ROTORCRAFT CONCEPTUAL DESIGN METHODOLOGY WITH COMMONALITY CONSTRAINTS

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ABSTRACT

This paper introduces a comprehensive methodology of commonality-based simultaneous design of multiple -different types of- helicopters so that, the time and budget allocated to the research, development, and production can be decreased significantly. In the presented synchronous design process, three levels of commonality are suggested as low, mid, and high-level in which engine; engine and transmission; engine, transmission, and rotor systems of the helicopters are assumed to be identical, respectively. To illuminate the methodology, simultaneous conceptual design studies of two helicopters -a transport and an attack helicopter- with high and mid-level commonality levels are presented. In this design process, fully parametric three-dimensional geometric models with embedded empirical formulations are created in order to increase the accuracy of the estimations in several considerations such as weight, dimensions, and flat plate drag area of the vehicle to be designed. This surrogate model approach is generalized with a response surface to create a design space, which can be analyzed by both designers and decision makers to assess and evaluate possible design scenarios for both helicopters, simultaneously.

1. INTRODUCTION

Identifying and responding to customer needs by offering a variety of products is significant for a company to establish a market presence. However, it is known that the proliferation of products results in escalated production and distribution costs; also, deterioration in manufacturing and logistic performance. In addition to the higher forecast errors and excessive overhead, and administrative costs; manufacturing costs increase due to more specialized processes, materials, changeovers, and quality assurance methods [1] [2]. Also, Child [3] states that product and process design will have an impact on manufacturing costs of 80%, quality problems of 50%, order lead times of 50%, and business complexity of 50%. As a solution to those issues, approaches such as modular product design and parts commonality are used to appease this trend in terms of cost, still offering a variety of products [1].

It is stated in the literature [1] that the subject of design commonality to reduce the cost of multi-item inventory is initially studied by Rutenberg [4] and Rutenberg and Shaftel [5]. In their approach, the issue of commonality is presented as a dilemma of economic equilibrium between economies of scale and the inefficiency of depriving each client segment of a product that precisely meets its needs. To help companies to have accelerated and accomplished design projects while reducing cost, the use of common design modules and packages is also recommended by Ulrich and Tung [6] in their discussion of product modularity. The use of standard components typically helps in lowering the complexity, cost, and lead-time of product development. From the product design and development point of view, any variation in design leads to increased cost due to the aforementioned reasons. As noted by Datar et al. [7], commonality results in activity reduction because only one component needs to be designed rather than two or more. Furthermore, it has been persuasively shown in the literature [8] that investment in design studies can reduce unit and/or life-cycle costs. Therefore, commonality constraints can be useful in design studies to reduce manufacturing costs farther down the supply chain [9].

The automotive sector is also experiencing a rapid change in customer demands and preferences. Utilization of a *product platform* is a great approach to efficiently manufacturing a variety of products, as a response to that demand in the market. The idea behind the product platform is to improve the efficiency of the development and production process through the sharing of essential components between different models [10]. However, the definition of the *platform* varies among different companies. For example, the platform may be defined as the combination of suspension, underbody, axles, and powertrain for an automobile [11]. Furthermore, many companies are using a *family approach* to product development in order to capitalize on the advantages of commonality while producing highly distinctive end products [12]. The vast majority of automobile manufacturers have built car models that share components, ranging from complex subassemblies to standardized commodity parts; since they have realized the advantages of component commonality.

The degree of component sharing varies greatly amongst models, though. There are some examples from the automotive industry dating back to the 1990s given by Ericsson et al. [13] [14] Chrysler used approximately 75% of the parts common in the driving regions of the Dodge Intrepid and Chrysler New Yorker. On the other hand, Mazda used only 15% of the parts that are common for its two models built on the 626 platform, the Mazda 626 and the Xedos 6. In addition to those, recent examples can be observed in the automotive industry. The application of the product platform approach is an example of a commonality approach from another perspective, as defined above. For instance, Volvo Cars currently uses two types of platforms which are named Scalable product architecture (SPA) and Compact Modular Architecture (CMA) introduced by Volvo Cars [15]; and used for larger and smaller car models, respectively. Besides, Volkswagen is another excellent example of the application of a product platform that produces 4 different cars on a single flexible platform, called MQB [15].

Given the definitions and examples from the literature and the –automotive- industry; in this paper, it is aimed that a clear definition of the term *commonality* and its *levels* can be done from a rotorcraft conceptual design point of view. Also, to exemplify the suggested design process, the proposed methodology is applied to a case in which helicopters are chosen as *transport* and an *attack* helicopter.

2. METHODOLOGY

The aim of the conceptual design studies with commonality constraints is to create expeditious design solutions that analyze fundamental design inputs consisting of high-level customer requirements, engineering requirements, optimization goals, etc., with relatively low fidelity methods for multiple rotorcrafts with common systems. Within the scope of these studies, potential solutions are compared in terms of applicability and feasibility by utilizing multidimensional and multidisciplinary optimization, before progressing into the following stages.

The fundamental goal of this methodology is to present the relations among conceptual level design parameters of two different helicopters, dynamically and swiftly in decision-making processes. First, the term *commonality* with different *levels*, the multi-dimensional dynamic parameter cloud, and the parametric geometric model is explained in detail. Then, the method and process suggested will be introduced.

2.1 Commonality in Rotorcraft Design

Helicopters stand out performing numerous tasks thanks to their hover and vertical flight capabilities. They provide services in several areas including search, rescue, logistics, transportation, surveillance, etc. with the utilization of various subsystems working in a harmony; therefore, the design of rotorcraft is a highly multidisciplinary process that needs a synchronous system among different design disciplines. Generally, the design process is divided into three main phases; the conceptual design, the preliminary design, and the detailed design as suggested in the references [15] [16]. According to Ulrich's taxonomy of the design phases [17] in the product design process, subsystem design is typically proceeded during the preliminary design phase, while the conceptual design phase concentrates on the helicopter's key design drivers. The conceptual design phase is a baseline of the whole project in which significant decisions, investigations, and evaluations are included. Ultimately, the most crucial determination of the external configuration occurs at the end of the conceptual design phase [18]. Furthermore, it should be noted that most of the cost impacts are defined in the earliest design phases, i.e. conceptual design phase with an approximate rate of 65% (Figure 1), whereas the greater part of the expenditures incur during the operation and support phase. Thus, the total time and budget allocated to the projects mainly rely on the studies conducted in the conceptual design phase. Since not only the concept decisions; but also product life management is a concern in that phase; production capabilities of the facility, tools needed for the production, engineering and production costs, maintenance, and logistics are the main constraints and drivers of the studies of this phase. Therefore, the higher the level of commonality of the helicopters to be designed and to be produced, the less the time and cost occupied for the projects. In other words, the idea of commonality-based simultaneous design of multiple helicopters would allow a significant amount of retrenchment of the time and the cost devoted to the research and development, and production.

The term *commonality* refers to the common sub-systems of different rotorcrafts, considered to be identical while initiating the conceptual design phase. As stated before, the aim of using common systems in multiple rotorcrafts is the fact that the life-cycle costs (engineering, production, maintenance, logistics, etc.) can be decreased significantly. Which systems should be assumed as identical is another concern that should be considered by both designers and decision-makers. To initiate the decision-making process, different levels of commonality can be defined to investigate which sub-systems should be considered identical.

Different from the preliminary and detailed design phases where design studies of every subsystem such as rotor controls, transmission, structures, etc. carried out separately in detail; the conceptual design phase deals with broader sizing and performance estimations of fundamental systems according to users' needs and customers' requirements. At this design phase, sizing and performance estimation of three main systems which are the rotor, transmission, and powerplant systems, composes the baseline of the whole design. Therefore, commonality levels should include these systems and the related sub-systems. Consequently, the aforementioned levels of commonality are named as low, mid, and high levels (Figure 2). In the low-level commonality, powerplant systems are assumed to be identical. That is, power requirements and engine rpm (revolutions per minute) must be the same for both rotorcrafts. Rotor diameter and rpm might be different while engines, and therefore the power requirements, have to be the same; whereas, studies should be conducted for different rotor diameters and rotor rpms. Secondly, in the mid-level commonality, the transmission design of both vehicles should be the same as well as the engine systems. Therefore, power transmission limits must be identical. The last one is named as high-level commonality in which it is assumed that all the dynamic systems of the second helicopter would be the same as of the first one. In other words, in addition to the transmission and the engine systems, rotor systems should be identical for high-level commonality. That is, rotor diameter, rpm, and blade geometries are assumed to be the same.

2.1 Process

To initiate the commonality analysis, first, without any geometric constraints; that is, just from the *performance parameters* perspective, *design space exploration* is completed; and then, preliminary functions are obtained. The aim of this study is to observe the *weight* and *performance* characteristics of the helicopters at different levels of commonality with each other, with function parameters of any value set. With related calculations and analysis, fundamental systems model formation by examining the parameters cloud of the helicopter worked on. Then, the scenarios, which are decided to be included in the conceptual evaluation, are generated.

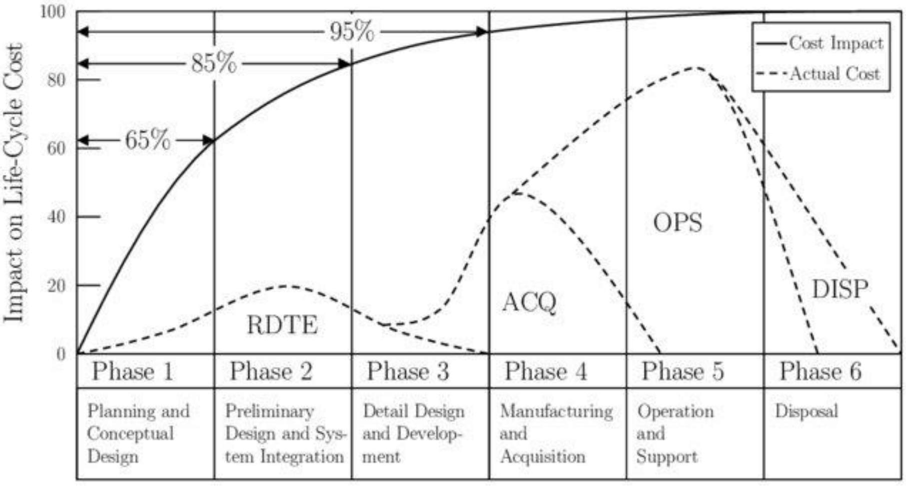


Figure 1: Impact of the design phases on life-cycle cost [19]

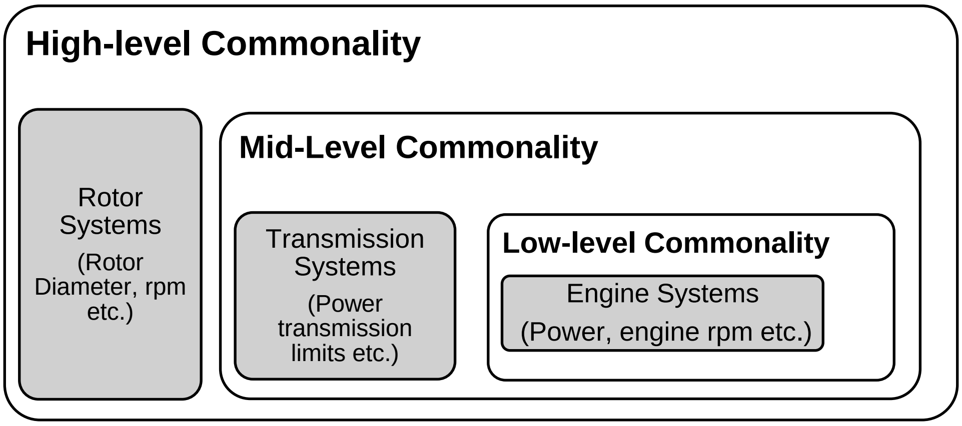


Figure 2: Commonality levels and design parameter constraints

Simultaneously high-level architecture choices are made. In the transition from the parameters cloud, formed and improved with the help of the process explained, to a performance-based design space; four fundamental sub-studies are conducted. These are statistical preliminary sizing, elimination test, creation of design of experiment tables, and generation of response surfaces and design space. In the statistical preliminary sizing, with the help of the helicopter database, geometrical sizes and weights are defined and assigned to the conceptual models in accordance with the scenarios. This statistical sizing is an initial point for the determination of the design space, whose parameters may be changed as a result of the analysis conducted. Since the number of parameters in the parameters cloud is considerably high, analysis/calculations may take a lot of time. Therefore, using mathematical methods, it has to be reduced down to a reasonable size. To do this, for a specific scenario, some inputs, which does not affect the outputs, should be eliminated using *physics-based analysis*. Using statistical methods, constants are assigned to the eliminated parameters. Generally, this elimination is based on sensitivity analysis. The other sub-study is the creation of design of experiment (DoE) tables, usually, they are complex and large, and can be loosely described as a bunch of data indicating the mathematical relations between the input and outputs. The last one, the creation of the response surface and design space; is basically a reinterpretation of the DoE tables, to make the usage of data more convenient. Response surfaces may be simple or considerably complicated. While initiating all the processes, the level of commonality becomes significant; thus, should be chosen wisely. To clarify all the steps of the process described, details are classified in the following subsections.

2.2.1 Selection and Categorization of Parameters

Conceptual level parameters like *performance parameters* are highly intercorrelated with each other. In the initial design stages, those relations become significant since most of which disclosure mathematical or physical variables need to be considered. Furthermore, those parameters, relations, and their importance may also vary depending on the configuration. It is essential to classify those parameters considering their importance. Within this classification study, the *design space* or *parameter cloud* -all the dependent and independent combinations of the parameters- should be generated. Categorization of the parameters as inputs or outputs is the groundwork for the generation of the cloud.

Inputs play a major role in this phase of an ongoing design. Three main sources of the inputs are user requirements; standards, regulations, and engineering requirements; contractor company’s structure, aims, and abilities. User requirements can be listed as performance requirements; equipment and load requirements; survivability and safety requirements; geometry and system architecture requirements. For instance, 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. On the other hand, in a 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, and 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 modeling. In addition to these methods, some assumptions are also integrated with certain experience-wise supported decisions.

2.2.2 Design Space Exploration

Helicopter parameters can be considered as dynamic variables such that the classification of a parameter as an input or output is case-specific. First of all, the design space should be constructed with helicopter parameters, which are dynamic parameters that can be treated as both inputs and outputs. For instance, as in the case given in the paper, for a civil transport helicopter number of passengers should be an important parameter; however, it would be meaningless to consider the same for an attack helicopter. Secondly, those parameters should be tagged as a requirement, limitation, input, or output. Then, the scenarios, which are decided to be included in the conceptual evaluation, will be generated. Simultaneously high-level architecture choices should be made. Finally, analyses, calculations, and simulations will be conducted. Thereafter, the decision-making operations should proceed. After completing particular calculations and analyses for specific scenarios, a design space will be obtained. Then, the exploration, evaluation, and decision-making concerning design become available.

There are four main steps in constructing the *performance-based design space* from the parameter cloud, which are statistical pre-sizing, elimination test, design of experiments (DoE), and response surfaces. The first one is statistical sizing, which is the first sizing study of a whole iterative process. In this step, historical trends of the market are observed in order to define an initial point for some basic parameters, i.e. weight and volume, of conceptual models derived in previous steps.

An elimination test is essential in order to decrease the degree of the complexity of the models. To do so, utilizing some mathematical approaches are necessary. Not only the complexity; but also, the computational time of the studies conducted can be decreased significantly with the help of elimination tests. Sensitivity analysis can be conducted at this phase to test and list inputs as significant or not observing their effects on some important outputs such as maximum take-off weight, hover ceiling, and required power. Ineffective parameters are fixed to certain values obtained using some statistics or calculated values at the previous stages.

The construction of the design of experiment tables is essential since they quantify the numerical relations between inputs and outputs as mathematical and statistical variables. It should be noted that, for some of the parameters such as flat plate drag area (FPDA) and weight, analysis and calculations may be needed. The very first estimation can be set by observing similar helicopters in the market or a statistical value obtained by historical trends, such as the ones given in Prouty [20] and Leishman [21].
The extremely large design of experiment tables can be represented with simplified mathematical relations, which can be obtained with the utilization of response surfaces. It should be noted that; mathematical relations obtained using response surfaces are not exact but relatively good estimations with an error in an acceptable range. The utilization of the response surface is explained in detail, in İbaçoğlu and Gündüz [22].

2.2.3 Fully Parametric CAD Models

Performance calculations based modeling and empirical relations give sufficient results to some extent; however, these methods generally include a significant amount of error regarding the effects of design decisions related to the geometry of the vehicle. For instance, pilot's view angles, placement of fuel tanks or avionics, etc., and their effect on FPDA cannot be observed clearly in the absence of a CAD model. Not only the inclusion of those parameters in the model but also a considerable increase in the resolution of the estimation of all parameters makes the CAD model necessary for the study. Therefore, it is vital to include a fully parametric and dynamic CAD model in the conceptual design studies.

Three-dimensional (3D) CAD models are prepared with commonality constraints for this study. CAD models normally are fully parametric, such that almost every parameter changes something in the model which results in a total change or update in terms of size, weight, and/or volume, in an iterative manner (see Figure 3). However, in this study, commonality considerations impose some restrictions on the models since some (sub)systems should be the same for both models prepared for different types of helicopters (attack and transport). Utilization of fully parametric CAD models enables accurate estimation of weight, the center of gravity (CG), and FPDA. Some empirical relations [20] [21] also include some geometrical data such as length, fineness ratio, wet area, cross-sectional area, etc. Therefore, all the calculations are highly dependent on the geometry of the vehicle, which varies as the mission or the purpose of the rotorcraft changes. For example, as in the example case of the paper, a transport helicopter and attack helicopter would have considerably different geometric characteristics. 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. The effect of these geometric parameters can only be represented with the help of a 3D CAD model. A detailed explanation of fully parametric CAD models utilizing the aforementioned empirical relations for a utility helicopter, focusing on a transport scenario was explained in Ibacoglu et al. [23] . Also, the algorithm of the CAD model can be seen in Figure 3.

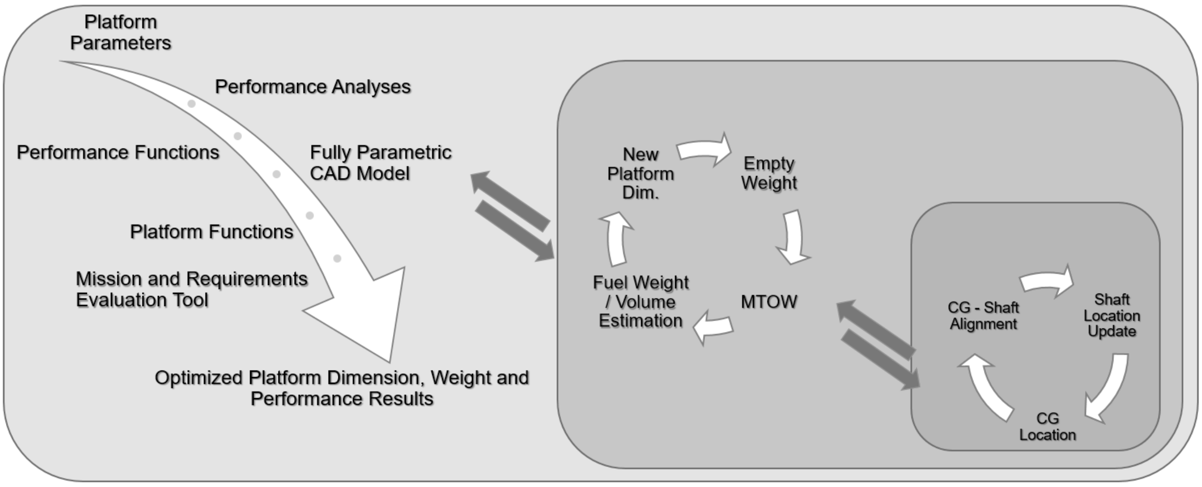


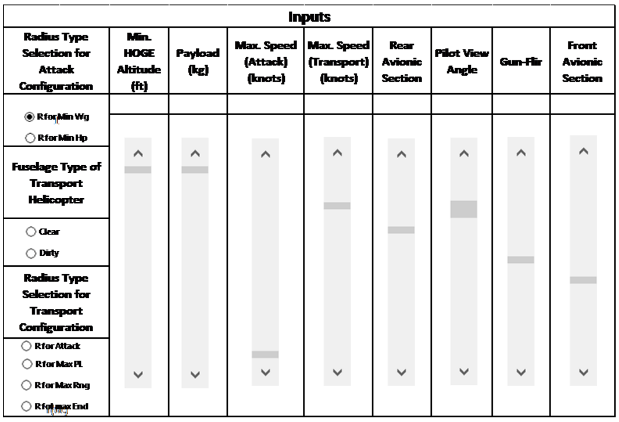
Figure 3: Design algorithm of CAD model approach [20]

Having completed the analysis using the CAD models in an iterative manner performance-based design space becomes available with the help of the response surface method. Using these response surface polynomials, geometrical parameters can now be related to the performance parameters, which would not be possible without the CAD model and the second response surface iteration. Therefore, indirect relations are available with the presence of final equations of the response surface.

2.2.3 Design Decision Support System

Mathematical relations obtained among those design drivers, geometrical and performance inputs, can be visualized with a simplified user interface so that the engineering and customer decision-making process becomes straightforward. Those relations are embedded in the user interface such that any variation in the inputs would result in a simultaneous update of the outputs. This user interface is beneficial for the user, designers, and customers to see all the physical and/or engineering limitations.

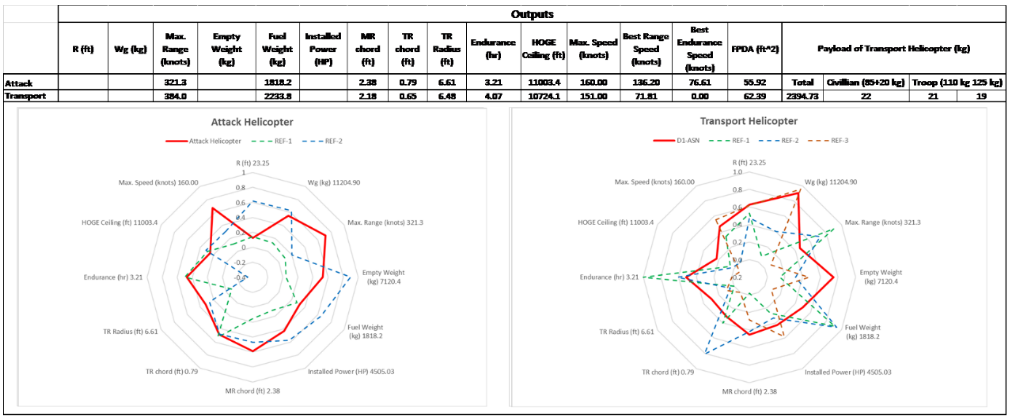
Since commonality constraints are in consideration for this study, and multiple helicopters are to be designed, while a single input section exists for the attack and the transport helicopter, two output sections present the results. In this basic user interface, some inputs are defined for both helicopters such as payload, minimum hover altitude out of ground effect (HOGE) altitude, maximum speed, pilot view angle, size and location of the avionic compartments, location of the weapons (for an attack configuration), fuselage type and so on. Some of the outputs can be grouped as weight, rotor geometry, and performance parameters. In the weight group, gross weight, empty weight, and fuel weight number of passengers (civilian or troop) can be listed. Some of the rotor geometrical parameters such as main and tail rotor diameter and chord length. Furthermore, there are many performance parameters that can be obtained as the output of those studies, some of them are required installed power, maximum range, endurance, HOGE ceiling, maximum speed at sea level, best range, and endurance speeds. In addition to those output parameters, FPDA is another (engineering) output that is significant since most of the performance parameters depend on that value. Also, in the case of multiple helicopters of different configurations such as attack and transport, FPDA and therefore almost all of the performance parameters would alter significantly. Another feature is added to the screen which is the spider chart to be able to compare the obtained configuration with similar helicopters in the market. The aforementioned simplified user interface created in Excel is given in Figure 4 and Figure 5.



Inputs

Radius Type Selection for Attack Configuration	Min. HOGE Altitude (ft)	Payload (kg)	Max. Speed (Attack) (knots)	Max. Speed (Transport) (knots)	Rear Avionic Section	Pilot View Angle	Gun-Flir	Front Avionic Section
● R for Min Wg ○ R for Min Hp								
Fuselage Type of Transport Helicopter								
○ Clear ○ Dirty								
Radius Type Selection for Transport Configuration								
○ R for Attack ○ R for Max PL ○ R for Max Rng ○ R for max End								

Figure 4: Configuration assessment interface



	Outputs																		
	R (ft)	Wg (kg)	Max. Range (knots)	Empty Weight (kg)	Fuel Weight (kg)	Installed Power (HP)	MR chord (ft)	TR chord (ft)	TR Radius (ft)	Endurance (hr)	HOGE Ceiling (ft)	Max. Speed (knots)	Best Range Speed (knots)	Best Endurance Speed (knots)	FPDA (ft^2)	Payload of Transport Helicopter (kg)			
Attack			321.3		1818.2		2.38	0.79	6.61	3.21	11003.4	160.00	136.20	76.61	55.92	Total	Civilian (85+20 kg)	Troop (110 kg 125 kg)	
Transport			384.0		2233.8		2.18	0.65	6.48	4.07	10724.1	151.00	71.81	0.00	62.39	2394.73	22	21	19

Figure 5: Output screen

3. APPLICATION

In this section, the methodology explained in the paper is applied to a case in which a transport and an attack helicopter are to be designed with commonality constraints. Different from the conceptual design study of a single helicopter, in this study, the basics of the commonality-based conceptual design approach is aimed to be presented. The fundamental purpose of this study is to investigate the possible positive and negative outcomes of the commonality-based design approach applied to those helicopters at the conceptual evaluation phase, which covers the very first studies conducted having a significant influence on the other stages of the project. It is stated before and should be noted that the commonality approach diverges the helicopters from the optimal point. Therefore, in this case, study, the aim is not to present optimized final design solutions; instead, it is to exemplify the methodology suggested, present a guideline and create a baseline for further design studies.

As stated in the previous section, parameters are chosen as rotor diameter, HOGE ceiling, payload, maximum speed, length of the avionic compartment located aft of the cabin, pilot view angle, the distance between the gun and FLIR (Forward Looking InfraRed), size of the avionic compartment at the nose. For different values of those inputs; many performance outputs such as gross weight, fuel weight, range, endurance, FPDA, best range, endurance speeds, etc. can be obtained.

2.1 High-Level Commonality

As stated several times, there are three levels of commonality between the two helicopters investigated, as shown in Figure 2. The first one is the high-level commonality in which it is assumed that all the dynamic systems of the second helicopter would be the same as the first one. Representation of this case is given in Figure 6 to exemplify the high-level commonality of an attack and a transport helicopter. An illustration of common dynamic systems (engines, transmission, main and tail rotors) can be seen at the top of Figure 6.

In this case, it is calculated that; with which function parameters of the transport helicopter, it can provide the same rotor parameters and power requirements of the attack helicopter. Function parameters of transport helicopter are chosen as rotor diameter, maximum take-off weight, flat plate drag area, and maximum forward flight speed. Rotor diameter is chosen as the same value obtained for the attack helicopter. The flat plate drag area is calculated using pre-geometry and the empirical relations chosen, depending on the maximum take-off weight and fuselage type. Maximum forward flight speed is considered a design requirement; therefore, the choice made by engineering judgement or may come from the customer directly. In this case, it should be analyzed that at which value of maximum take-off weight, maximum power requirement is met.

Figure 6: Representation of High-level Commonality for an Attack and a Transport Helicopter

For an input set defined for the attack helicopter shown in Table 1, performance outputs are obtained. As can be seen in Table 1, inputs are normalized using the maximum and minimum values of the range predefined for every single input. Therefore, input values are given from 0 to 1 in non-dimensional format. Inputs were defined in the previous sections. In addition to those it should be noted that *Avionic-1* and *Avionic-2* are abbreviations for the length of the avionic compartment located aft of the cabin, and width of the avionic compartment at the nose, respectively. For these inputs defined as the requirements of the attack helicopter, weight and performance outputs are obtained by the utilization of the *Design Decision Support System.* With the high-level commonality constraint, the rotor size and required power -or installed power- outputs have to be the same for the transport helicopter. Having decided the rotor size and the power requirements because of the constraints, input parameters available for the transport helicopter are only the maximum speed and the fuselage type (clear or dirty). The maximum speed value for the transport helicopter is determined to be 0.33 in terms of

Table 1: Example input parameters of Attack Helicopter

Input	Unit	Normalized Value
Min. HOGE Altitude	[ft]	0.62
Payload	[kg]	0.50
Maximum Speed	[kts]	1.00
Avionic-1	[mm]	0.40
Pilot View Angle	[deg]	0.70
Gun-FLIR	[mm]	0.48
Avionic-2	[mm]	0.61

normalized values. This value was taken as 1.00 for the attack helicopter. The fuselage type is chosen as dirty, to observe a case with high FPDA. Radius type selection is not available as input since the high-level commonality is the concern in this case; however, it will be available for the mid and low-level commonality-based studies.

With the selected values of the inputs, different gross weight values are investigated. Then, corresponding power requirements are calculated in order to find the maximum gross weight value of the transport helicopter with the installed power requirement and/or constraint predefined from the attack helicopter. In Figure 7, the attack helicopter –with the value of 1.00- is shown with an orange line as the power constraint of the transport helicopter which is shown with a blue line for different gross weight values. It is clearly seen that; both lines meet at a gross weight value of 1.10 for the equivalent required power value of 1.00. Other performance parameters are also calculated for the obtained configuration. Comparisons of those outputs are listed in Table 5.

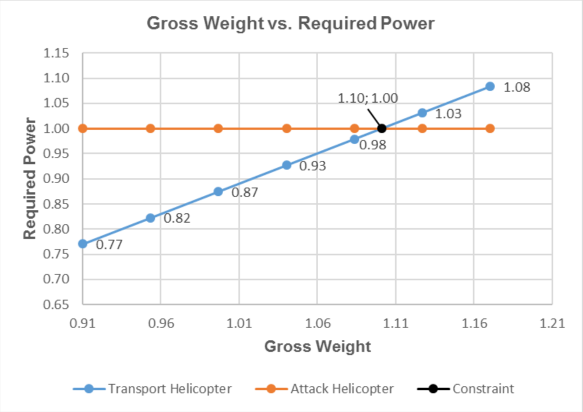


Figure 7: Required power for transport helicopter depending on gross weight

Having found the gross weight value for the transport helicopter using the limitation of the power, the payload can be determined for this configuration. As a normalized value, the payload is determined as 1.93. A comparison of the payloads for these two configurations is also given in Table 4. Then, the determined value of the payload can be represented as the cargo weight and the number of passengers. Further detailing of the number of passengers can be done considering civilians and troops. Example break-down can be found in Table 2; however, it should be noted that the given payload value is given for illumination purposes and does match the values of neither the attack nor the transport helicopter.

Table 2: Example payload capacity and corresponding number of passengers

Payload [kg]	Civilian (85+20 kg)	Troop (125 kg)	Troop (110 kg)
1155.23	11	9	10

3.2 Mid-Level Commonality

At the conceptual sizing studies of this level, it is assumed that engine and transmission systems are the same for both helicopters. Thus, while these helicopters may have different rotor diameters, it is aimed that maximum power and rotor rpms would be the same. The process of the high-level commonality needs to be followed for this level, as well. However, the process should be repeated with different rotor diameters for optimization concerns. Similar to the process followed for the high-level commonality, for the required power of the attack helicopter is considered by scanning the different values of different gross weight and rotor diameter. The fuselage type and maximum speed are flexible inputs, as well. Different from the previous section, it is stated that there is a need for calculations of different rotor diameters, which are given in Table 3 in terms of normalized values with respect to ones of the attack helicopter.

Table 3: Resultant outputs of transport helicopter with different main rotor radii

Main Rotor Radius	Gross Weight	Payload	Range	Endurance
1.000	1.101	1.925	1.194	1.176
1.011	1.110	1.974	1.196	1.179
1.023	1.116	2.012	1.197	1.186
1.034	1.125	2.058	1.199	1.189
1.045	1.131	2.094	1.201	1.192
1.057	1.140	2.138	1.203	1.196
1.068	1.146	2.171	1.204	1.199
1.080	1.153	2.202	1.206	1.202
1.091	1.162	2.240	1.208	1.202
1.102	1.168	2.267	1.209	1.205
1.114	1.175	2.293	1.210	1.205
1.125	**1.179**	**2.310**	**1.210**	**1.208**

It is seen that analyses are conducted up to the main rotor value of 1.125. The reason why the maximum rotor radius is 1.125 is the fact that a further increase in this value results in higher power requirements that cannot be achieved with the constraints of the attack helicopter. Therefore, the only available main rotor radius range is the one in Table 3. It is clear that as the radius increases, weight and performance outputs improve. As a consequence, a configuration with the maximum available main rotor radius would be the best one for the transport helicopter. This configuration's outputs are printed in boldface type at the end of Table 3. In terms of payload, mid-level commonality gives better results compared to high-level one. In the high-level case, the payload value was 1.93, while the one is 2.31 for mid-level commonality. That is, payload value is increased by 20% by switching commonality constraints from high-level to mid-level.

3.2 Comparison

The applications of the methodology developed for high and mid-level commonality are discussed in the previous sections of the paper. In addition to the results given for both levels, comparison tables are also created for further investigation on the subject. Because determining the extent to which to decide the level of commonality to be implemented on the conceptual level design studies is a question. Therefore, the methodology described herein should be repeated using different levels of commonality to be able to drive useful conclusions from the conducted trade-off studies. The aim of the case studies presented in this paper is to exemplify the methodology suggested, and not to drive a conclusion such that one commonality level is superior to another. Together with the performance analysis and design space exploration studies utilizing statistical methods, results are obtained for the high and mid-level commonality approaches. Some parameters of transport helicopters, which are designed with high and mid-level commonality concerns, regarding the geometry, weight, and performance are compared in Table 4 and Table 5. To do so, all the parameters of the transport helicopters were normalized with the parameters of the attack helicopter. Thus; in the first row of the tables (Attack Helicopter), one can see all the parameters are given as "1". It is obvious that main and tail rotor geometric parameters are constant for high-level commonality. On the other hand, they are calculated for mid-level commonality and all of them are found greater than the ones of attack helicopters as seen in the first four columns in Table 4. Not only geometric parameters of mid-level one but also calculated weight values of both transport helicopters are higher than the weight of attack helicopter. In Table 5, some of the performance parameters' results are given for comparison. The range and endurance values of both transport helicopters are higher approximately %20 than the ones of the attack helicopter. Maximum and best range speeds are almost the same; however, there exists a considerably high difference between the hover ceilings (out-of-ground effect) of transport helicopters, as expected. The reason why the high-

Table 4: Comparison of Geometric Parameters and Weights

	Rotor Diameter	**Main Rotor Chord**	**Tail Rotor Radius**	**Tail Rotor Chord**	**Gross Weight**	**Empty Weight**	**Fuel Weight**	**Payload**
Attack Helicopter	1	1	1	1	1	1	1	1
Transport Helicopter (High-Level Commonality)	1.00	1.00	1.00	1.00	1.10	1.07	1.28	1.93
Transport Helicopter (Mid-Level Commonality)	1.13	1.04	1.14	1.04	1.18	1.11	1.34	2.31

Table 5: Comparison of Performance Parameters

	Range	**Endurance**	**HOGE Ceiling**	**Maximum Speed**	**Best Range Speed**
Attack Helicopter	1	1	1	1	1
Transport Helicopter (High-Level Commonality)	1.19	1.17	0.91	0.89	0.57
Transport Helicopter (Mid-Level Commonality)	1.21	1.19	1.15	0.89	0.55

level common transport helicopter has a lower HOGE ceiling value than the attack helicopter is the fact that the main rotor parameters are the same but the weight of this configuration is higher than the attack configuration. For the mid-level configuration; since the main rotor geometric parameters are different and optimized for this configuration, there is no doubt that hover performance would be better, as seen in Table 5.

4. CONCLUDING REMARKS

The study presented here proses a thorough technique for commonality-based simultaneous design of rotorcrafts, which can drastically reduce the time and budget spent on research, development, and manufacture. Within de methodology suggested, the degree of commonality is also discussed. In conclusion, for all three levels, similar approaches are introduced to conduct conceptual level design studies of the attack and the transport helicopters with commonality constraints. As a part of this study, two different fully parametric CAD models of attack and transport helicopters, having a different set of parameters, except the ones related to commonality constraints, are created. The main purpose of the CAD models was to calculate the flat plate drag area (FPDA) and the weight of the helicopter, accurately. Together with the performance analysis and design space exploration studies, utilizing statistical methods, results are obtained for the high and mid-level commonality approaches. Obtained data presented in a comparative manner with tables to observe the alteration of the results depending on the level of commonality.

It is found that the conceptual evaluation studies with commonality concerns diverge the helicopter design from the optimal point, at which it would be there if it was designed according to the specified requirements only, independent of any commonality concern. That is, the higher the degree of commonality, the lower the number of optimization studies that can be conducted to fit the exact requirements specified for that configuration. As seen in the given example case study, performance parameters of the transport helicopter improve while changing the level of commonality from high to mid-level, as expected. Even though the commonality-based design approach results in configurations that are not at optimum points, the methodology would allow both designs to be in an acceptable range; close to the optima as much as possible. A considerable negative change in the performance parameters can be compensated with the reduction in time and money to be spent throughout the life-cycle of a product. Therefore, there is a need for a trade-off study of whether commonality should be a concern in the project or not. In the case of a decision in accordance with the inclusion of commonality constraints, another question, which is the level of commonality, emerges. Therefore, one more trade-of study should be conducted to be able to choose the optimum level for that specific case. To assess and evaluate possible design scenarios of both helicopters simultaneously, advantages of the commonality goals have to be taken into account, and the simultaneous design approach should be followed and analyzed by both designers and decision makers; then, the decision-making process needs to be led accordingly. The methodology explained herein would help this process to be followed with ease and in a more convenient way accelerating the conceptual design phase, and creating a baseline for further studies.

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