DIANA: Data Interactive Analysis and Navigation Application

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In the evolving landscape of aircraft design, data visualization is becoming an essential tool to support and enhance the decision-making process. As advanced methodologies such as Multidisciplinary Design Optimization (MDO) and system architecture optimization are adopted, the amount and complexity of design data have grown significantly. While these approaches enable more comprehensive exploration of the design space, they also introduce new challenges: interpreting extensive datasets, identifying interdependencies between parameters, and deriving actionable insights are increasingly difficult. To address this, data visualization is integrated into the design process as a core component that enables engineers to make sense of complex information and drive informed decisions. This paper presents a methodology for developing data visualization tools tailored to the specific demands of aircraft design. It also introduces DIANA, a new application built with these requirements in mind. The paper outlines DIANA's features and demonstrates its capabilities through a use case involving future aircraft concept studies.

Nomenclature

CDS	=	Central Data Schema
$CPACS$	=	Common Parametric Aircraft Configuration Scheme
$DIANA$	=	Data Interactive Analysis and Navigation Application
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
DV	=	Data Visualization
EIS	=	Entry Into Service
GUI	=	Graphical User Interface
$MBSE$	=	Model Based Systems Engineering
MDO	=	Multidisciplinary Design Optimization
$TLARs$	=	Top-Level Aircraft Requirements
TOW	=	Take-Off Weight
SAF	=	Sustainable Aviation Fuel
SE	=	Systems Engineering
XML	=	Extensible Markup Language

I. Introduction

During the last decades, aircraft complexity has increased [1]. This, combined with challenges such as the integration of innovative technologies for the reduction of aircraft environmental impact, has led to the need for new methodologies to explore novel configurations inside the aircraft design process [2]. As opposed to the traditional approach, in which a limited number of aircraft configurations are frozen at the start of the project, multiple system architectures are explored with these novel methodologies relying on modern techniques such as Model Based Systems Engineering (MBSE), Multidisciplinary Design Optimization (MDO) and system architecture optimization [3], allowing to investigate and assess a wider range of the design space.

Due to the exponential increase in the considered number of design points, the existing problem of analyzing the results and achieving proper decision-making reaches a new level of complexity [4]. Data visualization can be used to

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solve this problem. Data visualization allows experts to better understand their results, not only by answering questions such as their validity, but also through the formulation of new questions that were hidden behind the data [5]. This improved understanding of data allows experts to find and explain trends and outliers [6], guiding them through the design process and accelerating the decision-making process. Finally, it allows to analyze data and take better-informed decisions while maintaining the human factor in the loop [7], which is essential in complex environments where justified design decision have to be taken.

However, data visualization platforms face multiple challenges if they want to be incorporated into the aircraft design process. First, the aircraft design process requires the generation of highly specific charts, such as Take-Off Weight (TOW) breakdowns or aerodynamic polar, to compare the performance of different aircraft. Additional challenges come from the multidisciplinary nature of aircraft design, including the need to deal with different data structures (strings, arrays, matrices,...) or data coming from disparate tools and formats. Other challenges include displaying multiple charts simultaneously to assess the multiple and conflicting objectives of the design, and keeping track of the different design decisions taken during the design process in an automated and reusable manner. Of course, all this has to be achieved while maintaining simplicity, as the entry barrier should be as low as possible to allow the coordination of all the different experts involved in the project.

As modern data visualization platforms cannot deal with all these specific challenges, as discussed in more detail in section IV, a methodology for the design of data visualization applications adapted to the aircraft design process is established. This methodology is then implemented in a newly developed platform, called DIANA (Data Interactive Analysis and Navigation Application), which enables aircraft designers to create both specific aircraft design charts and personalized charts, as well as interactive dashboards, facilitating decision-making. Technical reports can also be generated in a semiautomatic way, to keep track, share, document and discuss design decisions.

The structure of the paper is as follows: first, an overview of the state of the art is provided in Section II. Section III encompasses the requirements that a platform for data visualization must satisfy to be used in the aircraft design process. After that, the methodology to implement those requirements is discussed in Section IV and its practical implementation in DIANA is widely discussed in Section V. Section VI presents a couple of practical use cases of DIANA in the aircraft design process. Finally, some conclusions are drawn in Section VII

II. State of the Art

A. Methodologies for aircraft design

The number of disciplines involved in the aircraft design process has increased during the last years, leading to a higher level of complexity of the systems [1]. To address this complexity and its derived challenges, Systems Engineering (SE) can be used. Traditionally, SE has been document based. This is now being replaced by MBSE, which uses models to guide the early stages of development, from requirements definition to validation [8]. This achieves a reduction of errors, time and costs [9].

In complex systems, an optimum solution can only be achieved considering the existing interactions between the multiple disciplines [10]. This can be implemented through MDO, which allows to consider all these interconnections simultaneously by formulating the design problem as an optimization problem [11]. However, there is a limitation with MDO, as it can only be used once the system configuration has been fixed. To solve this and link the upstream phase covered by MBSE and the design phase covered by MDO, system architecture optimization can be used [12].

In the traditional approach, a small number of possible aircraft architectures—defined as groups of system components and their relationships [13]—are frozen at the start of the project based on experts knowledge. However, system architecture optimization allows to further explore the design space through the automatic generation and evaluation of multiple system architectures, achieving a more objective and optimized design. This avoids the bias and conservatism of the traditional approach, especially with the inclusion of newer technologies [14].

Introducing these new methodologies in real design scenarios is challenging, especially when multiple experts from different backgrounds and companies are involved, as it happens in modern design processes [15]. One of the main challenges is to achieve the desired and necessary connection between the specific domain tools. To achieve it, a possible solution is to include a standardized Central Data Schema (CDS) which allows to integrate all the involved parameters in the aircraft design process under a centralized common language, highly reducing the number of interfaces to be made between disciplines. An example of CDS is the Common Parametric Aircraft Configuration Schema (CPACS) [16], which is an open-source, community-driven CDS for aircraft design based on XML and coordinated by the German Aerospace Center (DLR).

There are multiple examples where all these methodologies have been integrated successfully in the aircraft design process, especially in the AGILE 4.0 project [17]. Some examples include the design of a hybrid electric aircraft propulsion system [18] or the design of a business jet family [19].

However, an important challenge still remains. Even in the traditional approach based on Design of Experiments (DOE) to explore aircraft configurations, a considerable amount of data is created. As observed in the previous use cases, the inclusion of these new methodologies has led to a significant increase in the volume of data produced with respect to the traditional approach [4]. Consequently, the already complex processes of results understanding and decision-making have become even more complicated. This is where modern data visualization techniques can prove useful, as it is further discussed in the next section.

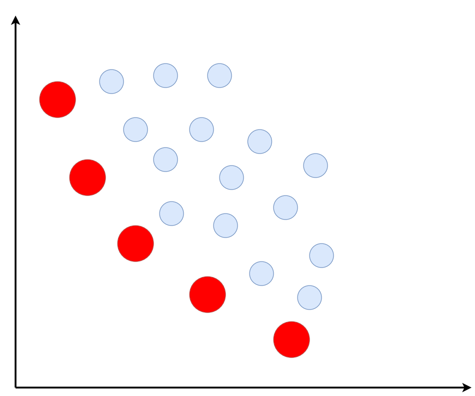
B. Data Visualization

Data visualization is a set of methods and techniques for graphically displaying information that aims to allow users to explore and analyze the data in an understandable and straightforward manner [20]. It has increasingly been introduced to different sectors, especially where large amount of data is produced [6]. The main advantage lies in helping experts interpret data more effectively and in streamlining the decision-making process, particularly when multiple objectives must be considered simultaneously [21], as is often the case in aircraft design. This is partly achieved through its ability to detect trends and outliers in the data [22].

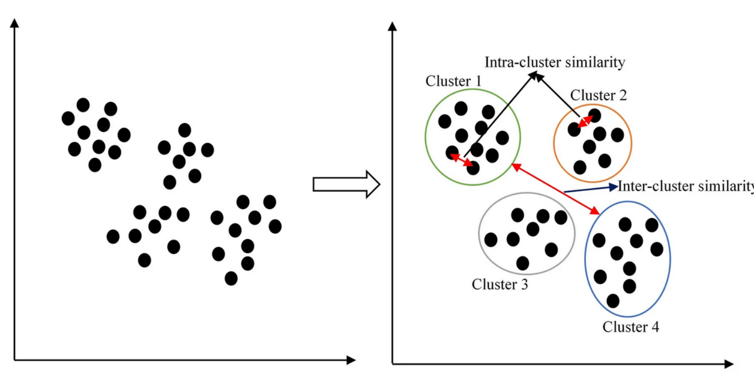
One of the main reasons for using data visualization in the decision-making process is maintaining the human in the loop [7], which is essential in the aircraft design process where the validity of results is often based on engineering judgment. Another important reason for keeping the human in the loop is the complexity of modeling all the different potential interactions between stakeholders, from policy-making to business, considered in the decision process. It is also valuable in cases where decisions must be justified, or in highly technical and specialized fields, such as this one.

There are different procedures to implement data visualization in the design, especially with regards to the decision-making process. When there are multiple conflicting objectives to consider, Pareto front are commonly used. Figure 1a illustrates an example of a Pareto front, which represents the set of optimal design solutions where improving one objective would require compromising at least one other [11]. Pareto fronts allow to visualize a set of solutions to a problem and facilitate comparison according to different objectives. However, there are two main drawbacks.

The first main drawback is that it does not allow to fully understand the data it represents. More specific visualization techniques are necessary to understand what each point represents, to validate the results and to take a final decision. The second drawback is that a new dimension is required for each objective, which significantly complicates the decision-making process when more than three objectives are considered. A possible solution to overcome the last shortcoming is to use value driven decision-making, where designers set weights for each objective in order to take decisions. This allows to summarize several objectives into one, reducing the problem again to 2D [23].



(a) Pareto front example case



(b) Clustering example case

Fig. 1 Example of techniques for visualizing data to enhance comprehension include: a Pareto Front on the left, representing the optimal points considering two objectives simultaneously, and automatic clustering on the right, where similar points are grouped and differentiated through color (Figure taken from [24]).

Data visualization can also support statistical analysis, making it easier to identify trends within the data. Examples of this include heat maps, where colors are mapped to data values, and regression analysis charts, which help to determine the relationships existing between two or more variables in a data set.

Figure 1b shows an example of clustering, which is another commonly used technique inside data visualization. Closely related to statistical analysis, it allows to group parts of the design space according to common characteristics. The process can be performed manually by selecting different markers in the data and visualizing the results, or it can be automated through the use of advance clustering methods, such as k-means [25].

There are two main stages where data visualization can be introduced in the aircraft design process. First, it can be used in the intermediate phases of the design, once the first results from a DOE or an optimization are obtained, to understand the data and to validate it. It can also lead to the discovery of trends and outlooks. Together with a better understanding of the data, these can be used to refine the design space to be explored in the subsequent design iterations. The second scenario is at the end of the design process, to visualize the results and compare the various aircraft concepts to take a final decision. In both cases, data visualization is used in the decision-making process, as shown in Fig. 2.

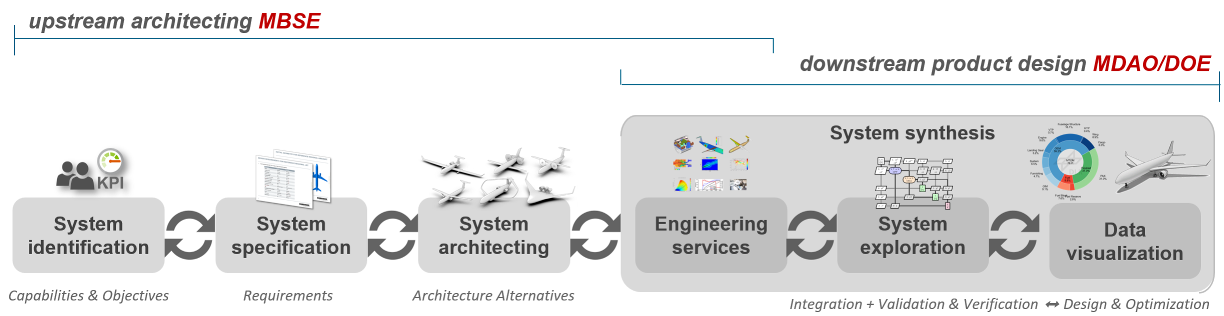


Fig. 2 Systems Engineering development process for aircraft design. Data visualization can be implemented in the second phase to better understand the results, both for tuning the next DOE or optimization, and for determining the final selection among the results of the design process.

To integrate these and others data visualization techniques into aircraft design and support decision-making, a global view is necessary due to the complexity and multidisciplinary nature of the process. This can be achieved using dashboards. A dashboard is defined as "a visual display of the most important information needed to achieve one or more objectives; consolidated and arranged on a single screen so that the information can be monitored at a glance" [26]. As shown by Guenov et al. [27], dashboards have already been successfully used in aircraft design. Different charts are integrated to compare multiple aircraft concepts and determine the best trade-off between environmental impact and performance.

More examples of high-level dashboards within the aerospace sector can be found in the literature, especially regarding climate and environmental impact. Some examples are Cascade [28] developed by Boeing, and ALICIA [29], developed by the DLR. Both of them aim to allow policy makers to analyze different aircraft configurations and technologies, helping them to take decisions for reducing aviation's emissions in the close future.

There are a significant amount of data visualization platforms already available. One of the most well-known is Tableau [30]. Tableau main characteristic is its extensive range of functionalities, such as a wide range of charts types or reusability, allowing the platform to adapt to a great variety of case scenarios, from business to academic. It is already been used by multiple prestigious companies, including the aerospace sector [31]. Another main actor in the data visualization field, especially in research, is JMP [32]. JMP, apart from its flexibility, is characterized by its capabilities in statistical analysis. It also has a wide range of functionalities regarding AI and machine learning, which are complementary to the traditional data visualization process. Another commonly used platform is PowerBI [33], which, while highly accessible and user-friendly, may not offer the same level of customization or flexibility for complex data analysis as the other mentioned platforms.

However, the aircraft design process is characterized by multiple specific challenges when trying to implement data visualization, and none of these applications were specifically designed to face them. To deal with these specific challenges, the application integrated has to satisfy a set of requirements. These challenges and requirements are extensively discussed in Section III.

III. Identified Needs and Requirements for Data Visualization in Aircraft Design

This section will first address the specific challenges of implementing Data Visualization (DV) in the aircraft design process. These challenges are then formalized into a set of requirements that any data visualization platform must satisfy to be included in the aircraft design process.

A. Challenges for the implementation of DV in the aircraft design process

Specific aircraft design charts: Highly specific and technical charts are needed to understand and compare multiple aircraft concepts. Examples are: TOW breakdowns, payload-range diagrams or aerodynamic polar. This wide range of specific charts are needed due to the multidisciplinary nature of aircraft design. It is also necessary that the application used inside the aircraft design process for data visualization allows the comparison of multiple missions and/or aircraft configurations in the same chart. Moreover, the application has to be capable of producing these specialized charts while maintaining enough flexibility to produce user-defined charts, such as scatter plots or bar charts.

Reusability: Given the iterative nature of the aircraft design process, the application must enable users to compare data across different design cycles. Consequently, the previously mentioned charts should be generated in a fast and simple manner, requiring as few manual steps as possible. Ideally, the charts should be regenerated automatically with almost no user input when new data is introduced.

Data complexity: The data necessary for the generation of the specific aircraft design charts usually comes from different software and in different formats. A possible solution to this problem is to use a Common Data Schema (CDS), which standardized all the necessary information and variables, providing a unique definition for each variable. This CDS must support different data structures, such as arrays, categorical variables or matrices (among others). One way to implement a CDS is through the usage of XML as a base, as done in DLR with CPACS.

Interactive generation of dashboards: As a consequence of the multiple and highly connected disciplines involved in the aircraft design, aircraft designers need a system-level view to analyze data and take design decisions. Once all the necessary charts have been generated, this larger perspective can be achieved by including several charts in dashboards. These dashboards should be interactive to facilitate the decision-making process.

Report generation: As a consequence of the multiple experts involved in the aircraft design process, as well as of its iterative nature, it is essential to keep track of the different design decisions that are taken during the process. Apart from the charts and dashboards generated, the DV platform has to be capable of producing and exporting technical reports in a semiautomatic manner. This is especially important for those people involved in the process that might not have access to the application (e.g. stakeholders), as well as for long-term data storage.

Learning curve: Finally, all these capabilities have to be implemented while maintaining user friendliness. The Graphical User Interface (GUI) should be simple and intuitive to use, facilitating the implementation of DV in the aircraft design process by reducing the time for both learning to use the application and for creating visuals used to explore the data and to take design decisions.

B. Requirements

This section formalizes the previous identified needs into a set of requirements. A DV application intended to be used in aircraft design must have:

REQ-01 Aircraft design charts: The application has to be capable of producing highly specialized aircraft design charts for several missions and operating conditions of multiple aircraft configurations simultaneously, allowing also a direct comparison in the same chart. These charts should include at least TOW breakdowns, aircraft geometries, payload-range diagrams and aerodynamic polar, as they represent the key disciplines in aircraft design. However, additional chart types should be supported where possible. These charts should be created in an easy and automated way, so that little to no additional user input is required when new data is provided.

REQ-02 Different plot types: Each plot type allows to visualize data from a different point of view, discovering different trends and information in the data. Also, according to the type of variables involved, some plot types might be more suitable for their representation (e.g. scatter plots for continuous variables or bar plots for categorical variables). This translates into the necessity of having multiple plot types (scatter plots, bar charts or line graphs, among others) to analyze data successfully [34].

Complex multidimensional plots are also needed, such as parallel coordinates, scatter matrices or heat maps. These are especially used for a first exploration of the data and for determining general trends. There are some occasions when 3D plots might be justified, such as for geometry visualization. However, they should generally be avoided because they increase the complexity of decision-making due to factors such as cognitive overload and perspective distortion [7].

REQ-03 Dashboards: A global point of view is necessary to take decisions when multiple and conflicting objectives have to be considered. Dashboards have been shown to be especially effective in these cases, allowing to display data from different disciplines at the same time. These dashboards should be interactive, supporting the user to rapidly change the data analyzed and to quickly explore it through functionalities such as filtering and zooming, with the final goal to facilitate the decision-making process. It is also essential for this goal that the different charts in the dashboard are interconnected. This means that when the user selects or filters data in one chart, the other charts should reflect this automatically.

REQ-04 Report generation: Reports are essential to communicate the findings and to keep track of all the decisions taken during the process. The application has to be capable of generating the report in a systematic and semi-automatic manner for multiple aircraft at the same time, each one with their own information and charts.

REQ-05 Marks styling: Markers allows multidimensional data to be visualized while a 2D plot is maintained. This can be done through the inclusion of additional variables using colors, shapes and/or sizes [7]. Marks are especially useful for the discovery of trends in the data by means of clustering.

REQ-06 Filtering: Datasets in modern aircraft design projects are characterized by their large amount of data points. Plotting all this information simultaneously would overwhelm designers, making the decision process even more complicated. To solve this problem, the user has to be capable of filtering the necessary data dynamically in order to explore it systematically [35]. Multiple filters must be permitted simultaneously.

REQ-07 Scrolling and zooming: This requirement comes from the guideline from Ben Shneiderman "Overview First, Zoom and Filter, Details on Demand" [36]. It is necessary to keep a balance between a general overview and the necessity to see details in the data. To achieve this, the charts generated have to be interactive, allowing the user to zoom and scroll over it to find trends and to understand the results.

REQ-08 Control over details: Although too much flexibility can be counterproductive, as the user would spend more time changing minor details than analyzing the data, the application must allow to modify at least basic settings such as legends, titles or ticks distances, among others. Specifically important is to permit changes in the chart scale through modifications in the axis properties, as certain trends can only be observed by adjusting the scale of the axis (e.g. logarithmic) [35].

REQ-09 Simple GUI: A simple GUI is essential for the successful implementation of DV in the design process, as it allows to reduce the time necessary to obtain the results not only by lowering the opening barrier, but also through the easier execution of the process.

REQ-10 Visual feedback: The user should have visual confirmations on the actions being done [7]. This can be done for example through the inclusion of warnings, indicating if the action was completed successfully or not. By including this visual feedback, the user not only is informed constantly on the current status of the app, but also is encouraged to learn and explore the data. It is also an important method to increase the user confidence in the results obtained.

IV. Methodology

There are some DV applications that satisfy many of the identified needs. However, none of them satisfy all the requirements, such as the ability to handle specific aircraft design data or great user-friendliness. Additionally, some of the fulfilled requirements do not reach the level of complexity, reusability, robustness and automation necessary for the aircraft design process. As a consequence of this existing gap, a new methodology for the development of data visualization applications adapted to the aircraft design process is proposed. It is based on four well differentiated parts, each related to a different step inside the data visualization process, as shown in Fig. 3.

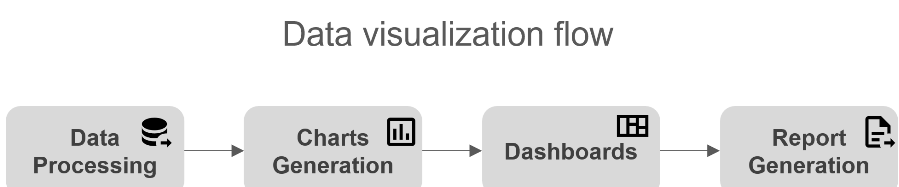


Fig. 3 The four steps of the data visualization process for aircraft design: data processing, charts generation, dashboards and report generation.

First, data has to be loaded and processed. This step should allow a first brief comparison of data. Then, in the second step, the user has to be able to generate both specific aircraft design charts and personalized charts. The third step focuses on dashboards generation, allowing users to obtain a more global view of the data and supporting decision-making. Finally, the results and the decision taken can be exported in the report section.

To achieve an easy implementation of data visualization in the aircraft design process, all these functionalities have to be integrated together in a user-friendly and easy to use GUI. The four steps of this methodology will be discussed in detail in the next paragraphs.

A. Data Processing

The first step of the process is loading the data to be analyzed. In order to generate aircraft design charts automatically, inputted data (one or multiple files) must conform to a standardized Central Data Schema. This is an essential functionality to achieve a fast regeneration of charts during successive design cycles. As previously mentioned, in the case of aircraft design a possible solution is an existing CDS called CPACS. To maintain enough flexibility, the application should also allow other input data formats, such as csv, for users aiming to explore data more broadly.

During the data processing step, the application must be able to handle missing elements in the data because different aircraft configurations with different components may be present simultaneously. The application has also to be capable of dealing with large datasets. Once the data has been processed, it is necessary to generate a table showing the most important parameters of the different aircraft, allowing the user to perform a first, superficial comparison. Usually a prefiltering should be performed for this task, as these files may contain thousands of parameters.

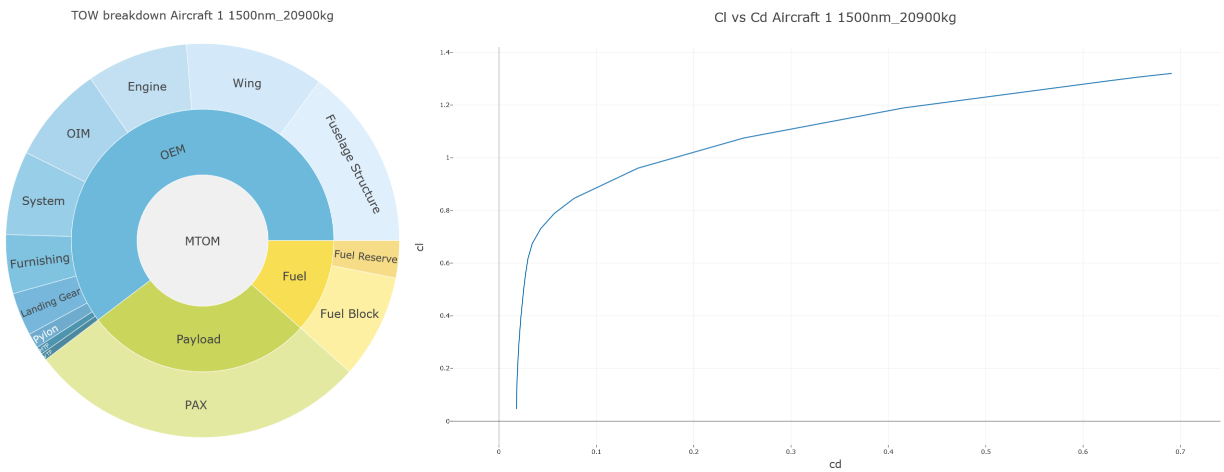
There are some occasions when additional variables not included in the dataset might be needed for the analysis. The application must allow users to create these new variables through different methods, such as expressions or the classification of data values in intervals.

B. Charts Generation

This part of the application presents all charts generated by the user. It supports two distinct categories of charts: aircraft design-specific charts and custom charts. Aircraft design charts enable users to efficiently compare aircraft performance, validate simulation results, and support decision-making processes. Custom charts are necessary when addressing specific research questions or unique analysis needs that the standard charts may not cover. These charts allow users to explore targeted scenarios, highlight particular variables, and visualize data in specialized formats. The system must allow the simultaneous representation of multiple aircraft and/or missions. While there are various types of aircraft design charts, the minimum required set includes:

1) **Aircraft Geometry:** Visual representations of each aircraft's configuration, including platform, side, front, and isometric views. These diagrams help users quickly understand the layout, verify the feasibility and compare geometric characteristics across designs.
2) **Mass Breakdown:** A detailed breakdown of the aircraft's total take-off weight into key components such as payload, fuel, propulsion system, airframe structure, and other subsystems, as shown in Fig. 4a. This chart is useful for identifying major weight drivers and assessing the efficiency of the design.
3) **Aerodynamic Polar:** Plots showing the relationship between aerodynamic parameters, such as lift coefficient (c_L) and drag coefficient (c_D), often across different angles of attack or flight conditions (see Fig. 4b). These charts are fundamental in evaluating the aerodynamic efficiency and overall performance of the aircraft.
4) **Payload-Range Characteristics:** A chart illustrating the trade-off between payload and range, typically showing the maximum payload, maximum range, and various combinations in between. It visualizes aircraft performance using a substitution curve, where payload and fuel are traded to achieve different operational scenarios. This diagram is essential for understanding how varying the payload impacts mission range and requirements.

Moreover, for a further understanding of data and for a broad comparison of the different aircraft, the application must support the generation of different charts types such as scatter plots or pie charts. It is necessary that different charts types are supported, as each one might provide different insights in the data. It is also important that for the same data the user can change the charts type easily if possible once the chart has already been generated. As mentioned in the requirements, more complex charts specially designed for comparing multi-objective datasets must be supported as well, such as parallel coordinates. Basic functionalities such as marks and filters must be included too. Finally, if new data is inputted from a different iteration, all charts must be regenerated automatically whenever possible.



(a) TOW breakdown

(b) Lift coefficient versus drag coefficient

Fig. 4 Example plots showing an aircraft take-off breakdown and aerodynamic polar for a specific mission.

C. Dashboards

Once all the necessary charts have been generated, the user has to be capable of integrating them together to obtain a system-level view of the data. To do so, the application must be capable of generating interactive dashboards, supporting design decision. It has been shown in multiple studies that there is a limit where adding more information to dashboards (regarding number of charts and of dimensions) starts to decrease the capability for taking decisions in an effective manner [21]. When this limit has been reached, users should be allowed to include new information through the creation of new dashboards. These dashboards must allow users to change the charts, the layout and the plot positions interactively, as well as their boundaries (for instance, through drag and drop). All charts must be interconnected between them regarding selection and filtering. Finally, if there is any change in the created charts, it must be reflected automatically in the dashboards.

D. Report Generation

When design decisions arise from the data analysis part, it is necessary to generate some output to keep track and to argument these choices. The application used has to be able not only to export the charts and dashboards generated, but also to generate one or multiple technical reports with the most important information. These technical report have to be generated in a semiautomatic manner and must support multiple aircraft simultaneously, containing different information depending on user selection, for example through the use of a common template. Apart from the charts and dashboards generated, additional technical information must be included in these reports, such as detailed mission information for the payload-range diagram or detailed weight breakdown tables for the TOW breakdowns. To achieve all this, it is essential that the application keeps track of which information and charts belongs to each aircraft.

V. Implementation in DIANA

To fill the existing gap in the literature, the previous methodology has been implemented in a new data visualization application called DIANA (Data Interactive Analysis and Navigation Application). DIANA is a web-based application implemented with Python in the backend and Vue in the frontend, allowing the desired balance between specification and flexibility. It is divided in four main tabs, each one implementing a different step described in Section IV. These four parts of the software are discussed in more detailed in the next paragraphs.

A. Data Processing

Different data formats are permitted in DIANA, considering the different types of users. The CDS for aircraft design used is CPACS, admitting both single or multiple files, as well as a zip folder containing multiple CPACS files. For general exploratory analysis of data, the csv format is also supported. Additionally, a previously saved project of

DIANA can also be used as an input.

After the data is processed, a table is created automatically showing the data. In the case of CPACS inputs, an automatic prefiltering is applied highlighting predetermined key aircraft parameters, such as cruise Mach number, range, or weights, for a first, fast comparison of data. The user is also allowed to import additional values by providing their location in the input file, and to derive new variables from existing ones in the dataset through intervals or through mathematical expressions. Also for smaller datasets new columns can be added manually. For a further exploration of the data regarding aircraft design, the user can generate aircraft design charts through the aircraft design kit (Fig. 5).

The aircraft design kit is an expandable menu containing a series of checkboxes, each one for a different aircraft design chart. The currently supported charts are: TOW breakdowns, wing / horizontal tail plane / vertical tail plane two dimensional geometry, aircraft 3D geometry, payload-range diagrams, two different types of aerodynamic polar (cl vs cd and L/D vs cl), power breakdown chart (Fig. 6), centers of gravity chart and specific block energy charts. To generate any of these charts, the user just needs to select the desired aircraft and charts through checkboxes. After that, by clicking on the "Generate chart(s)" button the charts will be generated.

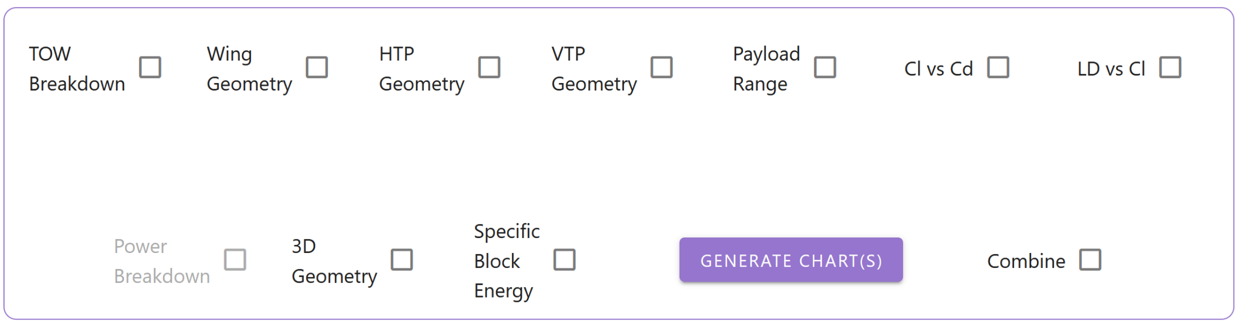


Fig. 5 Aircraft Design kit. Eleven different chart types are currently supported. Multiple charts can be created simultaneously for several aircraft at the same time. The "Combine" functionality allows the comparison of multiple aircraft in one chart.

The application is robust regarding the selection of charts. If a specific chart cannot be produced for any of the aircraft in the dataset, then its checkbox will appear as disabled (as for the power breakdown in Fig. 5). The same will happen if for a certain selection of aircraft any of them does not have the necessary data to generate that chart.

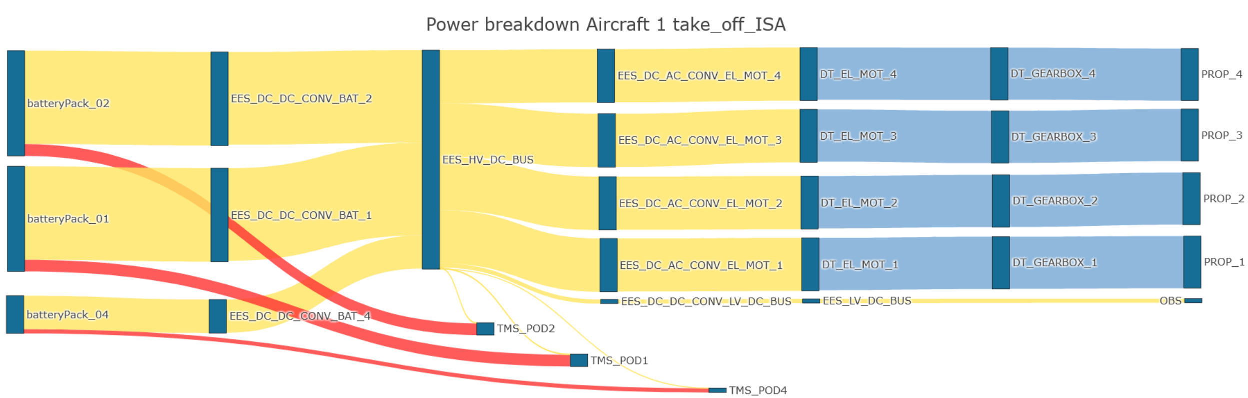


Fig. 6 Power breakdown chart generated with the aircraft design kit.

For some specific charts, the user needs to provide additional information. These are the TOW breakdowns, where the user has to select the mission, and the aerodynamic polar, where the user has to select the mission, the flight phase, the Mach number and the altitude to be analyzed. The same happens for the power breakdown chart, where it is necessary to select the desired system, and in the center of gravity chart, where the components to be included have to be selected. In those cases, pop-ups appear when clicking the respective checkboxes asking the user for the additional information, although there is always a default value to speed up the process (usually with the design mission data).

Finally, charts are built using Plotly [37], as it has built-in interactive functionalities such as the inclusion/exclusion of traces, zooming or hovering, among others. The aircraft design kit allows to generate the same chart type for multiple aircraft simultaneously, either in separate charts or combined together (clicking the "Combine" checkbox), as shown in Fig. 7.

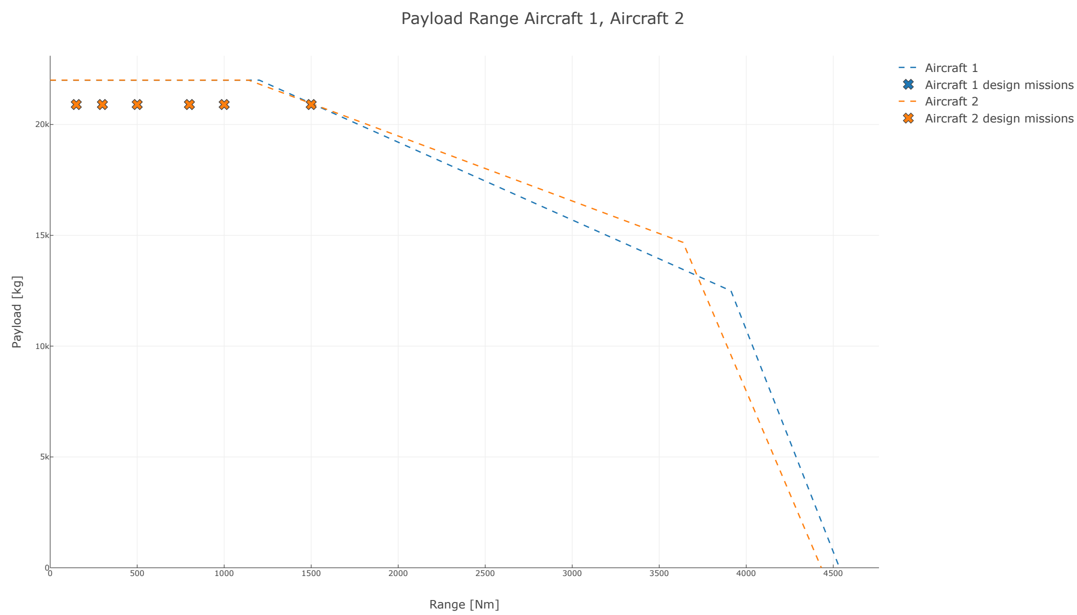


Fig. 7 Example of a chart generated with the combine option within the aircraft design kit. In this case, two aircraft payload range diagrams are shown together for comparison.

B. Charts Generation

This part of the application stores all the charts generated by the user in different tabs. First, it includes all the charts generated by the user with the aircraft design kit. Second, for a more detailed analysis of data, user personalized charts can also be generated. The GUI for the generation of these personalized charts is shown in Fig. 8.

The first step to generate a personalized chart is to select the variables to be included in the top part of the GUI. Then, depending on the type and number of variables that are given, the most suitable type of chart is suggested according to literature. However, as the same data can be represented in several ways, the user can select a different chart type among the available ones through an expandable menu on the right.

At the moment, six different chart types are supported: scatter plots (both 2D and 3D), bar charts, pie charts, line plots, parallel coordinates and scatter matrix. In most cases, once the chart has been generated, the user can visualize an additional variable through marks. Three different types of marks are supported, which are color, shape and size. It is possible to combine multiple marks simultaneously if needed.

Another important functionality are filters. These filters can be used at any time, and are applied to already generated charts as well, allowing the user to deal with complex and large datasets. These are interactive, so that the effects can be observed in the charts in real time. Right now, simple filters based exclusively on variables values are admitted. This means ranges for continuous filters and specific values for discrete variables.

Finally, additional settings for further customization are added. With these, the user can modify axes, legends, colors or titles, among others. Only few settings are introduced to avoid the user spending more time on customization instead on analyzing the data. This achieves a good balance between customization and ease of use.

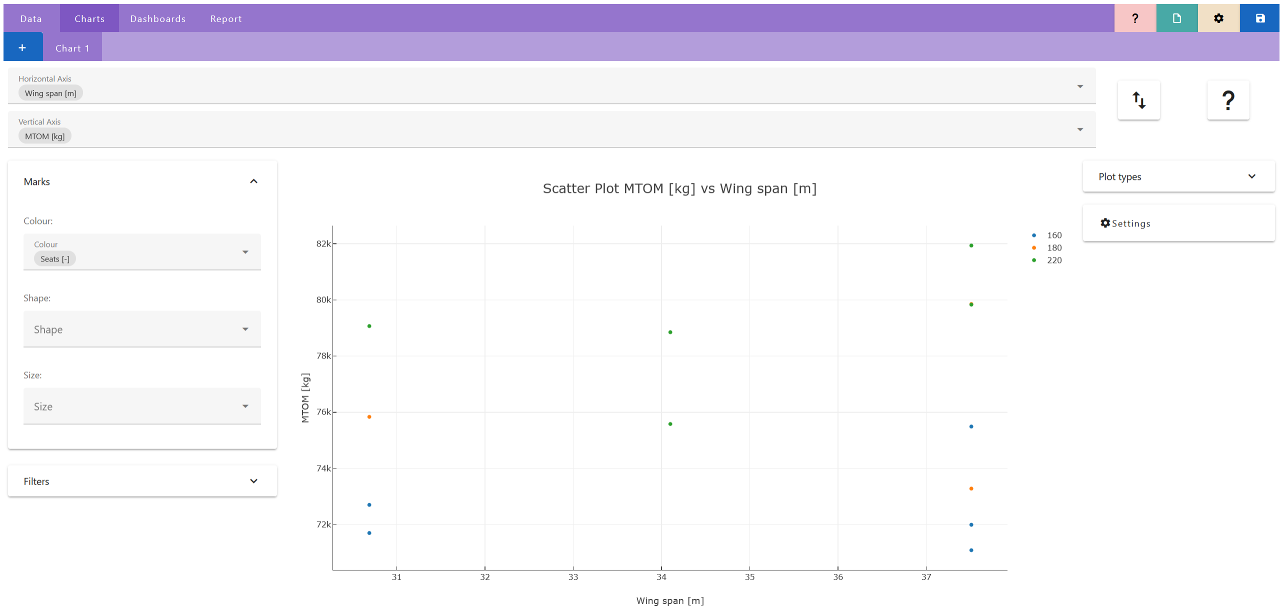


Fig. 8 GUI for the generation of user personalized charts. A scattered plot with wing span versus MTOW is provided as an example. An additional color mark representing the number of seats has been added.

C. Dashboards

Once all the necessary charts have been generated, these can be combined together for decision-making in the dashboard tab, as shown in Fig. 9. The process to create a dashboard is really simple. There is a selector at the top of the GUI with all the charts that have been generated, either aircraft design charts or personalized ones. The user just needs to click on the desired charts and they will be incorporated into the dashboard. To maintain an optimal balance between information density and readability needed for decision-making, users can generate new dashboards by clicking the blue addition button on the top left.

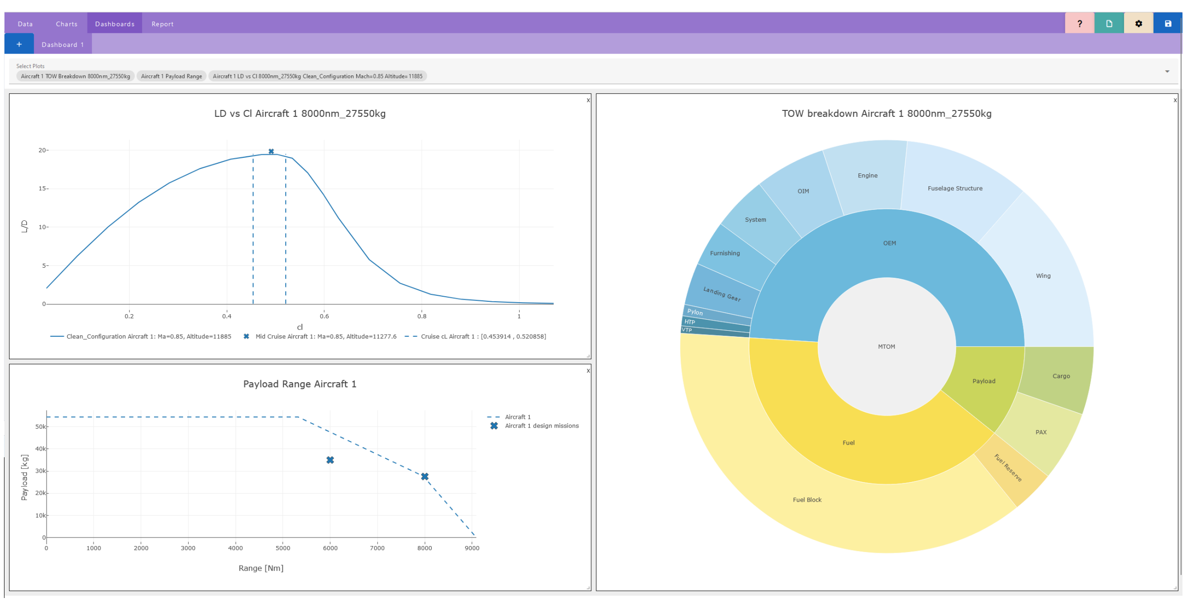


Fig. 9 Example of a single aircraft design dashboard. This dashboard includes the aerodynamic efficiency and the payload-range on the left, and the design mission TOW breakdown on the right.

Each dashboard is a white canvas, where the user can add as many charts as desired. Moreover, the user has full control over each chart size and positioning, through drag-and-drop functionality.

D. Report Generation

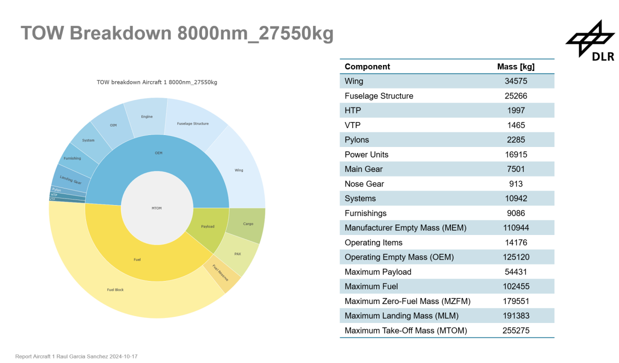
Two possibilities are supported by DIANA for this purpose. First, the user can export directly the desired charts in different formats (png, jpg, svg or html). The second option, only available when using aircraft design data, is to generate a report in PowerPoint following a specific template, as shown in Fig. 10.

A menu is available to select the aircraft to be included in the report, and to specify which charts should be exported. The user has also the possibility to select between the creation of individual reports or to merge all aircraft in one report. When more than one aircraft are selected, comparison plots can also be included in the exports.

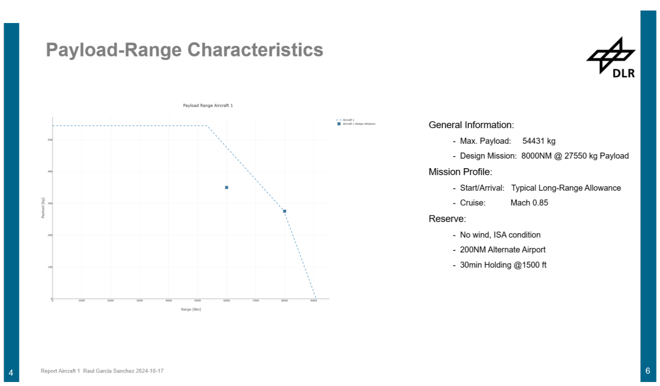
To automatize the report generation process for multiple aircraft, there is the possibility to first set a common template indicating the desired charts to be included. This will then be generated for each aircraft selected, with the application ensuring that the correct data is exported. Additional information is sometimes added to certain charts in their corresponding slides according to the aircraft design best practice. Some examples include a detailed weight breakdown table for the TOW breakdown chart or detailed mission information in the payload-range diagram, as shown in Fig. 10.

Finally, DIANA project files can be directly exchanged as reports. This is already a common scenario in data analysis with other applications due to its multiple advantages, such as maintaining the intrinsic interactivity of the application, and can be beneficial to refine results between various experts. It is still important however to permit the generation of more formal technical reports, also for long-term storage.

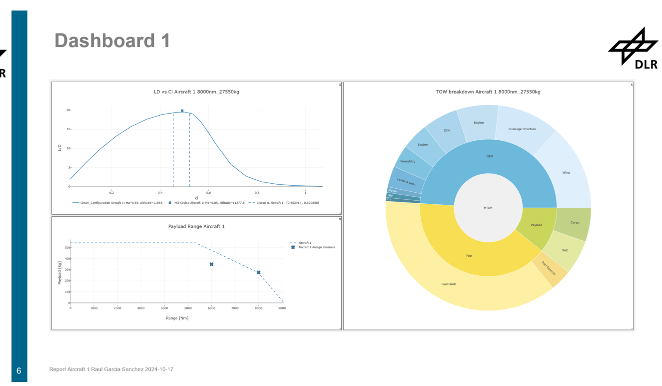
(a) Title slide



(b) TOW breakdown



(c) Payload range



(d) Dashboard

Fig. 10 These figures show some of the automated generated slides for an aircraft design report. Additional information is included for some cases such as the TOW breakdown or the payload range diagrams.

VI. Application cases

This section demonstrates how DIANA can deal with practical application cases. First, a verification case is presented to evaluate how DIANA can satisfy the different requirements that were presented in section III. Then an aircraft design scenario will be introduced to show how DIANA can support experts through the decision-making process.

A. Verification case

In aircraft design, it is common practice to select an existing reference aircraft that establishes a set of top-level aircraft requirements (TLARs) and a mean of calibrating the design process. In addition, when the goal of the design study includes the evaluation of innovative future technologies, it is appropriate to establish a baseline aircraft with the same Entry Into Service (EIS) as the main design object. This is an essential step to achieve fair comparisons and a good understanding of the results. The baseline is derived from the reference aircraft considering a technology evolution approach [38].

DIANA is suited to evaluate and compare the baseline aircraft design with respect to a given reference aircraft. To achieve this, the CPACS files of the two models can be loaded in DIANA, where the data tab offers a first comparison of the main aircraft parameters through its table. After that, multiple charts (both aircraft design and personalized), as well as dashboards, can be generated to compare both aircraft. Finally, reports for each aircraft including the details of the comparison can also be generated and used to share the findings with third parties.

As an example of this process, DIANA is used here to compare the DLR short-range aircraft concepts: the D239 reference aircraft (a DLR interpretation of the Airbus A321neo) and the baseline aircraft D250L-TF *, with assumed evolutionary technologies for EIS in 2040. These aircraft were designed using the well established DLR conceptual aircraft design workflow introduced within the scope of the project EXACT †. The workflow was used in the main studies conducted during the project, such as the ones of Ramm et al. [39] and Atanasov et al. [40]. The latest version of the workflow was published by Nugnes et al. [41].

Selected	Reference	Id	UID	Names	MTOM [kg]	Max. Payload [kg]	Seats [-]	Design Range [nm]	Cruise Mach [-]	Aircraft reference area [m²]	Aircraft reference length [m]	Wing span [m]
☐	☑	1	D239	D239L	95537 (0.00%)	25000 (0.00%)	239 (0.00%)	2500 (0.00%)	0.78 (0.00%)	131.33 (0.00%)	4.37 (0.00%)	35.8 (0.00%)
☐	☐	2	D250L-TF	D250L-TF	81422 (-14.77%)	25000 (0.00%)	250 (4.60%)	1500 (-40.00%)	0.78 (0.00%)	136.75 (4.13%)	4 (-8.47%)	42 (17.32%)

Fig. 11 Data table with main parameters of example aircraft.

Upon loading the CPACS files of the two aircraft in DIANA, a data table is immediately, and automatically, generated (Fig. 11). This table allows to have an overview of the main differences between the two aircraft, and it is particularly useful when comparing a baseline aircraft to its reference model as it provides a first measure of the effects of the assumptions applied in the design phase (technology evolution approach).

In a second phase, the comparison needs to be brought to a higher level of detail. Visualizing geometrical features, as well as mass information, while also keeping an overview of the aircraft performance, is essential to obtain a full picture of the aircraft specifics and it allows to validate the baseline design in comparison to the reference aircraft. For this reason, a dashboard including wing geometry plots, TOW Breakdowns, Payload Range diagrams, and aerodynamic polar of the vehicles was generated, and it is shown in Fig. 12. Here, a color code was set, with the D239 being represented in green and the D250L-TF in orange. With the generation of aircraft design specific plots of different type, grouped in one dashboard, REQ-01, REQ-02, and REQ-03 are verified.

Moreover, to keep the focus on the aircraft overall payload-range capabilities, the markers for single missions were filtered out of the diagram (REQ-06). On the other hand, the aerodynamic drag polar was plotted for cruise altitude and Mach number, and it was zoomed in to better appreciate the variation in drag coefficients (for cruise CL values) between the two aircraft (REQ-07). Note that for a better readability, horizontal dashed lines were added to mark the CL range during cruise, while the markers identify the mid-cruise point (REQ-05). To summarize, document, and share among stakeholders the results of the comparison, three reports were generated in DIANA (REQ-04). One for each aircraft, and an additional report for the combined data.

Regarding the style of the dashboard shown in Fig. 12, the titles and axes font sizes were reduced to improve the single charts visibility within the dashboard (REQ-08), allowing for a better comparison of the D239 and D250L-TF

*D250L-TF: `https://www.digital-hangar.de/portfolio/d250-tf-2040/`

†EXACT website: `https://exact-dlr.de/project-overview/`

specs. For the same reason, the legends of each plot were removed, and the general color code mentioned above was adopted. Finally, the whole process was possible thanks to a simple and friendly user interface (REQ-9), including warning and feedback messages (REQ-10), which allowed the aircraft designers involved in the study to quickly master DIANA.

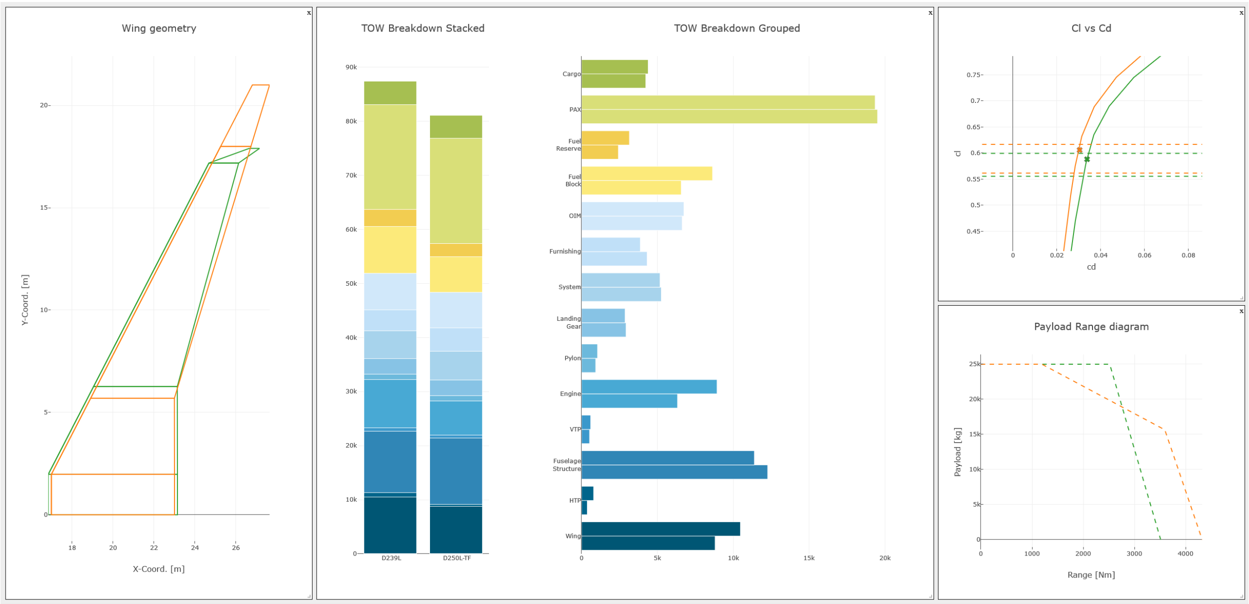


Fig. 12 Dashboard comparing wing geometry, TOW Breakdown, Payload Range diagram, and aerodynamic polar of the D239 (green) and D250L-TF (orange).

B. Aircraft design application case

In this section, a second aircraft design exercise is proposed, comparing the baseline seen above, the D250L-TF, to one of the main design concepts resulting from the EXACT project: the D250L-TFLH2-MHEP. The latter is a liquid hydrogen and battery powered mild hybrid short range aircraft whose specifics and data can also be found on the DLR digital aircraft hangar ‡. This aircraft will be represented in blue in all following figures.

The D250L-TFLH2-MHEP was designed for the same TLARs as the D250L-TF, but an additional improvement in gas turbine efficiency was considered for liquid hydrogen (LH2) combustion. Moreover, a wing mass penalty was introduced to account for the dry wing effect. In fact, the LH2 is stored in the rear fuselage, and the wing bending relief is lost. The MTOW breakdown chart shown in Fig. 13 allows to validate the correct implementation of these assumptions in the new model. As expected, the heavier wing, together with the hybrid powertrain components, LH2 tanks, and the longer fuselage needed to accommodate them, lead to an increased MTOW.

Moreover, from the wing and tail-plane geometry charts of Fig. 13, it appears that the wing of the D250L-TFLH2-MHEP is shifted backwards with respect to the baseline, and the horizontal tail-plane is increased in size. These effects are related to the shift in center of gravity due to the fuel tanks positioning in the rear fuselage.

In Fig. 14, the specific block energy consumption of the two aircraft is compared. This parameter indicates the energy consumed per passenger per nautical-mile travelled in the main mission block. Despite the increased MTOW, it appears from this graph that the specific energy consumption of the D250L-TFLH2-MHEP is very close to that of the baseline aircraft. From this plot it can be therefore inferred that the use of a mild hybrid propulsion system, with the employment of fuel cells in addition to two gas turbines, allows for an efficient use of fuel, with sustained energy consumption.

‡D250L-TFLH2-MHEP: `https://www.digital-hangar.de/portfolio/d250-tflh2-mhep-2040/`

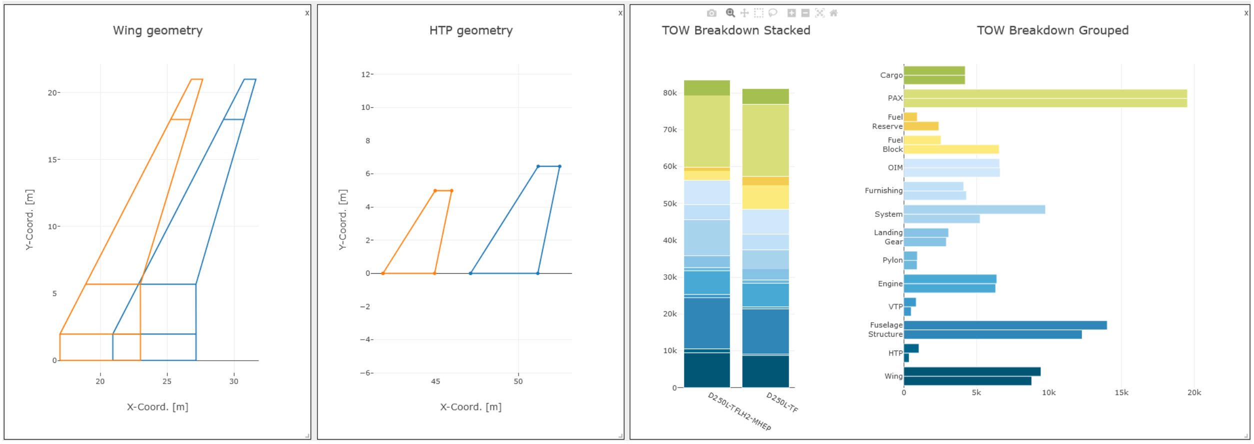


Fig. 13 Dashboard comparing wing and HTP geometry, as well as TOW Breakdown of the D250L-TF (orange) and D250L-TFLH2 (blue).

In the same dashboard, it is clearly shown that this comes with reduced payload-range capabilities. The D250L-TFLH2-MHEP presents a much shorter substitution line, typical of LH2 concepts, and therefore the maximum range is roughly half the D250L-TF one. However, the main areas of interest for the short haul market, with high payload and ranges between one thousand to two thousand nautical miles can still be covered.

In conclusion, from this brief overview some considerations can be done about the D250L-TFLH2-MHEP. Provided that the concept can cover a good enough portion of the short-range air transport market, and the costs of LH2 will be sufficiently low (in comparison to SAF), the D250L-TFLH2-MHEP offer potential for a high climate impact reduction. It does so by maintaining a low energy consumption and thanks to the employment of LH2 in a mild hybrid electric propulsion system, which brings the CO2 emissions during flight to zero.

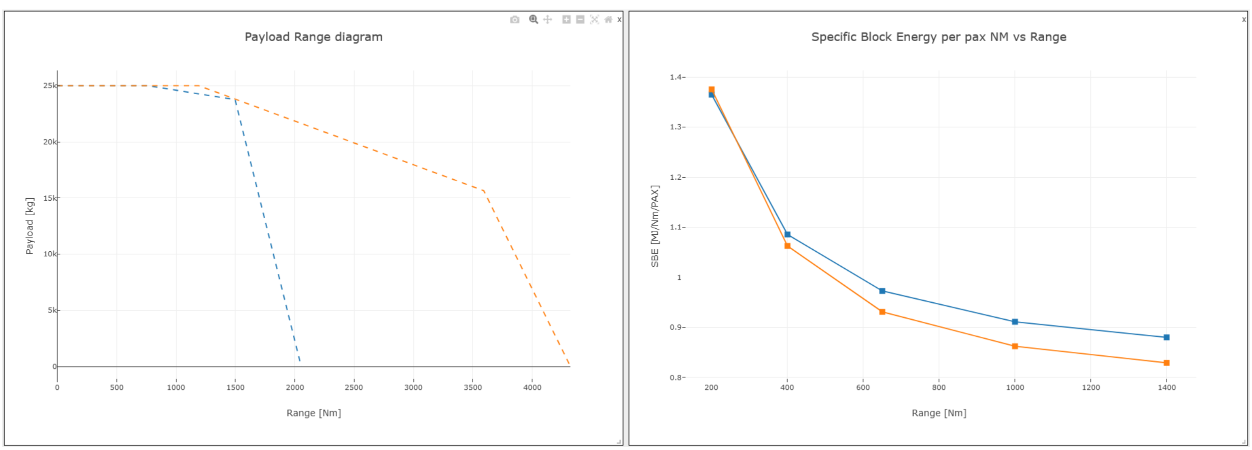


Fig. 14 Dashboard comparing Payload Range diagrams and specific block energy of the D250L-TF (orange) and D250L-TFLH2 (blue).

VII. Conclusions

To support the design of ever increasingly complex aircraft concepts, new methodologies have been developed to allow the exploration and assessment of broad design spaces. A direct result of this trend is the creation of larger amount of data and simulation results, making the already difficult process of decision-making even harder. Modern data visualization techniques are therefore necessary to understand all this data, simplifying processes while maintaining the human in the loop.

However, there are specific challenges that arise when implementing data visualization in the aircraft design process. Firstly, the necessity of specialized and complex charts, such as take-off weight breakdowns or aerodynamic polar. Secondly, the application also has to find a balance between ease of use and the ability to customize, reuse and flexibly generate other useful and more general charts. Finally, the data complexity specific to the aircraft design domain, as well as the need of semiautomatic technical reports generation represent additional challenges.

This paper formalized all the identified needs into a set of requirements. After a literature research, it was shown that there are no data visualization applications that satisfies all the requirements, at least to the level of complexity and reusability fitting for aircraft design. To address this issue, a methodology for the design of data visualization applications tailored to the aircraft design process has been developed and implemented in a new application, DIANA.

DIANA is based on a standardized common data structure, CPACS, which enables the rapid generation of aircraft design specific plots. These, together with personalized, user created plots, help to explore and to better understand the data. DIANA also includes the possibility of gathering these charts in interactive dashboards, which aids decision-making. The most interesting plots and dashboards can be easily exported in the form of report specifically adapted to aircraft design. Finally, the application satisfies all the previously mentioned requirements, allowing a faster analysis of the data and a better understanding of it, ultimately supporting the decision-making process.

Moreover, in order to further improve the application, additional features are planned to be added: first, the library of available aircraft design specific charts should be continuously expanded, to have a more comprehensive understanding and analysis of the available data. Also charts regarding other fields of the aerospace sector, such as on-board systems or climate impact are planned to be implemented. Another interesting functionality would be to implement automatic statistical analyzes such as correlation matrices or clustering, which can further support the decision process, especially when dealing with very large datasets. Finally, methods such as the automatic suggestion of charts (e.g. using machine learning) or Pareto fronts will be implemented to support the missing transition from bigger datasets to smaller ones where a more detailed analysis can be performed.

References

[1] DeTurris, D., and Palmer, A., "Perspectives on Managing Emergent Risk Due to Rising Complexity in Aerospace Systems," *INSIGHT*, Vol. 21, No. 3, 2018, p. 80–86. https://doi.org/10.1002/inst.12215.

[2] Boggero, L., Bussemaker, J. H., Donelli, G., Torrigiani, F., and Nagel, B., "Processes, Methods and Tools supporting the development of aeronautical systems," *ICAS Conference*, 2024.

[3] Bussemaker, J. H., Boggero, L., and Nagel, B., "System architecture design space exploration: Integration with computational environments and efficient optimization," *AIAA AVIATION FORUM AND ASCEND 2024*, 2024, p. 4647. https://doi.org/10.2514/6.2024-4647.

[4] Riege, J., Lee, R., and Ebrahimi, N., "Displaying data effectively using an automated process dashboard," *IEEE Transactions on Semiconductor Manufacturing*, Vol. 32, No. 4, 2019, pp. 530–537. https://doi.org/10.1109/tsm.2019.2938157.

[5] Wexler, S., *The Big Picture: How to Use Data Visualization to Make Better Decisions—Faster*, McGraw-Hill, 2021.

[6] Janvrin, D. J., Raschke, R. L., and Dilla, W. N., "Making sense of complex data using interactive data visualization," *Journal of Accounting Education*, Vol. 32, No. 4, 2014, pp. 31–48. https://doi.org/10.1016/j.jaccedu.2014.09.003.

[7] Munzner, T., *Visualization Analysis and Design*, A K Peters/CRC Press, 2014. https://doi.org/10.1201/b17511.

[8] Boggero, L., Ciampa, P. D., and Nagel, B., "An MBSE architectural framework for the agile definition of system stakeholders, needs and requirements," *AIAA Aviation 2021 Forum*, 2021, p. 3076. https://doi.org/10.2514/6.2021-3076.

[9] Obstbaum, M., Wurstbauer, U., König, C., Wagner, T., Kübler, C., and Fäßler, V., "From a Graph to a Development Cycle: MBSE as an Approach to reduce Development Efforts," *Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth eV*, 2017.

[10] Martins, J. R. R. A., and Ning, A., *Engineering Design Optimization*, Cambridge University Press, Cambridge, UK, 2022. https://doi.org/10.1017/9781108980647.

[11] Sobieszczanski-Sobieski, J., Morris, A., and Van Tooren, M., *Multidisciplinary design optimization supported by knowledge based engineering*, John Wiley & Sons, 2015.

[12] Bussemaker, J. H., Boggero, L., and Ciampa, P. D., "From system architecting to system design and optimization: A link between MBSE and MDAO," *INCOSE International Symposium*, Vol. 32, Wiley Online Library, 2022, pp. 343–359. https://doi.org/10.1002/iis2.12935.

[13] Crawley, E., Cameron, B., and Selva, D., *System architecture: strategy and product development for complex systems*, Prentice Hall Press, 2015.

[14] Roelofs, M., and Vos, R., "Technology evaluation and uncertainty-based design optimization: A review," *2018 AIAA Aerospace Sciences Meeting*, 2018, pp. 1–21. https://doi.org/10.2514/6.2018-2029.

[15] Baalbergen, E., Vankan, J., Boggero, L., Bussemaker, J. H., Lefèbvre, T., Beijer, B., Bruggeman, A.-L., and Mandorino, M., "Advancing cross-organizational collaboration in aircraft development," *AIAA AVIATION 2022 Forum*, 2022, p. 4052. https://doi.org/10.2514/6.2022-4052.

[16] Alder, M., Moerland, E., Jepsen, J., and Nagel, B., "Recent advances in establishing a common language for aircraft design with CPACS," 2020.

[17] Bussemaker, J. H., Boggero, L., and Nagel, B., "The AGILE 4.0 Project: MBSE to Support Cyber-Physical Collaborative Aircraft Development," *INCOSE International Symposium*, Vol. 33, No. 1, 2023, pp. 163–182. https://doi.org/10.1002/iis2.13015.

[18] Bussemaker, J. H., Sánchez, R. G., Fouda, M., Boggero, L., and Nagel, B., "Function-Based Architecture Optimization: An Application to Hybrid-Electric Propulsion Systems," *INCOSE International Symposium*, Vol. 33, Wiley Online Library, 2023, pp. 251–272. https://doi.org/10.1002/iis2.13020.

[19] Bussemaker, J. H., Ciampa, P. D., Singh, J., Fioriti, M., Cabaleiro De La Hoz, C., Wang, Z., Peeters, D., Hansmann, P., Della Vecchia, P., and Mandorino, M., "Collaborative design of a business jet family using the AGILE 4.0 MBSE environment," *AIAA Aviation 2022 Forum*, 2022, p. 3934. https://doi.org/10.2514/6.2022-3934.

[20] Sinar, E. F., "Data visualization," *Big Data at Work*, Routledge, 2015, pp. 115–157.

[21] Dy, B., Ibrahim, N., Poorthuis, A., and Joyce, S., "Improving visualization design for effective multi-objective decision making," *IEEE Transactions on Visualization and Computer Graphics*, Vol. 28, No. 10, 2021, pp. 3405–3416. https://doi.org/10.1109/tvcg.2021.3065126.

[22] Dzemyda, G., Kurasova, O., and Zilinskas, J., "Multidimensional data visualization," *Methods and applications series: Springer optimization and its applications*, Vol. 75, No. 122, 2013, pp. 10–5555. https://doi.org/10.1007/978-1-4419-0236-8.

[23] Donelli, G., Boggero, L., and Nagel, B., "Concurrent Value-Driven Decision-Making Process for the Aircraft, Supply Chain and Manufacturing Systems Design," *Systems*, Vol. 11, No. 12, 2023, p. 578. https://doi.org/10.3390/systems11120578.

[24] Ezugwu, A. E., Shukla, A. K., Agbaje, M. B., Oyelade, O. N., José-García, A., and Agushaka, J. O., "Automatic clustering algorithms: a systematic review and bibliometric analysis of relevant literature," *Neural Computing and Applications*, Vol. 33, 2021, pp. 6247–6306. https://doi.org/10.1007/s00521-020-05395-4.

[25] Karagoz, E., Tai, J., Sarojini, D., and Mavris, D., "Design space reduction using clustering in aircraft engine design," *2019 IEEE Aerospace Conference*, IEEE, 2019, pp. 1–8. https://doi.org/10.1109/aero.2019.8741654.

[26] Bach, B., Freeman, E., Abdul-Rahman, A., Turkay, C., Khan, S., Fan, Y., and Chen, M., "Dashboard design patterns," *IEEE Transactions on Visualization and Computer Graphics*, Vol. 29, No. 1, 2022, pp. 342–352. https://doi.org/10.1109/tvcg.2022.3209448.

[27] Guenov, M. D., Nunez, M., Molina-Cristóbal, A., Datta, V. C., and Riaz, A., "Aircadia-an interactive tool for the composition and exploration of aircraft computational studies at early design stage," *29th Congress of the International Council of the Aeronautical Sciences*, Vol. 130, 2014.

[28] Boeing, "Cascade," , 2025. URL https://cascade.boeing.com/, accessed: 2025-03-26.

[29] DLR, "ILA 2024 - Alicia," , 2025. URL https://event.dlr.de/ila2024/alicia/, accessed: 2025-03-26.

[30] Tableau, "Tableau," , 2024. URL https://www.tableau.com/.

[31] Tableau, "Lufthansa increases efficiency by 30%, gains flexibility and departmental autonomy," , 2024. URL https://www.tableau.com/solutions/customer/lufthansa-saves-30-time-gains-decision-flexibility-and-departmental-autonomy.

[32] JMP, "JMP," , 2024. URL https://www.jmp.com/en_us/home.html.

[33] Microsoft, "Power BI," , 2025. URL https://www.microsoft.com/en-us/power-platform/products/power-bi, accessed: 2025-03-26.

[34] Kelleher, C., and Wagener, T., "Ten guidelines for effective data visualization in scientific publications," *Environmental Modelling & Software*, Vol. 26, No. 6, 2011, pp. 822–827. https://doi.org/10.1016/j.envsoft.2010.12.006.

[35] Ward, M. O., Grinstein, G., and Keim, D., *Interactive data visualization: foundations, techniques, and applications*, AK Peters/CRC Press, 2010. https://doi.org/10.1201/b10683.

[36] Shneiderman, B., "The eyes have it: A task by data type taxonomy for information visualizations," *The craft of information visualization*, Elsevier, 2003, pp. 364–371. https://doi.org/10.1109/vl.1996.545307.

[37] Inc., P. T., "Collaborative data science," , 2015. URL: https://plot.ly.

[38] Fröhler, B. M., Alder, M., Wöhler, S., and Zill, T., "Assessing Uncertainties of an Evolutionary Baseline as Benchmark of Future Aircraft Designs," *AIAA SciTech Forum, Orlando, FL, USA, 2024.*, 2024. https://doi.org/10.2514/6.2024-2813.

[39] Ramm, J., Pohya, A. A., Wicke, K., and Wende, G., "Uncertainty quantification in hydrogen tank exchange: Estimating maintenance costs for new aircraft concepts," *International Journal of Hydrogen Energy*, Vol. 68, 2024, pp. 159–169. https://doi.org/https://doi.org/10.1016/j.ijhydene.2024.04.157.

[40] Atanasov, G., Wehrspohn, J., Kühlen, M., Cabac, Y., Silberhorn, D., Kotzem, M., Dahlmann, K., and Linke, F., "Short-Medium-Range Turboprop-Powered Aircraft as a Cost-Efficient Enabler for Low Climate Impact," *AIAA Aviation Forum, San Diego, CA, USA, 2023.*, 2023. https://doi.org/https://doi.org/10.2514/6.2023-3368.

[41] Nugnes, V., Silberhorn, D., and Fritzsche, F., "Overall aircraft design workflow: an overview of the aircraft design methods and analysis capabilities in EXACT2," , 2025. URL https://elib.dlr.de/213452/, accessed: 2025-04-16.