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A Data Management and Visualization Tool for Integrating Optimization Results in Product Development

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Abstract

This paper presents a data management and visualization tool that was developed in parallel with a Multidisciplinary Design Optimization (MDO) framework in order to enable a more effective use of the obtained results within the Product Development Process (PDP). To this date, the main problem is that the majority of MDO case studies conclude by suggesting a small number of optimal configurations, which do not really hold any meaningful value for the decision makers since they represent only a narrow area of the design space. In this light, the proposed tool aims to provide designers with new possibilities in respect to post-processing of large data sets, and subsequently, to allow the non-technical teams to be engaged and benefit from the use of MDO in the company practices. As an example, an Unmanned Aerial Vehicle (UAV) configurator developed by using the Graphical User Interface (GUI) of MATLAB is herein presented, and it is shown that a tool for handling the results can be the logical next step towards integrating MDO in the manufacturing industry. Overall, this work aims to demonstrate the benefits of the present visualization and management tool as a complementary addition to an existing optimization framework, and also to determine if this approach can be the right strategy towards improving the MDO method for an eventual use in the PDP of complex products like UAVs.

Keywords: Big Data, Digital Design

Introduction

Complex engineering systems are a class of products with many intricate synergies as well as numerous performance requirements, and as such, they are typically seen by the manufacturing industry as a major economic challenge. To no surprise, higher design quality but also faster development times have evolved into two key concepts, and it can be observed that those can often determine the success of the product and the organization's strategic advantage (Karniel & Reich, 2011). In this increasingly competitive market, it has become of utmost importance for companies to enhance their traditional Product Development Process (PDP), and according to the current paradigm, one way of achieving this is through the use of more efficient development methods and state-of-the-art design tools (Ulrich & Eppinger, 2012).

To this end, a field of engineering that has shown many successful results within the PDP of complex products is the use of simulation-based Multidisciplinary Design Optimization (MDO). Since the first applications of MDO almost 30 years ago, research has been constantly expanding, and today it is possible to implement a large number of analysis capabilities (Agte et al., 2009) but also to take advantage of even more powerful software and hardware solutions (Simpson & Martins, 2011). Nevertheless, research on MDO has been to this date focusing excessively on improving its technical aspects, whereas at the same time, its organizational and cultural integration have been often neglected or overlooked (Belie, 2002). As an example of this, there are numerous MDO case studies which conclude by providing optimization results, but very limited work on how those results can be effectively used by the decision makers, or how optimization can be used with the rest of the PDP activities (Wang et al., 2014).

In light of the above, this paper presents a holistic approach towards improving the PDP through the use of MDO, and it elaborates on the development of a data management and visualization tool that is intended to work in parallel with a traditional optimization framework. The industrial application that was selected herein was that of Unmanned Aerial Vehicles (UAVs) for search and rescue operations because they have an inherent system complexity and there is currently a very high market demand for better performance and more units (Camhi, 2016). For this paper, the MDO framework is only briefly summarized since it is based on a previous work by the authors (Papageorgiou et al., 2017a; Papageorgiou et al., 2017b), while the main contribution, and thus the primary focus is on the development particulars of the UAV "configurator" tool and its potential benefits for achieving organizational integration.

Overall, the paper is divided into 8 chapters with the introduction being the first and then followed by a brief literature review on relevant MDO topics that is presented in the frame of reference. The third, fourth, and fifth chapter are about the details of the optimization framework and the configurator tool, while the sixth chapter presents results from an example case study that aims to illustrate and evaluate the newly added possibilities. Finally, this paper sums up with a discussion section and then some concluding remarks.

Frame of Reference

Product development process

In its most common form, a typical PDP starts with an idea and ends with manufacturing, while in-between, the design goes through many stages of refinement as well as control gates that check if the desired requirements have been met (Cooper, 1990). In this process, the early stages are characterized by increased uncertainty, which means that the design is still not fully defined, but on the other hand, there is also significant freedom to make changes without generating additional monetary or time costs for the organization (Ulrich & Eppinger, 2012). To this end, two important considerations for the preliminary phases of the PDP are to be able to evaluate a large number of concepts as quickly as possible, whereas at the same time, the analysis of the results should be presented in an adequate manner that enables decision makers to make their own assessments before advancing to the next control gate (Karniel & Reich, 2011).

Aircraft multidisciplinary optimization

In order to enable a basic MDO it is first and foremost crucial to develop the necessary disciplinary models that can capture the physics of the problem (Gazaix et al., 2011), while at a secondary level, it is equally important to align the fidelity of the implemented tools with the development stage and the design maturity of the product (Piperni et al., 2013). A typical MDO framework for conceptual aircraft design needs to be able to go through numerous designs at very fast speeds, and thus, the common practice is to implement empirical equations that have very low computational demands but offer sufficiently good predictions for this initial stage (Amadori et al., 2007).

In its most common form, an MDO framework for conceptual aircraft or UAV sizing is comprised of several basic aeronautical models, like for example aerodynamics, weight, propulsion, and mission performance (Nguyen et al., 2015), whereas depending on the requirements, additional models like cost (Ceruti et al., 2012) and stability (Morrisey & McDonald, 2009) may also be added to enhance the calculations. In this respect, a category of further framework additions that can complete the calculations when the design has surveillance or observability requirements is to include models from the field of electromagnetics, and more specifically, for search and rescue scenarios this can be achieved by taking into account models for computing the radar signature as well as the sensor system performance (Papageorgiou et al., 2017a; Papageorgiou et al., 2017b).

Data management and visualization

Visualization of the results and data management have been reported since the earlier days of MDO as two elements that have been overlooked or entirely omitted from the optimization process (Giesing & Barthelemy, 1998). More specifically, there are increased demands by many experts in the field to develop frameworks that will enable users to access the optimization data in an efficient and intuitive way (Padula & Gillian, 2006), whereas it has also been stressed that the results and the framework should also be accompanied by various visualization alternatives so that they can be used in the decision-making and control processes of the PDP (Salas & Townsend, 1998). In actual optimization scenarios where there are numerous parameters, it is of utmost importance to be able to provide developers with flexible solutions, and it has been shown that advanced visualization techniques and data mining tools can be an essential step towards better MDO practices and in turn a more professional PDP (Ziemer et al., 2011).

In view of this, considerable efforts have been made by various researchers with the most notable being the development of a specialized graphical user environment (or “dashboard” or “configurator”) for the assessment of the capabilities and decision support in the PDP of aerospace vehicle technologies (Arruda et al., 2014). Further research on the same topic include the “design steering” tools which function similarly as the above, but with the main difference that they allow designers to steer the results and make decisions before, during, and after the optimization process (Winer & Bloebaum, 2002). Lastly, significant work has also been made in respect to data mining techniques for optimization problems, and it has been shown that there are various methods which can extract knowledge about the problem or assist in the future design iterations through an expert analysis (Bandaru et al., 2017).

Development methodology

Programming tools

The three central ideas behind the proposed configurator is to be easy to use and maintain, to be able to expand and adapt to changes, and lastly, to be based on tools that are readily available and easily obtainable by the majority of engineering companies. Although it is not a critical requirement, it is also important to have as much compatibility as possible, and in this respect, it is desirable to use tools that enable a user-friendly connection between the configurator and the analysis modules but also between the configurator and other post-processing software.

Working principle

The main principle of the proposed configurator tool is to first run numerous multi-objective optimizations of a given problem, and then collect the non-dominated Pareto designs in a large database so that they can be managed and visualized (see Figure 1). For this purpose, an automatic requirement generator is put in control of the overall data-collection process, which starts every time by defining a new set of design requirements as a fixed input, and then performs a new optimization in order to identify the best solutions. Those Pareto designs are subsequently collected into a central database that will later act as the main pool which the configurator will use in order to enable the various visualization and management alternatives.

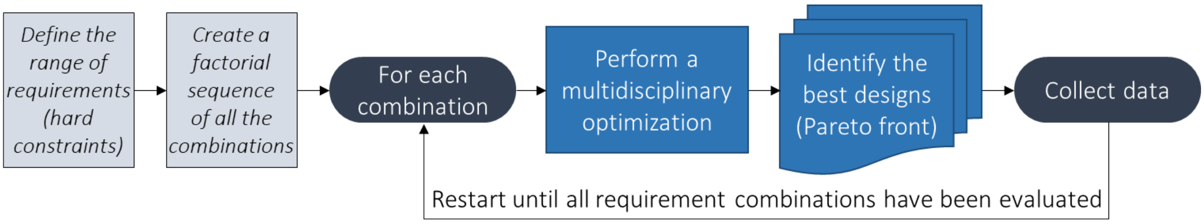


Figure 1. The methodology for generating, sorting, and collecting the optimization results.

Building blocks

For achieving the purpose of data visualization and management, a number of fundamental elements needs to be taken into account. As expected, the number and type of the configurator elements is in most cases specific to each design application, however, this research identified that five major categories must be considered in order to provide the basic operations:

- Data modularity: Data modularity is essential in order to safeguard that further cases can be added without the need to redesign the entire configurator. At a primary level this can be achieved by using classes of programming objects which are easily duplicated in the code structure, while at a secondary level, small changes can be enabled through the use of loading modules that allow users to include new or expanded data into the database.
- Control functions: The control functions in a configurator tool are a crucial part because they give the end user the flexibility to go through the obtained results and select those designs that are the most fitting for each application. Controlling the configurator should also be a straight-forward task that can be intuitively performed even by non-experts, and therefore, the control functions should ideally be expressed in a graphical way like for example with a button or a slider.
- Basic monitors: The basic monitors are an element that increases the speed of the decisions but also the understanding of the design space since they provide simple numeric and visual representations of each studied configuration. For the monitors to work, a design must first be chosen through the control functions, while a further useful feature that can help the decision makers is to hold the figures so that different designs can be simultaneously compared.
- Visualization features: The visualization features are the essence of any configurator tool, and as such, they should be able to provide the user with several alternatives that can capture the dependencies between the problem objectives as well as the effect of the design variables. Moreover, they should include additional analysis features that can help designers understand the objective dependencies, and they should also enable users to manipulate their properties and export the results.
- Management options: Management of large data sets in the design is one of the key topics that the configurator tool addresses, and thus, adequate functions should also be included in order to enable users to export the data in a format that can be easily used from other programs. First, this guarantees that everyone in and out of the organization who is involved in the PDP can receive a copy of the case study results, while secondly, it allows to save data for archiving or future continuation purposes.

Configurator Specifications

Overview

For this case study, the proposed UAV configurator tool was developed entirely in MATLAB by using the in-built Graphical User Interface (GUI) and the obtained optimization results from a MATLAB-based optimization framework. A general overview of the UAV configurator tool showing a division into 10 blocks (A to J) is presented in Figure 2.

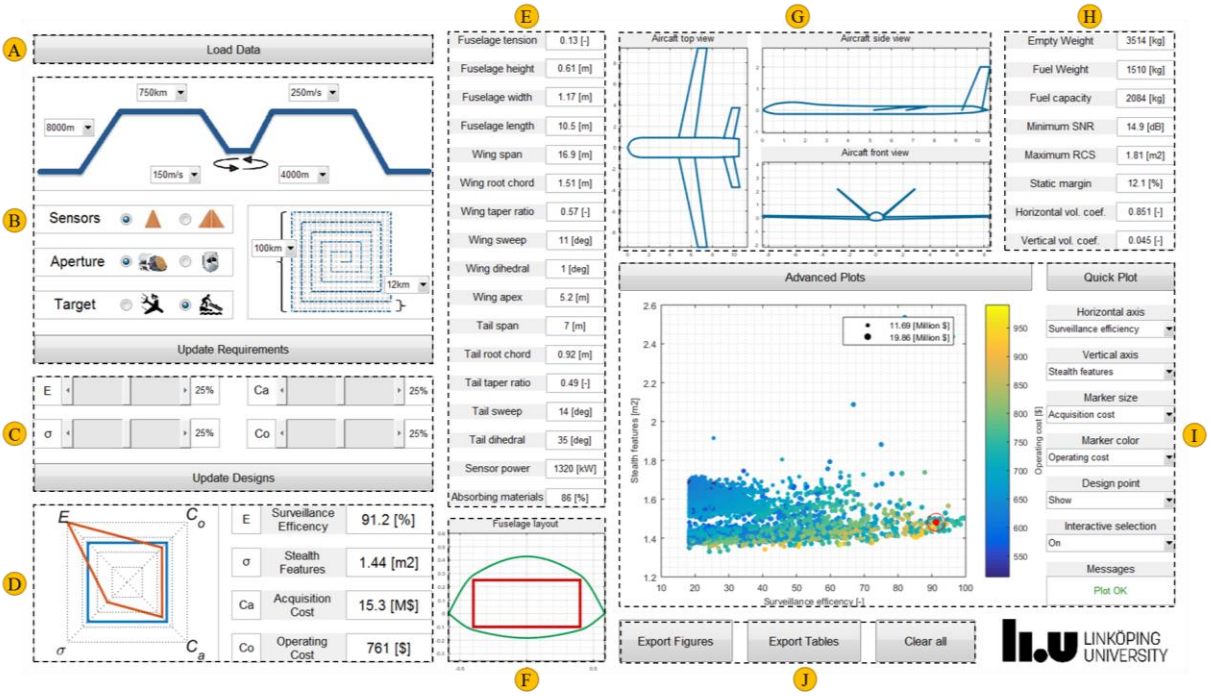


Figure 2. Overview of the UAV configurator tool showing the results from case study #5 (see next chapter).

Data modularity

Data modularity is enabled through the use of an object-oriented programming script that allows to reuse pieces of the code, whereas at the same time, the MATLAB GUI allows engineers to position the new items anywhere on the board by simple moving them around. Moreover, small additions are also permitted by the configurator, and this can be easily done by loading the appropriate set of data in block (A) which is also the start of the process. This function further increases the modularity of the configurator, and in turn lets users to replace the existing data if results from high-fidelity simulations or entirely new optimizations become available.

Control functions

The desired attributes of the UAV are updated in block (B), while once the new requirements have been set, it is possible to navigate within the non-dominated Pareto designs through the sliders in block (C). First, it is possible to customize the cruise (altitude, range, speed) but also the search (altitude, speed) phase; to select the number of sensors and the sensor aperture type; and to define the search pattern as well as the size of the search target. Finally, by means of moving the sliders, a user-defined weight factor is given to each one of the four objectives, and then the design characteristics are updated accordingly so that they can be monitored or visualized in the next blocks.

Basic monitors

The basic monitors for this application include blocks D to H. Block (D) prints the values of the four objectives and plots them in a spider plot of two-dimensions; block (E) prints the corresponding design variables at the chosen design point; block (F) plots a cross section of the fuselage which shows the surface tensions and the inner space in the avionics bay; block (G) plots a top, side, and front view of the aircraft; and lastly, block (H) prints the corresponding values of the critical case constraints at the chosen design configuration.

Visualization features

For this current version of the configurator, the visualization possibilities can be seen in block (I) and include a quick plot function as well as a set of more advanced plot options. The quick plot is a two-dimensional chart that has been directly integrated into the configurator window and can be used to provide a fast visualization of the Pareto designs for the chosen list of requirements. It can be used to simultaneously depict up to four variables by using a coordinate system of two axes as well as the size and colour of the markers, while its additional possibilities are to show the design point, to enable an interactive selection, and to print messages in cases of failure. The advanced plots open always in a new window where the user first defines the desired type, and then selects the data to be considered. Here, the advanced plots which were deemed necessary include a 3D scatter as well as a matrix (correlation) graph, whereas a further option is to generate a sensitivity (multivariate) analysis that can be seen later in the results of the optimization case study (See Figures 6 and 9).

Management options

In this application, the management of the data is handled in block (J), and it is about generating and then exporting the figures as well as the tables. The priority herein was to give full flexibility to the user in order to enable a seamless incorporation of the optimization data into the PDP. Upon activation, a new window opens, and then it becomes possible through an interactive selection to define the desired figure format to be exported or the type and number of variables to be included in the tables.

Optimization Framework

Problem formulation

The principle design problem of this research is the development of a UAV platform that will be used in search and rescue operations over potentially unfriendly territory (see Figure 3). First, the proposed solution should be able to efficiently scan a large area in order to find a hypothetical "hidden" target. Second, the aircraft's visual echo should be as small as possible in order to reduce its detectability by the observing ground radars. Finally, to achieve a strategic advantage over the competition, the identified configuration should be an affordable market option in terms of both acquisition but also operating costs.

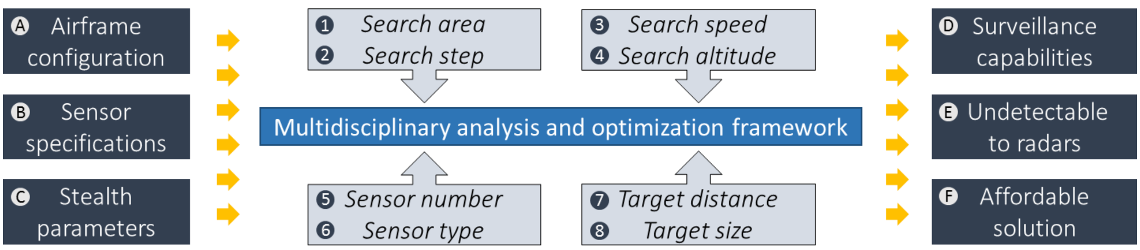


Figure 3. Overview of the optimization problem showing the unknown inputs (A,B,C), the user-defined system requirements (1-8), and the desired aircraft characteristics (D,E,F).

The main challenge here is that surveillance efficiency depends mainly on the sensor system, which in turn creates demands on the aircraft engine but it also has a negative effect on aerodynamics and radar signature especially if it includes protruding apertures. Furthermore, acquisition and operating costs depend mostly on the total and fuel weight respectively, and as a result, they are affected by changes in both the airframe configuration, the chosen sensor system, the desired payload, the amount of radar absorbing materials, and of course, the required range and endurance of the aircraft.

Objectives and constraints

In total, the present problem takes into account four objectives which are indicative metrics of the surveillance, stealth, and affordability capabilities. The first objective is related to surveillance, and it measures the detection efficiency (E) that the sensor system has over the search area in terms of percentage. The second objective (σ) is related to the stealth features of the aircraft, and it is expressed by the radar cross section (RCS) which is measured in m^2. The third and fourth objectives are in respect to affordability, and more specifically, about the acquisition cost (C_A) and operating cost per flight (C_O) which are measured in US dollars.

In addition to the above, there are several design constraints which express the customer desires and add further complexity as well as realism into the problem by ensuring that the concept is flyable with adequate airworthiness characteristics. Those constraints should not be confused with the design requirements which are mentioned and studied in chapter 3, and for this application, those include monitors for the stability and balance, the available payload and fuel space, and finally the minimum radar and sensor performances.

Design variables

The design variables which have been considered in this case study are a representative sample that can explore different airframe configurations but also various alternatives in terms of sensor system and stealth capabilities. The main aim herein was to enable fast and numerous optimizations which are an essential feature of conceptual design applications, and therefore, the number and range of the variables was intentionally kept small. A baseline design was initially defined based on the General Atomics MQ-9 Reaper (Predator B) concept, while the upper and lower bounds were established by using available data from UAVs with similar design requirements.

Disciplinary models

A number of disciplinary models were developed and subsequently integrated into a common analysis framework in order to be able to capture the inter-disciplinary couplings and the trade-offs between the four objectives. Since the main focus of this case study is on the early stages of the design, low-fidelity solutions were herein preferred over the complex analysis codes due to their ease-of-use and fast analysis times. Although there are several programming alternatives, the development of the models was performed in MATLAB because of its broad analysis features, universal availability, and compatibility with the configurator tool.

- Aerodynamic performance: Based on TORNADO (Melin, 2000), which is a vortex lattice method (VLM).
- Sensor efficiency: Based on analytical electromagnetic formulas that can be found in the relevant literature (Balanis, 2005).
- Propulsion specifications: Based on an interpolation of statistical data that were retrieved from engines of similar applications.
- Radar signature: Based on a three-dimensional rendering of the aircraft outer mold line and geometrical computations of the surface normal lines.
- Weight estimation: Based on empirical aircraft conceptual sizing equations that can be found in the relevant literature (Raymer, 2012).
- Stability and trim: Based on stability and balance equations with focus only on the longitudinal forces and moments.

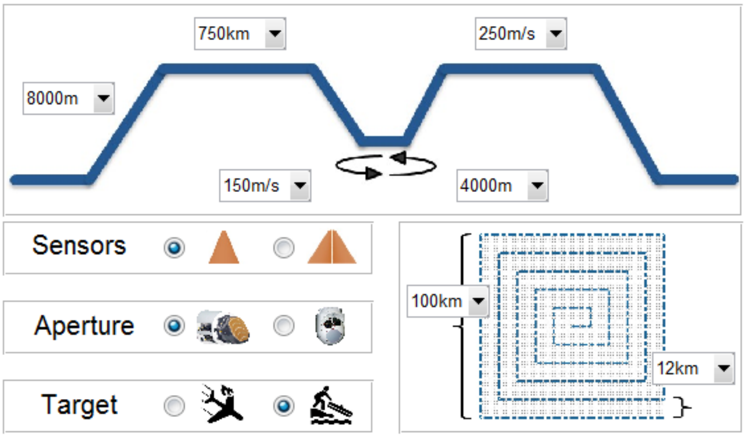
- Mission simulation: Based on empirical field performance equations (Torenbeek, 2013) which were applied at all mission stages.
- Cost assessment: Based on an interpolation of statistical pricing data from similar UAVs, available sensor system costs, and current fuel prices.

Optimization architecture

The multidisciplinary analysis and optimization problem in this work was solved at a single level, and more specifically, with a variation of the monolithic All-at-Once (AAO) decomposition architecture which is further elaborated in (Martins & Lambe, 2013). The motivation behind this choice was that the AAO has a very simple implementation since there is no need to develop complex iterative loops or include additional decoupling variables. For this application, the disciplinary models are executed in sequence, and then the couplings are solved by means of supplementary consistency constraints which have been added in the problem formulation.

Results

The framework and the configurator were used in an example case study for developing a UAV with search and rescue capabilities. A set of design requirements were initially put forward as fixed constraints which represent the customer preferences (see Figure 5 left). The resulting Pareto front was subsequently analysed in order to identify the configurations that show the best E, the best σ, the best C_A, the best C_O, and the best overall performance when the four objectives are equally weighted (see Figure 5 right).



	Objective weights			
	E	σ	C_A	C_O
Design #1	100%	0%	0%	0%
Design #2	0%	100%	0%	0%
Design #3	0%	0%	100%	0%
Design #4	0%	0%	0%	100%
Design #5	25%	25%	25%	25%

Figure 4. The chosen requirements (left) and the objective weights of the studied designs (right).

A genetic algorithm (GA) that was implemented in MATLAB was used for the optimization of the aforementioned problem. The main reason for this, is that GAs are able to handle problems with multiple objectives and constraints, while at the same time they can also enable a local parallelization of the process which can significantly reduce the total computational time. The settings included a starting population of 136 individuals which were allowed to evolve for 100 generations, whereas the crossover and mutation probabilities were set to 90% and 10% respectively.

The complete Pareto front for the above set of requirements is presented first in the bubble chart of Figure 2 and then in Figure 6 by using two advanced 4D visualization options of the configurator tool. In addition to this, a collective spider plot of the objectives and their corresponding numerical values for each one of the five studied designs can be found in Figure 7, while an overlapping plot of the aircraft configurations in three views and the fuselage layout is shown in Figure 8. Finally, as a supplementary means towards increasing the understanding of the design details, a sensitivity analysis that shows the effect of the design variables against the four objectives is given in Figure 9.

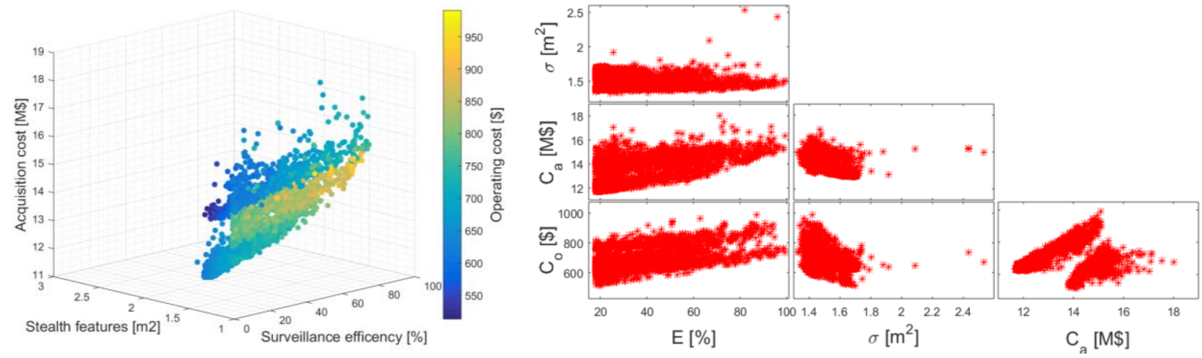
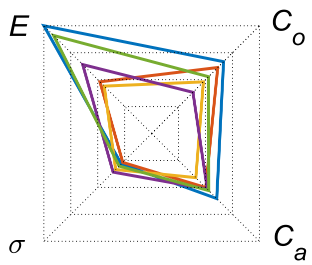
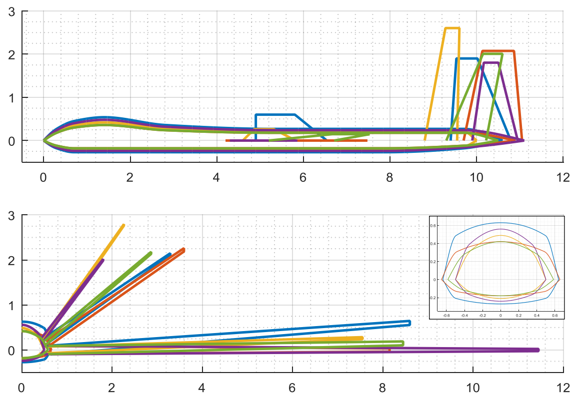


Figure 5. The Pareto front of designs by means of a 3d scatter (left) and a matrix (right) plot.



Design	E [%]	% impro-vement	σ [m²]	% impro-vement	C_A [M$]	% impro-vement	C_O [$]	% impro-vement
#1	100.0	+81.5	1.51	+9.6	16.3	-2.5	776	-0.5
#2	24.8	-54.9	1.33	+20.3	15.1	+5.0	735	+4.8
#3	18.4	-66.6	1.69	-1.2	11.7	+26.4	633	+19.2
#4	21.0	-61.9	1.75	-4.8	14.1	+11.3	513	+33.5
#5	91.2	+65.5	1.44	+13.8	15.3	+3.7	761	+1.4
Baseline	55.1	-	1.67	-	15.9	-	772	-

Figure 6. A spider plot (left) and the values (right) of the objectives for the five studied designs.



Design	#1	#2	#3	#4	#5
Sensor power [W]	1500	500	500	500	1320
Radar materials [%]	80	100	80	80	89

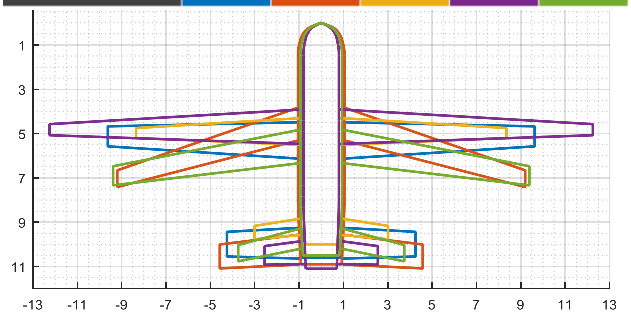


Figure 7. The aircraft and fuselage geometry that corresponds to each one of the five studied designs.

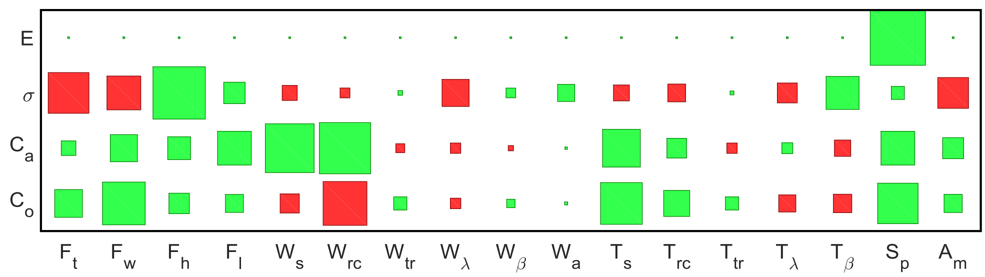


Figure 8. Sensitivity analysis of the design variables against the optimization objectives.

Discussion

A first analysis of the results can easily reveal that there are distinct trade-offs between the four objectives and that the proposed optimization was able to locate a set of Pareto optimal solutions with significantly better performance in respect to the desired design requirements (see Figure

6). Starting with the best of each objective, it can be seen that the proposed use of MDO can generally lead to considerably better configurations when compared to the baseline (see Figure 7). More specifically, it was identified that it is possible to have designs with 81.5% better surveillance performance (case 1), 20.3% lower radar signature (case 2), 26.4% lower acquisition costs (case 3), and 33.5% lower operating costs (case 4). In addition to this, the evaluation of a compromised solution (case 5) showed that a better design in respect to all four objectives is also a possibility, and in particular, it was found that the proposed point illustrated an improvement of 65.5% in E, 13.8% in σ, 3.7% in C_A, and 1.4% in C_O.

The corresponding design variables for each one of the aforementioned five design points are presented in Figure 8, where it can be seen that the final design depends on the weights of each objective. In particular, for high surveillance efficiency the sensor power is maximum; for low radar signature the fuselage shape has distinct edges and swept-back wings; for low acquisition cost the aircraft size has a compact geometry; and for low operating cost there is a good aerodynamic shape with high aspect ratio wings and a smooth fuselage. Accordingly, the same trends can also be identified through the sensitivity analysis (see Figure 9), where it can be seen that most influential parameter for E is the sensor power S_p; for σ is the fuselage geometry (F_t, F_w, F_h, F_l); for C_A is the wing span W_s and root chord W_{rc}; and lastly, for C_O is the fuselage width F_w, the wing root chord W_{rc}, the tail span T_s, and the sensor power S_p.

In general, this case study also identified that the low-fidelity disciplinary models which were implemented herein can be an efficient but also adequate choice for this conceptual design application. The suggested computationally inexpensive analytical functions allowed to capture the physics of the problem, but they also enabled a fast exploration of the design space which is an element of utmost importance when numerous designs have to be quickly evaluated. Furthermore, the choice to use MATLAB contributed towards the goal of faster computations, user-friendly interface, and framework modularity, while at the same time, its universal availability and compatibility features made it also possible to have direct access to various optimization algorithms, to be easily obtainable as well as maintainable by the industry, and to avoid the costly commercial integration software solutions.

As far as the configurator tool is concerned, it can be argued that this addition to MDO can help non-experts to comprehend the design space before advancing to the next stage of the PDP, and this is supported by the user-friendly GUI but also the various data management and visualization alternatives. First, the identified numerical values that correspond to each configuration offer all the necessary information that is needed, and then this is further complemented by the simple aircraft plots which provide a first but yet sufficient visualization of the concept. Moreover, the quick and advanced plots offer a complete representation of multi-objective problems in 2D, while it is also possible to generate further graphs like for example a sensitivity analysis which is typically an essential addition that can give more information regarding the disciplinary dependencies.

Compared to the commercially available integration and simulation software, the proposed configurator solution may have shortcomings in terms of functionalities, however, this is counterweighted by the fact that it is directly compatible with the optimization framework, it is customized in advance for each application, and lastly, it does not require any additional monetary cost. In terms of time, the development of the configurator poses an additional challenge for the PDP, however, it can be argued that its use is much more straight-forward, and thus it does not require any additional resources to be considered during the post-processing process. To this end, the configurator was also designed with modularity in mind, and therefore, it can be adapted to a wide range of UAV types, mission requirements, and optimization settings by simply reusing and recycling the existing functions in an appropriate manner.

On the whole, and in view of the state-of-the-art, the research configurator tool lies primarily within the area of decision support, whereas the topics of steering the design during optimization and data mining have been only partially addressed through the implementation of the quick and advanced visualization features. The primary contribution herein can be found in the method for incorporating data management and visualization alternatives directly in MDO, and this is exemplified by the introduction of a new data generation approach but also by a set of guidelines for identifying the most suitable functions for such applications. Furthermore, by using the presented UAV case study, the goal was to show some basic data management and visualization capabilities, but more importantly to argue that enabling a design space exploration is far more useful for the PDP than delivering one or two optimal designs which in reality have no true value for the decision making team. Overall, the present digital design tool should not be seen as a complete solution in terms of handling big data in the design, but as a first approach and an example of how the traditional simulation-based MDO frameworks can be enhanced so that they can be eventually used within the PDP.

Conclusions

This paper presents an approach to conceptual Unmanned Aerial Vehicle (UAV) development through the parallel use of a Multidisciplinary Design Optimization (MDO) framework and a data management as well as visualization tool. The primary focus herein is to assess the main features of this hybrid method for an application in the early phases of the Product Development Process (PDP), and to show that design space exploration techniques can be an instrumental tool during decision making. Overall, the importance of digital design methods and in particular simulation-based optimization are exemplified through a representative case study, while the results are subsequently assessed by means of a configurator tool that was developed specifically for handling big data.

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