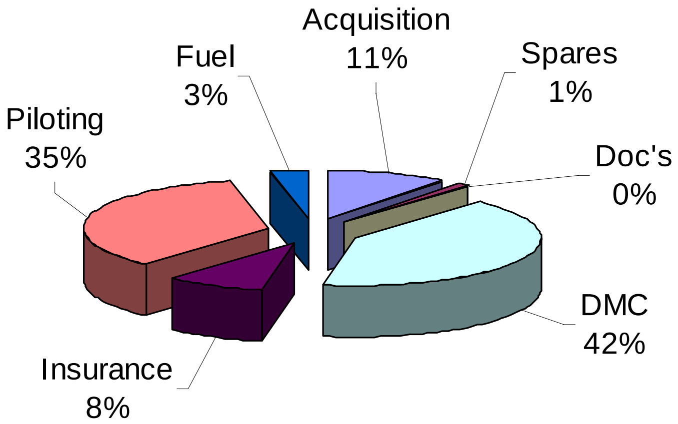
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Helicopter pre-design strategy: design-to-mass or design-to-cost?



Problem area
Traditionally a helicopter pre-design is driven by flight and mission performance requirements, with the helicopter mass being considered the design optimization criterion. Other important requirements, such as costs, are not treated in the same manner. The need for cost-effective operations is becoming increasingly important. The new design goal would be to find the optimum helicopter design which not only fulfils the required performance requirements, but also satisfies customer's requirements at the lowest possible cost. For that a helicopter Life Cycle Cost (LCC) model is needed which reflects the impact of both the major technical parameters and the major categories of customers and their (multiple) missions.

Description of work
A rotorcraft pre-design analysis tool from a European aeronautical research institute has been combined with an LCC model from a major European helicopter manufacturer. A rotorcraft design optimization for the evaluation and optimization of the design objectives has been created in an interactive environment. The applied optimization methodology is based on the formulation of a generic optimization problem that allows for single- or multi-objective optimization problems, non-linear constraints and discrete variables. The final objective was to include all enabling processes, models and tools available for use in an Aeronautical Collaborative Design Environment.

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Results and conclusions

The pre-design strategy that has been developed in this study, contributes to:

- a reduced number of iteration loops in the preliminary design process
- reduced development costs of future designs through better prediction of the LCC
- a better insight into the consequences of design choices
- reduced operational costs
- support to helicopter marketing by providing LCC relationships for multi-mission combinations

Applicability

The innovative design environment will support the (pre-)design of complete helicopters by providing optimal design information in an efficient way in the very early stage of the project.

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Helicopter pre-design strategy: design-to-mass or design-to-cost?

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Summary

Flight and mission performance requirements drive the design of a helicopter. Traditionally the helicopter mass has been considered the design optimization criterion. However, the need for cost effective operations urges the manufacturers to design helicopters which satisfy the performance requirements, not only at a low mass, but (also) at the lowest possible operating costs. For that 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 their (multiple) missions.

A rotorcraft specification analysis tool from a European aeronautical research institute has been combined with an LCC model from a major European helicopter manufacturer. Subsequently sizing optimization methodologies have been developed in an interactive environment, resulting in an innovative helicopter pre-design methodology and an implemented capability. Program objectives, tools, methodologies and sample calculation results are described.

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Contents

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
ATA	Air Transport Association
CAIV	Cost As an Independent Variable
CER	Cost Estimating Relationship
DL	Disk Loading
DMC	Direct Maintenance Cost
EMPRESS	Energy Method for Power Required EStimateS
FBW	Fly By Wire
FH	Flight Hour
GB	Gear Box
GSE	Ground Support Equipment
HC	Helicopter
MDO	Multidisciplinary Design and Optimization
MGB	Main Gear Box
LCC	Life Cycle Cost
MCP	Maximum Continuous Power
MMH	Maintenance Man Hour
MTOW	Maximum Take-Off Weight
NM	Nautical Mile
OEI	One Engine Inoperative
OGE	Out of Ground effect
TOP	Take-Off Power
RDTE	Research, Design, Technology and Engineering
SAR	Search And Rescue
SFC	Specific Fuel Consumption
SPEAR	SPEcification Analysis of Rotorcraft
SLL	Service Life Limit
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative Enterprise

Nomenclature

b	= Number of rotor blades
c	= Rotor blade chord
CdS	= Flat plate drag area
C_T/σ	= Blade loading
M_{gross}	= Gross mass
R	= Rotor radius
T	= Main rotor thrust
V_{tip}	= Rotor tip speed
W	= Weight
ρ	= Air density
σ	= Rotor solidity

1 Introduction

Traditionally a helicopter pre-design is driven by flight and mission performance requirements. Other important requirements, such as costs, mass and specific customer requirements have not been treated in the same manner. Also a formalized decision process for the assessment of different design solutions by trade-off analyses is often missing.

The need for cost-effective operations is becoming increasingly important. The new design goal would be to find the optimum helicopter design which not only fulfils the required performance requirements, but also satisfies the customer's requirements at the lowest possible cost. In contrast to fixed wing operators, helicopter operators often use the same helicopter for a diversity 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 in turn are effected by design choices (i.e. configuration, drive train architecture, chosen materials). To find an optimal compromise between the "driving" design parameters, a methodology is required that can find an optimal technical solution for the diversity in customer requirements. This requires the identification and evaluation of the cost impact of the 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 subsequent design process.

A "Multidisciplinary Design and Optimization" (MDO) case study has been defined, in which the following activities concerning the helicopter pre-design have been performed:

1. evaluation of existing (pre-design) methodologies/technologies and tools
2. development and integration of a Life Cycle Cost (LCC) model in a pre-design analysis tool
3. identification of the cost driving parameters and performing the sensitivity analysis
4. development and implementation of a multidisciplinary design methodology to optimize the LCC

The helicopter LCC model, which reflects the impact of both the major technical parameters and the major categories of customers and missions, has been developed by a major European helicopter manufacturer. A European aeronautical research institute has integrated the LCC-model into an in-house developed rotorcraft specification analysis tool and has developed a helicopter sizing optimization methodology that enables a multi-mission design with LCC optimization.

The final objective was to include all enabling processes, models and tools available for use in an Aeronautical Collaborative Design Environment, including the associated processes, models and methods. This innovative environment will support the (pre-) design of a complete helicopter by providing optimal design information in an efficient way in the very early stage of the project.

2 Rotorcraft analysis tool

The National Aerospace laboratory NLR has developed a pre-design rotorcraft analysis tool SPEAR: “SPEcification Analysis of Rotorcraft” (Ref. 1). This computer program (Fig. 1) is able to estimate the (minimum) size and mass of a rotorcraft capable of fulfilling a specified set of operational requirements (flight performance requirements and mission tasks) for a given rotorcraft configuration. Valid solutions are those that comply with the flight performance requirements and for which the available fuel equals the required fuel to fulfill the most demanding mission task. The tool determines the rotorcraft gross mass, its main physical dimensions (like the rotor dimensions), the installed engine power, the fuel capacity, and the mass breakdown for the major vehicle components. The consequences of operational requirements on rotorcraft sizing can be

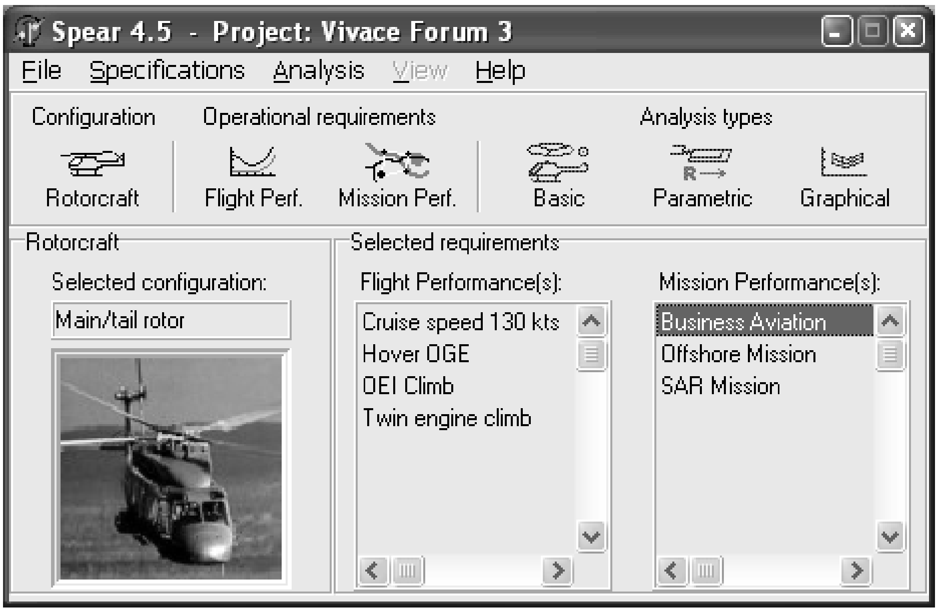

Fig. 1 Main window of the analysis tool

analyzed, 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). The tool contains a large amount of information on historical and current rotorcraft designs, such as major rotorcraft design relationships, major component characteristics, etc. Different kinds of graphical representations for the rotorcraft design results are included. The tool also includes the potential for LCC optimization or LCC trade-off studies. The tool runs on Windows Personal Computers, thereby taking advantage of the Windows features.

3 Specification of requirements

The rotorcraft designer has to specify a set of rotorcraft related requirements, which can be broken down into three parts:

1. rotorcraft configuration, describing the general layout plus some (aerodynamic) efficiency parameters
2. flight performance, containing the data for the flight performance requirement(s) to be met
3. mission performance, containing the data for the mission profile(s) to be met

Each of the individual requirements is stored in the database, from which one or more can be selected for the analysis (Fig. 2).

3.1 Flight performance requirements

Each flight performance requirement is defined by an airspeed, ground effect situation, atmospheric condition, number of engines operating, power setting, thrust and power margin, and a delta parasite drag area for any external equipment. Optionally a rotorcraft gross mass can be specified if the particular requirement has to be met at a specific gross mass.

3.2 Mission performance requirements

Each mission profile is specified by a number of mission segments, which are defined by a duration, airspeed, ground effect situation, atmospheric condition, change of mass and/or drag due to (un)loading of payload, and engine power setting. The payload can be made up of persons (not the crew), cargo, weapons (in case of military use), specific mission equipment or a mixture of these.

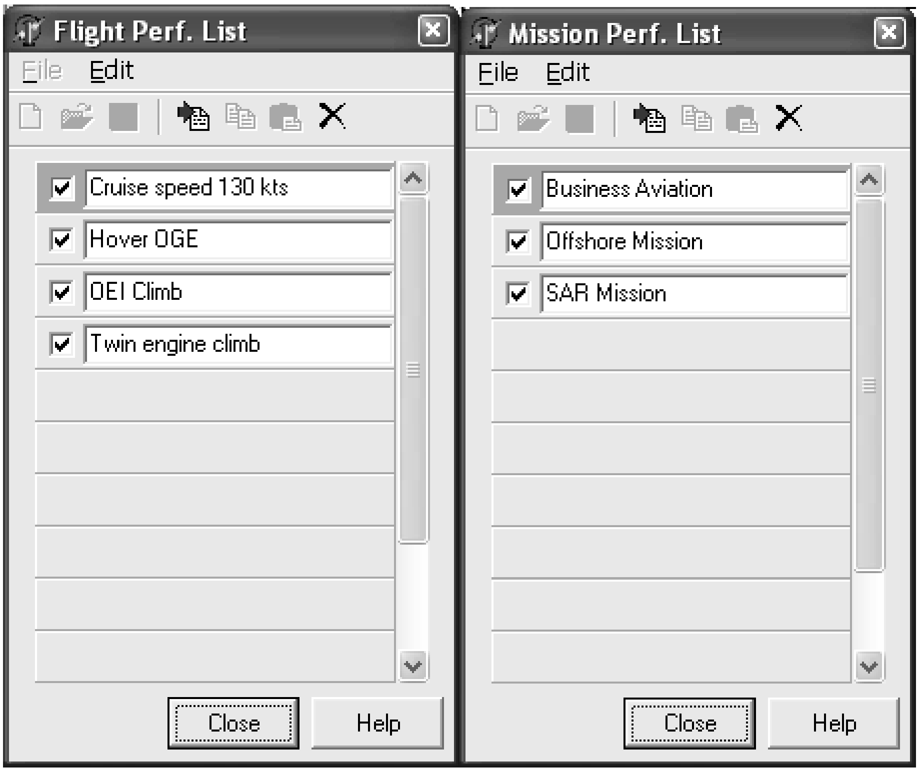

Fig. 2 Available/selected flight and mission performance requirements

4 Pre-design methodology

The methodology applied in the pre-design analysis tool is largely based on Ref. 3. The computer program will establish feasible rotorcraft dimensions that comply with the set of flight and mission performance requirements for the given rotorcraft configuration. Valid solutions are those that comply with the flight performance requirements and for which the available fuel equals the required fuel to fulfill the most demanding mission. The optimum solution is defined as the one that achieves these objectives at the lowest gross mass (traditionally helicopters are designed for lowest gross mass). As suggested in Ref. 3 other criteria may be defined for the optimal solution, e.g. the lowest LCC.

The actual sequence for the calculation of the various parameters is shown in figure 3. Comparing this pre-design methodology to other MDO cases (e.g. aircraft wing MDO) the multi-disciplinary calculations here are scheduled in sequential iterative loops. This combines the complete set of design calculations into one compact pre-design tool.

The calculation process runs efficiently by taking the main rotor disk loading as the driving variable. The rotor tip speed is fixed at a value compatible with the rotor technology state-of-the-art and e.g. with noise constraints. First the main rotor dimensions are determined, as these drive the other dimensions (like the rotorcraft length) and the flight performance. This is achieved by making an initial estimation for the Gross Mass (M_{gross}).

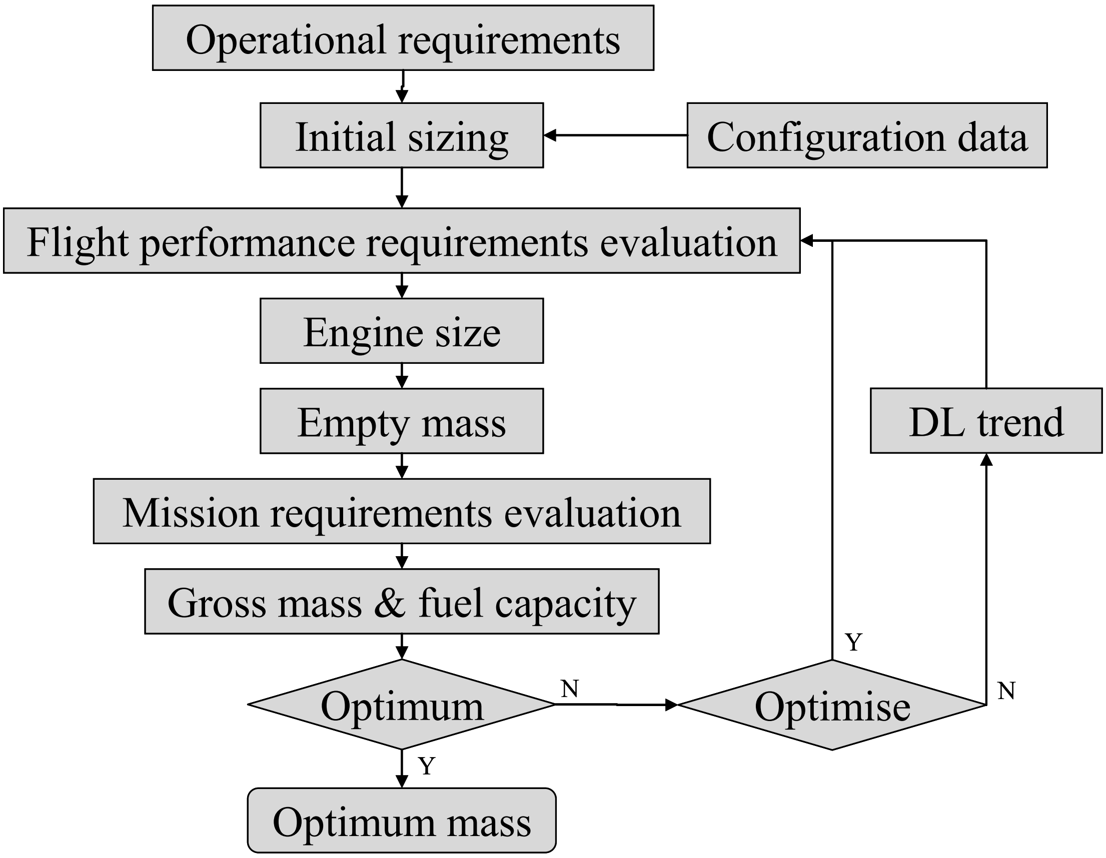

Fig. 3 Simplified flowchart for the calculation routine

The rotor Disk Loading (DL) follows from historic data for disk loading versus gross mass:

$$DL = 8.7188 * M_{gross}^{0.2264} - 23.685 \quad (1)$$

The main rotor radius (R) follows from the Disk Loading:

$$R = \sqrt{\frac{M_{gross}}{\pi\, DL}} \quad (2)$$

The maximum (limit) blade loading (C_T/σ) is a measure of the capability of the rotor blades to generate lift and depends on the rotor technology level. Maximum values for the main rotor blade loading are specified in the input data. The main rotor thrust (T) is the total thrust required for the specific flight performance requirement and thus includes the gross mass and the download on the airframe. For each of the specified flight performance requirements the rotor blade solidity (σ) follows from the relationship between main rotor thrust, rotor radius, tip speed and maximum blade loading:

$$\sigma = \frac{T}{\rho \, \pi \, R^2 \, V_{tip}^2 \left({C_T}/{\sigma} \right)_{max}} \tag{3}$$

The main rotor blade chord (c) follows from the relationship between blade solidity, rotor radius and number of rotor blades (b):

$$c = \frac{\sigma \, \pi \, R}{b} \tag{4}$$

The highest value of the blade chord (for all performance requirement cases) is the valid one, as that value will give an acceptable blade loading value for all those cases. Next the total power required is assessed. The most demanding flight performance requirement in terms of engine power defines the minimum engine power that is to be installed, and thus defines the engine(s). At that point, an initial assumption for the fuel capacity is made and the empty mass is assessed by estimating the masses of the major components, based principally on historic data. Next, the fuel required for actually fulfilling the various specified mission profiles is assessed. If the fuel mass needed to fulfill 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 design. Finally, the disk loading is varied with small steps, thereby no longer following the historic trend line. 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.

5 Analysis features

The tool incorporates three analysis levels with an increasing amount of design options and associated capabilities.

5.1 Basic analysis level

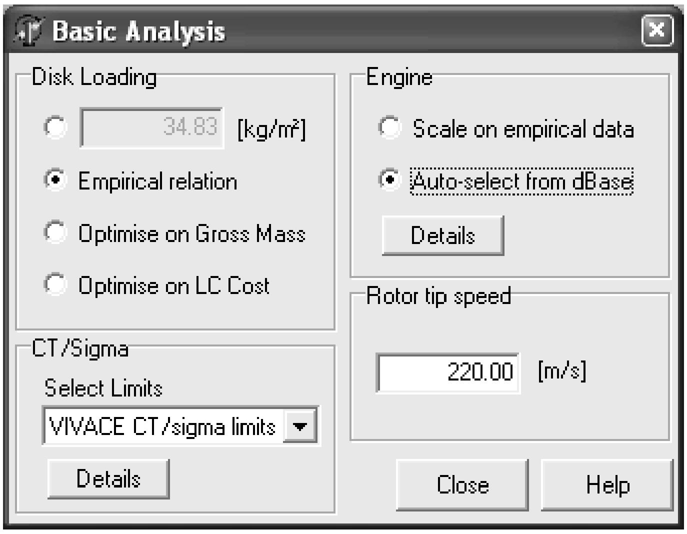

Fig. 4 Data input form for Basic Analysis

The Basic analysis (Fig. 4) determines the gross mass based on the selected rotorcraft configuration and operational requirements. For the limit blade loading (C_T/σ) in level flight (load factor equals one) several characteristic lines for various rotor designs are available in the database, and one of these designs has to be selected. For the engine there is a choice: either a hypothetical, fully compliant ('rubberized' on empirical data) engine or an existing engine can be automatically selected from the database. The value for the main rotor tip speed is defined by the designer. Historic data are used for fuselage parasite drag (assuming an 'average' drag level), engine specific fuel consumption and tail rotor diameter.

5.2 Parametric analysis level

The Parametric analysis (Fig. 5) provides more extensive options to further analyze the rotorcraft configuration. The effects of varying seven main rotor parameters can be analyzed: disk loading, blade loading, solidity, rotational speed, tip speed, diameter and chord. Three of these parameters must be selected for the analysis. However, not every combination of three parameters is valid (e.g. disk loading and diameter can not be selected at the same time). For some input data a selection can be made between a historic trend line value and a selected fixed value. This concerns the disk loading, the fuselage parasite drag area, the engine specific fuel consumption, the engine mass and the tail rotor diameter. In some cases the rotorcraft gross mass is limited to a maximum

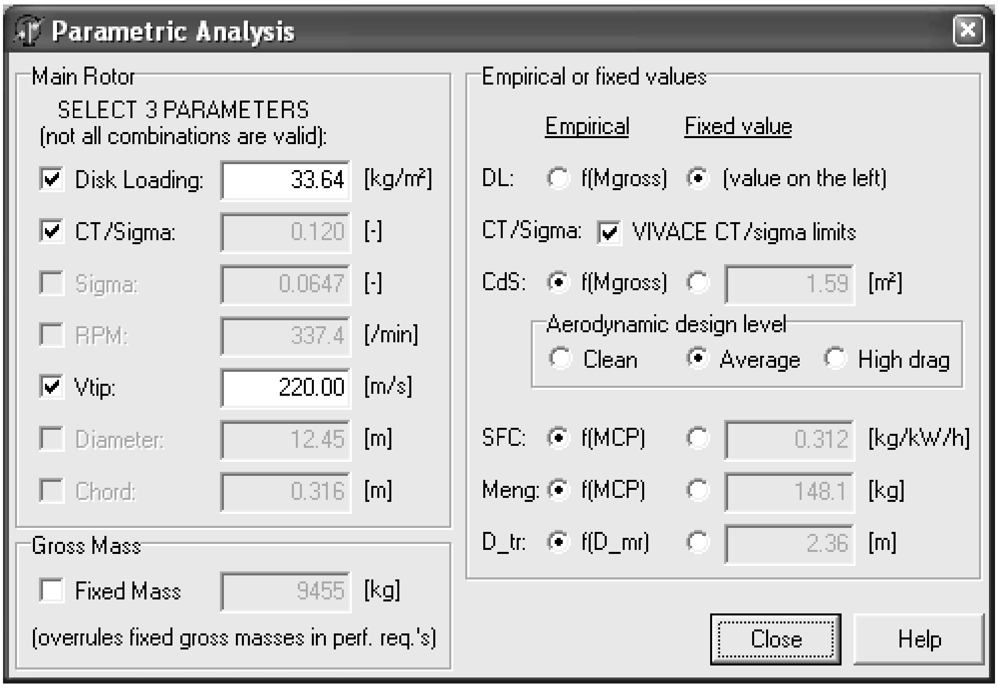

Fig. 5 Data input form for Parametric Analysis

value, e.g., due to the deck strength on-board a ship. For those cases the analysis process can be performed for a fixed gross mass (to be specified by the user), in which case the calculated rotorcraft gross mass is limited to the specified mass. It is possible, however, that the mission requirement(s) lead to a higher required mass than the one specified, implying that the design can not fulfill all mission requirements.

5.3 Graphical analysis level

The Graphical analysis presents the results in four types of graphs:

1. design chart (power required per kilogram of gross mass vs. rotor disk loading)
2. parameter analysis chart (mass or power required vs. one of the seven main rotor parameters); Fig. 6 presents the variation of rotorcraft gross mass vs. the main rotor disk loading
3. carpet plot (mass or power required vs. two of the seven main rotor parameters)

4. power curve (level flight power required vs. airspeed for given values of gross mass, altitude and temperature)

Just like in the *Basic* analysis level, historic data are used for fuselage parasite drag, specific fuel consumption and tail rotor diameter.

5.4 Analysis results

The analysis results window (Fig. 7) provides an overview of the main results of the analysis. The seven main rotor design parameters, the Figure of Merit (for the isolated main rotor), the rotor mass, the tail rotor dimensions, the engine data, the rotorcraft masses, the fuel capacity and the parasite drag area are shown. In addition it shows the names of the specific requirements (flight performance and mission profile) that have driven the main rotor design, the engine choice and the fuel capacity. Additionally detailed breakdowns for the rotorcraft mass, the total LCC and the mission result data can be shown.

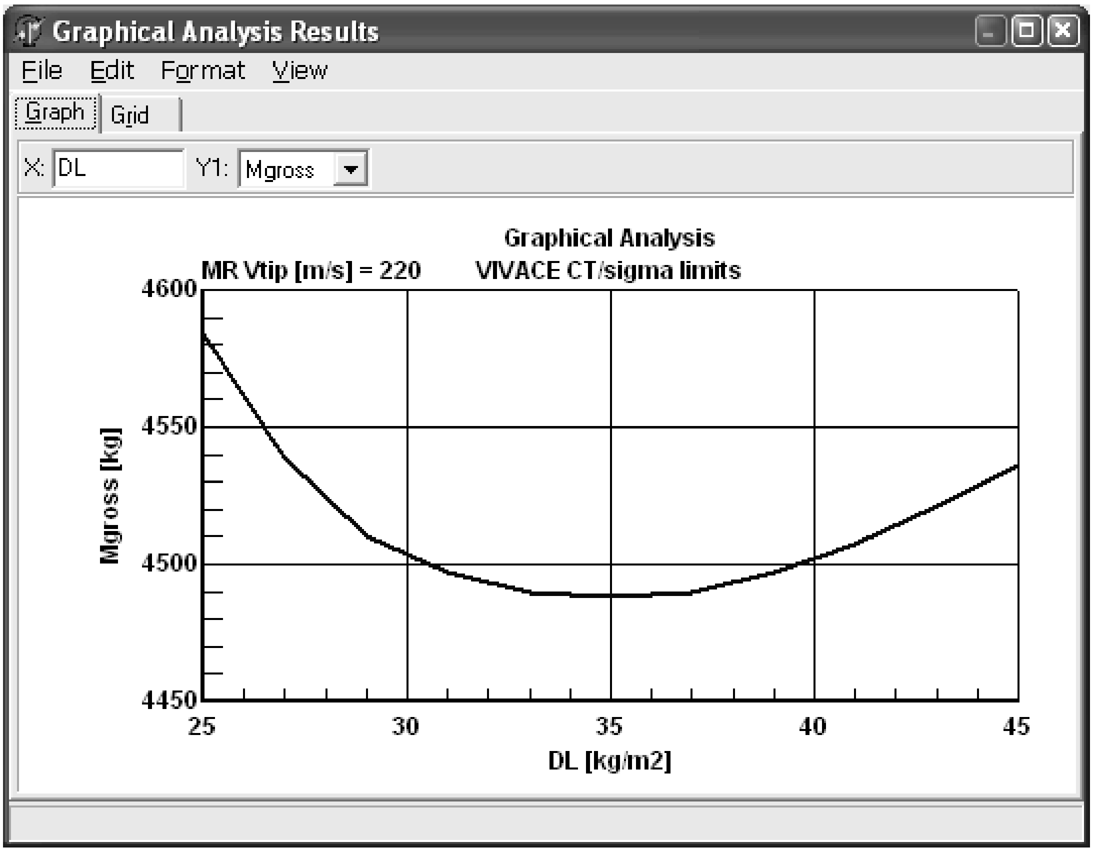

Fig. 6 Example output graph for Graphical Analysis

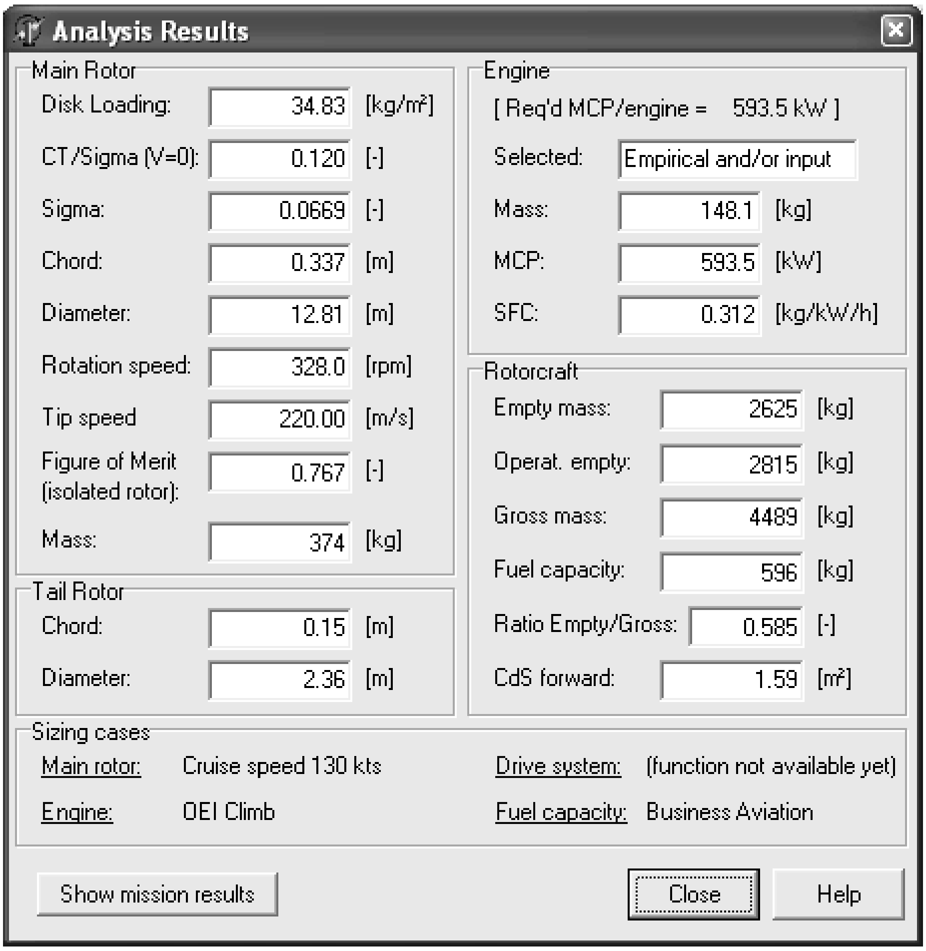

Fig. 7 Analysis Results for VIVACE example requirements

5.5 Mass breakdown

The detailed rotorcraft mass breakdown window shows the estimated masses for each of the individual major components. It also shows the required fuel capacity, the Empty Mass, the Operational Empty Mass and the Gross Mass.

5.6 Cost breakdown

The input data for the detailed cost estimation process are specified in the cost input data window. A choice can be made whether the rotorcraft will be used (primarily) for civil or for military purposes. The rotorcraft acquisition cost (‘the price’) can be calculated either as a function of the gross mass or be based on the sum of RDTE (Research, Design, Technology and Engineering) cost, production cost and profit.

The calculated LCC (total operating costs for the number of acquired rotorcraft) is shown in the Calculated Cost Results window (Fig. 8). The LCC is split into acquisition, disposal, operational and fabrication costs (costs of making the individual major components). The estimated operating cost per flying hour and per nautical mile is also provided.

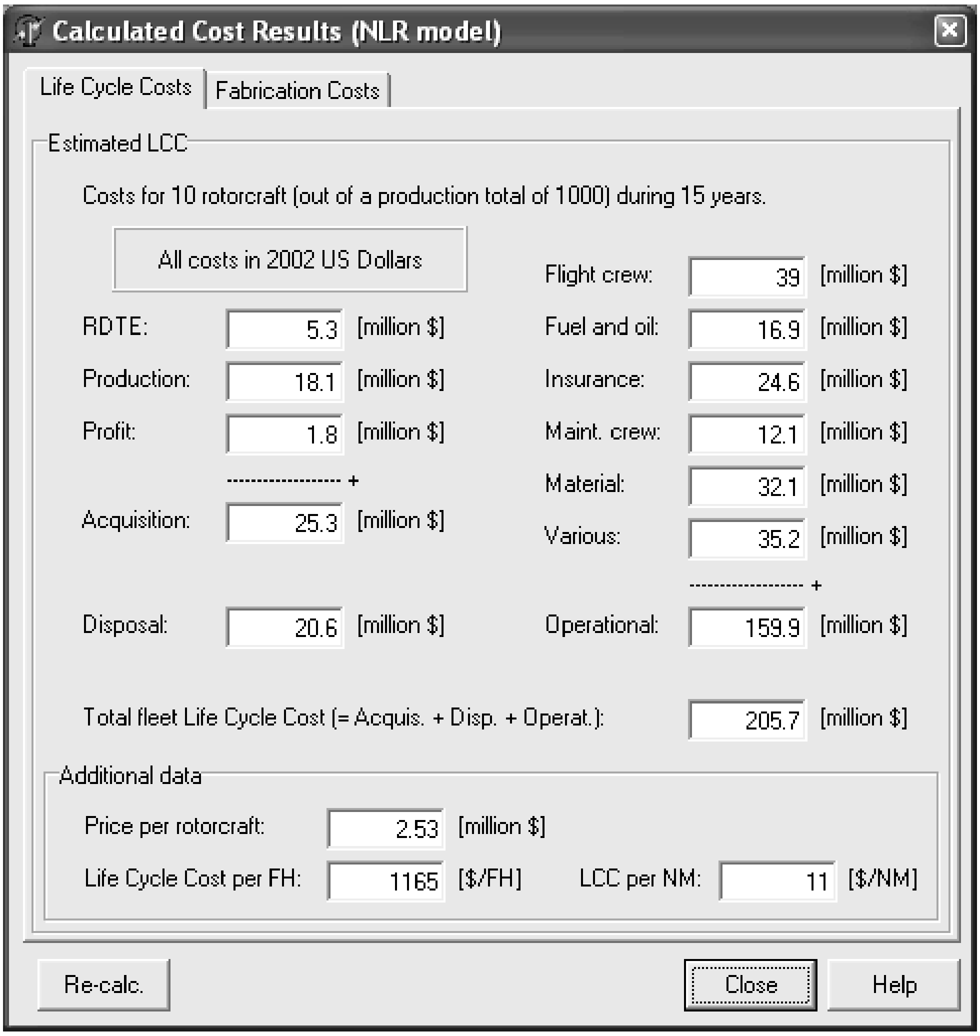

Fig. 8 Calculated cost results window

6 Life Cycle Cost model

6.1 Introduction

The previously mentioned cost model is based on historical data and thus may not be valid for modern rotorcraft designs. Eurocopter has developed an LCC model, which is intended for use in the frame of pre-design studies performed in-house. The model, largely based on Refs. 4, 5), calculates global ownership costs for rotary wing aircraft, either as costs per year, per helicopter, per flight hour or per passenger. The detailed cost breakdown structure as used in the LCC model is shown in Fig. 9.

- Initial purchase cost
  - Purchase cost
  - Initial Spare procurement & renewal
  - Documentation
- Mission personnel
  - Pilots salaries
  - Specific maintenance personnel
- Insurance
- Unit level consumption
  - Fuel consumption
  - Other
- Modification & upgrade

- Maintenance and operation
  - Direct Maintenance Cost (DMC)
    - Basic helicopter
    - Mission equipment
    - Consumables
  - Training
    - Ground training
    - Flight training
    - Simulator training
  - Ground Support Equipment
  - Sustaining Support
    - Support Equipment Replacement
    - Sustaining documentation replacement
    - Software Maintenance Support
  - Indirect Support
    - Infrastructure
    - Administration & management

Fig. 9 Cost breakdown structure for LCC

In this model the decommissioning/disposal costs are not (yet) considered. No rules have been defined at the moment, and there is not enough return of experience to compute it sufficiently accurate in a general model. However, upon customer demand it can be included in a later phase.

6.2 Helicopter breakdown

The major contributing parts in the cost analysis, the Initial Purchase Cost (Sale Price) and the Direct Maintenance Cost (DMC) are both determined by calculating their respective values for each of the major helicopter parts. The helicopter parts are chosen in accordance with the classical pre-design ATA chapter breakdown (see Fig. 10.)

Pre-design breakdown	ATA chapter
Fuselage	52, 53, 55, 56
Landing gear	32
Main rotor blades	62-10
Main Gear Box (MGB)	63
Rotor hub	62-20
Tail rotor	64, 65
Electrical system	24
Avionics	22, 31, 34, 46
Flight controls	67
Hydraulics	29
Engine	71, 72, 76-77, 80
Fuel system	28
Furnishing & Miscellaneous	21, 25, 26, 30, 33

Fig. 10 Helicopter breakdown for LCC

6.3 Cost estimation methods

The basic cost estimation method for each item of the helicopter tree structure is made up of so-called “Cost Estimating Relationships” (CERs). CERs are mathematical expressions relating cost as the dependent variable to one or more independent cost drivers. These relations can be simple averages or percentages, or more complex equations which result from regression analyses and which connect the cost (the dependent variable) to the physical characteristics of the product (such as the mass, the output power, the percentage of a given material, etc). Four cost estimation methods can usually be discerned:

1. *Analogy*: comparing a system to a similar system with known cost and technical data
2. *Parametric*: use of a database on similar elements to the item to be evaluated, to generate a cost estimate based upon parameters representative of the performance characteristics of the item
3. *Engineering*: bottom up estimate from lowest sub-components of a project (work breakdown structure)
4. *Extrapolation*: using information from the same system early in the project to estimate costs later in the project

The parametric method has been selected here. This method can be used as soon as the technical specifications of the design are defined, when knowledge of cost, technical data and hardware data is still limited. It consists of establishing a statistical correlation between the physical characteristics of the system (for example the weight, the volume or the power) and its estimated cost.

6.4 Cost drivers

For each major part of the helicopter, specific parameters - the so-called cost drivers - are used for the cost estimation equation. These cost drivers are representative for the cost of that part of the helicopter. To permit the further design-to-cost optimization process using the rotorcraft pre-design analysis tool, particular attention was paid to selecting these cost drivers as far as possible within the list of available parameters within that tool. The cost drivers are listed in Fig. 11.

Pre-design breakdown	Cost driver 1 (purchase cost)	Cost driver 2 (DMC)	Cost driver 3	Cost driver 4
Fuselage	Item mass (kg)	-	% of composite	
Landing gear	Item mass (kg)	Skids or wheels		
Main rotor blades	Item mass (kg)	Item mass (kg)	Technology factor (0 to 3)	
MGB	TOP limit (kW)	TOP limit (kW)	Number of accessory power outputs	Number of reduction stages
Rotor hub	Centrifugal force (daN)	Centrifugal force (daN)	Number of blades	Rigid, Starflex© or Spheriflex©
Tail rotor	Thrust max. (daN)	Thrust max. (daN)	Fenestron© or classic	
Electrical system	Item mass (kg)	Empty weight (kg)		
Avionics	Item mass (kg)	Item mass (kg)		
Flight controls	Centrifugal force (daN)	Centrifugal force (daN)	Fly-By-Wire or hydraulic	
Hydraulics	MTOW (kg)	Empty weight (kg)		
Engine	TOP limit (kW)	TOP limit (kW)	Reduction gear box or not	
Fuel system	Number of tanks	Empty weight (kg)		

Fig. 11 Technical data input for LCC

The column “Cost driver 1 (Purchase Cost)”, resp. “Cost driver 2 (DMC)”, lists the parameters most suitable for the calculation of purchase cost and DMC respectively. The columns “Cost driver 3” and “Cost driver 4” represent other significant parameters, which are also used in both calculations, but having less influence.

6.5 Cost estimation equations

Costs for all the items from the pre-design breakdown have been estimated using a mathematical method. The cost estimation equations have been established and validated based upon the manufacturer’s experience, using the cost drivers from Fig. 11. From experience, it is known that the cost of the hydraulic system, for sale price as well as for DMC, increases exponentially with the weight, whereby the rate of increase for each cost item is equal. The proposed laws are:

$$\text{Sale Price} = a_1\ \text{W\_MTOW}^{\alpha} \quad (5)$$

$$\text{DMC Price} = a_2\ \text{W\_Empty}^{\alpha} \quad (6)$$

For electrical systems however, even though the increase is also exponential, the rate of increase for each cost item is different. The proposed laws are:

$$\text{Sale Price} = b_1\ \text{W\_Elec}^{\beta_1} \quad (7)$$

$$\text{DMC Price} = b_2\ \text{W\_Empty}^{\beta_2} \quad (8)$$

The cost estimation equations are obtained by extrapolation from a sample of former designs (known costs) to the new design, and thus are based upon experience on previous existing designs. Therefore, the CERs cannot reflect the influence of new design factors on costs. A parametric model will be more reliable if the selected technical solutions for the new design are closer to those of the previous concepts.

6.6 Validation of the cost model

To validate the cost model the results have been matched with a database containing data on the manufacturer’s range of helicopter types. The mathematical relationships have been generated by data analysis (regression) and expert investigation. The model has been validated for both sale price (purchase cost) and DMC, with an achieved accuracy of 13% (see Fig. 12).

	EC120	AS350B3	EC130	AS365N3	EC155	AS332L1	AS332L2
Sale price (ref / calc)	1.03	1.13	1.06	1.02	0.93	1.00	1.02
DMC (ref / calc)	0.95	1.01	1.05	0.94	1.09	0.99	1.02

Fig. 12 Validation of the cost model over the manufacturer's product range

6.7 Mission equipment

The mission system sheet in the LCC model contains various generic mission equipment items, which have an impact on the LCC of the helicopter through the following three parameters:

1. acquisition cost of the equipment
2. maintenance cost of the equipment
3. life span (Service Life Limit, SLL) of the equipment

The selection of different mission equipment items is done by marking the relevant equipments in the mission system sheet.

6.8 Input and output of the LCC model

Fig. 13 and 14 show a typical set of operational input data and output results.

Fleet Data		
Number of H/C	5	[-]
Number of FH per year and per HC	600	[FH/year/HC]
Number of bases	1	[-]

Personnel and crew data		
Number of pilot per aircraft	2	[-]
MMH/FH	7.2	[h/FH]
Number of manager per base	2	[-]
Number of crew per aircraft	1.5	[-]
Annual cost for a Pilot	83333	[€/year]
Annual cost for a manager	62500	[€/year]
Annual cost for a technician	41667	[€/year]

Maintenance data		
Price for one GSE package	1166666	[€]
Documentation cost / Purchase price	1.5%	[%]
Spare parts rate / Purchase price	12%	[%]
Software support cost / Avionics Purchase price/year	3%	[%]
Ratio for GSE maintenance per year	2%	[%/year]
Ratio for Documentation upgrade per year	10%	[%/year]
Infrastructure cost per year per HC	14167	[€/year]
Major retrofit at mid life in % of the purchase price	10%	[%]
Upgrade per year in % of the purchase price	0.50%	[%]

Training data		
Ground training hours/year/base	200	h/year/base
Ground training cost per hour	125	€/h
Flight training hours per year per crew	10	h/year/crew
Flight training cost	6303	€/h/HC
Simulator training hours per year per crew	15	h/year/base
Hour cost of simulator	1667	€/h

General data		
Working hours / Day	8	[h/day]
Working days / Year	200	[days/year]
Insurance cost / Acquisition cost per year	7%	[%/Year]

Nb GSE package per HC	
Number of HC	Number of GSE packages
1	1
2	1.5
5	2
10	4
20	7
50	12

Fig. 13 Operational data input for LCC model

Life Cycle Cost	Costs per HC in € for the all life long	Costs per HC in € /FH	Total Costs for the all fleet and for the all HC life long
Initial Purchase cost	**17 300 000**	**1 115**	**86 500 000**
Purchase cost (P. Cost)	15 000 000	1 000	75 000 000
Initial Spare procurement & renewal	2 000 000	100	10 000 000
Documentation	300 000	15	1 500 000
Mission personnel	**11 000 000**	**650**	**55 000 000**
Pilots salaries	7 500 000	400	37 500 000
Specific maintenance personnel	3500000	250	17 500 000
Insurance	**40 000 000**	**2 222**	**200 000 000**
Unit level consumption	**2 141 603**	**119**	**10 708 017**
Fuel consumption	2 087 603	116	10 438 017
Other	54 000	3	270 000
Maintenance and operation	**38 075 000**	**2 115**	**188 750 000**
Direct Maintenance Cost (DMC)	**27 000 000**	**1 500**	**135 000 000**
Basic HC	20 000 000	2 000	100 000 000
Mission equipment	6 000 000	400	30 000 000
Consummable	1 000 000	50	5 000 000
Training	**6 150 000**	**500**	**23 750 000**
Ground training	150 000	50	750 000
Flight training	4 000 000	300	20 000 000
Simulator training	2 000 000	100	3 000 000
GSE	**400 000**	**100**	**2 000 000**
Sustaining Support	**3 500 000**	**100**	**19000000**
Support Equipment Replacement	600 000	20	3 000 000
Substaining documentation replacement	900 000	50	6 000 000
Software Maintenance Support	2 000 000	100	10 000 000
Indirect Support	**1 025 000**	**100**	**9 000 000**
Infrastructure	425 000	30	6 000 000
Admistration & management	600 000	30	3 000 000
Modification & upgrade	**6 000 000**	**200**	**30 000 000**
LIFE CYCLE COST	**114 516 603**	**6 421**	**570 958 017**

Fig. 14 Data output for LCC model

7 Life cycle cost model in pre-design analysis tool

The previously described LCC model has been integrated in the pre-design rotorcraft analysis tool. The goal was to add the possibility to optimize the design for minimum LCC. Dedicated windows have been added for the analysis costs input (Fig. 15) and the calculated cost results (Fig. 16). The calculated cost results data are shown on three data tab sheets (Fig. 16):

1. the Life Cycle Costs 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
2. 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

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

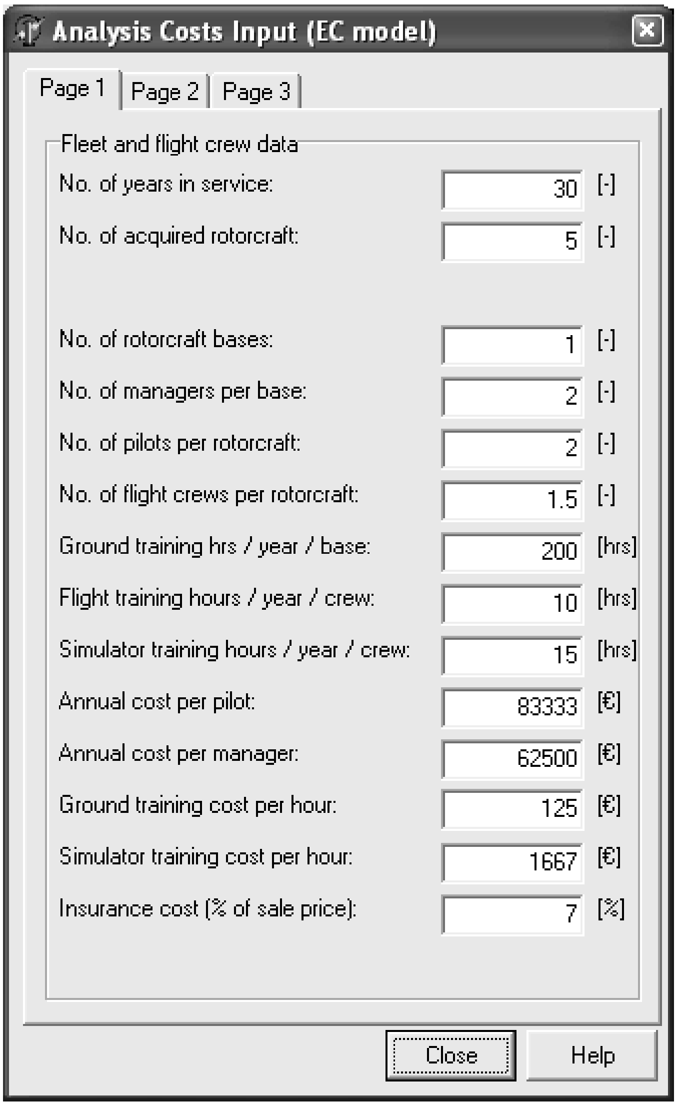

Fig. 15   Analysis costs input window

The foregoing methodology allows the optimization of the design, either for minimum gross mass or for minimum LCC, but not in an automated way. Many design choices have to be made, such as the percentage of composites material in the structure, the complexity of the rotor system, and the number of fuel tanks. All of these will affect the results of the design process and may mutually affect each other as well. An optimization methodology has been developed to ease the (pre-)design process.

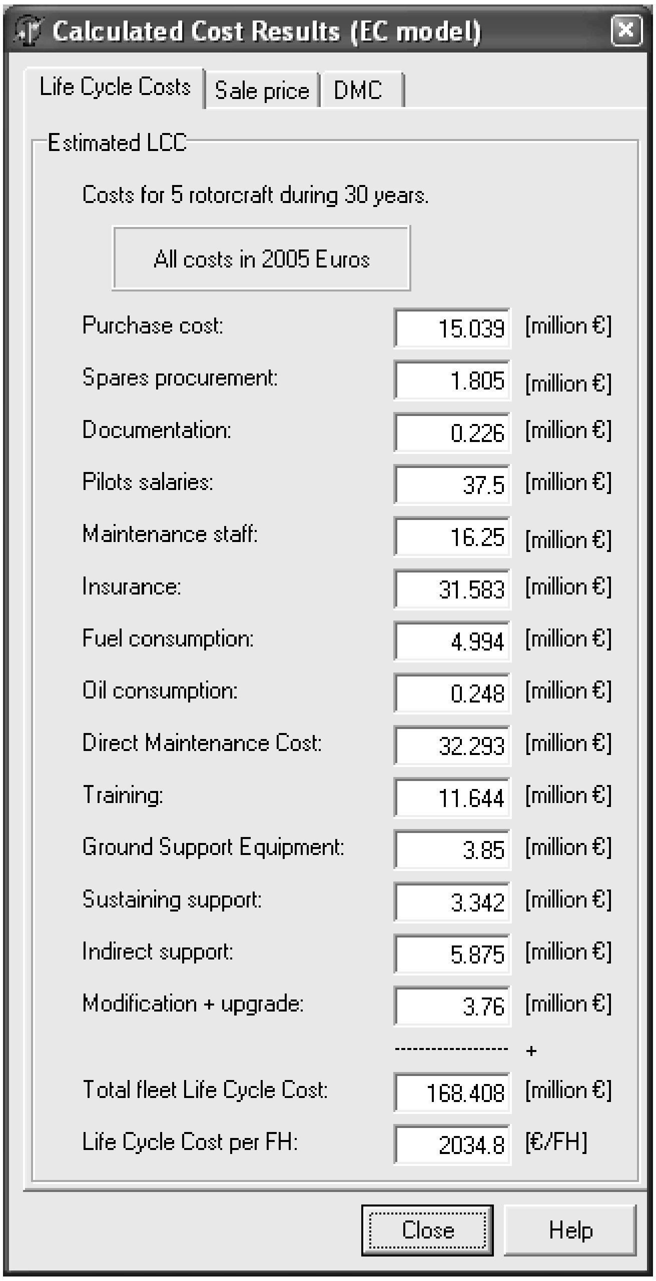

Fig. 16 Calculated cost results window

8 Optimization methodology

A helicopter design optimization environment has been created by putting the combined analysis/LCC tool in an interactive MATLAB environment (see www.mathworks.com), which was achieved by compiling the model into a Windows dynamic link library (.dll) file. The functions in the .dll file are called with the appropriate design parameters as arguments and the values of the design objectives, that is, the helicopter mass and the helicopter LCC are returned. The functions and toolboxes in the environment, such as gradient based algorithms (Ref. 6), genetic algorithms (Ref. 7, 8) and pattern search (Ref. 7) can then be used for the evaluation and optimization of these helicopter design objectives.

The optimization of the helicopter design can be characterized as a mixed-integer programming problem, either single- or multi-objective. Chapter 4 of this book gives a detailed description of optimization algorithms using continuous variables in general. The present chapter provides an extension of that approach by focusing on optimization using a combination of discrete and continuous variables. A specialized optimization algorithm ("fminconset") was applied, which combines a discrete branch-and-bound method (Ref. 9) with the general purpose non-linear constrained optimization algorithm "fmincon" from the optimization toolbox (Ref. 6). The optimization algorithm treats the complete calculation of the helicopter design objective functions (gross mass and LCC) as a black-box. Therefore it is currently unavoidable for the algorithm to perform exhaustive evaluations, i.e., to explore the whole discrete part of the design space. For the current tool and studies this still results in acceptable execution times in the order of a few hours on standard PCs. However, the concept of the branch-and-bound methods provides insight in the optimization problem and might contribute to future versions of the methodology.

The branch-and-bound algorithm (for single objective optimization) is explained below, followed by the general concept of multi-objective optimization.

8.1 Branch-and-Bound method

Branch-and-bound (BB) is a method applied in the area of combinatorial optimization, to find solutions of various types of integer optimization problems, e.g. the traveling salesman problem (Ref. 10) or other scheduling and assignment problems. The method is based on the idea that if one can predict that a specific branch of possible solutions has a better score than another branch, the other branch can be excluded from search, thus saving computation time.

The optimization problem is posed here as finding the minimal value of a function $f(x)$ (e.g., the helicopter LCC), where x belongs to a set S of possible and acceptable designs (the design space). A branch-and-bound procedure consists of two steps being applied in a recursive way:

1. First the *branching* step is performed. The set S of possible designs is divided into two or more smaller subsets S_1, S_2, ... that cover S. Note that the minimum of $f(x)$ over S is equal to the minimum of the minima of $f(x)$ over each subset S_i.

This way a tree structure is defined whose nodes represent the subsets of *S* (see Fig. 17)

2. Second the *bounding* step is performed. Upper and lower bounds for the minimum value of *f(x)* within a given subset S_i are computed

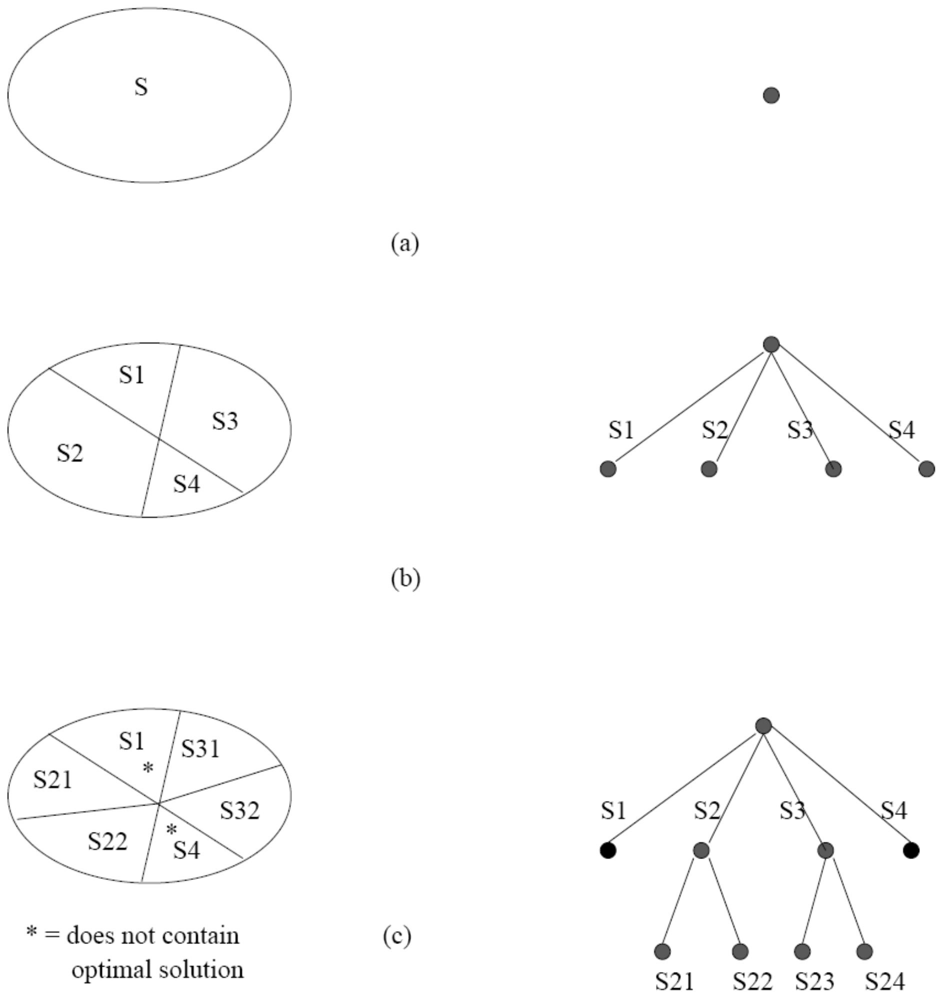

Fig. 17 Illustration of the tree structure created from a design set S with the branch-and-bound method. The set S of possible solutions is partitioned. Subsets S_1 and S_4 are not further subdivided in a tree structure because a bound function indicates that they do not contain the optimal solution (picture from Ref. 10).

If the lower bound of *f(x)* over some subset of candidate designs S_c is greater than the upper bound of *f(x)* over any other subset S_j, S_c may be safely discarded from the search. This can be implemented by maintaining a global variable *m* that records the minimum upper bound of all subsets examined so far. Any subset whose lower bound is greater than *m* can be discarded. Subsequently, the remaining subsets S_j are divided further into subsets $S_{j1}, S_{j2}, \ldots$ (see Fig. 17) to detect again possible subsets to be excluded from the search by means of the bounding technique. This process is repeated recursively until the set *S* of candidate solutions is reduced to a single element, or when the upper bound for set *S* matches the lower bound. Either way, any remaining element of *S* will be a minimum of the function *f(x)*.

The efficiency of the branch-and-bound method strongly depends on the effectiveness of the bounding algorithm used. For each particular problem a specific bounding technique should be designed. For this detailed information about the behavior of the objective function (which is to be optimized) is necessary. The structure of our combined analysis and LCC tool allows for application of the branch-and-bound method in future cases, e.g. if more design variables are to be explored.

8.2 Multi-objective optimization

A detailed description of the multi-objective optimization problem and the corresponding optimization search algorithms can be found in Chapter 4 of this book. The definitions and optimization approach are summarized here, using the same notation as in Chapter 6.

Multi-objective optimization, which can be considered as a generalization of single-objective optimization, deals with vector-valued objective functions $\mathbf{y} = \mathbf{f}(\mathbf{x})$, e.g. both helicopter mass and LCC are minimized simultaneously. The definition of optimality in this case is non-trivial, because of the indefiniteness of the relation among the multiple objective functions. To resolve such kind of optimization problems, consider the following definition, which is based on the concept of Pareto optimality (Ref. 11). According to this concept, an objective vector $\mathbf{y}^1$ is said to *dominate* any other objective vector $\mathbf{y}^2$ $(\mathbf{y}^1 \prec \mathbf{y}^2)$ if the following two conditions hold: no component of $\mathbf{y}^1$ is greater than the corresponding component of $\mathbf{y}^2$; and at least one component of $\mathbf{y}^1$ is smaller than $\mathbf{y}^2$. Accordingly, it can be stated can say that a solution $\mathbf{x}^1$ is *better* than another solution $\mathbf{x}^2$, i.e., $\mathbf{x}^1$ *dominates* $\mathbf{x}^2$ $(\mathbf{x}^1 \prec \mathbf{x}^2)$, if $\mathbf{y}^1 = \mathbf{f}(\mathbf{x}^1)$ dominates $\mathbf{y}^2 = \mathbf{f}(\mathbf{x}^2)$. For example, let decision vector $\mathbf{x}^1 = -1$ and $\mathbf{x}^2 = 1$, and their corresponding objective vectors are $\mathbf{y}^1 = (1,1)$ and $\mathbf{y}^2 = (9,1)$, i.e. in that case $\mathbf{y}^1$ dominates $\mathbf{y}^2$. Additionally, a solution vector $\mathbf{x}^u \in \mathbf{X}$ is said to be *Pareto optimal* if there exists no $\mathbf{x}^v \in \mathbf{X}$ for which

$f(\mathbf{x}^v)$ dominates $f(\mathbf{x}^u)$. The set of (Pareto) optimal solutions in the decision space $\mathbf{X}$ is in general denoted as the *Pareto optimal set* $\mathbf{X}^* \subseteq \mathbf{X}$, and we denote its image in objective space as *Pareto front* $\mathbf{Y}^* = f(\mathbf{X}^*) \subseteq \mathbf{Y}$. One can derive the Pareto front of an objective space with calculated objective function results: $\{y^i = f(x^i) \mid x^i \in X\}$ by so-called *non-dominated* sorting. The decision space $\mathbf{X}$ is divided in to classes of decision vectors that do not dominate each other. Then each class is given a *Pareto rank*. The decision vectors that are not dominated by any other decision vector get rank 1. Subsequently the decision vectors that are dominated only by the decision vectors with rank 1 get rank 2, etc. The rank maps the multi-dimensional output vectors in the objective space to one-single dimension. The optimization search algorithms that calculate the Pareto optimal set, are concerned with the shape of this rank mapping. This concept fits in with the generalization of the single-objective problem.

As an example (see also Chapter 4), consider the following being the simple multi-objective optimization problem:

$$\min_{x} \; y_1 = \sin(x) \quad , \quad y_2 = \cos(x) \quad ; \quad x \in [0, 2\pi] \tag{9}$$

The solution of this problem consists of the Pareto front for y_1, y_2 as indicated by the thick part of the lines in Fig. 18 ($x \in [\pi, 3\pi/2]$). There are many different algorithms to find the Pareto optimal set. Examples of methods, with the focus on so-called evolutionary algorithms, are described in Chapter 6 of this book.

8.3 Formulation of the optimization problem

The multi-objective optimization problem of helicopter design with respect to gross mass and LCC can be formulated as follows: minimize both the helicopter gross mass and total life-cycle cost as a function of the following 13 design parameters, which have been chosen from the parameters listed in Fig. 11 (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 fight control system (0 = mechanical, 1 = Fly-By-Wire, FBW)

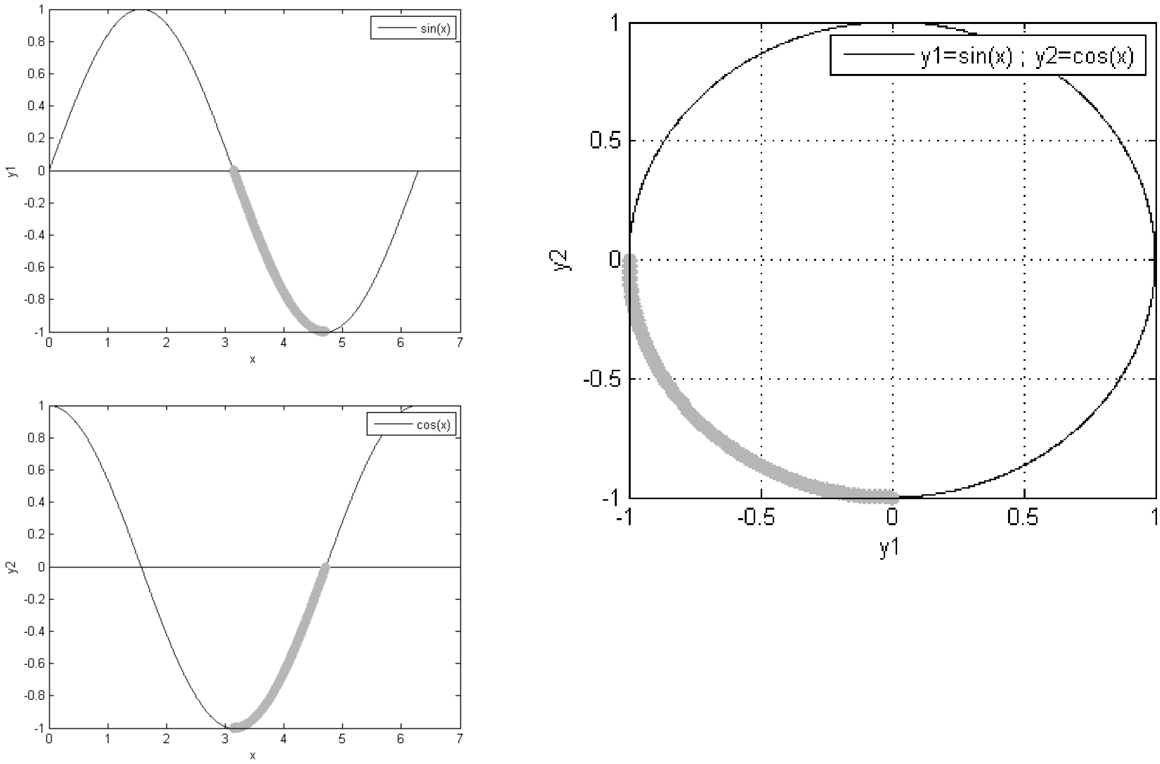

Fig. 18 Illustration of the solution of a general multi-objective optimization problem

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. fleet wide number of business flights per year (0 - …)
12. fleet wide number of offshore flights per year (0 - …)
13. fleet wide 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.

8.4 Reference design

For the illustration purposes of the MDO case study, a selection of certain parameter values has been made to limit the total number of potential combinations, i.e. the search space. On the basis of engineering judgment and state-of-the-art technology the following values have received a fixed value (except the engine reduction gearbox) for the optimization 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 (its effect on mass and cost is not clear beforehand, as the reduction step is moved from the engine to the main gear box or vice versa)
10. no critical environment for avionics (lower mass and cost)

For the mission combination a possible division of flights per year has been chosen (the effect of changing this division will be shown 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 about 3870 kg and total LCC of about 180 million Euros with engine reduction gearbox, or 3860 kg and 170 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 optimization strategy.

8.5 Optimization evaluations

As described before, a mixed-integer programming algorithm can be applied to the design optimization problem as a whole. However, because it is expected that this algorithm will perform an exhaustive search, first a global evaluation of the effects of 4 design variables (the first 4 parameters given before) on the design objectives is performed, to gain insight in the design space. Because the LCC objective function is non-linear, the global exploration of the design space also allows to regard LCC as an independent variable (Cost As an Independent Variable, CAIV, Ref. 12, which is becoming more frequently used in military design cases and which may be desirable in future cases.

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 Fig. 19.

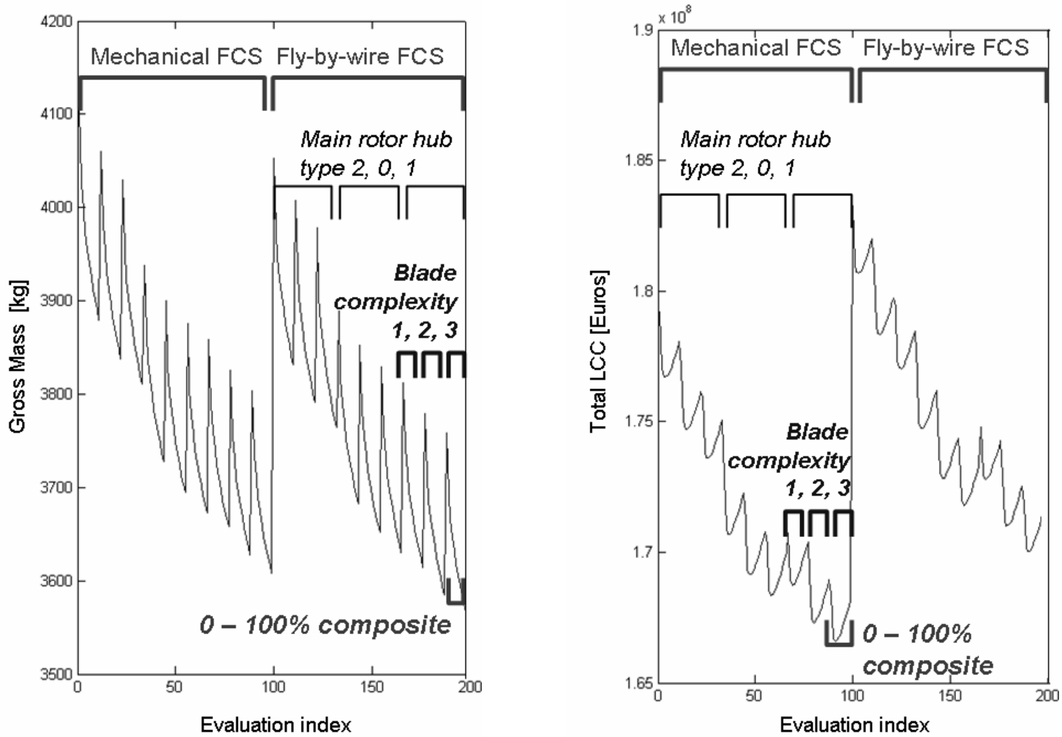

Fig. 19 Global evaluation of helicopter mass (left) and LCC (right): their dependency on the 4 different design variables

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 FBW flight control system. However, for minimum LCC 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 LCC is 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 optimizations 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 minimizations 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 mixed-integer programming algorithm “fminconset”, as mentioned before, was used for the minimization over the percentage composite mass and the type of flight control system. The results of these optimizations for helicopter mass and LCC are given in figures 20 (circle) and 21 (square).

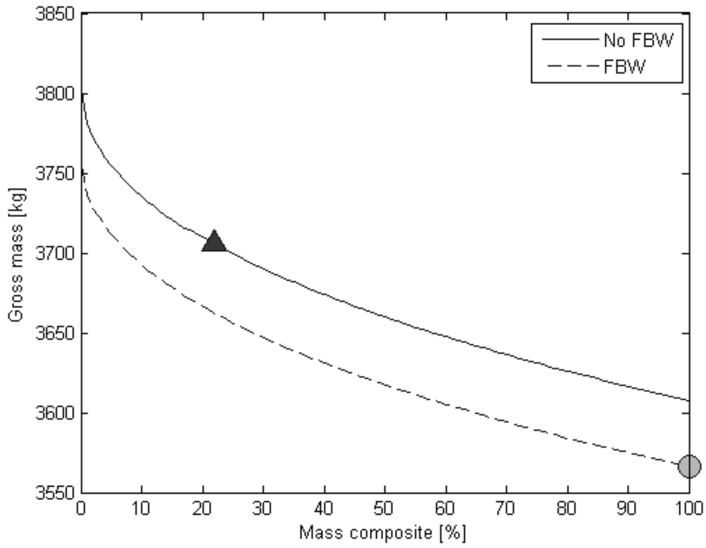

Fig. 20 Minimum helicopter mass (circle) found for 100% composite mass in the fuselage and a fly-by-wire flight control system

The triangle in both figures indicates the optimum design for the other objective. The triangles show that the design that is optimized for mass has a corresponding LCC value of about 172 million Euros, which is higher than the minimal LCC value of about 167 million Euros. At the same time the design that is optimized for LCC has a corresponding mass value of about 3705 kg, which is higher than the minimal mass value of about 3565 kg. Hence, these single objective optimum design points provide poor values for the other design objective that is not optimized.

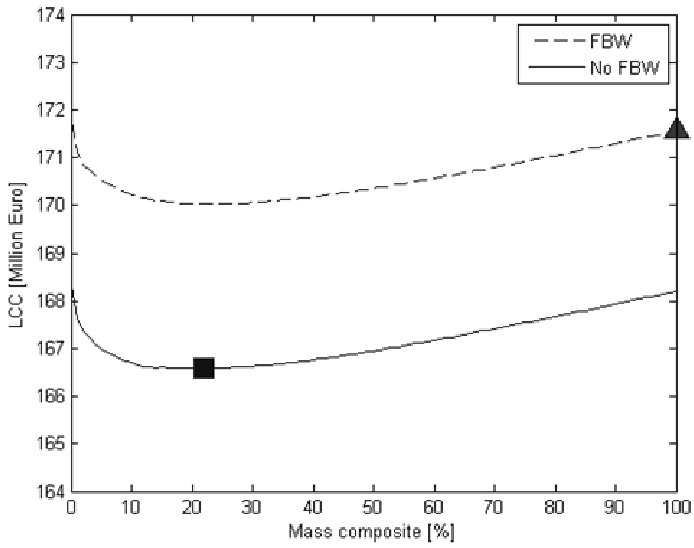

Fig. 21 Minimum helicopter LCC (square) found for 22 % composite mass in the fuselage and a mechanical flight control system

In order to efficiently take into account more than one design objective in the helicopter design optimization study, a multi-objective optimization approach can be used. Efficient algorithms for solving such multi-objective optimization problems are available (see Chapter 6 of this book or Ref. 8). 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 optimization problem can be formulated as a Pareto optimal (Ref. 11) design problem (see previous section), having a set design points as the optimal solution, the Pareto optimal set (or Pareto front in the objective space). This Pareto optimal set is shown in the Fig. 22.

The result was found for the optimization 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 optimizations. 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. The results shown in the figure 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 represented by the star-symbols. In the figure also the single objective optimum design points for mass (circle) and LCC (square) are indicated.

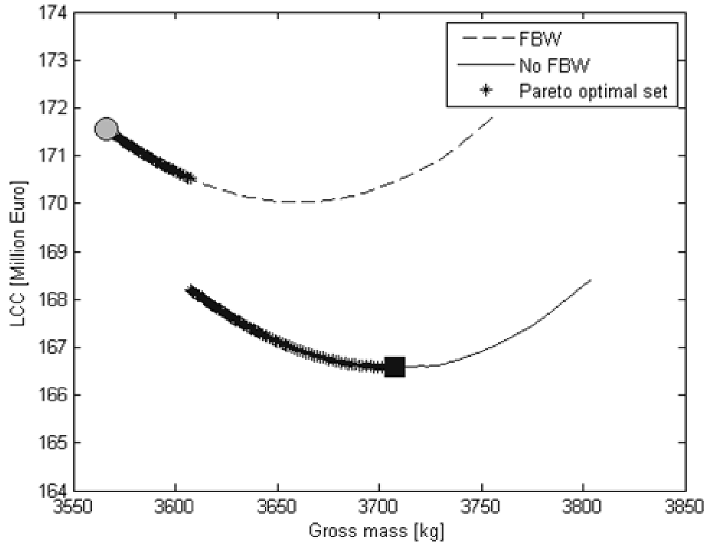

Fig. 22 Results of helicopter mass and LCC multi-objective optimisation problem

8.6 Comparison with reference helicopter design

Figure 23 shows the reference helicopter design (star) together with some results

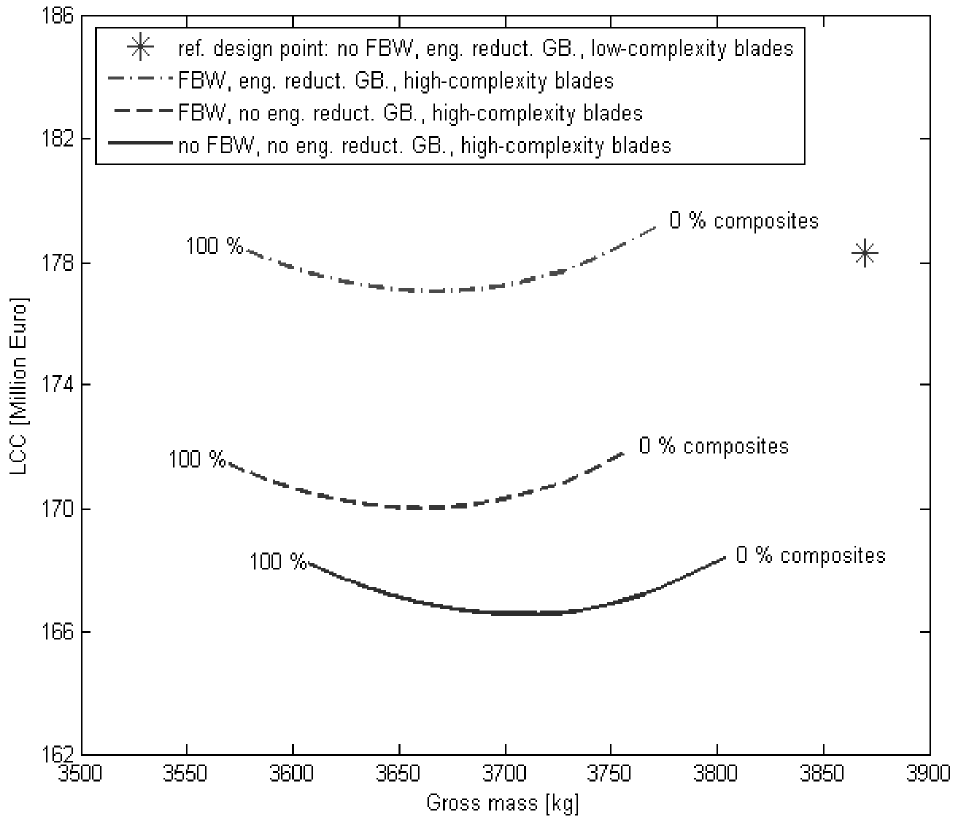

Fig. 23 Combined results of reference helicopter design and optimisation results

from the preceding optimization strategy. In comparison to the reference design, the introduction of high complexity blades and a FBW flight control system does significantly reduce the helicopter mass, but has almost no effect on the total LCC due to the higher acquisition cost being balanced by the lower maintenance effort (moving left in the graph).

As shown before, the removal of the engine reduction gear box (GB) has a small effect on the helicopter mass, but significantly 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 one, 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.

8.7 Design for multiple mission combinations

In the preceding part the optimization process has concentrated on optimization 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), illustrating how this method can help operators gain insight into the consequences of their requirements. A helicopter manufacturer however is interested in multiple operators having multiple mission combinations. Therefore a next step in the optimization process is to optimize 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 optimization of LCC has been performed for two different mission combinations during the life cycle: combination 1 represents the LCC 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 LCC 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 optimized for both these two mission combinations.

Figure 24 shows the optimum design point for combination 1 that was found in the previous mass-LCC optimization (square; helicopter design with 22 % composite mass).

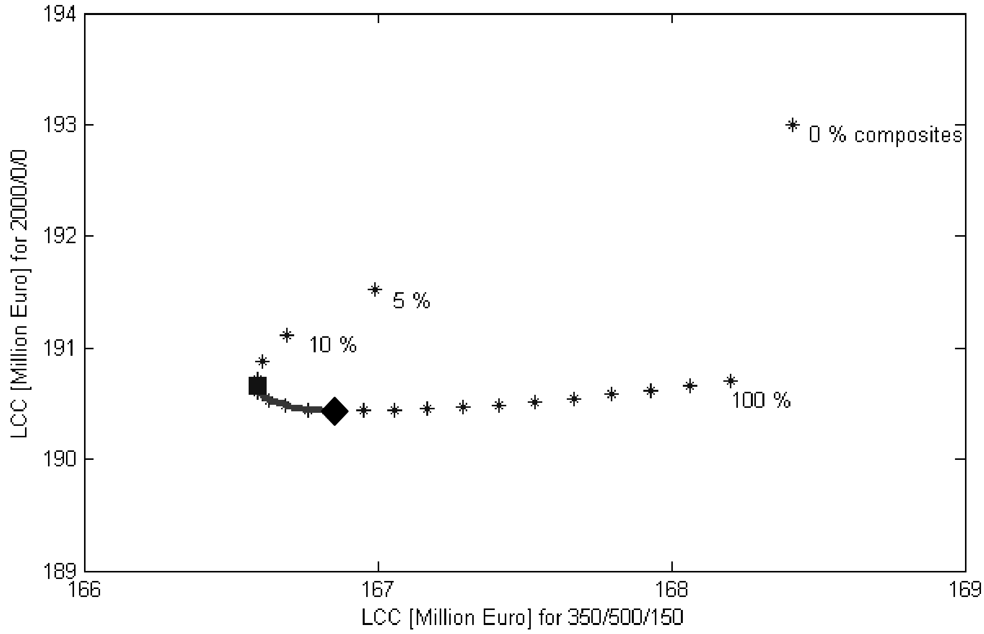

Fig. 24 Results of helicopter multi-objective optimisation problem for mission combination 1 (horizontal axis) and mission combination 2 (vertical axis)

Additionally the optimum design point for combination 2 is found (diamond; helicopter design with 45 % composite mass). The line in the figure connects a series of design points, the so-called Pareto optimal set, which represent a compromise 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 %.

9 Concluding remarks

The helicopter pre-design is normally driven by performance requirements and traditionally the helicopter mass is considered the design optimization 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 case study the LCC model has been integrated into a rotorcraft pre-design analysis tool. A helicopter design optimization environment for the evaluation and optimization of the helicopter design objectives has been created in an interactive environment. The optimization methodology applied in this study is based on the formulation of a generic optimization problem that allows for, among others, single- or multi-objective optimization problems, non-linear constraints and discrete variables.

The results of the optimization 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 optimization 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. It should be remarked that the LCC calculations in the objective function are partly based on estimations of the future and therefore have a statistical uncertainty margin in absolute sense. However, it is expected that the relative uncertainty of these calculations is much smaller and that the same optimization strategy is applicable if new LCC estimates are performed in the future.

Since helicopter manufacturers are interested in multiple operators each having multiple mission combinations, an additional optimization study has been performed to optimize 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 represents the set of compromise optimal helicopter designs. The optimal design point depends on the actual combination of the defined missions.

The discussed method and supporting tool can likewise be used by helicopter operators to select the optimal helicopter configuration for their combination of missions. It also allows the operators to assess the consequences of individual mission requirements in terms of the resulting helicopter configuration and total LCC. The Pareto approach and global exploration of the design space also allow to regard LCC as an independent variable, which is becoming more frequently used in military design cases and which may be desirable in future cases. The resulting pre-design strategy contributes to:

1. reduced number of iteration loops in the preliminary design process; applying the Pareto technique summarizes the set of compromise optimal helicopter designs in an effective way, leading to a less time consuming preliminary design phase
2. reduced development costs of future helicopter designs through the ability to better predict the LCC of the helicopter
3. reduced operational cost for the operators/owners of helicopters
4. support to helicopter marketing by providing the LCC relationship for multi-mission combinations

5. a better insight into the consequences of design choices

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

Acknowledgements

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