACE project, a “Multidisciplinary Design and Optimisation” (MDO) Use Case has been defined, in which the following activities concerning the helicopter pre-design have being performed:

- evaluation of existing (pre-design) methodologies/technologies and tools,
- development and integration of a Life Cycle Cost model in a pre-design sizing tool,
- identification of the cost driving parameters and performing the sensitivity analysis,
- development and implementation of a methodology to find a multidisciplinary design solution to optimise Life Cycle Cost.

Eurocopter has developed a helicopter Life Cycle Cost (LCC) model which reflects the impact of both the major technical parameters and the major categories of customers and missions.
NLR has developed a sizing optimisation methodology to enable a multi-mission design with LCC optimisation. and has integrated the Eurocopter LCC-model and the optimisation routines into the in house developed NLR helicopter analysis tool SPEAR.

SPEAR



Selected configuration:
Main/tail rotor

Flight Performance(s):
Cruise speed 130 kts
Hover OGE
OEI Climb
Twin engine climb

Mission Performance(s):
Business Aviation
Offshore Mission
SAR Mission

Figure 1 Main window of the SPEAR program

NLR has developed a computer program called SPEAR: "SPEcification Analysis of Rotorcraft", see figure 1. This program is able to estimate the main dimensions and minimum mass of a rotorcraft capable of fulfilling a specified set of operational requirements (flight and mission tasks) for a given rotorcraft configuration. Valid solutions are those that comply with the flight performance requirements and for which available fuel equals required fuel to fulfil the most demanding mission. The program determines the rotorcraft gross mass, the main physical dimensions, the installed engine power, the fuel capacity and the mass breakdown for the main vehicle components. The consequences of operational requirements on rotorcraft sizing can be analysed, trade-off studies can be performed, and the effects of technological developments on optimal rotorcraft mass and size can be assessed. The computer program uses the flight and mission performance calculation routines from the EMPRESS (Energy Method for Power Required EStimateS) code (Ref. 2) and contains a large amount of information on historical and current helicopter designs. Extensive use is made of databases for major helicopter design relationships, major component characteristics, etc. SPEAR runs on Windows NT/2000/XP Personal Computers, thereby taking advantage of the Windows features. The current version is SPEAR 4.5, dated June 2007.

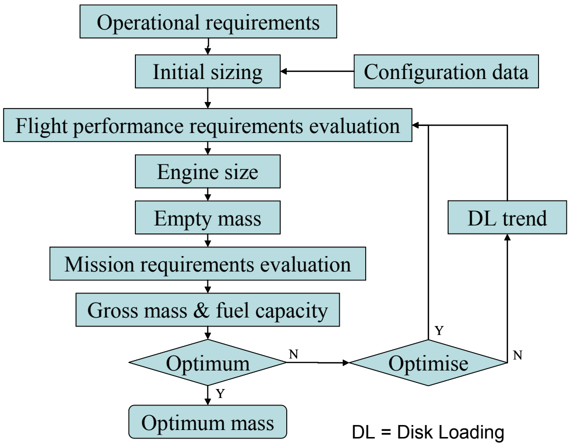
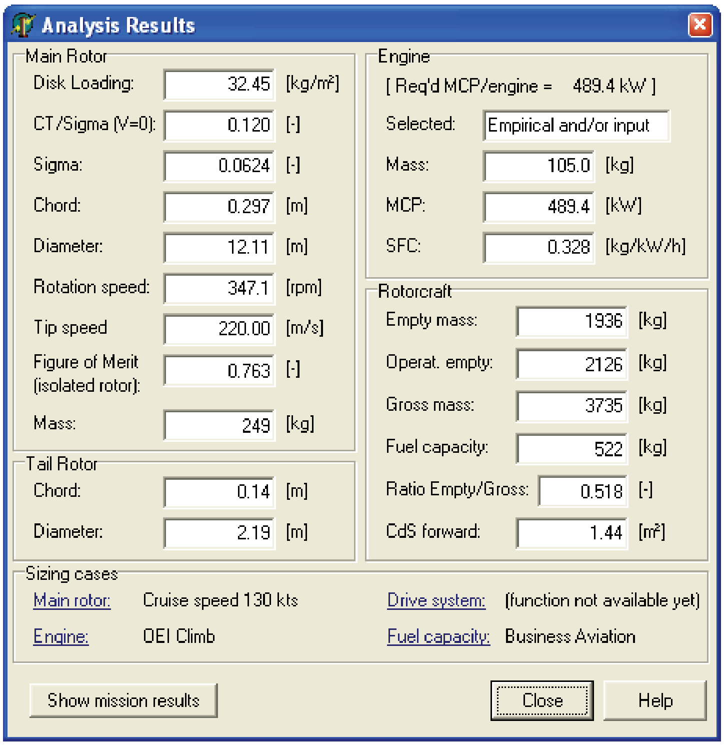


Figure 2 Simplified flow chart for the SPEAR calculation routine

The actual sequence for the calculation of the various parameters is shown in figure 2. First an initial Gross Mass estimation is made and from this an assumption is made for the disk loading, based on historic data. Then, suitable main rotor dimensions are determined for the specified flight performance requirements. The most demanding flight performance requirement in terms of engine power defines the engine(s). At that point, an initial assumption for the fuel capacity is made and an empty mass assessment based principally on historic data. Next, the fuel required for actually fulfilling the various specified missions is assessed. If the fuel mass needed to fulfil the most demanding mission appears to be different from the fuel mass available, the earlier assumptions for gross mass, fuel capacity and disk loading are revised and the calculation process is repeated. When the required and available fuel masses have been found to be equal, the process has converged to a valid solution. Finally, the disk loading is varied with small steps, thereby no longer following the historic trend. The calculation process is repeated in order to find the lowest gross mass at which the fuel criterion still holds, hence providing the optimum solution. As suggested in Ref. 3 other criteria e.g. lowest LCC may be defined for the optimal solution.



Main Rotor
Disk Loading: 32.45 [kg/m^2]
CT/Sigma (V=0): 0.120 [-]
Sigma: 0.0624 [-]
Chord: 0.297 [m]
Diameter: 12.11 [m]
Rotation speed: 347.1 [rpm]
Tip speed 220.00 [m/s]
Figure of Merit (isolated rotor): 0.763 [-]
Mass: 249 [kg]

Tail Rotor
Chord: 0.14 [m]
Diameter: 2.19 [m]

Engine
[Req'd MCP/engine = 489.4 kW]
Selected: Empirical and/or input
Mass: 105.0 [kg]
MCP: 489.4 [kW]
SFC: 0.328 [kg/kW/h]

Rotorcraft
Empty mass: 1936 [kg]
Operat. empty: 2126 [kg]
Gross mass: 3735 [kg]
Fuel capacity: 522 [kg]
Ratio Empty/Gross: 0.518 [-]
CdS forward: 1.44 [m^2]

Sizing cases
Main rotor: Cruise speed 130 kts
Drive system: (function not available yet)
Engine: OEI Climb
Fuel capacity: Business Aviation

Figure 3 Analysis results for VIVACE example requirements

In addition to the calculated results, the program shows the names of the requirements (flight performance and mission profile) that have driven the main rotor design, the required engine power and the fuel capacity, see figure 3. A detailed rotorcraft mass and LCC breakdown are also presented. The LCC (as total operating costs for the number of acquired rotorcraft) are broken down in acquisition, operational, disposal, and fabrication costs (costs of making the individual major components). It also provides the estimated operating cost per flying hour and per nautical mile.

Life Cycle Cost model

For the VIVACE MDO Use Case Eurocopter (EC) has developed a helicopter Life Cycle Cost (LCC) model which reflects the impact of both the major technical parameters and the major categories of customers and missions. This LCC model is based on civil operations and is composed of three major items

- *Rotorcraft acquisition cost*: the estimation of the helicopter price is based on its major physical parameters, such as the installed power, Maximum Take-Off Mass, rotor diameter, fuselage size, etc.; the level of detail of the acquisition cost breakdown is consistent with the level of detail used by the preliminary design team.
- *Direct Maintenance Cost*: the estimation of the cost to maintain the helicopter follows the same lines as the rotorcraft acquisition cost estimation.
- *Life Cycle Cost*: this is the total cost of a helicopter fleet for a certain period of time; it therefore combines the acquisition cost and the Direct Maintenance Cost, but also takes into account the procurement cost of spare parts and documentation, the insurance cost, the pilots salaries and fuel cost.

At the current level of the LCC model, the list of parameters has been limited while still allowing computation of a realistic result. This list can be further refined when needed or when more data becomes available.

LCC model in SPEAR

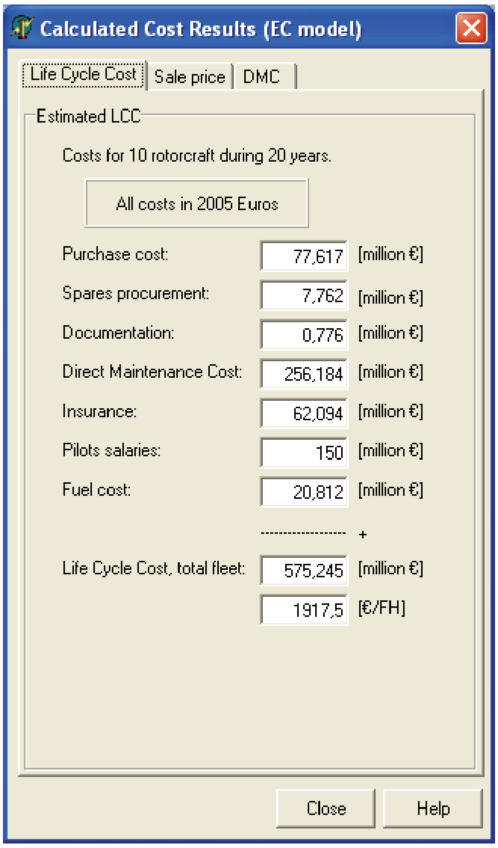
The Eurocopter life cycle cost model has been integrated in the NLR analysis program SPEAR. The goal was to optimise the design for minimum LCC.

A dedicated “Analysis Costs Input” window is used to provide the relevant input data for the Eurocopter LCC cost model. The “Calculated Cost Results (EC model)” window shows the estimated total Life Cycle Cost, the Sale price and the Direct Maintenance Cost (DMC) on three data tab sheets, see figure 4.

The Life Cycle Cost tab sheet shows the estimated total operating cost for the number of acquired rotorcraft during the stated period. The purchase cost is taken from the Sale price tab sheet, the direct maintenance cost from the DMC tab sheet. Finally the estimated operating cost per flying hour is provided.

The sale price tab sheet will show in detail the estimated costs of producing the individual major components. These add up to the sale price per rotorcraft.

The DMC tab sheet will show in detail the estimated Direct Maintenance Costs per flight hour for the individual major components.



Costs for 10 rotorcraft during 20 years.

All costs in 2005 Euros

Purchase cost: 77,617 [million €]
Spares procurement: 7,762 [million €]
Documentation: 0,776 [million €]
Direct Maintenance Cost: 256,184 [million €]
Insurance: 62,094 [million €]
Pilots salaries: 150 [million €]
Fuel cost: 20,812 [million €]
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Life Cycle Cost, total fleet: 575,245 [million €]
1917,5 [€/FH]

Figure 4 Calculated Cost Results (EC model) window in SPEAR

Optimisation methodology

A helicopter design optimisation environment has been created by putting the combined SPEAR/LCC model in a MATLAB environment (Ref. 4). This was achieved by compiling the SPEAR/LCC program into a Microsoft Windows dynamic link library (.dll) file. The MATLAB environment calls the functions in the .dll file with the appropriate design parameters as arguments, and in return receives the values of the design objectives, being the helicopter mass and the helicopter life cycle cost. The MATLAB functions and toolboxes, such as gradient based algorithms (Ref. 5), genetic algorithms (Ref. 6, 7) and pattern search (Ref. 6) are then used for the evaluation and optimization of these helicopter design objectives.

The optimisation methodology applied in this study is based on the formulation of a generic optimisation problem that allows for, among others, single- or multi-objective optimisation problems, non-linear constraints and discrete variables.

The following 13 helicopter design parameters are submitted from the optimisation environment to the SPEAR/LCC functions in the .dll file (possible values are indicated between parentheses):

1. Percentage of composite material (mass) in the fuselage (0 - 100 %)
2. Complexity of the main rotor blades (1 = low complexity or metal blade, 2 = moderate complexity or hybrid blade, 3 = high complexity or full composite blade)
3. Type of main rotor hub (0 = rigid, 1 = Starflex, 2 = Spheriflex)
4. Type of Flight Control System (0 = mechanical, 1 = FBW)
5. Type of tail rotor (0 = conventional, 1 = Fenestron)
6. Number of accessory gearboxes (1 - 5)
7. Number of reduction steps in the main gearbox (2 - 5)
8. Number of fuel tanks (1 - 5)
9. Presence of an engine reduction gearbox (no, yes)
10. Presence of a critical environment for avionics (no, yes)
11. Fleetwide number of business flights per year (0 - …)
12. Fleetwide number of offshore flights per year (0 - …)
13. Fleetwide number of search/rescue flights per year (0 - …)

Note that the first parameter is continuous, whereas all other parameters have discrete values. Parameters 11-13 express the numbers of missions that will be flown by the operator, expressed as total number of flights per year flown by its fleet.

Reference design

For the context of this paper and illustration purposes of the VIVACE use case, a selection of certain parameter values has been made to limit the total number of potential combinations. On the basis of engineering judgment and state-of-the-art technology the following values are fixed for the optimisation calculations:

5. Conventional tail rotor (lower mass and cost than Fenestron tail rotor)
6. One accessory gearbox
7. Two main gearbox reduction steps
8. One fuel tank
9. With and without engine reduction gearbox (effect on mass and cost not clear beforehand)
10. No critical environment for avionics (lower mass and cost)

For the mission combination a possible division of flights per year has been chosen (these values can be varied at a later stage):

11. 350 business flights per year
12. 500 offshore flights per year
13. 150 search/rescue flights per year

It should be noted that the results presented here are based on a study with a reduced set of input parameters to illustrate the capabilities of the methodology only.

A reference helicopter design has been determined based on the aforementioned parameter choices, complemented with full metal construction, low complexity rotor blades, Starflex rotor hub and mechanical flight control system. The reference helicopter will have a calculated mass of 3872 kg and total LCC of 178.2 million euros with engine reduction gearbox, or 3859 kg and 170.8 million euros without engine reduction gearbox. As the removal of the engine reduction gearbox has a beneficial effect on mass (minor) and costs (major), it will no longer be used in the optimisation strategy.

Optimisation evaluations

The optimisation of the helicopter design can be characterized as a mixed-integer programming problem. A specialized optimisation algorithm implemented in MATLAB ("fminconset") was applied, which combines a discrete branch-and-bound method[1] (Ref. 8) with the general purpose non-linear constrained optimisation algorithm "fmincon" from the MATLAB optimisation toolbox (Ref. 5).

A mixed-integer programming algorithm can be applied to the design optimisation problem as a whole. However, to gain insight in the design space, first a global evaluation of the effects of 4 design variables (the first 4 parameters given above) on the design objectives is performed. The first parameter (percentage of composite mass in the fuselage) is evaluated at 11 discrete values {0, 10,..., 100} %, and for the parameters 2 to 4 all possible values are evaluated. The resulting 198 evaluations of helicopter mass and LCC are given in figure 5.

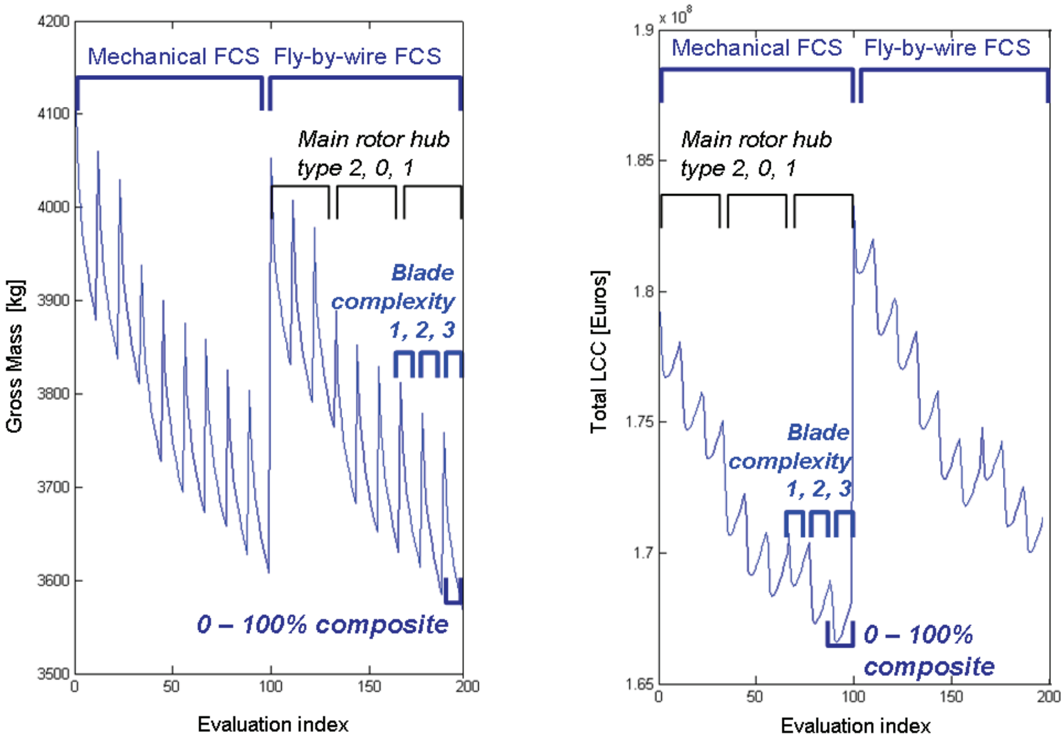

Figure 5 Global evaluation of helicopter mass (left) and LCC (right): their dependency on the 4 different design variables.

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[1] **Branch-and-bound (BB)** is a general algorithmic method for finding optimal solutions of various optimization problems, especially in discrete and combinatorial optimization. It is basically an enumeration approach in a fashion that prunes the non-promising search space.
The method was first proposed by A. H. Land and A. G. Doig in 1960 for linear programming.

From these results it is obvious that, to obtain a design that has minimum mass, a Starflex type main rotor hub must be used in combination with a high complexity rotor blade and a fly-by-wire flight control system. However, for minimum life cycle cost a mechanical flight control system should be selected. Also, to achieve minimum helicopter mass a high percentage composite mass in the fuselage must be used, whereas the lowest life cycle cost are achieved for a lower percentage composite mass in the fuselage. It is therefore decided that more detailed analyses are needed to find the best value for the percentage composite mass. Hence, separate minimisations are performed for the helicopter mass and LCC as a function of the percentage composite mass and the type of flight control system. In both these minimisations the optimal area, already indicated by the global evaluations, is zoomed-in. The Starflex type main rotor hub and a high blade complexity (i.e. full composite blades) are used. The MATLAB based mixed-integer programming algorithm, as mentioned before, was used for this minimisation. The results of these optimisations for helicopter mass and LCC are given in figures 6 and 7 (green circle and blue square).

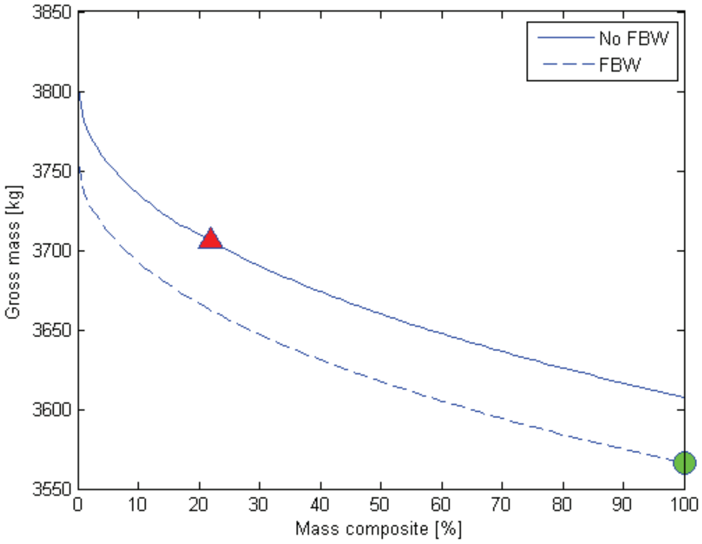

Figure 6 *Minimum helicopter mass (green circle) is found for 100% composite mass in the fuselage and a fly-by-wire flight control system.*

The red triangle in each figure indicates the optimum design for the other objective. The triangles show that the design that is optimised for mass has a corresponding LCC value of 171.6 million Euros, which is higher than the minimal LCC value of 166.6 million Euros. At the same time the design that is optimised for LCC has a corresponding mass value of 3705 kg, which is higher than the minimal mass value of 3566 kg. Hence, these single objective optimum design points provide poor values for the other design objective that is not optimised.

In order to efficiently take into account more than one design objective in the helicopter design optimisation study, a multi-objective optimisation approach can be used. Efficient algorithms for solving such multi-objective optimisation problems are available (Ref. 7). This approach is used for the helicopter mass and LCC objectives. A trade-off between mass and LCC can be performed by plotting these objectives directly against each other. A switch is performed from the design space to the objective space. The key in this approach is that the compromise solutions for the best values for both objectives are pursued. Such optimisation problem can be formulated as a so-called Pareto

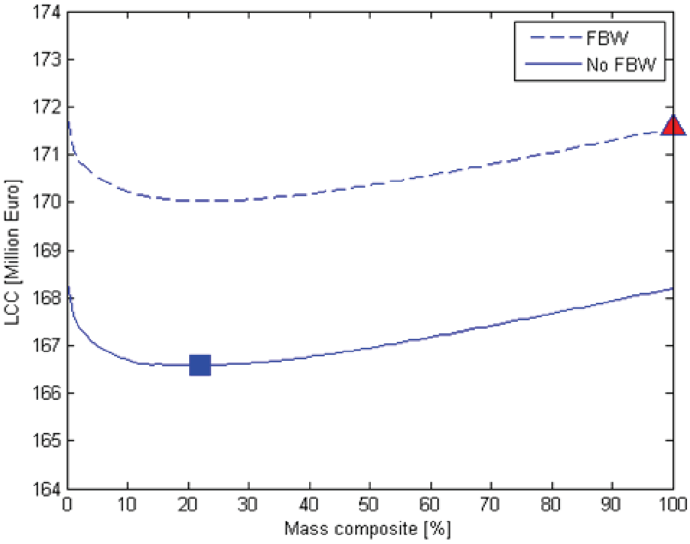

Figure 7 *Minimum helicopter LCC (blue square) is found for 22 % composite mass in the fuselage, and a mechanical flight control system.*

optimal (Ref. 9) design problem, having a set design points as the optimal solution, the so-called Pareto optimal set (or Pareto front). This Pareto optimal set is shown in the fig. 8. The result was found for the optimisation of mass and LCC as a function of the percentage composite mass in the fuselage and the type of flight control system, just like the previous single objective optimisations. Also here, the Starflex type main rotor hub and a high blade complexity (i.e. full composite blades) were used. Obviously, from this Pareto optimal set the optimum design points for mass or LCC can be easily selected. Also the trade-off between mass and LCC can be directly made.

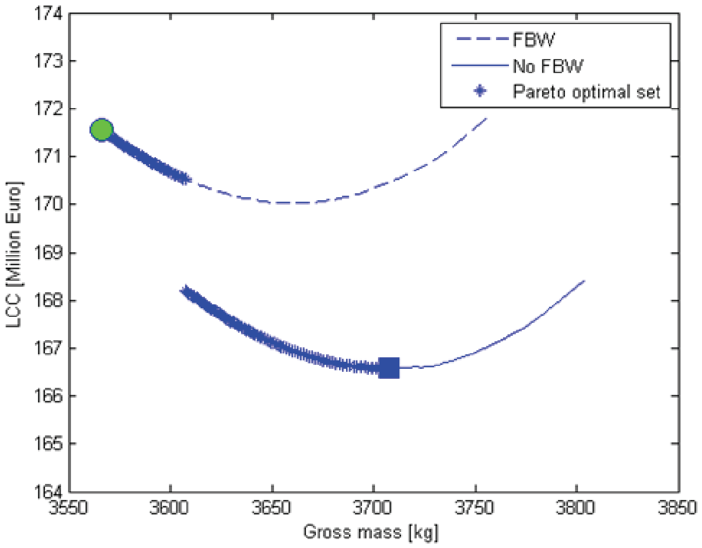

Figure 8 Results of the helicopter mass and LCC multi-objective optimisation problem.

The results shown in figure 8 are given in the objective space, i.e. the resulting LCC values plotted versus the mass values. The Pareto optimal set of helicopter designs is marked by the blue "*"-symbols. Also indicated in figure 8 are the single objective optimum design points for mass (green circle) and LCC (blue square).

Comparison with reference helicopter design

Figure 9 shows the reference helicopter design (red star) together with some results from the preceding optimisation strategy. In comparison to the reference design, the introduction of high complexity blades and a FBW flight control system does drastically reduce the helicopter mass, but has almost no effect on the total LCC due to the higher acquisition cost combined with the lower maintenance effort (moving left in the graph).

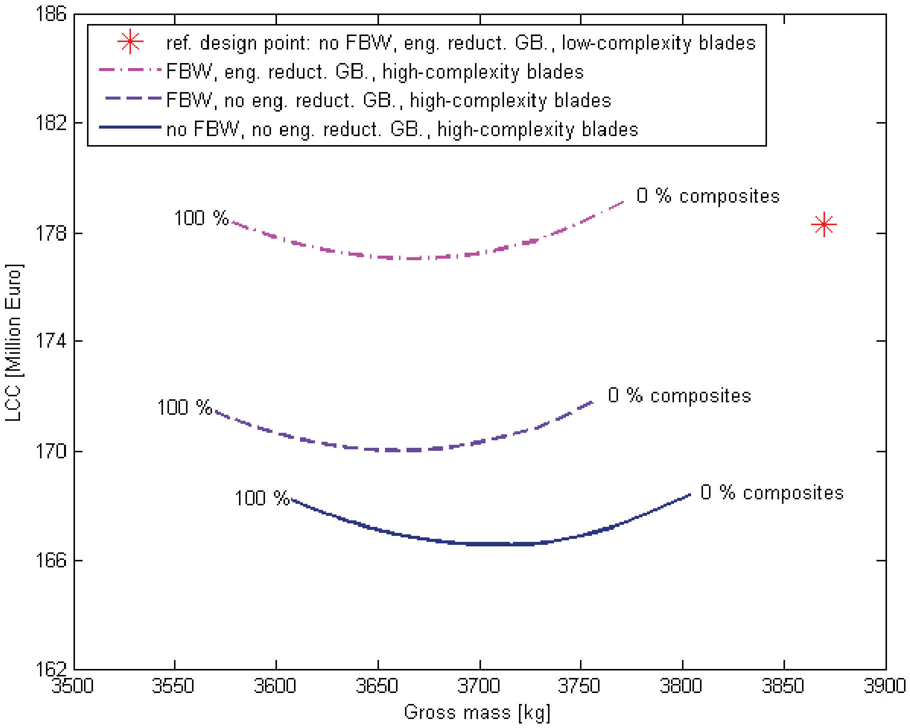

Figure 9 Combined results of reference helicopter design and optimisation results.

As shown before, the removal of the engine reduction gear box (GB) has a small effect on the helicopter mass, but drastically reduces the total LCC due to a lower maintenance effort (moving down in the graph). A further reduction in total LCC can be achieved by replacing the FBW Flight Control System by a mechanical FCS, but then the helicopter mass will slightly increase again (moving to the bottom line in the graph). From the different design points in the graph it becomes clear that a helicopter design can be either optimized for lowest mass or for lowest total LCC, however these designs will have a different configuration with respect to the systems used.

Design for multiple mission combinations

In the preceding part the optimisation process has concentrated on optimisation of the combined mass and LCC design objectives. This has been done for a single helicopter operator with one specific mission combination (defined as 350 business flights, 500 offshore flights and 150 search/rescue flights per year).

A helicopter manufacturer however is interested in multiple operators having multiple mission combinations. Therefore a next step in the optimisation process is to optimise the LCC for these multiple mission combinations. This results in different LCC values for the helicopter design that is being used for different mission combinations during its life cycle.

As an illustration, a multi-objective optimisation of LCC has been performed for two different mission combinations during the life cycle: combination 1 represents the life cycle cost if 350 business, 500 off-shore and 150 search/rescue flights per year would be flown during the life cycle, and combination 2 represents the life cycle cost if 2000 business, 0 off-shore and 0 search/rescue flights per year would be flown during the life cycle. The helicopter design is then optimised for both these two mission combinations.

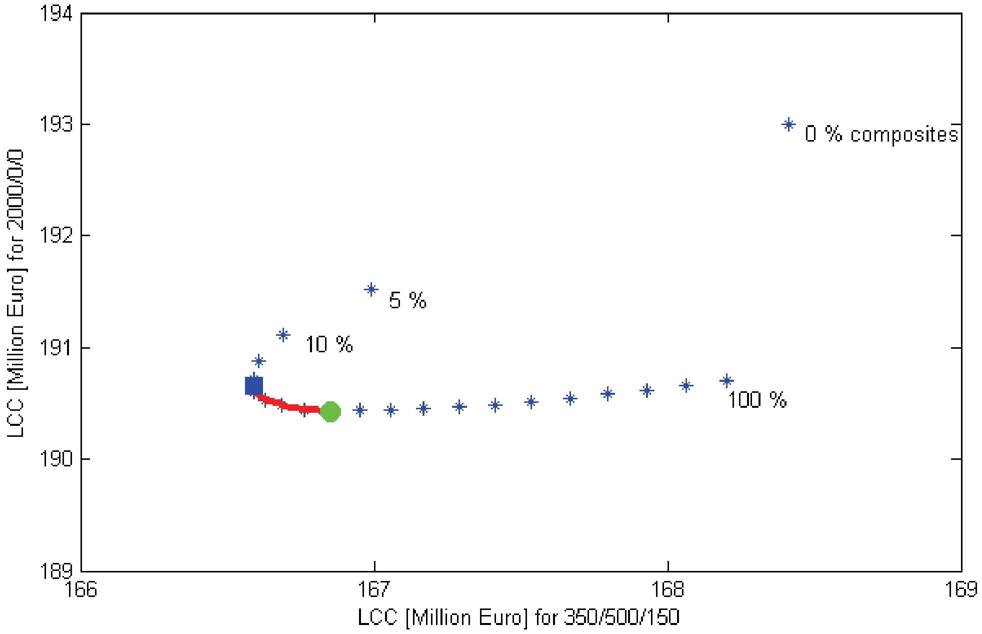

Figure 10 Results of the helicopter multi-objective optimisation problem for mission combination 1 (horizontal axis) and combination 2 (vertical axis).

Figure 10 shows the optimum design point for combination 1 that was found in the previous mass-LCC optimisation (blue square; helicopter design with 22 % composite mass). And now also the optimum design point for combination 2 is found (green circle; helicopter design with 45 % composite mass). The line in figure 10 connects a series of design points, the so called Pareto optimal set, which represent the compromised optimal helicopter designs for both combination 1 and combination 2. These design points are found for helicopter designs with the percentage composite mass increasing from 22 % to 45 %.

Concluding remarks

The helicopter pre-design is normally driven by performance requirements and the helicopter mass is considered the design optimisation criterion. However, the need for cost effective operations urge the manufacturers to design helicopters which reach the performance requirements, not only at a low mass, but (also) at the lowest possible operating costs. Therefore a Life Cycle Cost (LCC) model is needed which reflects the impact of both the major technical parameters and the major categories of customers and missions.

In the VIVACE "Multidisciplinary Design and Optimisation" (MDO) Use Case, NLR has integrated the preliminary LCC model developed by Eurocopter into its helicopter analysis tool "SPEcification Analysis of Rotorcraft" (SPEAR). A helicopter design optimisation environment has been created using a MATLAB environment for the evaluation and optimization of the helicopter design objectives.

The optimisation methodology applied in this study is based on the formulation of a generic optimisation problem that allows for, among others, single- or multi-objective optimisation problems, non-linear constraints and discrete variables.

The results of the optimisation strategy have been compared with a reference helicopter design. From the resulting different design points, it becomes clear that a helicopter design can be either optimized for lowest mass or for lowest total LCC, resulting in different design choices. The strategy gives a clear insight in what design choices contribute to a reduction in mass and/or a reduction in LCC. A trade-off analysis can be performed using a Pareto optimal set of designs.

Since helicopter manufacturers are interested in multiple operators each having multiple mission combinations, an additional optimisation study has been performed to optimise the LCC for these multiple mission combinations. This resulted in different LCC values for the helicopter design that is being used for different mission combinations during its life cycle. The calculation results show the Pareto optimal set of design points, which represent the compromised optimal helicopter designs. The optimal design point depends on the actual combination of the defined missions.

The resulting pre-design strategy contributes to:

- reduced number of iteration loops in the preliminary design process, and therefore a less time consuming preliminary design phase;
- reduced development costs of future helicopter designs through the ability to better predict the Life Cycle Cost of the helicopter;
- reduced operational cost for the operators/owners of helicopters;
- support of helicopter marketing by providing the LCC relationship for multi-mission combinations.

Further research is necessary to improve and validate the models and enable useful optimisation strategies for the development of cost efficient multi-role helicopters for multiple operator defined combinations of missions.

Acknowledgement

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