Helicopter Life Cycle Cost reduction through pre-design optimisation[1]

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Executive summary

This paper presents the NLR analysis tool SPEAR "SPEcification Analysis of Rotorcraft" and the work currently being performed on helicopter preliminary design to cost optimisation. This work is part of the EU-project Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE). A description of the analysis tool SPEAR, the methodology, features, and applications are given and the VIVACE project objective, status and planned activities are discussed. Some preliminary calculation results will be presented using the Eurocopter preliminary Life Cycle Cost model which has been integrated in SPEAR. This demonstrates the potential of the analysis tool for Life Cycle Cost reduction through pre-design optimisation.

Abbreviations

DMC	Direct Maintenance Cost
EC	Eurocopter
MDO	Multidisciplinary Design and Optimisation
LCC	Life Cycle Cost
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, weight 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 goal is 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 have the lowest cost while performing a diverse mix of missions. These 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). This requires a multidisciplinary optimisation approach at the preliminary design phase.

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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 has 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 are 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 is developing 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, is developing a sizing optimisation methodology to enable a multi-mission design with LCC optimisation and will integrate the Eurocopter LCC-model and optimisation routines into the NLR helicopter analysis tool SPEAR "SPEcification Analysis of Rotorcraft".

SPEAR

NLR has developed a methodology for the analysis of specifications for a rotorcraft that should be capable of fulfilling a set of flight and mission tasks. The methodology has been implemented in the computer program called SPEAR: "SPEcification Analysis of Rotorcraft", see figure 1. This program is able to estimate the size and minimum mass of a rotorcraft capable of fulfilling a specified set of operational (flight and mission performance) requirements. The program determines the rotorcraft gross mass, the main dimensions, the installed engine power, the fuel capacity and the mass

Figure 1 Main window of the SPEAR program

breakdown for the main vehicle components. The consequences of operational requirements 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 EMPRESS (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. Different kinds of graphical representations for the helicopter design results are included. The program basically includes the potential for Life Cycle Cost optimisation or trade-off studies. SPEAR runs on Windows NT/2000/XP Personal Computers, thereby taking advantage of the Windows features. The current version is SPEAR 4.4, dated September 2005. NLR plans to further extend the program for Unmanned Aerial Vehicles (UAV) applications.

Specification of requirements

In order to be capable of performing needed missions, an operator has to specify a set of vehicle related requirements. These can be broken down into three parts, being the:

- rotorcraft configuration (lay-out),
- flight performances,
- mission performances

The rotorcraft configuration contains data that describe the general lay-out of the rotorcraft plus some (aerodynamic) efficiency parameters. The flight performance and mission performance parts contain the data for respectively the specific flight performance requirements and mission profile(s) that the rotorcraft must be capable of fulfilling. The individual requirements are stored in the database, from which one or more can be selected for the analysis, see figure 2.

Flight performance requirements

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

Mission performance requirements

Each mission profile is specified by a number of mission segments, which are defined by the 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, specific mission equipment or a mixture of these. Within each segment the pressure altitude and temperature are constantly updated, depending on the vertical speed, whereas other parameters remain unchanged.
The mission equipment package is taken into account by means of a mass provision complemented by an additional parasite drag area for any external equipment.

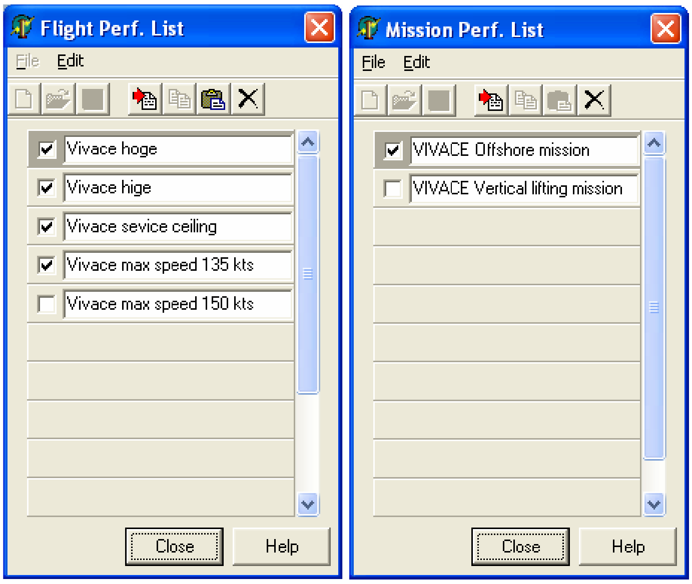

Figure 2 Available/selected flight and mission performance requirements

Methodology

The methodology applied in SPEAR is largely based on Ref. 3. The task of the computer program is to 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 available fuel equals required fuel to fulfil the most demanding mission. The optimum solution is defined as the one that achieves these objectives at the lowest gross mass. As suggested in Ref. 3 other criteria may be defined for the optimal solution, e.g. one that achieves the lowest Life Cycle Cost.

The ratio of rotorcraft Empty Mass to Gross Mass is a function of the main rotor disk loading and tip speed, the rotorcraft gross mass and the power loading. The calculation process runs efficiently by taking the main rotor disk loading as the driving variable. The user fixes the tip speed at a value compatible with the rotor technology state-of-the-art and e.g. with noise constraints. The actual sequence for the calculation of the various parameters is shown in figure 3. It is essential to first determine the main rotor dimensions. This is achieved by making an initial Gross Mass estimation and from this an assumption for the disk loading, based on historic data. Then, suitable main rotor dimensions are determined for the specified flight performance requirements. For each of the specified flight performance requirements the power required is calculated and the minimum engine power that is to be installed. The most demanding 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. Together with the calculated results, the program shows the names of the specific requirements (flight performance and mission profile) that have driven the main rotor design, the required engine power and the fuel capacity.

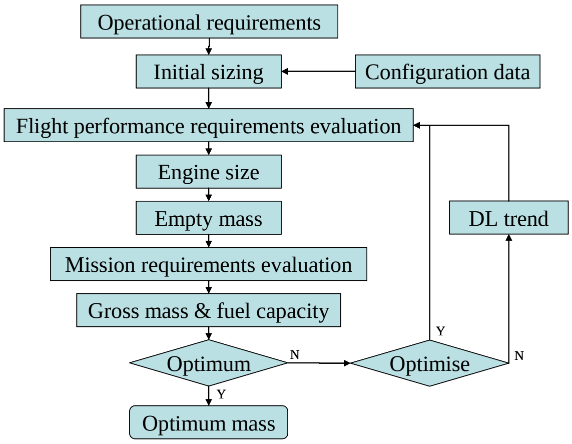

Figure 3 Simplified flow chart for the SPEAR calculation routine

SPEAR determines the main rotorcraft parameters: the main rotor dimensions, the gross mass, the installed engine power and the fuel capacity. In addition, and derived from these quantities, other detailed rotorcraft design data are estimated.

Features

An analysis in SPEAR can be carried out at three levels with an increasing amount of input data and possibilities:

Basic

The Basic analysis will determine the gross mass based on the provided rotorcraft configuration, operational requirements and a user selected main rotor tip speed value. Historic data is used for fuselage drag, specific fuel consumption and tail rotor diameter. For the limit blade loading (C_T/σ) in level flight (load factor equals one), one of the characteristic lines in the database is selected. For the engine there is a choice, either for a hypothetical, exactly compliant ('rubberised' on empirical data) engine or for an existing engine to be automatically selected from the database.

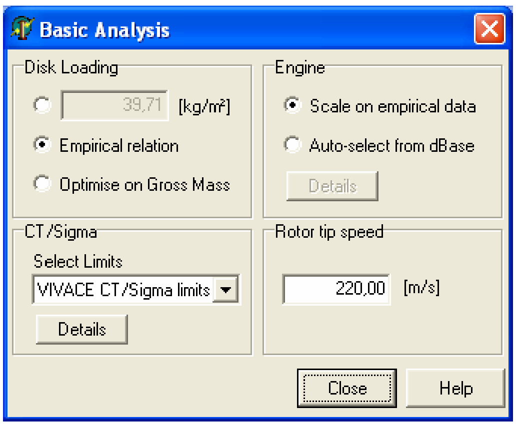

Figure 4 Data input form for Basic analysis

Parametric
The second analysis level provides more extensive options to further analyse the configuration proposed. The effects of varying the following seven main rotor parameters can be analysed: diameter, blade chord, tip speed, rotational speed, disk loading, blade loading and solidity. For the analysis a value must be selected for three parameters. However, not every combination of three parameters is valid (e.g. disk loading and diameter can not be selected at the same time).

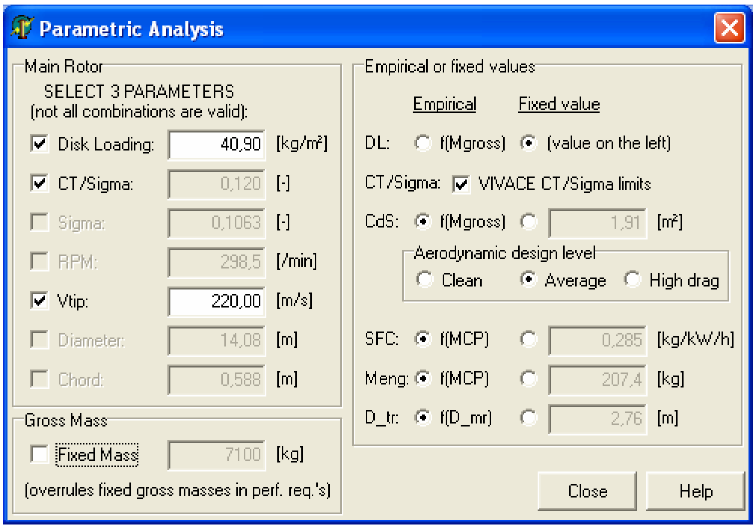

Figure 5 Data input form for Parametric analysis

For several input data a selection can be made between a historic trend line value or 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. The analysis process can also be run for a fixed gross mass (specified by the user), in which case the 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. This will be indicated.

Graphical
The third analysis level automatically presents the results in a graph, for which four different types are available:

- design chart (power required per kilogram of rotorcraft gross mass as function of the disk loading),
- parameter analysis chart (per kilogram of mass or power required as a function of one of the seven main rotor parameters),
- carpet[2] plot (per kilogram of mass or power required as a function of two of the seven main rotor parameters),
- power curve (level flight power required for calculated rotorcraft size as a function of airspeed for given values of gross mass, altitude and temperature).

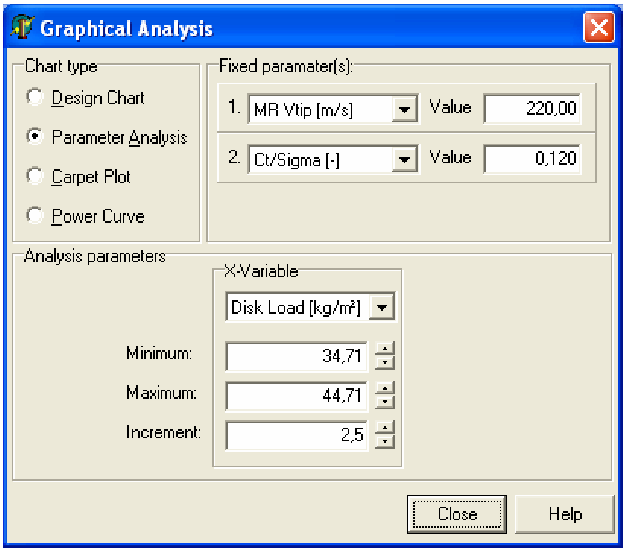

Figure 6 Data input form for Graphical analysis

Just like in the *Basic* analysis level, several options have been set to use historic data. This concerns the fuselage parasite drag area (assuming an 'average' drag level), the engine specific fuel consumption, and the tail rotor diameter.

[2] A carpet plot is a means of displaying data dependent on two variables in a format that makes interpretation easier than normal multiple curve plots. A Carpet Plot is often used in multi-dimensional parametric studies.

Analysis results

The analysis results window provides an overview of the main results of the analysis. It shows the seven main rotor design parameters and the Figure of Merit (for the isolated main rotor), the tail rotor dimensions, the engine data, several masses, the fuel capacity and the rotorcraft parasite drag area. In addition it shows the names of the specific requirements (flight performance and mission profile) that have driven the main rotor design, the required engine power and the fuel capacity, see figure 7. Also a detailed breakdown of the mission result data for each of the selected mission profiles can be shown.

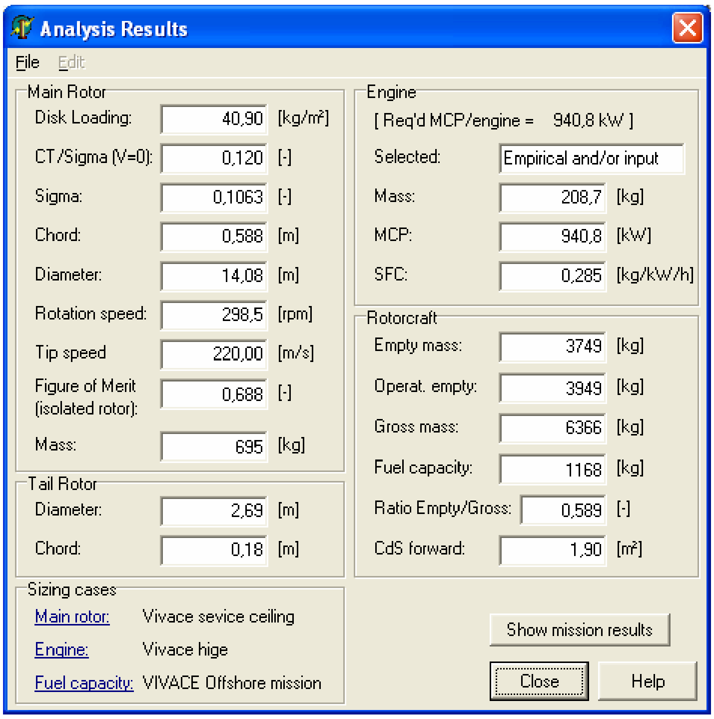

Figure 7 Analysis results for VIVACE example requirements

Mass breakdown

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

Cost breakdown

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

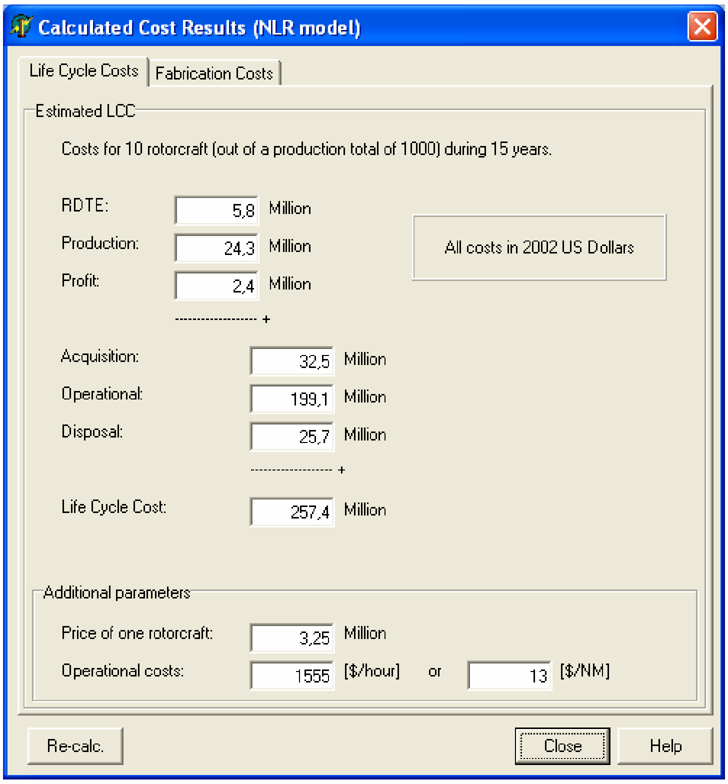

Figure 8 Calculated Cost Results (NLR model) window

The life cycle costs (total operating cost for the number of acquired rotorcraft) is estimated and shown in the Calculated Cost Results window, broken down in acquisition, operational and disposal cost, and the fabrication costs (costs of making the individual major components). It also provides the estimated operating cost per flying hour and per nautical mile, see figure 8.

Applications

Though SPEAR is basically a helicopter sizing program able to perform the initial sizing of a helicopter during the preliminary design, NLR generally uses the program as an analysis tool. SPEAR is a valuable tool for a diversity of applications:

- determining the benefits of technological developments on rotorcraft gross mass, either for existing ones or for those under development;
- performing parametric analyses to study the effect of parameter variations around the value proposed by the program;
- the analysis of operational requirements, e.g. as stated in a request for proposal for a new rotorcraft, to identify the ‘driving’ requirement;
- performing trade-off studies between maximum take-off mass, maximum payload and mission performance so as to optimise operational requirements definition;
- the estimation of size, mass and fuel of the lightest hypothetical rotorcraft that complies with the full set of flight and mission requirements;
- the assessment of the extent to which an existing rotorcraft is still optimal for the required task after modifications have been implemented;
- defining a long-list of existing rotorcraft that, possibly after modifications or adjustments, can comply with the specified operational requirements;
- performing trade-off studies of engine characteristics and type(s) that optimally suits the flight and mission requirements.

After having successfully established an ideal (virtual) rotorcraft, the relevant rotorcraft and mission data can be exported for use in the EMPRESS computer program. This enables the performance of all kinds of detailed studies, e.g. to generate operational diagrams comparable to those normally provided in flight manuals (power required curves, hover ceiling and climb performance diagrams, etc.).

Life Cycle Cost model

Eurocopter is developing a helicopter Life Cycle Cost model which reflects the impact of both the major technical parameters and the major categories of customers and missions. The preliminary LCC model delivered to the VIVACE “Multidisciplinary Design and Optimisation” (MDO) Use Case takes into account civil operations and is composed of the following three calculation routines, Life Cycle Cost, Rotorcraft Acquisition Cost, and Direct Maintenance Cost (DMC).

Life Cycle Cost

This calculation routine aggregates mainly the rotorcraft acquisition cost (sale price) and the Direct Maintenance Cost of a fleet for a certain period of time. The major parameters related to the use of the helicopters (but not directly connected to the manufacturer), are also taken into account. The Life Cycle Cost is therefore based on the following estimated cost items:

- rotorcraft acquisition cost,
- cost of spare parts procurement,
- cost of documentation,
- Direct Maintenance Cost,
- insurance cost,
- pilot overall cost,
- fuel cost.

At the current preliminary level of the LCC model, the list of parameters has been limited while still allowing computation of a realistic result. This list will be refined to be consistent with the rotorcraft acquisition cost and Direct Maintenance Cost routines level of detail.

Rotorcraft acquisition cost
This routine estimates the price of a helicopter according to its major physical parameters, such as the installed power, Max Take-Off Weight, rotor diameter, fuselage size, etc. The cost breakdown within the model is representative, but the total acquisition cost is scaled to represent the published sale prices.

The level of detail of the cost breakdown is consistent with the level of detail used by the preliminary design team in its first loop, see figure 9.

The analysis of new helicopter cost data may modify the choices of the cost drivers. However, the cost driver parameters will be limited to the number required to reflect the impact of both the major technical parameters and the major categories of customers and missions.

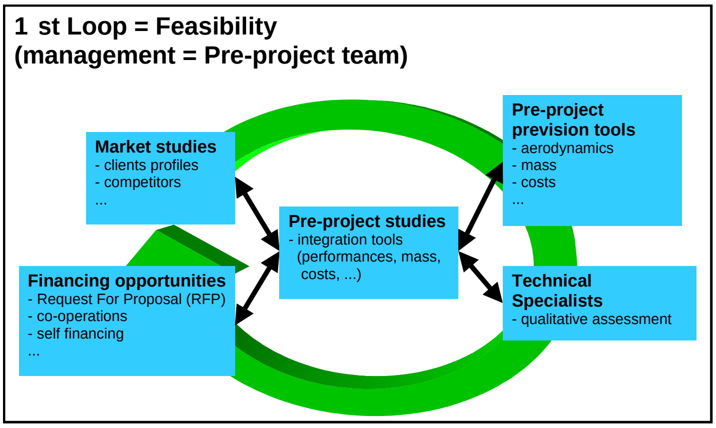

Figure 9 Feasibility phase (1st loop) of helicopter development process (Ref. 4)

An updated LCC model will also take into account the effect of the level of optional equipment. Optional equipment is generally applicable to heavy helicopters, while light helicopters are typically sold close to the baseline configuration with only very limited optional equipment.

Direct Maintenance Cost
This routine is quite similar to the rotorcraft acquisition cost routine, which means that the description given under rotorcraft acquisition cost is also applicable for this routine. The main difference with the rotorcraft acquisition cost routine is a much lower scatter of the results around the average as compared to the rotorcraft acquisition cost routine results.

The preliminary cost model equations will be updated based on the latest information.

LCC model in SPEAR

The Eurocopter (EC) preliminary cost model has been integrated in the NLR analysis program SPEAR.

An "Analysis Costs Input (EC model)" window, see figure 10 is used to modify input data for the detailed cost estimation process according to the Eurocopter preliminary Life Cycle Cost model. This LCC model only takes into account civil operations. The input data is self-explanatory. All changes to the cost data will automatically be stored in the database.

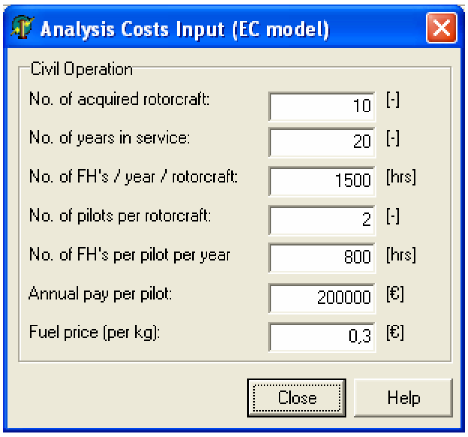

Figure 10 Analysis Costs Input (EC model) window in SPEAR

The "Calculated Cost Results (EC model)" window shows the estimated life cycle cost, the sale price and the Direct Maintenance Cost (DMC) on three data tab sheets, see figure 11.

The Life Cycle Cost page also shows the estimated total operating cost for the number of acquired rotorcraft. 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 page shows in detail the estimated costs of producing the individual major components. These add up to the sale price per rotorcraft.

The DMC page shows in detail the estimated Direct Maintenance Costs per flight hour for the individual major components.

The rotorcraft analysis is not (yet) influenced by the cost, which means that the minimum LCC occurs at the same Disk Loading as the minimum gross mass. Eurocopter and NLR work respectively to improve the LCC model and to develop a pre-design optimisation method. The objective is that the LCC model will reflect the impact of both the major technical parameters and the major categories of customers and missions, and that the optimisation method will enable a multi-mission design to LCC optimisation.

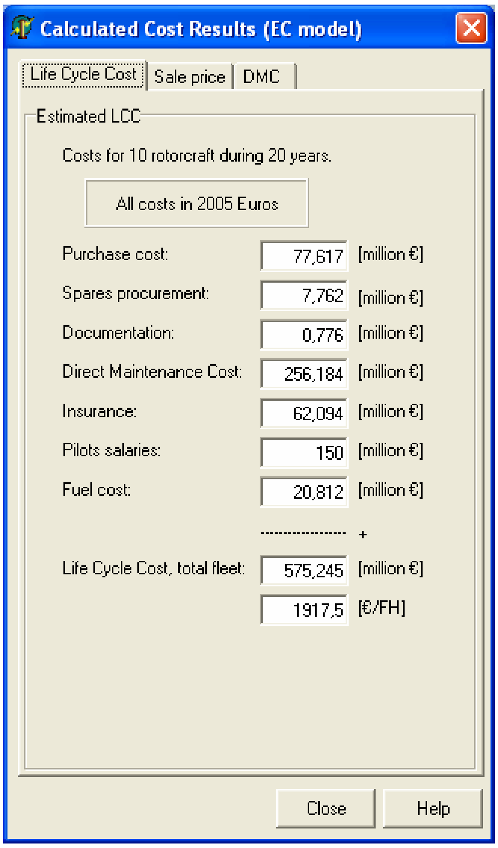

Figure 11 Calculated Cost Results (EC model) window in SPEAR

Preliminary calculation results

To illustrate the capabilities of SPEAR, two practical example applications are discussed. The first is the possibility to evaluate the performance requirements and to identify a possible severe requirement, which drives the helicopter design and thus be the cause of high LCCs. Adjustment of this one requirement can substantially reduce the size of the helicopter and thus reduce the LCC. Figure 12 shows two so called design charts, the first with one severe requirement which on it's own will "drive" the design, and the second in which the requirements have been harmonised.

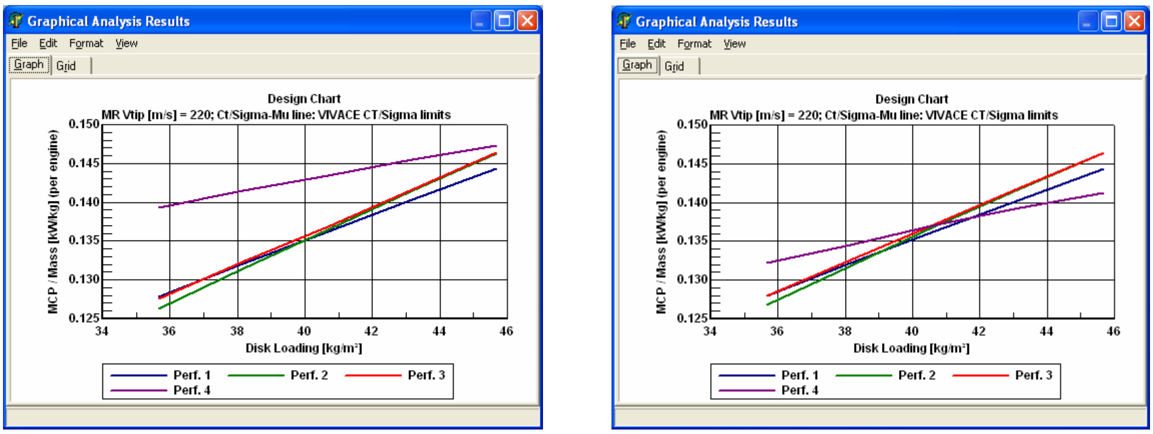

Figure 12 Calculated Design Charts in SPEAR for performance requirements evaluation

The second example application shows the results of an evaluation of two different missions. For this example an offshore mission and a vertical lift mission have been defined. For the offshore mission a maximum speed requirement of 150 kts has been used and for the vertical lift mission a maximum speed requirement of 135 kts has been used.

Figure 13 shows the resulting graphs for Gross Mass versus Disk Loading. The effect of the different mission requirements can be seen in the Disk Loading at which the optimum (minimum) Gross Mass for each mission occurs (about 41 kg/m2 for the offshore mission and 35 kg/m2 for the vertical lift mission). Since the LCC in this version of SPEAR still are dependent on the mass of the helicopter only, the optimal LCC also occurs at the same Disk Loadings. However, as mentioned earlier the ultimate goal is to optimise the LCC for the major categories of customers and missions for which the shown capabilities of SPEAR will be useful.

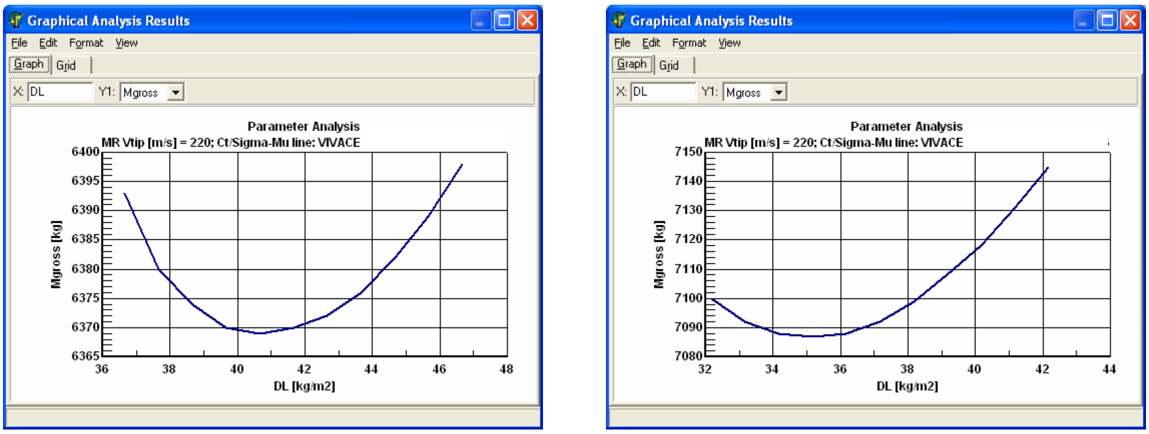

Figure 13 Calculated Gross Mass versus Disk Loading for offshore and vertical lift missions

Concluding remarks

The pre-design is normally driven by performance requirements. Operators however, need cost effective helicopter designs, which not only reach the required performance requirements, but also satisfy their requirements at the lowest possible 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 it’s helicopter analysis tool SPEAR "SPEcification Analysis of Rotorcraft" and is developing a sizing optimisation methodology to enable a multi-mission design to LCC optimisation.

Eurocopter and NLR will continue the work respectively to improve the LCC model and to develop a pre-design optimisation method.

Acknowledgement

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