Rotorcraft Conceptual Design Methodology by Using Fully Parametric CAD Model with Embedded Empirical Formulations

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ABSTRACT

Rotorcraft design needs a synchronous design method that connects different design decisions. This is due to the reciprocal nature of design drivers, and their corresponding consequences. Therefore, there is a need for a comprehensive design methodology that includes and connects different design considerations including performance, configuration, ergonomics etc. This paper introduces a rotorcraft design methodology which utilizes a fully parametric computer aided design (CAD) model. In the CAD model, performance calculations, weight estimations, and volume allocations are empirically formulated, and embedded into the model. This study enlarges the boundaries of conceptual design scope as it includes ergonomics factors such as pilot view angle, seating types and seating configurations. Moreover, alternative landing gear configurations, fuel tank configurations, different cabin types and design choices with their corresponding effects on weight and performance are discussed.

INTRODUCTION

Helicopters are complex machines that contains subsystems working in a harmony within standards, certification procedures, and technical constraints. Design process of a helicopter needs a synchronous system among different design disciplines. Using the classification of design phases introduced by Ulrich et al. (Ref. 1) in product design process, subsystem design is usually initiated during preliminary design phase, whereas conceptual design phase focuses on major design drivers of the helicopter. It is a challenging fact that design process of subsystems needs the overall conceptual design phase of the helicopter to be progressed at a certain point. This point requires major sizing and performance envelopes of the helicopter. Thus, a comprehensive conceptual design method should include considerations that is investigated in preliminary phase, resulting in an improved conceptual design solution. This solution will posit initial weight, volume envelopes for a subsystem more accurately, which will result in improved design process, overall.

Improvements concerning geometrical design decisions including fuel tank configuration, cabin types etc. were carried out by creating parametric CAD models. Lier et al. (Ref. 2) developed a toolbox for conceptual design and preliminary design, considering these two stages separately. This study included configuration selection of the helicopter by defining some compartments in the helicopter such as front fuselage, mid-fuselage, and rear fuselage. However, this study did not include major considerations stemming from human factors and ergonomics. This study uses CAD models to create inputs for fluid simulations and structural simulations which require time budget. It should be mentioned that a similar work for fixed-wing aircrafts were done by Trapp and Sobieczky (Ref. 3) focusing on geometry creation.

Parametric CAD model utilizes empirical formulations regarding weight allocations and some performance estimations as its initial estimation method. Empirical formulations were presented in literature like Prouty's (Ref. 4) statistical studies. Those studies were further reviewed and an application of them was presented by İbaçoğlu (Ref. 5). Aforementioned estimation formulae were improved to get contemporary results more accurately. Improvement procedure is explained under the section which elaborates on the CAD model, deeply. In addition to this estimation approach, response surface methodology was used in order to formulize performance calculations as it was discussed in Ref. 6.

DESIGN METHOD

Helicopter conceptual design phase treats the helicopter in the broadest manner where the subsystems needed for the vehicle to operate are not investigated independently. Naming the approach where every subsystem such as rotor controls, rotor aerodynamics, structures etc. as *subsystem level* design; conceptual design phase will deal with issues concerning main dimensions and sizing processes according to users' needs and customers' requirements, and hence it will be named as *helicopter level* design. In a helicopter level design

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approach, major design drivers like rotor configurations, payload and fuel allocations regarding performance requirements and mission profile requirements are negotiable among the contractor, customer, and the designer/manufacturer company. Therefore, it is expected that comparably radical changes regarding the design may be demanded, such as altering endurance requirement in a trade-off with payload requirement. In order to foresee what would happen regarding other major design decisions like vehicle dimensions, required power etc. when this alteration is applied; the design team should respond with quick but accurate estimations. It should be mentioned that this type of negotiations may also be discussed inside the design team to compare different alternatives responding to the same requirements where there are similar trade-off studies among performance and mission parameters. A quick and accurate estimative design decision-support tool is again needed for this type of occasions.

Algorithm

Design process starts with major performance requirements which can be considered as the task which behaves as the initial step of a planning and design process by Pahl and Beitz (Ref. 7) Those performance requirements are investigated within a given common mission profile including climb, hover, forward flight, descend and landing. Clarification of this mission profiles gives implications regarding range, endurance, maximum forward flight speed, required power by rotors, operation altitude, temperature envelopes etc. Estimating these indicated performance parameters requires some quantitative technical data such as gross weight and flat plate drag area (FPDA). This poses a problem since, those type of knowledge will be obtained after some initial design iterations. In order to cope with this problem, very first estimations are made through the investigation of competitor vehicles in the market. Studying the specifications of competitor helicopters that are similar in the sense of their operation capability. Capability to operate the mission profile needs are investigated within definite ranges. For instance, payload requirement is not treated as a fixed parameter; instead a range of payload values are taken into consideration. Combining each parameter range in a structured manner, one may obtain a *design space*. In this design space, every point indicates a combination of parameters such as range, altitude and payload. Each of those parameters are defined within ranges and with acceptable increments. Preliminary performance analyses on simplified flight scenarios such as climb, hover, forward flight etc. is carried out at each points in the design space. Those performance analyses are based on iterative blade element momentum theory solutions including numerical and empirical corrections. It was aimed to get quick results in these performance solutions. Compared to more detailed calculations including detailed aerodynamic calculations on stability and trim calculations, simplified assumptions on lift and drag characteristics were made. For instance, instead of conducting a detailed computation based on Navier-Stokes solutions on vertical stabilizers, a simple lift distribution was assumed according to 2-dimensional airfoil polars. Using those lift characteristics, trim analyses were carried out iteratively aiming to estimate some major-sizing dimensions on the helicopter.

Preliminary performance calculations basically estimate how much fuel is needed on which combination of performance inputs; that is a specific value of range with payload and hover altitude with a given engine power. In performance calculations terms, the inputs are rotor characteristics, gross weight, fuel weight, FPDA, power and specific fuel consumption. Using those inputs, performance estimations were made resulting in range, endurance, and maximum forward speed values. Differing these inputs, like engine power or rotor characteristics such as rotor radius, airfoil, chord and twist distributions etc. a relation between those parameters with range or endurance can be obtained. This is done by using response surface methods as it was explained in Ref. 6. After this response surface calculation, several functions in polynomial form can be obtained. Putting the relation into a reversible functional form, inputs and outputs become interchangeable in mathematical terms. A reverse functional definition between range and fuel weight may result in a mathematical model that uses range as an input and fuel weight as an output. It is obvious that the relations are not one dimensional, rather multi-dimensional including all performance-wise inputs while estimating performance-wise outputs.

A clear definition of performance-wise inputs and outputs is needed in order to prevent further confusions. Considering solely a hovering case for instance, rotor characteristics, gross weight and engine power are inputs. Maximum hovering altitude is an important output of this calculation. In this case, engine power is a performance-wise input; on the other hand, hover altitude is a performance-wise output. After setting a response surface; and hence obtaining a function among those parameters, every performance-wise input can be considered as an output; as well as the fact that every performance-wise output can be considered as input. In other words, now, setting a response surface system, required engine power can be estimated that satisfies the intended hover altitude. This conversion of inputs and outputs has two major advantages. First advantage is that the customer defines their needs in these terms. Operating hover altitude is a parameter defined by customer and user according to their operational needs. Therefore, before starting engineering design process, hover altitude is treated as a design-input. However, a preliminary performance calculation is needed to assess its implication on other parameters such as engine power. The conversion of inputs and outputs serve this purpose. It creates a reversed system allowing the design process to proceed in a more sequential manner. Second advantage is visible while they are used in CAD medium, which will be explained in detail.

Having defined the nature of inputs and outputs, it becomes evident that almost all parameters affecting helicopter sizing and performance can be assessed an evaluated according to each other. Nevertheless, for the sake of simplicity and time limitations, throughout the results of this paper, dynamic systems (rotors, transmission and power plant) were kept constant.

Relations and formulations obtained upon this point of design may give rough estimations on the evaluation of user needs. However, this analysis would be insufficient to estimate FPDA, and be lacking of additional design choices like fuel tank configuration or landing gear configuration. Some other design choices include cant angle, tail rotor transmission shaft angle, seating layout, pilot view angle etc. Those design decisions are included in CAD model as inputs affecting several different components and other decisions throughout the model. Rough estimation formulae based on references areas and mass information will be embedded in this CAD model to give detailed estimation of fuel weight, gross weight, and FPDA for further analyses.

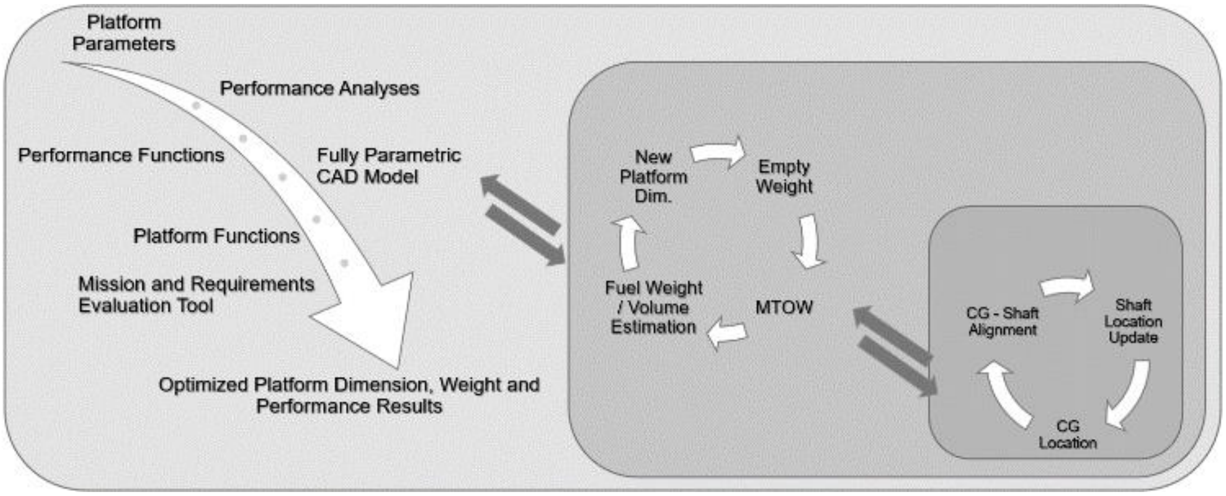

Figure 1. Design algorithm of CAD model approach

Detailing process can be exemplified considering a payload allocation regarding number of passengers. Let a response surface lay on 3 points of payloads, namely 0 kg, 200 kg, and 400 kg. Required fuel weight was obtained using those 3 points initially. As it is known that the more input points, more accurate the response surface becomes, except for over-trained cases. One may include a detailed allocation regarding number of passengers assuming 1 civilian passenger will weigh 100 kg including the seat and its assembly parts for simplification purposes. Increasing the passenger number one by one from 0 kg to 400 kg will increase the input points to 5 compared to 3 initial points. If there was not a CAD model considering the seating layout, this will yield no difference compared to a pure mathematical model. Seating layout will yield the differences on cabin length and cabin width corresponds to each passenger configuration. Therefore, increasing or decreasing passenger number will also affect FPDA. Increasing the number of passengers may also increase FPDA, resulting in more amount of fuel required; and hence, more increase in gross weight than what was estimated by the initial estimations.

CAD model not only estimates empty weight and hence gross weight more accurately, it always keep some helicopter design variables like center of gravity (CG) envelope in an acceptable range. At the conceptual design phase, CG allocation is at its most flexible position; therefore, it is possible to keep CG point at coincidence with main rotor shaft during all iterations. Effects of this alignment regarding FPDA and weight is also calculated at each iteration. When these iterations converge, a more detailed input sets are available for a second response surface calculation to obtain the final set of formulae.

The second response surface calculation uses more points to produce more accurate formulae representing the final conceptual design of a helicopter within given customer requirements. After utilizing the CAD model, inputs are diversified including number of passengers and cargo weight, instead of just saying payload; fuel tank configurations, landing gear placement etc. Those inputs are easily interpreted by the customer or the user as they are more compatible with their way of listing required attributes.

In summary, Figure 1 shows the general algorithm explained in a schematic. Following section will explain the details of CAD model and its properties regarding design decisions and detailed inputs.

FULLY PARAMETRIC CAD MODEL

A fully parametric CAD model is a model where all variables are connected to each other whenever it is possible via inner laws using parametric design approach, or kept as a free input which is at the control of the user, and regarded as design choices. CATIA V5 software (Ref. 8) was used for this calculations. CAD model includes various geometrical parameters and design decisions such as seating layout, fuel tank configuration, ramp, landing gear position etc. In this paper, a utility helicopter with a ramp will be presented for simplicity reasons. The existence of ramp will affect landing gear position, forcing the landing gear to be a wheeled one, and having 1 wheel under the nose and 2 wheels at the rear of the helicopter with retracting ability. Fuel tank configurations are also affected by ramp selection as some other variables do. Those decisions, and variable will be explained in corresponding subsections.

Cabin Type, Seating Layout and Passenger Type

Investigating utility helicopters competing in the market, their cabin types regarding cabin width was categorized into two categories; namely a wide and short cabin, and a narrow and long cabin. For simplicity, those configurations will be called as wide cabin and narrow cabin. Wide cabin type is seen at helicopters which allow passengers to seat in a long row of 4 or 5. Allowing the passengers to seat in this manner, the number of rows needed reduces, making the cabin a shorter one compared to other layouts. A typical wide cabin uses a sliding door which reflects its door area onto middle rows altogether. An example for a 19-passenger model can be seen in Figure 2.

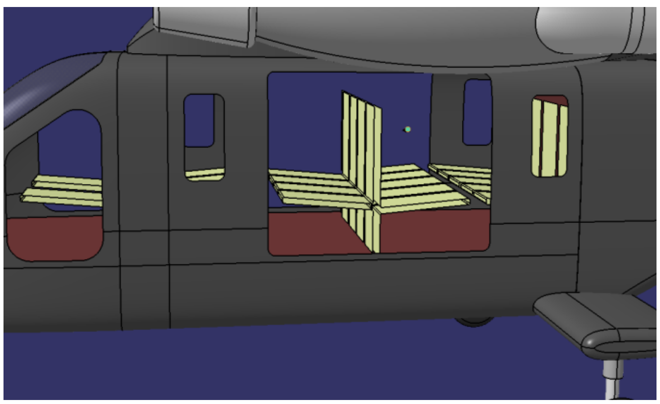

Figure 2. Sliding door representation for a wide cabin

The door projects onto mid-rows of seats which consists of 5 seats side by side. Row numbers increase when the maximum number of 5 seats are exceeded, adding another row at the rear. This operation will not increase the length of the door, instead, a T4 emergency exit regulated window is added. Odd number of passengers will change the position of odd-numbered seat-row, keeping its CG at the x-z plane. This configuration allows minimum of 4 passengers, and maximum of 24 passengers. Number of passengers more than 24, will be more likely that of narrow cabin layout as it will keep adding additional rows. After the 5th row of seats, the need for aisle allocation will come to light, which will make it more similar to what narrow cabin does. An example of 24 seats in a wide cabin configuration demonstrating the extra row of seats with T4 emergency exits can be seen in Figure 3.

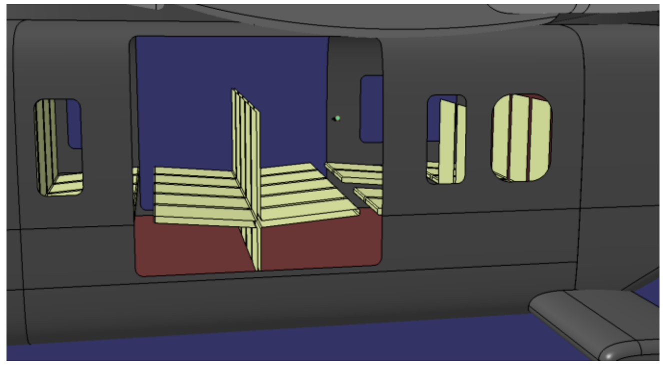

Figure 3. An extra row of seats with a T4 emergency exit window

Narrow cabin layout was decided to have 2+1 seating layout according to commonly used utility helicopters in the market. 2+1 means 2 seats side by side at one side of the aisle, and 1 seat on the other side of the aisle. Aisle width, and corresponding emergency exit regulated door sizes were decided according to laws written inside the model, based on EASA CS-29 Large Rotorcraft Regulations (Ref. 9). Exceptional cases include number of passengers which cannot be divided to 3, that is, there should be seats violating this rule. Those seats are located to the other side of the door, and the vacant volume is filled with avionics, indicating a closet-type avionics section. An example of 20 seats can be seen in Figure 4. This extra avionics section is represented as a simple prismatic shape with purple color.

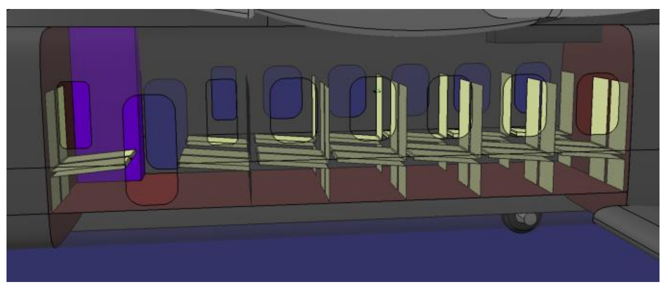

Figure 4. Narrow-cabin seating layout with 20 seats having an extra avionics compartment

In order to compare how the decision of using a wide cabin configuration or narrow cabin configuration can be demonstrated as in Figure 5.

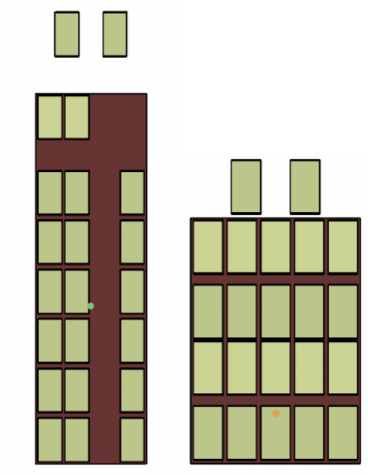

Figure 5. Comparison of narrow and wide cabin configurations for 20 seats

Passenger type is another major input for the CAD model. Two passenger types were defined as civilian and troop passenger types. This was declared into the model as a free-input. Passenger type affects the total mass allocated to the seat. This total mass includes both the human weight and seat mass. Not only the human weight changes, but also seat mass is different according to passenger type as well as seat dimensions. Civilian seats are usually said to be allowing a larger seat pan compared to troop seats where comfort is not the primary consideration in ergonomics.

Volume Allocation for Fuel Tank, Avionics, and Cargo

There are 5 fuel tank configurations decided and embedded inside the model. These include 2 combinational allocations, and 3 sole use of location. The main locations are decided as follows: below the cabin, behind the cabin, and sponsons next to the cabin. These three main locations can be seen in Figure 6. Fuel tank allocation was modeled as prismatic volumes, and colored as blue.

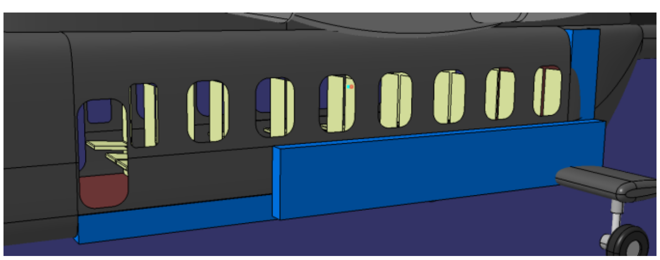

Figure 6. Main fuel tank locations

In addition to these 3 main locations, and their sole use as a fuel tank configuration, 2 combinational configurations were mentioned. These are the combination of below the cabin and sponson, and the combination of below the cabin and behind the cabin. While allocating the required fuel volume in those combinational configurations, there should be some laws about how these combinations are decided. In both combinational configurations, the thickness obtained below the cabin was limited. After this upper limit of thickness is reached, remaining fuel was placed into other locations (i.e. behind or sponson). There are two factors that also affect the fuel tank below the cabin; one of them is the minimum thickness of this section whether or not there is fuel. This is about crashworthiness requirements, and is considered fully structural. This minimum thickness without fuel volume is considered in the fuel volume calculations. Another factor is structural deduction that will occur in those representative prismatic volumes. This is valid for all prismatic allocations, which are fuel tank, avionics, and cargo sections. There are empirical deduction coefficients based on manufacturing and assembly experience of Turkish Aerospace. Considering these two factors, required volume at each prismatic section is calculated in an overestimating manner.

Avionics sections are mainly based on fuel tank allocations. There is no explicit input selection for the avionics allocation configuration, it basically follows the main allocations of fuel tank. For instance, if behind the cabin option is available for fuel tank, an avionics section is added into this region, too. Main locations for avionics are represented in Figure 7.

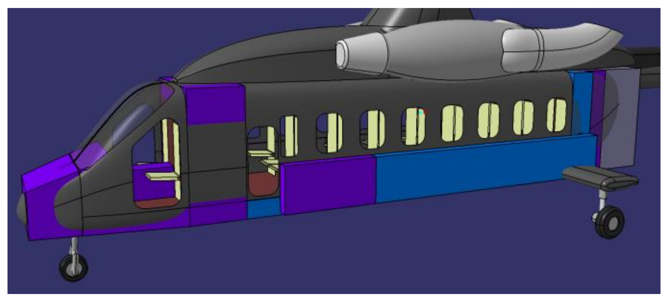

Figure 7. Fuel tank, avionics, and cargo allocation as in prismatic volumes

In Figure 7, blue colors represents fuel tank locations, purple color represents avionics sections, and light-grey colored prismatic volume behind the cabin represents cargo section. Always-used avionics sections are the ones around and inside the cockpit. Avionics section between the cockpit and cabin, and the section behind the cabin works inversely. If there is no fuel tank allocation behind the cabin, there will be no avionics section at that position, neither. There is possibility that there may be still the need for avionics volume. In this situation, a volume is created between the cabin and the cockpit, and the required volume is allocated there. Considering these two locations, another important factor is that there may be a need for a door which will allow the access to the cockpit or to the cargo section. This is satisfied with a gap having the same width as the aisle in narrow cabin, and a vacancy in the volume having the width of a seat in wide cabin configurations. Those factors will overestimate the required volume. In addition to the aforementioned structural deduction, this factor is also added to the calculations.

One of the major effects that should be considered while calculating the required volume given in each region is in their prismatic natures. This is an inherent problem while deciding to use prismatic calculations for the ease of calculations, and hence being quick regarding computational time. Exterior surfaces that form the body of the helicopter is not planar; therefore, there are discrepancies while representing the volume using planar prismatic basic shapes. This phenomenon is clearly visible at the nose section of the helicopter, which can be seen in Figure 8.

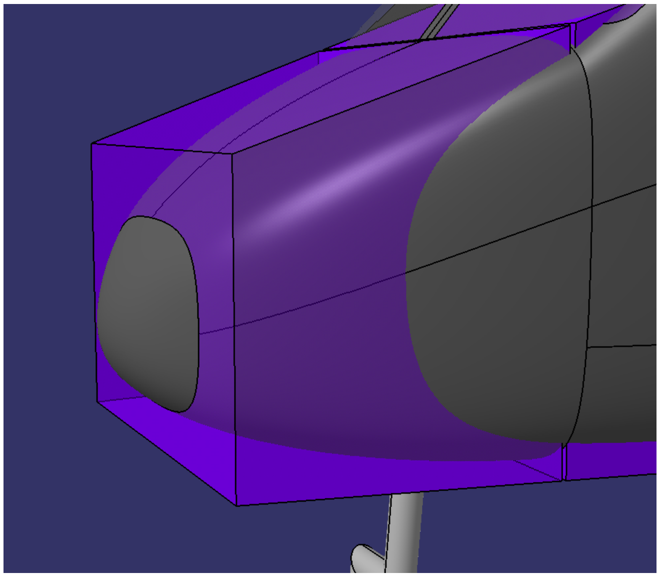

Figure 8. Intersections of a planar prismatic volume and a non-planar surface

The required volume was overestimated beforehand regarding structural deductions. Another major deduction will occur due to this phenomenon. There is another deduction coefficient in the parameter set that is included in calculations, which estimates at which ratio the prismatic volume decreases with respect to the *realistic* volume enclosed by non-planar surfaces. This *realistic* volume is calculated by using numerical approaches such as rectangular integration. The volume enclosed by a non-planar surface is usually defined between two planes indicating the starting position and ending position. The cross-section defined by the intersection of the plane and the surface is created at both planes. Dummy planar surfaces were created using the cross-sectional borders defined at these planes. Surface areas of those planar cross-sectional surfaces were measured. Using this area value and the distance between the starting and ending planes, as in a rectangular integration, a *realistic* volume is calculated. The discrepancy between the realistic volume and prismatic volume is obviated by iterating the value of this volumetric deduction coefficient. This iteration is done by macros written within CATIA software. As it can be expected, converged values usually lie within 0.6 and 1; 1 indicates the realistic volume and prismatic volume are identical.

One major consideration regarding this volume convergence calculation is the configuration changes. In order not to cause singularities including division by zero, no volume or dimension is directly set to zero; instead, quasi-infinitesimal values are used. Therefore, if there exists a prismatic value for any reason, its realistic value is also computable, and it is computed. Nevertheless, the volume convergence computation is not conducted by questioning its necessity inside the calculation macros.

Fuel volume values are obtained via aforementioned performance estimations as response surface polynomials. Cargo volume is estimated with a *cargo density* which was calculated according to commonly used proportions between the cargo mass and cargo volume, in the helicopters exist in the market. For the avionics volume calculation; firstly, the necessary avionics parts, and their *uninstalled* volumes are summed up. Then, an estimation of *installed* volumes regarding structural and thermal necessities was calculated according to previous manufacturing experience of Turkish Aerospace.

Landing Gear

Landing gear design is itself an iterative process. It needs CG location to be known, and it changes CG location by its position and configuration. Landing gear may also be a major component for total FPDA estimation if it stays in a fixed manner where wheels are open. Therefore, it affects required fuel mass, and this also changes CG location according to fuel configuration. Therefore, it is essential to include a landing gear model inside the CAD model to get a more accurate design estimation compared to a performance based calculation.

CAD model includes two configurations. Naming the two wheels with a shock-absorber suspension system as main wheels, one configuration posits main wheels at the rear side of the cabin, and places the *one wheel* at the front side of the cabin. This configuration is called as 1+2 configuration. Another configuration is called 2+1 configuration where main wheels are located at the front side of the cabin whereas one wheel is located at the rear side. There is another option regarding the position of this *one wheel* inside 2+1 configuration. It can be placed at the place where optimum angle needed for landing stability, or it can be placed at the tail where the most stability is obtained to ensure a safe margin for the pilot when dangerous landing scenarios are needed. One drawback of this positioning option is the fact that FPDA generated by this one wheel is usually greater than that of optimum position; because, more part of the strut is open to airflow in this option. Figure 9 shows an example visual of 2+1 fixed landing gear configuration with a tail at the tail.

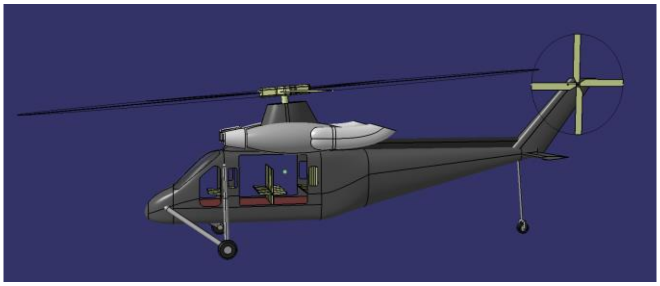

Figure 9. 2+1 landing gear configuration having a wheel at the tail

Wheel positioning is decided according to AMCP 706-202 (Ref. 10) for both configurations. Angles needed for stability were decided as the minimum of what is suggested. Main driver angles were kept as parameters giving capability to alter them by the user. Another major design driver is whether the wheels will be retractable or not. 2+1 configuration is kept as fixed or non-retractable; since its usage scenario is mostly consists of rapid landing scenarios, as it was discussed in one-wheel-positioning case. 1+2 configuration is embedded into the model as retractable. Retracted wheels are placed into smaller sponsons compared to fuel tank sponsons. Those sponsons also affect FPDA and gross weight calculations. Displacements needed for shock absorbers need maximum permitted acceleration for the helicopter structure and hard landing velocity specified in the agreement phase of a project. These parameters are also kept as free inputs, allowing the user to negotiate the effects of them.

Rotors, Transmission and Engine

Main rotor was modeled using its diameter, number of blades, and chord values. Blade mass and hub mass given in Prouty (Ref. 4) uses tip speed as an input, too. Therefore, it is included in the model in order to estimate these mass values. Equations provided in Prouty (Ref. 4) is multiplied with a correction factor. The value of this correction factor is calculated by inserting the inputs for a helicopter previously manufactured by Turkish Aerospace for a similar purpose, and the deviation is obviated by this correction factor. This approach is used at almost every mass and FPDA estimation. FPDA value of main rotor is estimated by creating a correlation between its diameter and FPDA values. There is also an angle parameter which alters the main rotor tilt plane.

Tail rotor modeling has similar input and outputs compared to that of main rotor. Cant angle is another option while modeling tail rotor considering stability. It is controlled with an angle parameter embedded in the CAD model.

Transmission design is a complex process which again uses its inputs as outputs in an iterative approach. Basic cylinders were used to model main components of a transmission similar to prismatic approach introduced for the fuel tank, avionics and cargo volume allocation. Transmission design also drives cowling designs which was modeled in two levels, namely bottom cowling and top cowling. Bottom cowling intends to cover main and base parts of the transmission, whereas top cowling covers the top parts of the transmission and rotor control parts such as swashplate. Sizing of the cowlings are mainly determined by the cylindrical dimensions of transmission parts. Transmission modeling also includes the shaft angle of the tail rotor driver shaft with respect to the ground. This is also kept as free input in an angle parameter.

Engine sizing is modeled in a very similar manner to that of transmission sizing. Basic cylindrical surfaces were embedded to estimate the sizes of a turboshaft engine. The distance between the engines if there are two engines, their location with respect to transmission are independent variables. Engine power can be estimated via response surfaces, and its corresponding mass can be embedded using rubber engine models which creates a closed loop for engine sizing. Engine cover and propulsion subsystems were included in FPDA and mass calculations as giving by Prouty (Ref. 4) and they are corrected by factors as explained in main rotor mass calculations.

Cabin Height and Pilot View Angle

Pilot view in vertical manner is a major design-driver in two ways. Upward angle is in relation with cabin height and glass position. In most cases, cabin height overdrives pilot view angle in upward-vertical manner. Therefore, it is more effective to control downward pilot view angle. This angle is in relation with frontal avionics prism, and hence the nose of the helicopter. As the angle increases, the allowed space for the nose gets shrunk.

Figure 10 shows pilot view angle reference lines. The line below was mentioned as downward view angle, and the upper line was mentioned as the upward view angle. The circle represents the outer boundaries of the pilot's helmet. This was used as a reference deciding the curves of the cockpit glass. The point located well below the helmet is the reference H-point of the pilot. Seat and avionics inside the cockpit were hidden for the ease of inspection.

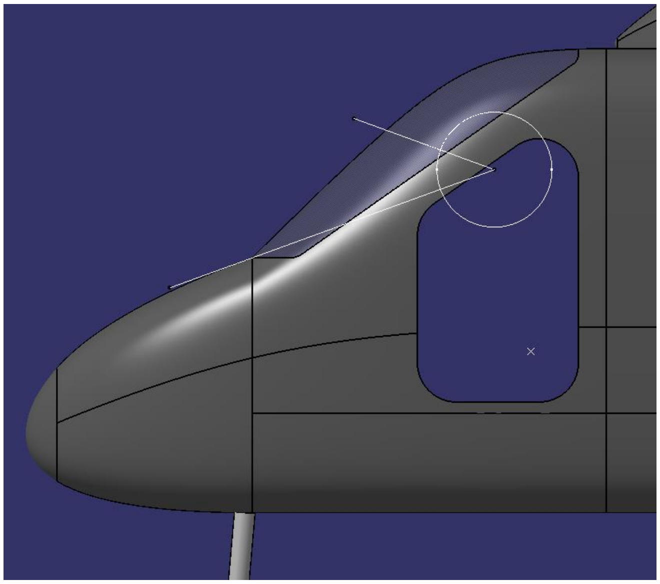

Figure 10. Pilot view angle lines with other ergonomics references

Cabin height is calculated at discrete locations. These values are selected from different helicopters serving for different purposes in the market. After obtaining improved estimation values from CAD modeling stage, cabin height is included in response surface calculations; in order to make it a continuous input for the user.

Horizontal and Vertical Stabilizers

Horizontal and vertical stabilizers are essential parts for the stability of the helicopter. Their sizing process mainly stems from trim moment analyses. Horizontal tail's chord is calculated from a simplified moment analysis on pitch moment equation. Span is set to value which maintains a fixed aspect ratio. Both horizontal tail's and vertical tail's mass values are estimated by improved versions of Prouty's (Ref. 4) equation as explained before.

Cabin to Tail Transitions and Ramp

Cabin to tail transition geometry is a significant factor to define the form of the fuselage. Two options were set in the CAD model, one being a tangent transition from cabin to tail, and the other being a non-tangent abrupt transition. Two possibilities have pros and cons regarding cabin usage scenario and hence ramp selection. Non-tangent abrupt transition examples can be observed in Figure 6 and Figure 9. An example of tangent transition can be observed in Figure 12. This transition affects FPDA value of fuselage which was estimated using statistical comparison methods between helicopters with similar usage and different transitions.

Figure 12. Tangent cabin to tail boom transition

Ramp selection is a discrete parameter which affects landing gear configuration and fuel tank configuration. Considering the usage scenario of a ramp, it can be said that rear side of the cabin will be used as loading/unloading interface. Therefore, there should be no avionics of fuel tank compartment that is blocking this passage. Hence, if ramp is selected, fuel tank selections regarding behind the cabin becomes unavailable. In such a case, if there is no sufficient space to allocate avionics by using nose section of the helicopter, cockpit, below the cabin or sponsons, depending on the selected configuration, a new avionics space becomes available which is located between the cockpit and the cabin.

Landing gear configuration is affected by ramp selection, regarding loading/unloading scenarios. If a 2+1 landing gear

Figure 11. Left: narrow cabin with 24 passengers and middle cabin height, fuel tank located below. Middle: narrow cabin with 18 passengers and low cabin height, fuel tank located below and at sponsons. Right: wide cabin with 20 passengers and high cabin height, fuel tank located below.

configuration is selected, the single wheel is forcedly located into its optimum location which is usually rear side of the cabin. The option which locates this wheel at the tail becomes unavailable in the presence of a ramp due to the fact that it would become an obstacle for loading/unloading scenarios. In order to shrink the boundaries of the design space and to reduce computation time, the database used in configuration assessment section, a helicopter with a ramp and with 1+2 landing gear configuration is used. Number of passengers were limited between 18 and 24. Ramp selection also reduces fuel tank configurations into three; namely, using only below of the cabin, only sponson, and the combination of these two. Database used in assessment section excludes the option of using only sponsons, either; thus, 2 fuel tank configuration options are presented in the sample assessment interface.

FPDA Estimations

FPDA estimations are mainly based on Leishman (Ref. 11) and Prouty's (Ref. 4) statistical curve-fitting suggestions. Those equations need some measurements from the geometry directly. Reference measurement surfaces and geometries are created which yields simultaneous measurement results for these calculations. An overall view of those reference geometries can be seen in Figure 12. For some components which do not have any suggested statistical regression equations in aforementioned literature, projected areas are used such as landing gear sponson's above-projected area as can be seen in Figure 12, too. Those projected areas are compared within similar geometries' computational or experimental results.

Figure 14. FPDA reference geometries

Total FPDA value calculation is an iterative one; because FPDA directly affects required fuel weight, and it alters the geometry which alters FPDA calculation. Therefore, as in gross weight and fuel weight calculations, an initial and final FPDA parameters are created inside the model. Convergence computations are conducted using macros embedded inside the CAD software. Those three main iteratively obtained parameters, gross weight, fuel weight and FPDA, are main outputs of this CAD phase. Using these three parameters, a more improved version of performance parameters can be calculated.

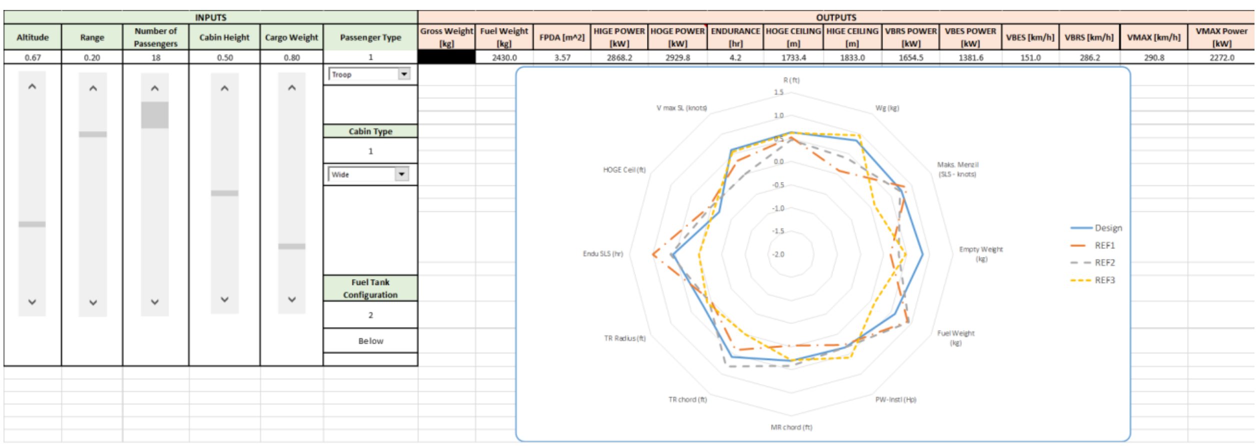

Figure 13. Configuration assessment interface

CONFIGURATION ASESSMENT

CAD model generates improved estimation values for gross weight, fuel weight, and FPDA values as well as conceptual visuals as can be seen in Figure 11 with some sample results. At the very beginning of performance calculations, some performance parameters like range, endurance, hover altitude, maximum forward flight speed were also included as response surface equations, and they were converted into inputs for the CAD model. After obtaining CAD model's outputs with better estimations regarding performance parameters, an improved version of response surfaces is created according to results of CAD model. After this stage, user inputs like number of passengers, fuel tank configuration, and landing gear position can be linked to fuel weight, FPDA etc. Consequently, a simultaneous assessment tool can be created which allows the user to give their user inputs, and see the changes in performance outputs according to these inputs.

A sample was created to set an example as can be seen in Figure 13. User inputs are defined as altitude, range, number of passengers, cabin height, and cargo weight as continuous variables which were nondimensionalized according to their minimum and maximum values defined; passenger type, cabin type, and fuel tank configuration as discrete variables. Giving these inputs to the overall design tool, significant performance outputs are calculated; namely, gross weight, fuel weight, FPDA, power required for hover-in-ground-effect, power required for hover-out-of-ground-effect, endurance, hover-in-ground-effect ceiling, hover-out-of-ground-effect ceiling, power required to fly at best range speed, power required to fly at best endurance speed, speed values at those scenarios, maximum forward flight speed, and power required to fly at maximum forward flight. It should be noted that, some of those performance outputs can be treated as inputs, as it was explained before.

CONCLUDING REMARKS

User/customer inputs and parameters needed for an initial conceptual design process may differ in terms of their quantitative or qualitative characteristics. Therefore, a comprehensive conceptual design method is needed to convert those inputs into computable parameters. Moreover, the performance calculations should be presented in a manner that they compensate the user/customer's demands.

Calculations in conceptual design phase needs quantitative weight and FPDA data in order to estimate performance parameters like range and altitude. The design method introduced in this paper converts the performance outputs into inputs in a manner that they are alterable by the user/customer. This method allows rapid assessment and comparison with respect to other available options before detailed design phases or even before agreement phase as it acts as an improved feasibility tool to evaluate different alternatives.

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REFERENCES

1. Ulrich, K. T., Eppinger, S., and Yang, M. C., *Product Design and Development*, McGraw-Hill/Irwin, New York, NY, 2012, Chapter 1.

2. Lier, M., Krenik, A., Kunze, P., Kohlgrüber, D., Lützenburger, M., and Schwinn, D., "A Toolbox for Rotorcraft Preliminary Design," AHS 71st Annual Forum, Virginia Beach, VA, May 5-7, 2015.

3. Trapp, J. C., and Sobieczky, H., "Interactive Parametric Geometry Design," Paper AIAA 99-0829, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 11–14, 1999.

4. Prouty, R. W., *Helicopter Performance, Stability, and Control*, Krieger Publishing Company Inc., Malabar, FL, 1986, Chapter 10.

5. İbaçoğlu, H., "Helicopter Preliminary Design Otomation," Master's thesis, Istanbul Technical University, Institute of Science and Technology, Turkey, 2007.

6. İbaçoğlu, H., and Gündüz, M. E., "Software Tool for Helicopter Sizing Using Response Surface Methodology," 7th Asian/Australian Rotorcraft Forum, Jeju Island, Korea, October 30-November 1, 2018.

7. Pahl, G., and Beitz, K., *Engineering Design: A Systematic Approach*, edited by K. Wallace, translated from German by K. Wallace, L. Blessing, and F. Bauert, Springer-Verlag Ltd., London, 1996.

8. Dassault Systemés, CATIA V5 R2012 (R22), Vélizy-Villacoublay, 2012.

9. European Aviation Safety Agency, "Large Rotorcraft," CS-29, 2003.

10. Army Materiel Command, "Engineering Design Handbook: Helicopter Engineering, Part Two, Detail Design," AMCP 706-202, 1976.

11. Leishman, J. G., *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, NY, 2000, Chapter 6.