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# Analysis of Axiomatic Design Influence on Aircraft Design Process

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**ABSTRACT:** Today, product design has experienced fundamental changes. Design criteria have changed from focusing on product performance to sustainable criteria. This has increased the contrast between traditional and new requirements and consequently increases the design complexity. In this regard, traditional methods are incapable of solving the problems of product design. Therefore, many efforts have been made to solve these challenges to improve the design process. As a result of these efforts, various design methodologies such as multidisciplinary design optimization and knowledge-based engineering were developed. These approaches could support the evolutionary improvement of current product designs or the study of the novel complex product or could reduce the coupling between various FRs and design parameters (DPs). In this article, the authors discuss the effect of using the Axiomatic Design approach in the aircraft conceptual design process. The results obtained in this study indicate the high efficiency of this method in reducing the coupling between the FRs defined for the aircraft, as well as in reducing repetitive activities, thus optimizing the time and cost of the aircraft design process.

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## 1- Introduction

Product design is an iterative, complex, and decision-making engineering process. It starts by identifying a need, continues through a sequence of activities to seek an ideal solution, and ends with a detailed product description[1]. It is described as a progression through a set of "what-if" questions and answers that engage human, computing, and manufacturing resources, supported by laboratory results[2]. This process is very repetitive and needs continuous adaptation and modification during the design loops.

During the last decade, product design has been changed. Performance and durability criteria changed to sustainable design criteria such as being environmentally friendly, considering global warming, reducing energy consumption, reusing, recycling, and remanufacturing[3]. Consequently, in the last years, engineered systems become more complicated due to the increase in the number of FRs. Thus, the design process of a new product needs many decomposition layers[4].

Therefore, the complexity of the product design increases, which strongly relates to the dimensionality, size, and topology of the possible design space[5]. As a result, the traditional design approach represents some inherent limits, such as increasing evident interaction of many parameters, which make large sets of coupled equations for modelling the behaviour of systems[6]. Disability for compiling models needed in various disciplines, high risk of inconsistency by different actors or tools, and using more time to set up various analysis applications are other limits in using traditional design approaches. These limits lead to traditional design approach disability in handling such complexity with efficiency and effectiveness[7].

To solve these problems, a design approach needs which allow more design freedom in the conceptual design and provide more knowledge at an early phase about the design simultaneously. In this regard, designers try to develop and adopt new theories and methods during the conceptual design phase to improve the complex product design process. Thus, some new design methods and tools can support the evolutionary improvement of current product designs or support studying novel complex products developed in the last decades. Multidisciplinary Design Optimization (MDO) [8], Knowledge-based engineering (KBE) [9], and Multidisciplinary Design Analysis and Optimization (MDAO) techniques[10] are some of the most popular of these approaches.

In this article, the authors try to use the Axiomatic Design (AD) approach in the aircraft conceptual design process to identify the impact of this method on reducing the complexity of the design process. The results indicate the high efficiency of this method in reducing the coupling between different disciplines and decreasing repetitive activities, which leads

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to optimizing the time and the cost of the design process.

In this regard, the paper is structured as follows: Section 2 introduces a brief overview of AD place in the aircraft conceptual design process. Section 3 focuses on a UCAV design process as a case study to prove the influence of AD theory to increase design process modularity. Finally, the result of using AD and other tools in the UCAV design process is provided in Section 4.

## 2- Why AD in the airplane design process?

In the last few decades, to design complex products, some promising design methodologies developed to improve traditional design approaches. Despite their promise, they are not as widely applied as was expected at their birth. Both technical and non-technical challenges have hampered their successful exploitation and eventually reduced their scope to cases involving either a limited amount of disciplines or the application of low-fidelity analysis tools.[11]. One of the most important challenges is coupling between the different FRs of the primitives. This led to an increase in the design iteration. Consequently, the time and the cost of the design process are increased too.

In recent years, detailed research has been done in system design and modeling (such as MDO and KBE) of various disciplines related to aircraft, such as performance, aerodynamics, and flight mechanics. However, some other vital issues, such as system interactions(coupling), have received less attention, and a comprehensive solution to address them has not yet been stated[12].

On the other hand, one of the most essential approaches which could reduce coupling in the design process is the modularity natures of different disciplines involved in product design. The modular architecture is necessary for supporting collaborative and scattered design in new design approaches such as MDO, KBE. In these approaches, different discipline specialists must be able to take part in the design process with their own trusted tools[6]. The primary motivation for using these approaches is that the performance of a multidisciplinary system is driven not only by the performance of the individual disciplines but also by their couplings. By solving these problems early in the design process and taking advantage of advanced computational analysis tools in the following design steps, designers can simultaneously improve the design and reduce the time and cost of the design process. Therefore, the designers should try to define suitable FRs and Design Parameters(DPs) for the product to avoid or limit coupling between different disciplines that can disrupt the ability of design approaches[13].

In this regard, because modular architecture is commonly defined as having a one-to-one mapping from functional elements in function structure to physical parts of the product, it could be supported by the independence axiom in AD. Based on this axiom, FRs should be kept uncoupled with DPs[14].

Also, in modular architectures, there are more uncoupled or decoupled parts that cause less interference between products and consequently reduce the complexity of the product design process. It means the modular structure is consistent with the minimum information axiom of AD[7]. It is worth noting that such airplanes need more modular and less information (complexity) between DPs defined for the product, which considers as critical parameters for designing the complex product. Therefore, this feature guides us to consider the AD approach proposed by Suh (1990) in the airplane design process.

In this paper, FRs and DPs defined based on the independence axiom of AD for decomposing FRs and DPs. Then, modules are defined using DSM to modularize DPs at the bottom level of the zigzagging process. Concerning this explanation, we could determine the place of AD in the aircraft design process. Figure 1 shows the design algorithm this research considers for designing a UCAV.

## 3- Case Study

### 3- 1- A summary of the case study title

The aircraft design process is considered as an act of creativity. There is no one correct and absolute method that could ensure the best possible design for the product. In the 20th century, designers suggested the overall conceptual design process using techniques based on successive iterations[15]. These approaches

reported promising results for conventional aircraft that break up into different airframe parts with distinct functions( such as wings, tails, etc. )that could fulfil its requirements, and designed and optimized relatively independently from others. But today, due to the emergence of new requirements for aircraft and the introduction of innovative concepts for satisfying these requirements, the traditional design approach represents some inherent limits in the design process.

On the other hand, Unmanned Combat Air Vehicles (UCAVs) are a type of drone designed to perform missions previously performed by manned fighters or bombers. These drones, which are categorised in a class between fighters and bombers[16] have some contrasting characteristics such as stealth, suitable stability, controllability, high manoeuverability, and agility. UCAV design involves a higher integration of multiple aircraft design disciplines from the earliest design stages due to the dominance of stealth and high-performance constraints and requirements[17]. Technological challenges, particular configuration, and high contrast and coherence between the requirements defined for this type of drone have increased the complexity of its design process. The lack of a robust database due to the new configuration and very limited production of this kind of UCAV is another challenge of this type of drone. Consequently, using the traditional design approaches significantly increases the required time and cost of the design process and is less suited for new configurations such as UCAV [18]. In this paper, designers will investigate the effect of the AD principle in UCAV conceptual design at two different levels. The first one is the disciplinary level which examines the impact of using the AD approach in improving the design process of the various disciplines involved in the aircraft design, such as weight sizing, performance, stability, etc. In the second level

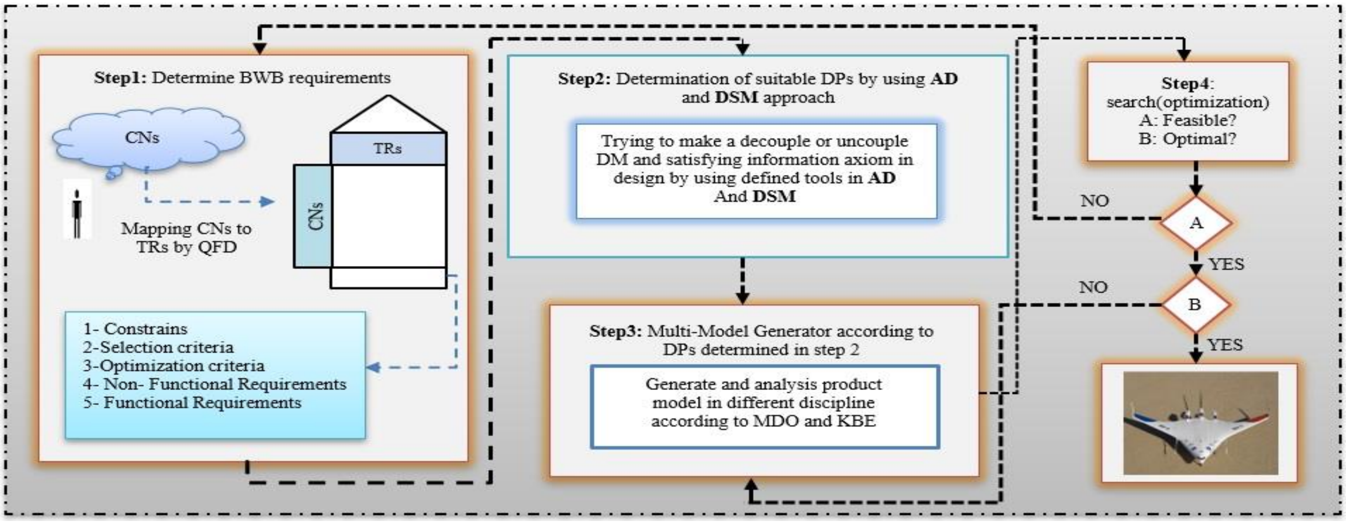



**Fig. 1. The architecture of the UAV by using AD frameworks**

that named system level, designers examine the influence of the using AD approach on the whole design process. In fact, at this level, the designers try to achieve an optimal design cycle for the UCAV design process by using appropriate solutions and controlling the coupling between different disciplines involved in aircraft design.

### 3- 2- Name and academic information of the authors

In the past century, different methods such as Torenbeek, Roskam, Rentema, or Raymer methods were suggested for aircraft design. These traditional conceptual design approaches could select new system concepts by interpolating or extrapolating existing system concepts[19]. All of these design processes consist of some iteration cycle that helps designers develop the suggested concept to meet customer requirements[20]. These iteration processes lead to increased design time and cost. In other word, in these traditional methods, aerodynamics and propulsion generally were the two most critical disciplines that should achieve the required aircraft performance[21]. Consequently, these methods are very powerful when extending on existing system concepts because the method's inherent simplifications shorten the conceptual design process[19].

But in the last decades, requirements have changed from performance criteria to sustainable criteria such as considering global warming and reducing energy consumption. These changes led to increasing complexity in engineered systems[4].

The question that should be answered here is that, with such changes in aircraft requirements, will the traditional design methods and related design cycles still be appropriate? Can designers use these traditional methods for UAVs (especially stealth UCAV) design process? And most importantly, is it possible to improve and optimize these traditional approaches according to newly represented requirements and new aircraft concepts?

In this research, designers apply AD principles in the UCAV design process based on the Roskam design method and investigate its influence on design cycle improvements. Therefore, according to Fig.1, the following steps should be done respectively:

***Step 1-determine UCAV design requirements:***

UCAV is a combat platform with lower cost and performance characteristics than traditional manned combat aircraft and is mainly used for high-risk ground attacks. The nature of the developed UCAV is between the fighter and bomber, close to the traditional attacker conceptually[16]. Therefore, we could determine the original requirements for a UCAV and summarize them to:

- Armament carrying capability of 2x1000[kg] bombs or missile (according to X-47B [22];
- Service ceiling: 42,000 ft (12,190 m) [22];
- Cruise speed @ M=0.9 for 2,100 nm [22];
- Direct climb to 42,000 ft at max WTO in 8 minutes is desired[23];
- Take-off and landing ground run of fewer than 700m at sea level and a 95 F0 day;
- UCAV has performance specifications near A-10 and Northrop Grumman F5F Tiger II [16].
- The operation range should be 2100 NM with refuelling

**Table 1. CNs and corresponding TRs**

| Non-FRs | Constrains |
|---|---|
| **Low life cycle-cost (9)** | Tailless configuration (9) |
| **Light structural weight (8)** | Carrying 2000kg bombs (6) |
| **Reliability and safety (9)** | 10 min aerial refuel & 20 min loiter (8) |
| **UCAV CNs** | **Equal FRs for UCAV CNs** |
| **Performance near A-10 & F5F (8).** | To have suitable performance. |
| **Surviving against different countermeasures (9)** | To use stealth technology |
| **Suitable controllability and stability (8).** | To satisfy standards handling quality |
| **Having adequate aerodynamic performance (9)** | To try optimizing aerodynamic characteristics. |

capability [22].

- UCAV must have a low life cycle cost and a survivable design [24].
- UCAV needs to have Stealth technologies to survive against countermeasures[25].
- UCAV needs to have adequate manoeuverability between that of fighter and bomber.[16].
- UCAV needs to have a high lift over-drag ratio [26].
- UCAV should have a light structural weight [26].
- UCAV should have good handling quality and trim ability [27] and autonomous vehicles[24].
- UCAV should have a tailless configuration for stealth reasons;
- UCAV should be designed for reliability and safety.

The above requirements are expected characteristics of the UCAV that customers need. These Customer Needs (CNs) are not suitable for starting the design process because of their ambiguous description and may confuse physical objects for FRs. Also, customers usually provide vague (subjective) specifications or provide very general ideas [28] about the product characteristics. Consequently, the designer should define appropriate Technical Requirements (TRs) of the UCAV, which are related to determined CNs.

Generally, QFD is a suitable method to translate these ambiguous CNs into measurable TRs through a cascading series of relationship matrixes. The relationship matrix ensures that every CN is addressed by at least one element in design and further helps designers better understand the most essential design elements [29]. Therefore, in this paper, designers try to use QFD for mapping determined CNs to suitable TRs. Table1 demonstrates CNs and their importance to the user and their corresponding TRs related to UCAV design which was obtained by using the QFD tool.

***Step 2- Determination of suitable DPs by using AD and DSM:***

Corresponding DPs consist of the main FRs-DPs in the first level of design. However, they could not represent UCAV specifications entirely because of their comprehensive. Therefore, they should be decomposed into adequate sub-FRs and sub-DPs based on the AD approach. In this article, the designer uses D.D Tate guidelines[30] to decompose main FRs-DPs. All parent FRs-DPs use a similar decomposition format based on Tate guidelines. The decomposition process will continue until the function associated with the final sub-FRs is classified as a secondary function that does not belong to the primary path[30]. In this project, main FRs-DPs are decomposed to the fourth level of design hierarchy according to represent guidelines. Because of brevity in this paper, only sub-FRs and their corresponding DPs FR2 is illustrated as follows:

**$FR_1$:** To have suitable performance specifications based on the mission profile.

**$FR_2$:** To use stealth technology for UCAV.

**$FR_{2.1}$**: To scatter energy in directions away from the radar[31].

**$FR_{2.1.1}$**: To reduce UCAV RCS by using Suitable configuration.

**$FR_{2.1.2}$**: To avoid specular returns from the body.

**$FR_{2.1.3}$**: To avoid specular scattering from the critical surface (cavities etc.).

**$FR_{2.1.3.1}$**: To avoid specular scattering from cavity inlets and exhausts.

**$FR_{2.1.3.2}$**: To avoid specular scattering from the intersection of a trailing edge at right angles with a fuselage.

**$FR_{2.1.4}$**: To avoid scattering because of end-region discontinuity (Sidelobe Scattering).

**$FR_{2.1.5}$**: To avoid specular returns because of edge diffraction.

**$FR_{2.1.6}$**: To avoid scattering because of tip diffraction.

**$FR_{2.2}$**: To reduce energy reflected back to radar[31]

**$FR_{2.2.1}$**: To reduce energy reflected back to radar from critical components.

**$FR_{2.2.1}$**: To cancel reflected energy from UCAV.

**$FR_3$:** To try optimizing aerodynamic characteristics.

**$FR_4$:** To satisfy handling quality for the UCAV based on standards.

**$DP_1$:** Suitable weight and take-off thrust to weight ratio sizing for UCAV [2].

**$DP_2$:** Trying to reduce radar cross section (RCS) [6].

**$DP_{2.1}$**: Suitable decision about UCAV shape and configuration[31].

**$DP_{2.1.1}$**: Using diamond flying wing configuration (Northrop Grumman X-47B) for UCAV.

**$DP_{2.1.2}$**: Having no surface (planar, singly or doubly curved) normal pointing into the threat region.

**$DP_{2.1.3}$**: Using multiple bounce structures for critical surface.

**$DP_{2.1.3.1}$**: Designing cavity inlets and exhausts with covering screens or by serpentine shaping

**$DP_{2.1.3.2}$**: Using multiple bounces structures for the intersection of a trailing edge at right angles with a fuselage.

**$DP_{2.1.4}$**: Minimizing end region area to reduce discontinuity scattering.

**$DP_{2.1.5}$**: Sweeping horizontal wing and tail leading and trailing edges.

**$DP_{2.1.6}$**: Reducing included angle.

**$DP_{2.2}$**: Using radar absorbing materials, passive and active cancellation methods[31].

**$DP_{2.2.1}$**: Using radar absorbing materials to reduce energy reflected back to radar from critical components.

**$DP_{2.2.2}$**: Using passive and active Cancellation to reduce RCS.

**$DP_3$:** Trying to have a high lift-to-drag ratio and minimized aerodynamic drag [6].

**$DP_4$:** Using MIL-F-8785C and MIL–STD–1797A to satisfy handling quality requirements [32].

Finally, we have the complete sets sub-FRs and sub-DPs, in different levels of the design hierarchy. Consequently, designers could construct the final DM. This DM could demonstrate the influence of FRs on each other satisfaction. Identifying coupling between different FRs and reducing iterative activities in the UCAV design process are other functions of this DM.

Unfortunately, because of the complex nature of the UCAV, DM cannot satisfy the independence axiom completely. This causes increasing iterative activities in the design process. To overcome this challenge, designers could manipulate DM to translate it to lower triangle DM. At this stage, a certain amount of layout design, such as integration of components or translating parent FR-DPs to a lower level of the design hierarchy, may need to be done[33]. The approach that could be used to solve this problem is DSM. This tool can reorder and minimize feedback loops and render the matrix as "lower-triangular" as possible [33]. The first stage of this approach is obtaining DSM from DM of the fourth layer achieved in the decomposition process and consists of three steps presented by Dong and Whitney altogether[34]. In the next stage, the constructed DSM should be partitioned to eliminate feedback and move DM as close as possible to the diagonal matrix. There are several approaches used in DSM partitioning, such as path searching (used in this project) and powers of the Adjacency Matrix Method; however, they are all similar with a difference in how they identify cycles (loops or circuits) of information [35]. At the end of these processes, the final DM could be constructed. The comparison between this final DM (Figure 2) and DMs in the third and fourth layers demonstrate the influence of using mentioned strategies to improve the design process.

Finally, DM is not a diagonal or triangular matrix that is ideal for the design process of a product. But using AD, QFD, and DSM, helps designers to reduce coupling and consequently repetition in the design process. In fact, according to steps 1 and 2 of the design algorithm shown in Figure 1, considering QFD, AD, and DSM in the design process could avoid or limit coupling between different FRs. This helps designers to eliminate inherent limitations presented by design frameworks because of less modularity in various product disciplines.

***Step 3- Develop a proper design cycle for UCAV:***

According to the Roskam design approach, designers should determine aircraft configuration after the aircraft weight sizing. In this phase, designers decide parameters such as overall configuration, fuselage layout, propulsion system, etc. Also, this process is broken down into two sequences. Preliminary design sequence I involve 16 design steps and preliminary design sequence II with 30 steps. In this research, only the first sequence has been examined. This process is shown in Figure 3 in the form of a diagram. According to this diagram, it should be noted that the configuration design process is a non-unique and iteration process. During this phase, almost 90 percent of the life cycle cost of the airplane gets locked[36]. Therefore, it is necessary to use appropriate approaches that could reduce the iteration process of the design cycle.

As shown in Figure 3, there are three iteration cycles in the Roskam preliminary design approach in sequence I. For example, if the stability and control results are not satisfactory based on aircraft type, designers should make minor adjustments to wing and landing gear location. Also, in step 11, if the L/D computed value is not compatible with sizing requirements considered in preliminary design phases, designers should go back to step 2 and repeat the design process with new decisions. This means that to get the right size of the L/D parameter, designers should repeat ten steps (from step 2 to step 11). But in this article, it is shown that by using AD principles, we can get a better and more optimized cycle for the UCAV design process to the Roskam design cycle.

For example, according to DM constructed based on the

| | DP2.2.1 | DP2.2.2 | DP1.1.1.1 | DP2.1.4 | DP2.1.6 | DP2.1.3.1 | DP2.1.3.2 | DP2.1.5 | DP 2.1.2 | DP2.1.1 | DP4.1.1 | DP4.1.2 | DP1.1.1.2 | DP1.1.1.3 | DP1.2.1 | DP1.2.2 | DP1.2.3 | DP1.2.4 | DP1.2.5 | DP1.2.6 | DP3.1.1.1 | DP3.1.1.2 | DP3.1.2.1 | DP3.1.2.2 | DP3.1.2.3 | DP3.3.1 | DP3.3.2 | DP3.3.3 | DP3.2.2 | DP3.2.1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FR2.2.1 | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.2.2 | O | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR1.1.1.1 | O | X | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.4 | O | O | O | | X | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.6 | O | O | O | X | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.3.1 | O | O | O | O | O | | O | X | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.3.2 | O | O | O | O | O | O | | X | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.5 | O | O | O | X | O | X | X | | X | O | X | X | O | O | O | O | O | O | O | O | X | X | O | X | X | X | O | O | O | O |
| FR2.1.2 | O | O | O | O | O | X | X | X | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR2.1.1 | O | O | O | O | O | O | O | O | O | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | X | X | X | O | O |
| FR4.1.1 | O | O | X | X | X | O | O | X | O | O | | X | X | X | X | X | X | O | X | X | O | X | O | O | X | X | O | O | O | O |
| FR4.1.2 | O | O | X | X | X | X | X | X | X | X | X | | X | X | O | X | X | X | X | O | O | X | O | O | O | O | O | O | O | O |
| FR1.1.1.2 | X | X | O | X | O | O | O | X | O | O | X | X | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR1.1.1.3 | X | X | O | X | O | O | O | X | O | O | X | X | O | | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| FR1.2.1 | X | X | X | X | O | O | O | X | O | O | X | O | X | X | | X | X | X | X | X | O | X | O | O | X | X | O | O | O | O |
| FR1.2.2 | X | X | X | X | O | O | O | X | O | O | X | X | X | X | X | | X | X | X | X | O | X | O | O | X | X | O | O | O | O |
| FR1.2.3 | X | X | X | X | O | O | O | X | O | O | X | X | X | X | X | X | | X | X | X | O | X | O | O | X | X | O | O | O | O |
| FR1.2.4 | X | X | X | X | O | O | O | X | O | O | O | X | X | X | X | X | X | | X | X | O | X | O | O | X | X | O | O | O | O |
| FR1.2.5 | X | X | X | X | O | O | O | X | O | O | X | X | X | X | X | X | X | X | | X | O | X | O | O | X | X | O | O | O | O |
| FR1.2.6 | X | X | X | X | O | O | O | X | O | O | X | O | X | X | X | X | X | X | X | | O | X | O | O | X | X | O | O | O | O |
| FR3.1.1.1 | O | O | O | O | O | O | O | X | O | O | O | O | O | O | O | O | O | O | O | O | | O | O | O | O | X | O | O | O | X |
| FR3.1.1.2 | O | O | X | X | O | O | O | X | O | O | X | X | X | X | X | X | X | X | X | X | X | | O | O | O | X | O | O | O | O |
| FR3.1.2.1 | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | | O | O | O | X | X | X | O |
| FR3.1.2.2 | O | O | O | O | O | O | O | X | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | | O | O | X | X | X | O |
| FR3.1.2.3 | O | O | X | X | O | O | O | X | O | O | X | O | X | X | X | X | X | X | X | X | O | O | X | X | | O | X | X | O | O |
| FR3.3.1 | O | O | X | X | O | O | O | X | O | O | X | O | X | X | X | X | X | X | X | X | X | X | O | O | O | | O | O | O | O |
| FR3.3.2 | O | O | X | X | O | O | O | O | O | O | X | O | X | X | O | O | O | O | O | O | O | O | X | X | X | O | | O | O | O |
| FR3.3.3 | O | O | X | X | O | O | O | O | O | O | X | O | X | X | O | O | O | O | O | O | O | O | X | X | X | O | O | | O | O |
| FR3.2.2 | O | O | X | X | O | O | O | O | O | O | O | O | X | X | X | X | X | X | X | X | O | O | X | X | O | O | O | O | | O |
| FR3.2.1 | O | O | X | X | O | O | O | O | O | O | O | O | X | X | X | X | X | X | X | X | X | O | O | O | O | O | O | O | O | |

**Fig. 2. Final Design Matrix**

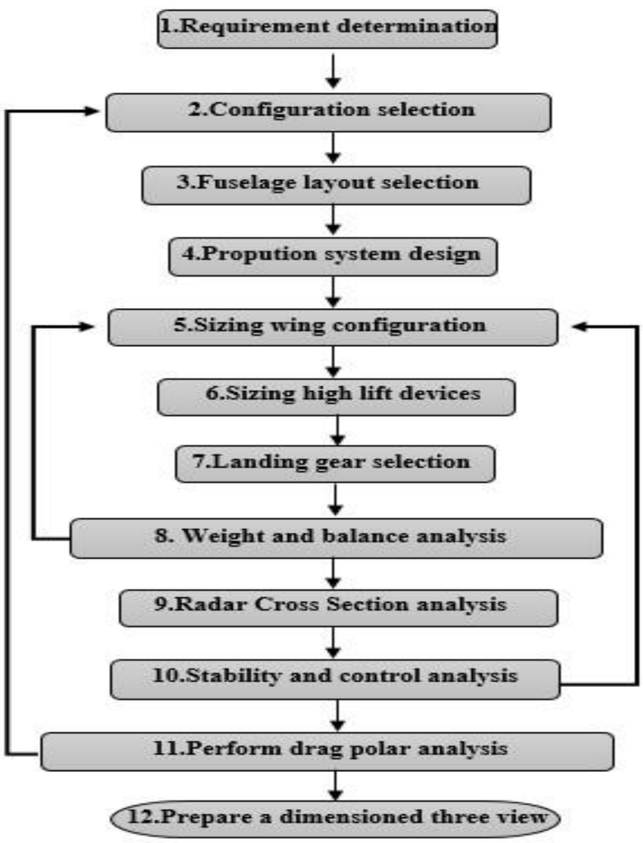



**Fig. 3. Airplane Roskam design cycle**

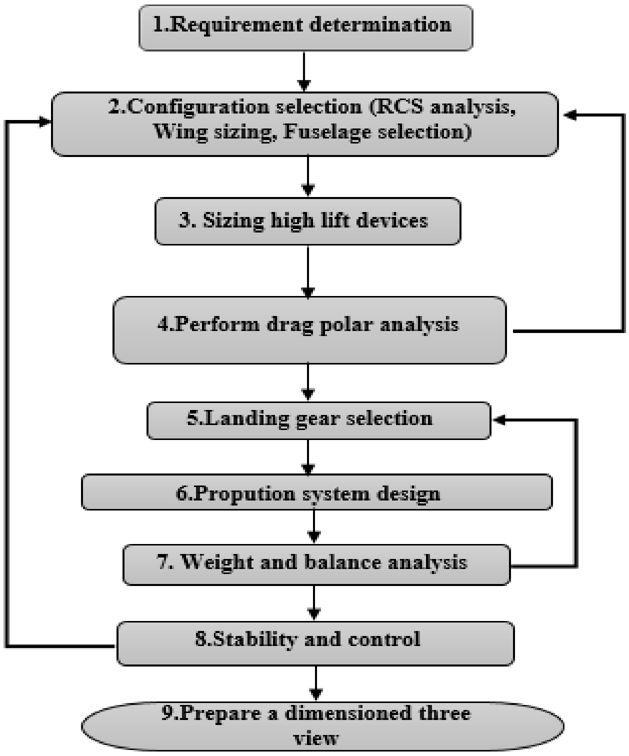



**Fig. 4. Design cycle according to AD**

independent axiom of the AD approach (Figure 2) and the configuration used for the UCAV, it is easy to understand that the configuration selection, fuselage layout selection, wing sizing, and RCS analyses steps have high coupling with each other. Consequently, these steps can be combined into one step as a configuration selection step. This combination has a high impact on the design step and iteration cycle reduction. Also, the L/D and CD0 parameters size (FR4.1.1 and FR4.1.2 in Figure 2) only depend on the UCAV configuration and the high lift device. Consequently, if the L/D value can not satisfy the expected requirements, only step 2 to step 4 of the new diagram shown in Figure 4 should be repeated. It means that the number of iteration processes reduced from ten steps in the Roskam cycle (Figure 3) to four steps in the design cycle optimized by AD principle.

Therefore, by using the AD approach at the system level, designers can construct a more optimized design cycle compared to the Roskam approach. Also, it is necessary to say that this new design cycle has been constructed according to UCAV represented requirements. Consequently, by changing these requirements or UCAV missions and constraints, the design cycle will be changed.

### 3- 3- Using AD at the disciplinary level

After analyzing the impact of using the AD approach in the system-level design of the UCAV design process, it is necessary to examine the effect of this approach at the disciplinary level. In this regard, designers should use the AD principles in different UCAV disciplines design processes such as weight sizing, performance, stability analysis, and aerodynamic disciplines. Therefore, in this paper, the weight sizing and performance disciplines are designed based on the AD approach as a case study.

To better verification of the obtained results from this approach, this process is done based on the Roskam design approach too. First, designers only use the Roskam approach in the weight and performance sizing process and then repeat the design process by applying AD principles and finally compare the results of these two ways with each other. The result of these processes is expressed as follows:

#### 3- 3- 1- UCAV Weight sizing by Roskam approach:

According to the Roskam approach, the first step of the airplane design process is the prediction of the minimum airplane weight and fuel weight needed to accomplish a given

**Table 2. CNs and corresponding TRs**

| | $DP_{2.2.1}$ | $DP_{2.2.2}$ | $DP_{2.1.1}$ | $DP_{2.1.5}$ | $DP_{4.1.1}$ | $DP_{4.1.2}$ |
|---|---|---|---|---|---|---|
| $FR_{1.1.1.1}$ | --- | --- | --- | --- | --- | --- |
| $FR_{1.1.1.2}$ | * | * | * | --- | --- | --- |
| $FR_{1.1.1.3}$ | --- | --- | * | * | * | * |

**Table 3. Estimated weight in Roskam and AD**

| | Roskam | AD | X-47B |
|---|---|---|---|
| $W_{TO}$ | 20000 | 20000 | 20000 |
| $W_{PL}$ | 2000 | 2000 | 2000 |
| $W_{OE}$ | 10312 | 7995 | 8000 |
| $W_F$ | 9687 | 10005 | 10000 |

mission[23]. He suggests that to estimate the take-off weight ($W_{TO}$), designers could breakdown $W_{TO}$ as follows:

$$W_{TO} = W_{OE} + W_{PL} + W_F \quad (1)$$

$W_{OE}$, $W_{PL}$, and $W_F$ are airplane operating weight empty, payload weight, and mission-fuel weight, respectively. Roskam suggests seven-step to estimating the value of these three parameters used for airplane weight sizing in this research. The results of weight sizing by using this guideline are 10312 kg, 2000 kg, and 9787 kg, respectively.

### 3- 3- 2- UCAV Weight sizing by using AD principles:

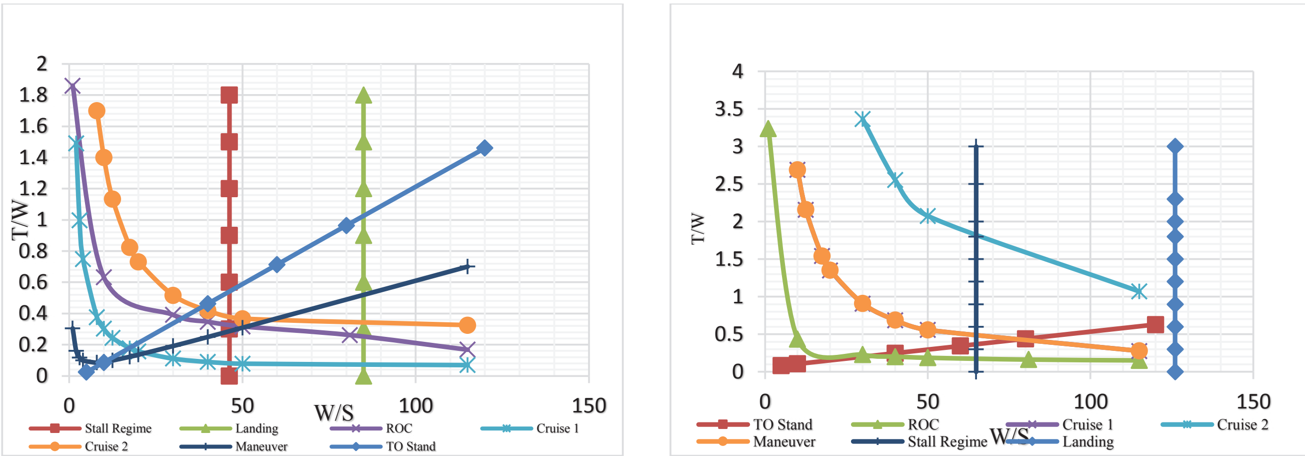
In this section, we try to estimate UCAV weight according to AD principles. In this regard, the designer should use DM constructed based on AD shown in Fig. 2. According to this figure, the solution defined for some requirements such as $DP_{2.2.1}$ and $DP_{2.2.2}$ has been influenced by the satisfaction of WOE, WPL, and WF ($FR_{1.1.1.1}$, $FR_{1.1.1.2}$, and $FR_{1.1.1.3}$) requirements. The coupling between weight sizing requirements and other UCAV requirements is shown in Table 2. According to this table, the solution of stealth and aerodynamic requirements influences weight sizing requirements. Therefore, it is necessary to consider the effect of these requirements on the weight of the UCAV. This activity eliminates the probability of the iteration of the weight sizing process due to failure to meet these requirements. For example, according to Table 2, the solution of the $FR_{2.2.2}$($DP_{2.2.2}$: Using absorbing materials) influences UCAV's empty weight due to the weight of the absorbing material. Consequently, the designers should satisfy the $W_{OE}$ depending on the weight of the absorbing materials.

### 3- 3- 3- The comparison of the result of using Roskam and AD approach in weight sizing

In this research, the designers design a UCAV similar to X-47B. Consequently, this UCAV is considered as a design criterion. Therefore, designers could compare the result of the weight sizing process by Roskam and AD approaches with the X-47B specification. This helps designers identify better the influence of the AD approach in the weight-sizing process. Table 3 shows the weight parameters for the Roskam approach, AD approach, and X-47B information. According to this table, in both methods, $W_{TO}$ and $W_{PL}$ are selected similar to X-47B. In contrast, the $W_{OE}$ and the $W_F$ are different entirely. In this regard, the $W_{OE}$ estimated by the AD approach is 7995 kg which is very similar to X-47B. In this case, weight sizing is completed, and the designer should not repeat it. On the other hand, the $W_{OE}$ estimated by the Roskam approach is 10312 kg which has almost a 20% difference with the X-47B empty weight. Therefore, it is necessary to repeat the weight sizing process to obtain suitable weight values. Therefore, using the AD approach reduces repetition cycles and saves time and the cost of the design process.

### 3- 3- 4- Using AD in performance sizing:

After obtaining the final design matrix (Figure 2) based on AD, the preliminary aircraft design process can be started. Generally, the wing area and take-off thrust should be determined in such a way that could satisfy the aircraft requirements in various flight phases. Consequently, to meet the performance requirements, sizing these two parameters




**a) Matching Diagram based on AD**

b) Matching Diagram based on the Roskam approach

**Fig. 5. Matching diagram based on the Roskam approach**

must be assessed in the Stall speed, Take-off field length, Landing field length, Cruise speed (sometimes maximum speed), Climb rate and Maneuvering categories. According to Roskam methodology, the standard approach to sizing wing area and required take-off thrust is to determine a range of values of wing loading(W/S) and thrust loading(T/W) within which specific performance requirements are met. From these data, it usually follows that the combination of the highest possible wing loading and the lowest possible thrust loading, which still meets all performance requirements, results in an airplane with the lowest weight and the lowest cost [23]. But based on the proposed algorithm in Figure 1, before sizing wing area and thrust loading, the designer should determine the relation between performance FRs (FR1.21-FR12.6), that influenced wing area and required take-off thrust, and other FRs (Figure 2). In this paper, we size the wing area and required take-off thrust by using both proposed approaches based on AD and the traditional Roskam method. Then compare the results of these two approaches to analyze the impact of using AD in the design process.

Roskam suggested that by having the required rate of climb (ROC), it is possible to find adequate wing loading and thrust to weight ratio according to equation 2.

$$\left(\frac{T}{W}\right)_{ROC} = \frac{ROC}{\sqrt{\dfrac{2}{\rho\sqrt{\dfrac{C_{D_0}}{K}}}\left(\dfrac{W}{S}\right)}} + \frac{1}{\left(\dfrac{L}{D}\right)_{\max}} \quad (2)$$

In this equation, ROC determined 96 fps based on UCAV requirements. Also, $C_{D0}$, $\left(\frac{L}{D}\right)_{max}$, and $K$ are estimated according to equations and data proposed by Roskam for jet-driven military aircraft. In this regard, these parameters are 0.09, 10, and 0.7, respectively. Consequently, the allowable wing loading ratio and thrust-to-weight ratio to meet ROC requirements according to the traditional Roskam approach are shown in Figure 5-a.

Also, according to DMs constructed based on AD axioms, the defined DPs of FR2.1.1, FR2.1.4, FR2.1.5, FR4.1.1, FR4.1.2, FR3.1.1.1, FR3.1.1.2, and FR3.1.2.3 have an impact on the satisfaction of ROC requirement (FR1.2.3). Consequently, if the designer tries to satisfy FR1.2.3 without considering related FRs (determined in DM), related DP(DP1.2.3) may have an undesirable effect on the satisfaction of other FRs. In such cases, the designer must do the design process repeatedly to achieve desired goals, which increases the time and cost of the design process.

Therefore, the designer should try to satisfy FR1.2.3 according to the final DM (Figure 2) in such a way that does not hurt the fulfilment of other requirements. In this regard, they should determine the main parameters of equation 2 to be consistent and appropriate to BWB UCAV configuration (FR2.1.1) and other FRs (FR2.1.4, FR2.1.5, FR4.1.1, FR4.1.2, FR3.1.1.1, FR3.1.1.2, and FR3.1.2.3). This causes that the response of FR1.2.3 does not conflict with other FRs. Consequently, the repetition cycle in the design process is reduced.

For example, the designer could select the value of $C_{D0}$ and $\left(\frac{L}{D}\right)_{max}$ and k parameters based on the similar BWB UCAV. In this paper, the value of these parameters is 0.01 and 16, respectively, according to X-47B UCAV [37]. Also,

**Table 4. The value of W/S, T/W, S and T for X-47B, AD and Roskam approaches**

| Parameter | Unit | Roskam | AD | X-47B |
|---|---|---|---|---|
| W/S | Lb/$ft^2$ | 64.85 | 46.26 | **---** |
| T/W | --- | 1.647 | 0.541 | **---** |
| S | $Ft^2$ | 679.9 | 953 | **954** |
| T | lb | 72621 | 23854 | **24957** |

the suitable value of aspect ratio (AR) of this configuration is considered four due to similar UCAV[22], and Oswald's efficiency factor (e) for a tailless configuration is 0.7. This value is entirely different from those provided in Roskam airplane design books. Also, the ROC value was determined 96 fps based on UCAV requirements. Finally, the allowable wing loading and thrust-to-weight ratio to meet ROC requirements according to the Roskam approach by using AD axioms is shown in Figure 5.

This process should be done for sizing other performance requirements. Finally, designers should match all of them together and determine the lowest possible thrust-to-weight ratio and the highest possible wing loading as design points consistent with all requirements. Figure 5 shows these two-matching diagrams and the design point for AD and Roskam approaches. Therefore, point p (for Figures 5-a when the AD approach is used) and point Q (for Figures 5-b when the Roskam approach is used) are selected as a suitable design point.

Since the purpose of this study is to design a combat drone similar to X-47B, the wing area and take-off thrust value are obtained from diagrams 12. a and 12. b should be compared with X-47B values. This helps us to understand well the influence of using AD axioms and their DM in the design process. Table 4 shows the value of W/S, T/W, S, and T for these three cases. According to Table 4, the value of wing area and take-off thrust obtained by using the AD approach is closer to X-47B specifications compared to the Roskam approach. These results were obtained in other parts of the design process, such as weight sizing and preliminary configuration design. The result could prove the positive influence of the AD approach in the correct decision-making of the designer and the reduction of repetition in the design process.

## 4- Conclusion

In the last decades, some new approaches such as MDO, KBE, etc. have been developed to improve complex product design processes. But some different challenges can adversely affect the performance of these approaches. The coupling between FRs and disciplines involved in product design is one of the most important of these challenges that can significantly reduce the efficiency of these approaches. Consequently, in the last years, many efforts have been made to reduce the coupling in complex system design processes. In this paper, designers tried to analyze the influence of AD to reduce the coupling in the aircraft design process. In this regard, they first discussed the challenges and limits of the traditional design process. Next, the place of AD in the aircraft design process is discussed, and a framework based on AD approaches is proposed (Figure 1) to limit coupling between different FRs and improve the probability of success of the design process. Finally, they use the final DM constructed based on AD axioms to start the initial sizing of UCAV. In this way, the conceptual design process of the UCAV is discussed based on the traditional Roskam approach and AD principle, respectively. The comparison of these two approaches demonstrates the positive influence of AD axioms in the design process. According to this information, the results of this research can be listed as follows:

1- According to the result of the research, the AD concept can be used as a multi-level optimization template in complex product conceptual design processes (at both system-level and disciplinary levels).

2- In the system-level optimization process, designers could achieve an appropriate and optimized design cycle by using AD principles. In this paper, Figure 4 shows the optimized design cycle completed, according to DM (Figure 2) constructed by AD axioms. The comparison of Figure 3 and Figure 4 shows the iteration design steps reduced from 20 in the Roskam approach to 13 in the AD approach causing the reduction in time and the cost of the design process.

3- At the disciplinary level, designers can identify the coupling between different FRs and select the best solution to satisfy them. Consequently, the iteration probability of the FRs sizing process, due to ignoring other FR's constraints, will be reduced.

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