Conceptual Level Sizing, Evaluation and Design Space Exploration Tool

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Keywords: multi-fidelity military vehicle design, rotorcraft conceptual design, parametric design, response surface, design space exploration, design-decision support system.

ABSTRACT

Rotorcrafts are complex machines that requires numerous subsystems to work in harmony. Conceptual design of such systems utilizes multiple disciplines in various fidelity design levels. Conceptual design stage is the place where decision makers may alter major design drivers. Therefore, an evaluation and design space exploration tool is introduced in order to make intertwined relations among different user requirements, certification standards and engineering limitations. The tool uses statistical and historical trends that can be related into each other as its initial point. Eliminations of possible design ideas and the analysis areas are defined by design of experiments methods, and preliminary calculations are generalized utilizing response surface methodology. A three-dimensional geometric model is created in order to increase the fidelity and the resolution of the estimations and analyses in several considerations such as weight, dimensions, and flat plate drag area of the vehicle to be designed. This surrogate model approach is once again generalized with response surface to create a design space, which can be analyzed by both designers and decision makers to assess and evaluate possible design scenarios of a rotorcraft.

1.0 INTRODUCTION

Vehicle design is a highly dynamic process depending on its purpose and operating conditions. Military conditions make the vehicle sophisticated concerning rigorous environmental conditions and survivability requirements. Albeit vehicle design follows homogeneous design philosophies concerning mechanical trade-off of performance and customer requirements, this paper will focus on a design and exploration tool of military-purpose helicopters. Design and development procedure of a helicopter is an intertwined multidisciplinary process. This process includes market analyses, requirement engineering, conceptual preliminary sizing and component selection, high resolution aerodynamic analyses, mechanical design, manufacturing operations, assembly line organizations, tests, certification and qualification in an intersectional fashion. Consequently, the question how to handle this complexity in terms of technical approaches like engineering, and operational-financial approach in which there are scientific and academic dimensions has become one of the crucial areas in operational research and design research. To that end, there are sundry methods and tools developed in academia and industry. A paramount contribution to that area and specified quandaries would be develop a perspective in a multidisciplinary window that utilizes system engineering approaches, synchronous engineering concept, product life-cycle management techniques including both low-fidelity and high-fidelity analysis tools, as well statistical techniques. Product development processes in helicopter industry are studied in several works such as Integrated Product and Process Development (IPPD) which was developed by Schrage (1999) and modified by Chae et al. (2009). Apart from the whole product life-cycle approaches in literature, focus of the paper is conceptual design step and its interface with preliminary design.

Conceptual design step, inherently consists of less resolution certainty in engineering practices; hence, the uncertainty increases as the strength of the proximity between conceptual design and other steps lessens. For instance, the territories between conceptual assessment and evaluation in *helicopter level* with exploration and analyses, and the conceptual design per se may become blurry. Therefore, this distinction including the conceptualization of *helicopter level conceptual evaluation* and analysis will be explained in detail.

Paper first starts with explaining the background calculation of the exploration process. Since, this process is an iterative one, it was defined as the design and exploration tool. This section pictures the loop from a design method perspective. Multi fidelity approaches as different resolution of calculation or estimation processes are embedded and explained with the term *level*, and its specialties in helicopter design work. This term will be used throughout the paper. Third section explains the main structure of the method used for the creation of the tool with 6 inner steps that are followed chronologically in an iteration. Concluded remarks are listed in the final section.

2.0 DESIGN AND EXPLORATION LOOP

Building methods for design practices has a history within design research and its historical counterpart, operational research which became the preeminent paradigm in engineering throughout industrialization. Design methods movement in 1960s tried to structuralize and rationalize the design practice in general. Although the validity of design methods in terms of structuralizing any creative practice had been criticized by the founders of design movement, themselves in 1970s; engineering design which is said to be more willing to conserve its paradigms had transformed some of these methods, and tried to implement them in industry. Ulrich et al. (2012) has labelled three steps in a generalized way, namely conceptual design, preliminary design, and detailed design.

Conceptual design step aims to present fast-paced design solutions which analyses fundamental design inputs consisting of high-level requirements reduced into design practice level, engineering requirements, optimization goals etc., in a relatively low resolution or fidelity in terms of technicality. Potential solutions are compared in terms of applicability and feasibility utilizing multidimensional and multidisciplinary optimization, before progressing into following stages. One method to define and create the potential solutions is surrogate modelling which models the design space with particular samples and create a surrogate representation for the design space limited by certain requirement sets.

In preliminary design stage, several major design decisions are already taken in conceptual design stage. Therefore, further analyses are conducted in higher resolution compared to that of the former. Specialized tools are utilized by field experts in particular disciplines such as structural engineering, aerodynamics, electric, etc. When preliminary design is completed, it is expected to have the interfaces among different disciplines like manufacturing and design to be concluded in a significant proportion. It should be noted that some issues that had been seen as obsolete or could not be seen in conceptual design stage, are reconsidered during preliminary design stage after detailed studies by experts. This requires going back to conceptual stage once again, and bring updates to preliminary design. Each such loop costs both time and financial burden on the organization. Therefore, it would be beneficial if the conceptual design stage is completed flawless considering the outputs of this stage. Even though, this iterative process is considered natural in a gated waterfall method, it is not wanted to have these kinds of loops, as much as possible; or the loops should be conducted at the earliest stage as possible.

In conceptual design process, several tools are used in order to structuralize the inner loops. Sample solutions are created following a surrogate modelling approach. Those samples are evaluated and presented for further assessment. Conceptual evaluation and analyses are formed and shaped to this end. It will be discussed within and compared to conceptual design processes.

2.1 Level of a Design Work

Helicopters consist of numerous subsystems that can be broken down into more subsystems. At this point, in order to clarify the resolution of a design work, and what level of a resolution or fidelity is needed to design a system; requires the definition of the *levels*. The resolution of the calculations or estimations also refer to the fidelity level of the design. The intertwined nature of a multi-disciplinary design work has multi-level interrelations. The level of a design work is an important concept to prevent some subsystems' design invisible in the face of other subsystems that can dominate the whole process and create the illusion that helicopter design is a single design loop. Considering a design work regardless of its level causes poor practice resulting in technical and administrational communication issues as well as poor data flows and interfaces between and among disciplines and departments. In order to solve those issues, low level design works which include less disciplinary work inside, should be investigated in a work-specific manner; and should be placed inside the development process efficiently. Nevertheless, it is not convenient to posit the *helicopter level* works which considers the helicopter as a single system at hand, like other levels inside a process due to its special issues. The specialties are explained, and a method is suggested afterwards.

2.1.1 Specialties in Helicopter Level Design Work

Helicopter level design work which was posited at a higher level compared to subsystems design work, is also placed chronologically beforehand than the rest of design work. It may be required to have *helicopter level analyses* and evaluation, even though there is no agreement or contracted program. In some instances, this type of analysis work can go back to market analyses, business targeting and visioning stages. Therefore, it would be a natural and inevitable outcome to have significant amount of uncertainties. High level design requirements, user needs, design goals, company's vision according to market dynamics and optimization goals may be negotiable and disputable. In those conditions, it would not be a wise decision to design the helicopter with definitive, determinant and distinctive inputs with specialized optimization; since it would be delimitative in terms of designer's freedom and market's variability. The organizational procedure among stakeholders, and agreement negotiations would also be restricted with this type of design approach.

The parameters and design decisions during helicopter level conceptual design work should be re-considerable and dynamically negotiable. That kind of variability can be extended and transformed into a helicopter level design space. This design space should be analyzed, monitored and explored, swiftly. Parameters such as maximum forward flight speed, altitude, range, useful load, required power, weight, hover ceiling, environmental conditions, etc. can be considered as both inputs and outputs, case-specifically. Relations among those parameters should be monitored synchronously and live, and hence the information pool required for decision-making should be created, as this is the fundamental aim of helicopter level design work.

Helicopter level design work is defined regarding the dynamics of conceptual design stage. This level of work is again an iterative work utilizing different combinations of design parameters with different optimization goals. There exist different design cycles concerning several aircraft concepts in systematic interaction with each other. Therefore, this paper considers helicopter level conceptual evaluation and analysis in a higher level than a case-specific conceptual design work with distinctive optimization goals.

3.0 HELICOPTER LEVEL CONCEPTUAL EVALUATION AND ANALYSIS METHOD

Helicopter level conceptual evaluation and analysis is usually placed beforehand any product development procedure. The fundamental aim is to present the relations among high level helicopter parameters, dynamically and swiftly in decision-making processes. As the ambiguity of inputs and outputs was discussed, the dynamic input-output system and multi-dimensional optimization will be explained in detail. Then, the method and process suggested will be introduced.

The general flow of the method is shown in Figure 1. Although it is represented as sequential between each stage, there are possible iterations and feedback loops. External inputs were represented with snip single corner rectangle whereas calculation steps were shown with rectangles. Response surface calculations were represented with rounded rectangles to emphasize the changing fidelity level.

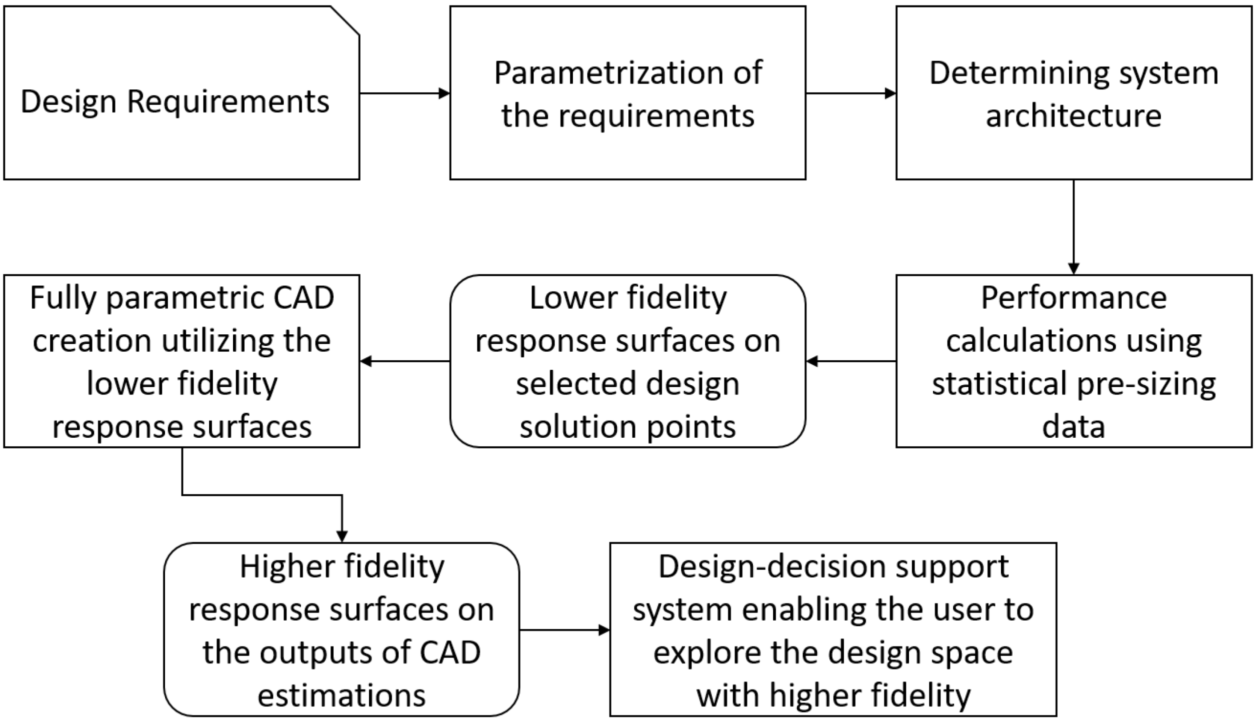

Figure 1: Design and exploration process.

3.1 Classification of Helicopter Parameters and Preliminary Evaluations

Helicopters are complex systems. Higher level helicopter parameters like performance parameters are in complex relation with each other. The articulated nature of those relations may result in some abstract but important mathematical or physical variables to be considered during initial design stages. Moreover, those parameters, relations, and their importance may also vary according to helicopter type.

It is important to classify and decide the importance of those parameters with their relations defined between and among them. This requires utilizing the cloud consisting of the dependent and independent combinations of those parameters. This will set a starting point for the following design stages such as preliminary design. The dynamic conceptualization of inputs and outputs as the foundation of this cloud or space are classified in following subsections.

3.1.1 Inputs of the Design Exploration Process

Inputs play a major role while projecting the near future of any design work, or the current process of an on-going design. These shape the aim and the usage of the helicopter. There are three sources where the inputs are formed. These are user requirements; standards, regulations, and engineering requirements; contractor company's structure, aims and abilities.

User requirements are tried to be converted or transformed into engineering terms with acceptable technicality. Those type of requirements can be listed as performance requirements; equipment and load requirements; survivability and safety requirements; geometry and system architecture requirements. *Performance requirements* consist of maximum speed, range, endurance, hover ceiling, maneuverability, etc. In addition to these, there can be specific missions to be operated within certain altitude and temperature conditions with certain loads. *Equipment and load requirements* are defined with some useful loads and payloads. It is sometimes desired to have certain type of equipment and systems from potential users. *Survivability and safety requirements* are especially critical for military purpose vehicles. Armors, weapon systems, warfare systems, crashworthiness, and hard landing conditions are typical user requirements under this topic. Safety is important for both military purpose and civil purpose vehicles. Landing, take-off requisites can be listed for safety requirements, additionally. *Geometry and system architecture requirements* can vary regarding the missions required. The shape of the fuselage, types of subsystems, geometrical allocations of pilot equipment can be listed as design-driven requirements.

Standards and regulations are referring to aviation authorities' certifications requirements and international standards mostly concerning safety. The authorities on regulations include European Union Aviation Safety Agency, Federal Aviation Administration; whereas, standards are determined by institutions like International Organization for Standardization. Engineering requirements are connected with physical limitations such as altitude limitation for hover with respect to available power, structural limitations of a rotorcraft concerning the maneuverability, etc. Requirements concerning contractor company include project schedules, total budget issues, technical and technological limitations on manufacturing ability, and the company's strategies for competition in the market.

3.1.2 Outputs of the Initial Calculations

Besides the fact that inputs play a definitive role for helicopters, their complexity includes the inputs as definitive parameters, additionally. In order to assess and evaluate a helicopter meaningfully, outputs should be calculated or estimated from inputs by using several analysis and computation methods. In general manner, systems such as rotors, transmission, and body with different weights such as empty weight, gross weight and individual weight of systems; power and engine requirements with so many performance defining parameters can be classified as outputs.

Relations between inputs and outputs are constructed using analytical or empirical calculations, as well as statistical and numerical estimations and modelling. In addition to these methods, some assumptions are also integrated with certain experience-wise supported decisions. There is no definite consensus on the method which will be utilized throughout those procedure regarding the tool's resolution and design level. The dynamic conceptual evaluation method introduced in this paper aims speed at one of its major contributions to literature; therefore, low resolution analyses and calculations are preferred. It should be noted that as the level decreases to a more detailed design approach, the resolution should be increased and the uncertainty level should be decreased.

3.1.3 Dynamic Parameter Cloud

Business development in helicopter design work concerning new designs or development projects considers helicopter parameters (both inputs and outputs) as dynamic variables. At business development stage, it is beneficial to show different requirements in relation to each other to a customer regarding business projections and market analyses. Therefore, the definitions whether a parameter is an input or output per se, is a dynamic definition; and the classification of a parameter can change case-specifically and in a fluid manner.

As an initial step of the method introduced in this paper, the following activities should be conducted. Those stages can be operated through different software packages or computer-supported tools. Firstly, the parameter pool of helicopter parameters should be decided. This pool consists of dynamic parameters which can be treated as both inputs and outputs. For instance, number of passengers should be an important parameter for a civil transport helicopter; however, it would not have the same importance for an attack helicopter. It is not in this stage to prioritize some parameters over the other, but the selection of the pool or cloud regardless of their classification as inputs, outputs, or limitation. Secondly, a system model will be constructed such a way that those parameters can be tagged as requirement, limitation, input, or output. It is also possible to make decisions regarding the conceptual design scenario of the vehicle in helicopter level, in order to speed the process up. (Scenarios are basically design possibilities consisting of particular input-output combinations and design goals.) Lastly, a general guideline for the analyses, calculations, simulations, and decision-making processes. After completing particular calculations and analyses for selected scenarios, a design space will be obtained. Then, the exploration, evaluation and decision-making concerning design become available.

3.2 Determining System Architecture or Conceptual Selection

Having constructed the parameter cloud and the system model with selected scenarios, some high-level decisions are investigated. Those decisions are usually definitive for the calculations, analyses, and mathematical-physical modelling in following stages. Therefore, they should be treated accordingly and separately. The major design drivers are determined as the type of the rotorcraft, rotor type, engine type and number of engines, and landing gear configuration.

Different missions with different conditions may require and align well with different rotorcraft configurations such as conventional single main rotor, co-axial rotor, tilt-rotor, tandem rotor, etc. Selection of the main configuration has connection to almost every design choice. It also affects the physical-mathematical modelling tools and approaches. If there are tools available for every configuration, the choice of configuration per se becomes another parameter in the cloud explained before. This paper mainly focuses on single main rotor and single tail rotor configuration, as it usually known as the conventional configuration. Therefore, it is not treated as a parameter, instead a design decision. This type of decisions is conducted through quality function deployment, Pugh matrix etc. (Sinsay, 2018) and previous experiences.

Rotor types include fully-articulated rotors, hingeless-bearingless rotors for main rotors and fenestron, notar and conventional rotors for the tail. Similar to the case in rotorcraft configuration types, modelling and computational assumptions are heavily affected on the rotor type, as well as the design decisions including blade number and blade geometry. Depending on the readiness and availability of the computational models, rotor type can also be included in the parameter cloud.

Power required for a helicopter is calculated according to performance requirements and load requirements. It affects the engine type such as piston engines, electric engines, and turbine engines; and hence, the geometrical attributes of the powerplant. Engine type is again considered as a design choice.

Landing gear configuration both includes the selection of wheels or skid, as wheels option includes fixed landing gears and retractable landing gears. Placement of the wheels may differ as front or rear. These will be included in computer-aided design (CAD) based calculations. The design decisions or design driver parameters are not the only variables in analysis processes. As new technologies emerge, new options can be added.

3.3 Constructing the Design Space

Design decisions and the processes discussed before the construction of the design space aims to build the necessary medium for the steps that will be explained in this section. Those processes are in line with the surrogate modelling technique. Particular sample solutions corresponding to the pre-defined points in the parameter cloud are the surrogate models which is intended to represent the whole design space. After the decisions and experience-based eliminations, a parameter cloud is constructed. Next step is to build a *performance-based design space from this cloud*. There are mainly four steps. These are statistical pre-sizing, elimination test, design of experiments (DoE) and response surfaces.

3.3.1 Statistical Pre-Sizing

Conceptual models decided in previous steps are allocated with some weight and volume, by utilizing the historical trends observed in helicopter market. This is the very first sizing process that is considered as the initial point of an iterative process. These values are flexible and can vary as the design work progresses.

3.3.2 Elimination Test

It was stated numerous times that helicopters are complex machines in which many subsystems work in a harmony. Another natural outcome of this fact, is the computational complexity if every subsystem is included in calculations or analyses. This complexity can be maintained and control to some extent with the help of the approaches introduced in design decisions. However, it is possible to further control this intricacy by mathematical approaches, additionally. In order to speed some analysis-work up, some inputs can be listed as ineffective to alter some significant outputs such as maximum take-off weight, hover ceiling, and required power. Initial values obtained from statistical pre-sizing are tested by elimination tools such as sensitivity analysis. The parameters that are decided to be ineffective are fixed by using some statistical values obtained, calculated, or estimated by statistical pre-sizing step.

3.3.3 Design of Experiments

This step is the essential stage where major background calculations are conducted, and long lists of DoE tables are created. These tables quantify the numerical relations between inputs and outputs as mathematical and statistical variables. Background calculations requires the utilization of helicopter sizing tools in a software or similar form to automatize the process. The parameters that can be treated both as input and output can be listed as traditional parameters and engineering parameters. Traditional parameters include payload, range, maximum speed etc. Engineering parameters include rotor tip speed, rotor radius, chord, twist angle, airfoil, taper ratio, flat-plate drag area (FPDA), etc.

It should be noted that, before the main calculations, pre-assessment and analyses may be needed especially for the latter class of parameters. For instance, FPDA estimation can be modelled by firstly setting an initial value from a similar helicopter in the market or a historical trend. The historical trend such as the ones given in Prouty (1986) can be improved by comparing some results from computational fluid dynamics (CFD) calculations or wind tunnel test data available.

3.3.4 Response Surfaces

Response surface methodology is a statistical approach to find a representative equation that models a particular set of variables. Helicopter performance parameters in relation with geometrical constraints and design parameters pose as a very complex design space. This complexity is hardly possible to define or represent in perfectly analytical equations. Although, there may be numerous reasons that can be mentioned as the reason of this issue, FPDA estimation which requires a detailed drag calculation based on non-linear partial differential equations (e.g. Navier-Stokes equations) makes it too involute to represent the intra-parameter relations in an analytical way. Surrogate modelling technique is a technique that aims to represent this highly dynamic design environment within feasible limits by using surrogate models. Response surface method is used as a surrogate modelling technique, and the particular design points are decided with the help of design of experiment tables. Nevertheless, design of experiment tables can easily get large enough to make the analyses nearly impossible in a convenient manner. These data should be re-usable and comprehensible. This can be done by response surfaces as they create meaningful mathematical relations between and among them. Response surfaces inherently are not analytical direct results, instead estimations with acceptable errors. Utilization of response surface are explained in detail, in İbaçoğlu and Gündüz (2018).

3.4 Parametric Geometry Modelling

Air vehicle modelling based on performance calculations and historical trends in statistical and mathematical manner may give sufficient results in lower fidelity, regardless of the geometric changes. However, this may include significant amount of error when some effects of design decisions are included such pilot's view angles and their effect on FPDA. Therefore, a parametric and dynamic CAD model is included in the study, which makes it possible to include some parameters that were not included in the analyses, or to increase the fidelity of the calculations of the parameters to a comparably higher level.

Physical attributes investigated in elimination procedure are listed, and a three-dimensional (3D) CAD model is prepared accordingly. This model is majorly used for subsystem sizing process, and contribute to the maturity of the design space. CAD model is a fully parametric one, such that virtually every parameter transmutes something in the model which results in a total change or update in terms of size, weight, and/or volume. Independent variables used in the following representations of this study are main rotor radius, maximum forward flight speed, avionics allocation in terms of lengths, pilot's view angles, safe distance between the turret and forward looking infrared. (The model and the method allow more parameters to be included as independent parameters to construct the design space. These limited number of parameters were selected in order to constraint the design space within the limits of easy computability.) Utilizing this model, it is possible to estimate weight, center of gravity (CG), and FPDA accurately. Each iteration is backed by response surfaces obtained before.

FPDA estimation is a crucial part for most of the performance parameters, as the calculations or estimations heavily rests on FPDA estimations. It is possible to set initial values for FPDA and some weight values empirically (Prouty, 1986; Leishman, 2000). Estimation functions also include some geometrical data such as length, fineness ratio, wet area, cross-sectional area etc. Embedding those estimations solely would make the fidelity of the design approach become higher than the initial design stage. Nonetheless, the fidelity or the resolution can be increased by concerning different design choices, deviations, and previous experiences.

The FPDA data in literature can vary as the mission or the purpose of the rotorcraft changes. Geometrical characteristics of a transport helicopter and attach helicopter differ significantly, for instance. A transport helicopter would prioritize landing gear configuration, interior placement of the cabin etc., on the other hand, an attack helicopter prioritizes weapon placement and pilot view angles. Those parameters with their effects on geometry is represented by constructing and utilizing a 3D CAD model. Although the main goal of such a model is to estimate these parameters more accurately, the surfaces obtained in this step, may become the initial point for a master geometry study which will be essential for further design steps such as preliminary design.

In order to define and calculate the major sizes of the helicopter, it is required to estimate the weight and volumes of several subsystems such as cockpit, transmission, fuel tank, and landing gear. To that end, each fundamental subsystem should be modelled conceptually. The level of this modelling includes sizes, weight, required power, and efficiency. Weight and volume of those subsystems also affects and alters CG location of the vehicle. CG location is in direct relation with rotor placement and landing gear placement. These are decided iteratively. Some fundamental subsystems, especially for an attack helicopter is explained in further subsections. Subsystems and a parametric CAD model creation for a utility helicopter, focusing on a transport scenario was explained in Ibacoglu et al. (2022).

3.4.1 Cockpit

Geometrical attributes of the cockpit for an attack helicopter read one of the most essential components deciding the overall height of the helicopter. Cockpit and its interior have many parameters that affect the overall cockpit design; however, in a helicopter level, pilot's view angle becomes the most dominant one. Cockpit placement is also considered as the center of other subsystems' placements and allocations. Position of the cockpit is used as the initial reference point for the other systems. Sizing of the cockpit concerning physical ergonomics and anthropometrics are decided for the desired pilot population's 95 percentile of male's in maximum and 5-percentile of female's dimensions. Design eye point is placed in a position that this point and the following references can be obtained regardless of the pilot's dimensions in this region. Pilot's seat plays the adjuster role for this alignment. View angles are defined two-sided: upper and lower. Upper view angle defines the structural placement of cockpit glass, and the lower angle defines the nose's position and angle. Distances to instruments and glass have been affected by any potential helmet or night vision goggles. Therefore, that equipment had also been considered for the initial referencing of the pilot's physical ergonomics.

Seating of the pilots are considered as tandem seating. Thus, the position of the front pilot (gunner) becomes another important parameter for the view angles of the rear pilot. Increasing the view angles significantly increases the height of the helicopter and hence FPDA, as well as the vulnerability of the helicopter which becomes crucial in warfare scenarios. Utilizing the CAD model plays an essential role to estimate the outcomes of those alterations. Pilot's view angle in downward position with 15 degrees and 25 degrees can be compared in Figure 2 and Figure 3. Corresponding power, gross weight and FPDA changes are represented with bars.

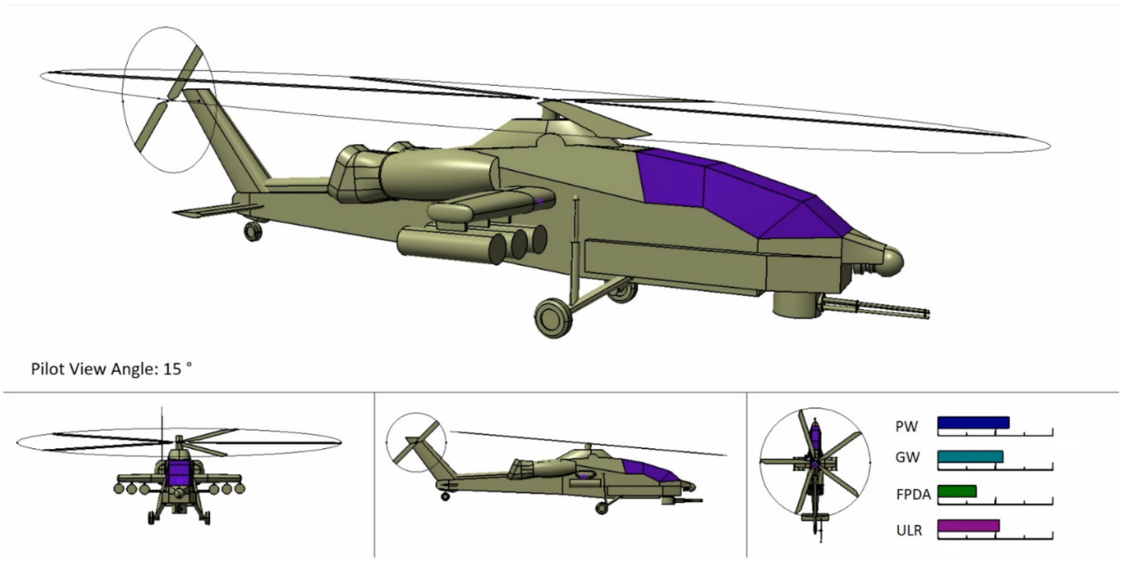

Figure 2: Sample CAD result with 15 degrees of pilot view angle.

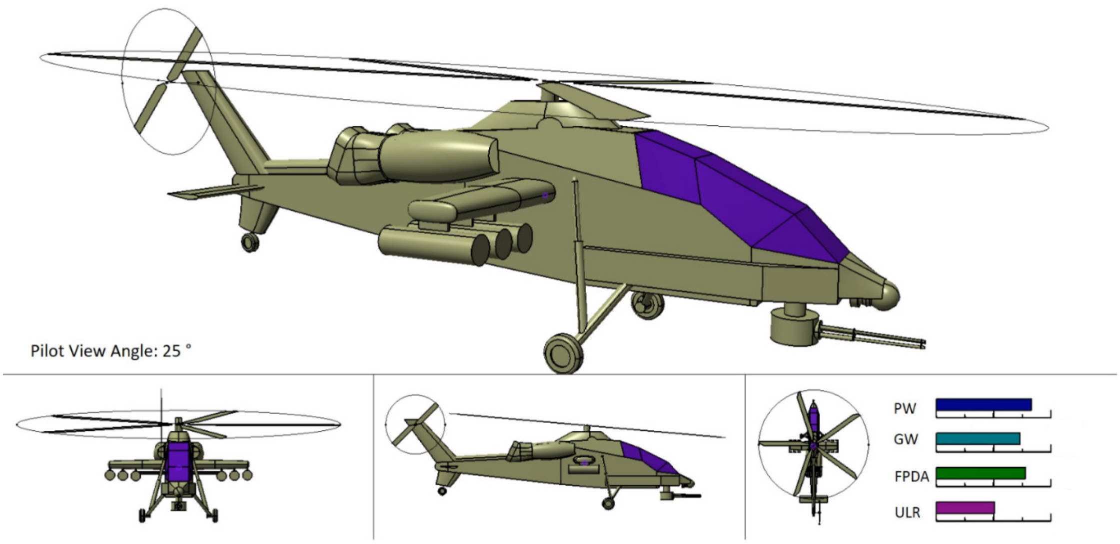

Figure 3: Sample CAD result with 25 degrees of pilot view angle.

3.4.2 Fuel Tank

Required fuel weight is calculated using the performance requirement and engine selection. It is mainly decided by the range and has a significant portion in maximum take-off weight. Fuel weight has withal a variable characteristic during the flight. As an important portion of the weight is variable, CG location becomes dynamic; hence the location of the fuel tank plays a role in the control stability of the aircraft. Consequently, it would be safer to place the fuel tank as close as to the main rotor shaft axis, and limit the CG envelope resulting in decreasing fuel weight during flight. Placement of fuel tanks can become configurational choices, especially when additional fuel tanks are placed under wings where weapon systems can also be attached. This option also comes with FPDA penalty. Amount of fuel needed is calculated in an iterative manner, since increasing the fuel volume also increases FPDA resulting in more fuel needed for compensation of the performance required. Placement of the tank inside the rotorcraft also affects other subsystems allocations such as landing gear.

3.4.3 Landing Gear

Landing gear's major design driver is the displacement during the landing. The required amount of displacement is determined by the landing speed and structural loading limits. Therefore, the stroke and the diameter of the suspension parts are sized according to those limitations. Moreover, the energy needs to be damped and the amount of plastic deformation should be considered. Designing the landing gears too safely has its costs on FPDA and weight considering longer suspension arms and larger wheel diameters. Incremented FPDA has its cost on fuel weight, too; as discussed afore. Thus, landing gear sizing becomes an important agent in conceptual evaluation.

Placement of landing gears is directly related to ground loading scenarios such as taxi and towing. There have been some historical and experience-wise developed guidelines for the angles related to landing gear placement (Army Materiel Command, 1976). Besides the effect of CG location on landing gear placement, landing gear itself has an effect on CG location. For instance, weapon carrying pods should be placed considering the fact that the loads on the pods should not contact the landing gear part during jettisoning. Furthermore, landing gear placement is related to door sizes, especially in sliding doors. Those articulated effects on weight and CG adjustment should be calculated iteratively in landing gear design in helicopter level conceptual design and evaluation phase. Those effects are easily observable in a conceptual CAD model.

3.4.4 Power Transmission System

Power transmission system includes multiple gearboxes designed to transfer the power from engines to rotors and auxiliary and supporting units such as oil pumps and generators. In conventional single main rotor configuration, power transmission system is usually placed above the cockpit and below the main rotor; therefore, it raises the CG location up. Moreover, it has major effect on cowling geometry which has a significant effect on FPDA. Transmission has also an interface with the structural limitations as it should be aligned properly with landing gear placement. Those geometrical effects are modelled inside the CAD model. The weight and the volume of the gears used in gearboxes are estimated basic analytical tools used machine elements theory (Budynas, et al., 2011).

3.4.5 Power System

Required power is calculated according to gross weight, required performance and required loading scenarios. This is pretty much all design inputs as design requirements considering Pahl and Beitz's (1996) definition of requirements. Conceptual analyses of performance requirements also require some engine parameters such as specific fuel consumption to estimate range and endurance as well as the required fuel weight. This paradoxical issue is overcome by using an elastic engine model. Engine specifications are generated utilizing historical trends in engine market, and a generative model of the engines in the market. The trends include engine weight, basic cylindrical dimensions of the engine, specific fuel consumption, and the manufacturer's location in terms of country or multinational cooperative organization. The general trend reads as the required power increases, the sizes and weight of the engine increases which results in an increase in FPDA values. Increased FPDA will again result in an increase in required power. Geometrical changes and estimations of FPDA is monitored by the CAD model.

3.4.6 Avionics and Weapon Systems

Avionics and weapon systems not only play a major role in the estimation of gross weight, but also in volume allocation inside and outside the helicopter body. Those equipment's installed volume compared to their uninstalled volume may change significantly. Therefore, assembly experience becomes an important input for the volume estimation. The difference between an installed volume and uninstalled volume can be calculated by investigating the present helicopters in the market, or it can be statistically gathered utilizing the contractor company's in-house data.

Weapon systems may be placed inside the body or outside the body. Each option has its pros and cons concerning FPDA, volume allocation, and operability. In this study, weapons are placed on pods under wings. FPDA values of the weapons can be gathered through wind tunnel tests or CFD analyses. In the lack of these data, statistical estimations can be conducted. Root thickness of the wings is the fundamental parameter while sizing the wing structurally. It is estimated with a beam assumption on the wing with some loaded stations. The bending moment at the root is monitored and the thinnest root possible is calculated and embedded inside the CAD model.

3.4.7 Control Surfaces

Control surfaces are essential for stability analyses of the rotorcraft. In addition to this, their dimensions are required for both weight and FPDA estimations. For the sizing of those surfaces, rotor interactions and moment equilibrium were considered. Required moment arm dimensions are iteratively embedded inside the CAD model.

3.4.8 Fuselage

Fuselage is the heaviest system compared to its counterparts in the same level. Similarly, it has the greatest contribution to total FPDA. Therefore, the estimation of both its weight and FPDA plays a significant role in the estimation of the whole rotorcraft. Its dimensions are determined by cockpit, landing gear, power transmission system, engines, rotors and almost every other subsystem present in the helicopter. FPDA estimation requires the overall length, width, height and the resulting wet area. Those values are parametrically and automatically calculated inside the CAD model. Historical trend curves given in Prouty (1986) and Leishman (2000) are modified and improved as they were adjusted with some current helicopters in the market. Those modified and improved formulae are embedded inside the CAD model, and the FPDA calculation is conducted iteratively. Modified and improved formulae carry the fidelity level of the statistical estimations to a higher point compared to solely statistical approach utilizing the historical trends. On the other hand, this level of fidelity is still lower than CFD results, wind tunnel experiments, and flight-test results which can be considered as the highest fidelity level concerning this parameter.

3.4.9 Rotors

Rotor design includes blade geometry as planform geometry, airfoil selection, chord and twist distribution as well as rotary speed of the rotor. Optimized blade parameters are obtained during the performance calculations according to required performance and gross weight values. Response surface equations are obtained with respect to performance inputs, and they are embedded in rotor radius and rotor chord parameters inside the CAD model. Rotor hubs are also effective while estimating the total FPDA and weight of the helicopter. Hub FPDA values as well as rotors' own FPDA are estimated using rotor radius and frontal projection areas. Those values are statistically adjusted using the data present in the market.

3.5 CAD and Performance Based Design Space

Having found the corresponding geometrical parameters as well as their FPDA and performance contributions in each DoE point, another response surface is fitted using those accurate estimations with a directed-indirect interface between and among them. The interface between a performance parameter such as range and a geometrical constraint such as pilot view angle is in fact an indirect one; since, the mathematical relation cannot be obtained analytically. However, conducting the steps explained, a response surface polynomial can directly present the relation in between. Thus, it was named as directing the indirect relation. This approach also increases the maturity of the performance estimations as the interfaces between and among many components are live and synchronous after CAD estimations. The increased fidelity level compared to historical data or performance-based response surface estimations, is not one of the highest fidelity levels that can be achieved during the design of a vehicle. However, it can be utilized during and before the conceptual design phase where much higher fidelity levels such as CFD analyses for FPDA values may require an extravagant amount of time. It should be noted that this exploration tool is also intended to be used for decision making before preliminary design starts. This phase is highly dynamic concerning the nature of the under-defined requirements. Therefore, the aim is to present a sufficient level of fidelity with quick responses.

Mathematical relations obtained among those design drivers and key-points of design decisions can now be presented with a user-interface, considering the decision maker as a user. The user may dynamically manipulate the inputs and observe their effect on the outputs. Consequently, they can make decisions according to physical mathematical and engineering-wise limitations. The design space is constructed with these statistical relations, and the designer's freedom can be visualized as the available parameters and their acceptable limits dynamically adjusted. The end product of this design space exploration process can be named as a design-decision support system.

3.6 Design-Decision Support System

User requirements and their classification as inputs and outputs, and the nature of the fluidity of these definitions were discussed. There are intertwined relations between and among them. Therefore, it is not always obvious and predictable for the decision makers to estimate and foresee the consequences of design-decisions in terms of their effect in final product. In order to support their decision-making, a visualized interface is constructed utilizing the mathematical relations operating in the background. The system can generate synchronous graphs in two-dimensional basis with the freedom to change related parameters with respect to each other. A sample visualization of numerous synchronous graphs can be seen in Figure 4.

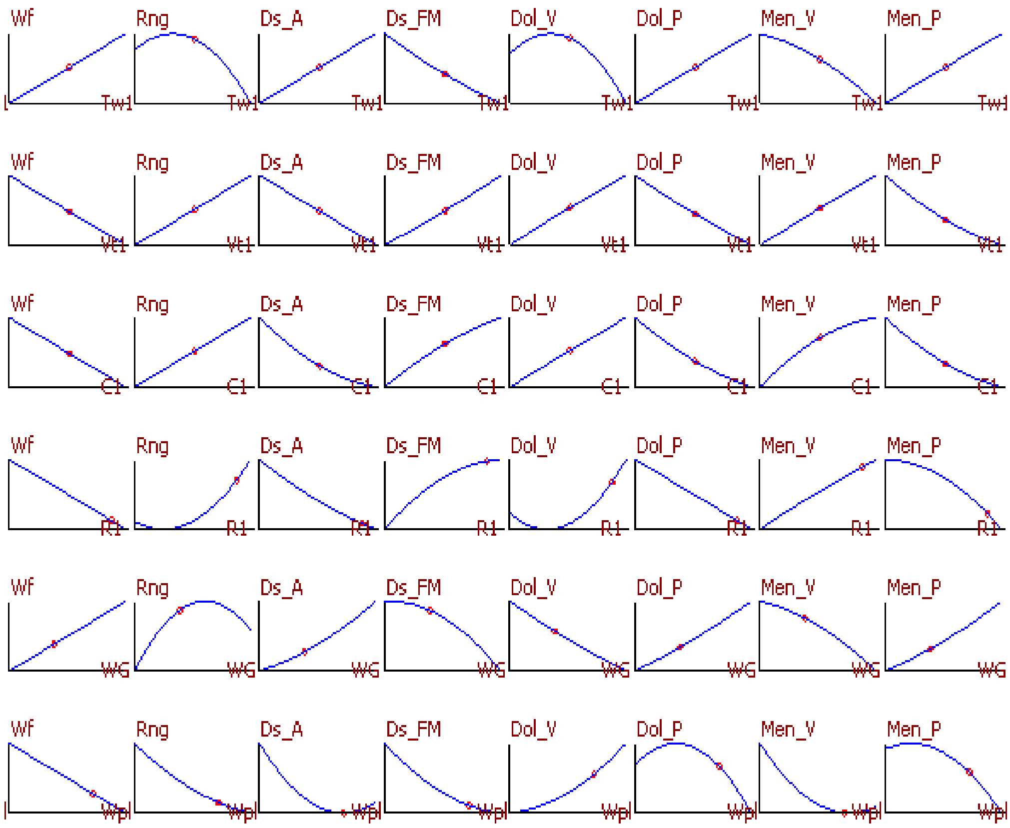

Figure 4: Synchronous graphs relating numerous design parameters.

In Figure 4, interrelations among some rotor parameters, weight, and performance parameters can be seen. Those graphs can be studied dynamically and synchronously. In the first raw of graphs; fuel weight (Wf), range (Rng), required power in hover at sea level (Ds_A), figure of merit at sea level (Ds_FM), loiter speed (Dol_V), required power for loiter (Dol_P), best range speed (Men_V), corresponding power for the investigated range (Men_P) are compared with respect to the twist angle of main rotor blades (Tw1). The same variables are graphed with respect to tip speed of the main rotor (Vt1), chord of the main rotor blades (C1), main rotor radius (R1), gross weight (WG), and payload (Wpl); in the following rows, respectively. What variables will be compared, and what parameters will be included in those charts are decided by the user. Figure 4 presents only a sample result that can be generated.

Apart from the differing fashions of variability between the parameters, their limitative relations are also important for decision makers. For instance, limiting the engine power may limit range and pilot view angle with its proximity to FPDA estimation. Therefore, a dynamic representation of parameter limits is also presented in this system. A sample of synchronous limits can be observed in Figure 5.

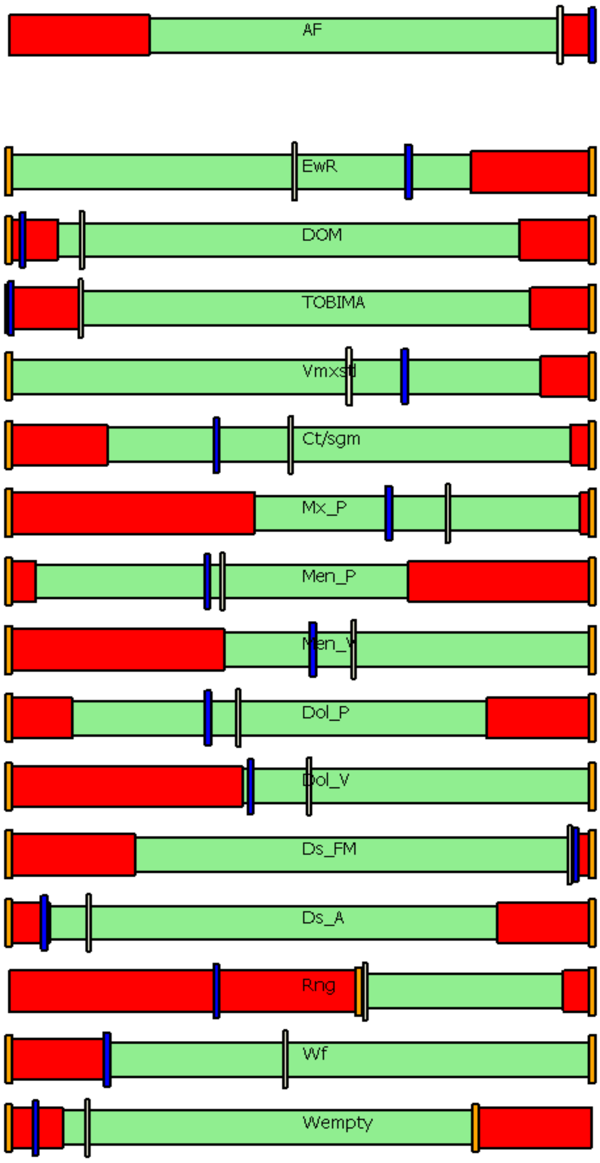

Figure 5: Dynamic and synchronous limits of design parameters.

In Figure 5, green areas inside every bar indicates the designer's freedom area where a design is possible in terms of physical-mathematical constraints, engineering limits, standards and user requirements. At the top bar, there is an objective function (AF) which can be customized by the user as manipulating the weights of the parameters. The following bars include some of the parameters explained before. The remaining ones are empty weight ratio (EwR), direct operational cost (DOM), total unit cost (TOBIMA), maximum cruise speed (VMxs), thrust coefficient to solidity ratio (Ct/sgm), maximum power (Mx_P), and empty weight (Wempty). This limited view with red bars indicating *impossible design* areas, is obtained with some limitations are entered. The system automatically sets the objective function at its maximum, this scene can be observed with blue vertical lines. Each vertical blue line in each bar represents the optimized points. Orange vertical lines represent the limits. For instance, if the user alters the minimum range as in Figure 5, in which the initial optimum solution is not available (blue line is at the red region), the maximum available value for the objective function changes. System automatically sets the new maximum value for the objective function within the new limitations. The new optimized results are shown with white vertical lines. These white lines represent the new solution as each line is placed within green regions.

4.0 CONCLUSION

Conceptual evaluation of a rotorcraft is defined by introducing design level concept and the design scope within helicopter level design. Evaluation procedure is explained by pre-sizing, elimination, design of experiments, response surfaces and three-dimensional computer-aided design model, and second response surface stages. This method had idiosyncratic contributions to conceptual design phase as it considers geometrical parametric changes while they are monitored synchronously. The design space is constructed by the geometrical analyses and modelling as it satisfies the points defined by design of experiments. This stage can be considered as a surrogate-modelling technique. The design space is represented as a design-decision support system to be integrated in decision-making processes inside a contractor company, and during the negotiations among client and user institutions. This conceptual evaluation and design space exploration tools with its design-decision support system intends to rationalize the conceptual design decision-making stage and to enhance the whole conceptual design stage with rational outputs to following design stages.

4.0 ACKNOWLEDGEMENTS

The authors would like to thank Mustafa Emre Gündüz and Murat Ceyhan for their contributions and fortifies during the studies of modelling and inditing.

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