

An interactive framework to facilitate probabilistic set-based multidisciplinary design optimisation studies

Gustavo P. Krupa, Andrea Spinelli, Timoleon Kipouros

Cranfield University, School of Aerospace Transport and Manufacturing, Cranfield, MK43 0AL, UK

Abstract. The upcoming stringent environmental aircraft regulations and the environmental, social and governance (ESG) framework targeting net zero emissions has forced aircraft manufacturers to seek innovative feasible technical solutions. Often, there is the need to consider entirely radical solutions, such as hybrid-electric aircraft, which are not fully understood when compared with conventional kerosene driven aircraft. The recent development of a probabilistic set-based multidisciplinary optimisation methodology has demonstrated the ability to explore trade-offs when the requirements are uncertain. In this way, the weaknesses and potential to enable the feasibility of hybrid-electric aircraft can be studied from a systems perspective but maintaining the connection with more detailed trade-off studies of components of the sub-systems. We have developed an interactive interface, where the user is guided through the steps of the design methodology and the produced data is visualised to aid an informative decision-making process. In our illustrative case study, decision-makers are enabled to interactively explore the hybrid-electric propulsion design space while considering the impact to the figures of merit from expected improvements in the coming years of key enabling technologies, such as energy storage.

1. Introduction

Aviation is vital to the European economy and integration. It is an industry that generates more than £500 billion per year and supports more than 9.3 million jobs. However, flying is responsible for more than 2% of global greenhouse gas emissions. Despite the fact that the aviation industry has been hit hard by the COVID-19 pandemic, causing a drop in air traffic, it is forecast that air traffic is going to increase 5% yearly until 2030. This increase in air traffic obviously conflicts with the goals set in Agenda 2030 and promoted by the World Economic Forum. Thus, the environmental impact of aviation must be tackled by the development of sustainable aeroplanes in order to meet the European Union's target of net zero greenhouse gas emissions [1]. In addition to the net zero target, the Environmental, social and governance (ESG) framework is set to financially reward organisations that operate in a more sustainable and green manner. Hence, making air travel sustainable is seen as key to Europe's recovery.

Recent research in novel propulsion architectures for sustainable aviation highlights the increase in the design complexity of hybrid-electric designs when compared to conventional aircraft. This result from the fact that current design methodologies rely on aircraft level analysis and do not normally consider sub-systems designs and their impact on aircraft level during the conceptual design phase. The possibility of evaluating a system of systems is recognized as a key



factor for the development of future hybrid-electric aircraft and their systems. As an example, one may consider that energy management strategy (EMS) is associated with a given aircraft and its mission. For a hybrid-electric aircraft, an EMS study is not straightforward, because the additional power sources may be combined in many different ways, thereby expanding not only the design space but also the operational space of the aircraft.

As part of the FUTPRINT50 project, a methodology capable of exploring the design space using set-based design principles has been developed. This methodology incorporates probabilistic assessment of requirements with multidisciplinary optimisation. In the first phase of the process, the set-based framework developed explores every design parameter combination in a given performance model of the system under design, by evaluating the probability of satisfying a minimum required set of figures of merit (see table 2). In this way, the configurations that do not meet the probabilistic requirements set by the optimiser are discarded, speeding up the process. In the second phase, a multidisciplinary optimiser obtains the best points in each surviving configuration, together with their quantified uncertainty, building a set of Pareto optimal solutions.

The purpose of this paper is to introduce a web application tool that facilitates the use of the probabilistic set-based framework used for multidisciplinary design optimisation studies. The originality of this work lies in the fact that given a design methodology, we are able to facilitate its use using a web application tool, which is tailored to support decision-making in early conceptual design and also to support technology and product forecasting activities in complex design spaces, such as illustrated by the hybrid-electric aircraft design case.

2. Methodology

2.1. The use of probabilities in engineering

The concept of probability as formalized in Measure Theory by Kolmogorov [2] can be used as a mathematical model for uncertainty, risk and confidence. One of the most common ways to translate our knowledge or lack of it to a variable or mathematical parameter is to model it by a random variable. A random variable is a mathematical quantity that can take any arbitrary value from a given set of values. Normally, one can assume that the random variable models a “degree of belief”. In this way, one can say that a particular random variable is distributed according to a probability distribution function. For instance, for a continuous random variable x to be normal or Gaussian it must have a probability distribution function of the form

$$f_x(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2} \quad (1)$$

where μ and σ are two scalar parameters characterising the Gaussian probability distribution function, with σ assumed non-negative. Figure 1 shows a normal or Gaussian distribution which is used to model the uncertainty assigned to a variable or parameter.

2.2. Probabilistic set-based multidisciplinary design optimisation

Set-based as a design philosophy is defined by Sobek [3] as an engineering design philosophy where engineers are supposed to “reasoning, developing, and communicating about sets of solutions in parallel independently”. This definition, albeit informal, links concurrent engineering (CE) to set-based design (SBD), which some authors distinguish [3]. Set-based concurrent engineering (SBCE) originated from the Toyota Product Development System (TPDS). SBCE takes advantage of parallel evaluation of multiple configurations in the early stages of design by using sets of possible solutions [4]. The SBCE process consists in the mapping of the design space and feasible regions, concurrently designing different alternative systems or candidate architectures. The concept of sets allows these candidate architectures

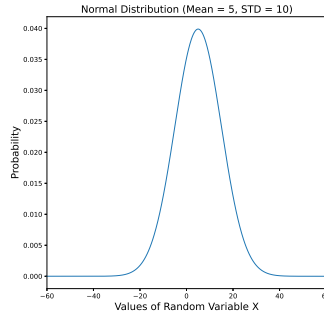


Figure 1: An example of normal or Gaussian probability distribution function (PDF)

or systems to be developed in a fully functional way across all discipline, identifying possible overlaps. Then as detail level design considerations increase the sets are narrowed down, with the consensus of all Integrated Product development Teams (IPDTs). It is possible, however, with some limitations, to perform this tasks in a computational environment since in set-based concurrent engineering, it is straightforward to generate configurations for systems that can be described by discrete design parameters such as subsystems or components. The initial step is to tabulate the identified design system parameters along with their possible options. These parameters are recombined for each new alternative configuration and evaluated according to a predefined set of performance metrics. The configurations that do not satisfy the design requirements are discarded and the remaining ones are stored for future use. This process continues until a desirable configuration or set of parameters emerges.

2.3. Optimisation Results

To illustrate the probabilistic set-based study and to demonstrate how the tool being developed can facilitate such set-based studies by providing a practical way for high-dimensional visualisation and uncertainty quantification, the problem investigated in Spinelli et al. [5] is restated here. The goal was to solve the optimisation problem in equation 2, for the hybrid-electric propulsion architecture represented in figure 2. Table 1 shows the nominal parameters adopted in the architecture.

$$\begin{aligned}
 &\underset{X}{\text{minimise}} && M_{fuel}, M_{NO_x} = f(X) \\
 &\text{subject to} && M_{\text{takeoff}} \leq 20000 \text{ kg} \\
 &&& P_{\text{sat}} \geq 0.5
 \end{aligned} \tag{2}$$

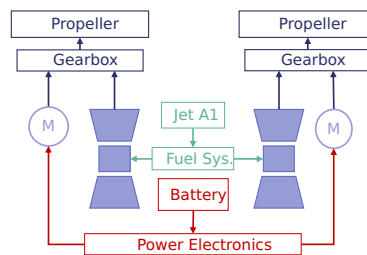


Figure 2: Hybrid-Electric Propulsion Architecture

Table 1: Parameters of the Hybrid-Electric Aircraft

Maximum Take-Off Mass [kg]	21000	Electric Motor Efficiency	0.98
Operating Empty Mass [kg]	11550	Power Electronics Efficiency	0.985
Payload Mass [kg]	5000	Cable Distribution Efficiency	0.996
Gearbox Efficiency	0.99	Pack-to-Cell Mass Ratio	1.5
L/D (Climb)	16	Pack Energy Density [Wh/kg]	500
L/D (Cruise)	14.5	Cell Total Capacity [Ah]	7.2
Propeller Efficiency (Climb)	0.73	Cell Nominal Voltage [V]	3.7
Propeller Efficiency (Cruise)	0.86	System Nominal Voltage [V]	500

The figures of merit calculated during the optimisation procedure are and indexed by a set id are: Climb h_0 , climb h_1 , cruise h_0 , cruise h_1 , take-off mass, burned full mass, emitted NO_x , battery mass, emitted CO and emitted CO_2 . For this initial study, the battery energy density (Wh/kg) is deemed constant and is going to provide the use case for the formulation of a technology forecasting problem in section 3. Table 2 shows the different figures of merit as a function of its set id.

ID	Optimisation input x_i						Optimisation output y_i				Const
Sets	Climb h_0	Climb h_1	Cruise h_0	Cruise h_1	Take-off mass [kg]	Burned fuel mass [kg]	Emitted NO_x [kg]	Battery mass [kg]	Emitted CO [kg]	Emitted CO_2 [kg]	Bat. energy density [Wh/kg]
0	0.02	0.04	0.18	0.14	18488.12	1053.12	6.39	885.00	0.29	11.3	3159.35
0	0.25	0.25	0.25	0.25	19570.91	1019.60	6.01	2001.32	0.30	11.59	3058.81
1	0.19	0.02	0.11	0.25	18830.09	1042.60	6.22	1237.49	0.29	11.76	3127.78
1	0.24	0.11	0.22	0.45	19924.61	1009.55	5.85	2365.07	0.30	14.63	3028.65
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4	0.25	0.21	0.41	0.25	19992.22	1007.33	5.83	2434.90	0.30	14.04	3021.99
4	0.25	0.20	0.41	0.01	19258.76	1030.27	6.05	1678.48	0.30	12.76	3090.82
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
208	0.77	0.41	0.11	0.10	19701.79	1017.95	5.82	2133.85	0.31	13.47	3053.83
208	0.75	0.25	0.01	0.00	18873.93	1044.22	6.06	1279.71	0.30	13.04	3132.66

Table 2: Figures of merit calculated during the optimisation

2.4. Visualisation tool for decision-making

As important as the capability to output results is the capability to visualise the results and draw useful conclusions from it. Therefore, as part of the research activity, a visualisation tool has been under ongoing development. This tool is designed as a three-layered application. The first layer represents research codes in general. It is one of the aims of this tool to provide a modular and flexible tool that is capable of working with different research codes written primarily in Python programming language. In this work, the code PD-OPT used in Spinelli et al. [5] to investigate energy management strategies for novel hybrid-electric propulsion aircraft. The second layer of this application corresponds to data-driven analytics, in particular, uncertainty quantification [6] and sensitivity analysis [7]. The third layer corresponds to the high-dimensional visualisation capability, which consists of an interactive parallel coordinates and scatter plots. This structure is shown in figure 3. The interface as being designed to be ease to use and very intuitive. It

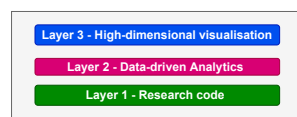


Figure 3: Application overview

consists of a top bar containing a “hamburger menu” where options for file uploading and general settings such as layout are located. In this bar it is possible to select which research code will be used in a given research task. By selecting a code, the left panel will change to provide the user with options to input data, run, stop or restart the analysis. After the run is complete, the data will be ready to be visualised using interactive parallel coordinates and scatter plots in the central canvas. It is also possible to inspect the data in table format. With this tool we aim to facilitate probabilistic set-based studies in multidisciplinary optimisation and provide an easier access to some tools of uncertainty quantification and sensitivity analysis. This tool will be released as a open-source web application and a desktop one, as well, as part of the FUTPRINT50 project.

2.5. Interactive Parallel Coordinates

In the late 80s, researchers in computer graphics recognized a specific stream of applications as an emerging field and called it visualisation. Parallel coordinates are widely used visualization technique for multivariate data and high-dimensional geometry. The parallel coordinates [8] methodology provides a multidisciplinary visual language and paradigm. Parallel coordinates

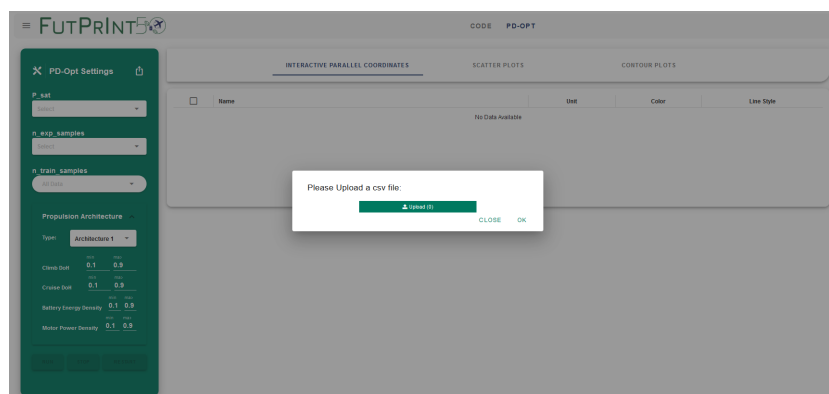


Figure 4: Visualisation tool for decision-making

transform the search for multivariate relations in a data set into a pattern-recognition problem. In the Euclidean plane $\mathbb{R}^2$ with xy Cartesian coordinates, N copies of the real line $\mathbb{R}$ labeled $\bar{X}_1, \bar{X}_2, \dots, \bar{X}_N$ are placed equidistant and perpendicular to the x -axis. They are the axes of the parallel coordinates system for the Euclidean N -dimensional space $\mathbb{R}^N$, all having same positive orientation as the y -axis. A great deal of applications of parallel coordinates are in exploratory data analysis (EDA), in which the aim is to discover data subsets (relations) that fulfill certain objectives and guide the formulation of hypotheses. This is certainly the case when novel engineering systems, that exhibit high complexity, such as future aircraft equipped with hybrid-electric propulsion.

For novel aircraft configurations, it is desirable to be able to understand how the multiple subsystems can positively impact the overall aircraft system and its mission. By performing exploratory data analysis with parallel coordinates, designers can explore and synthesize multiple alternative solutions in a problem space that involves the system (the aircraft) and its subsystems. An example of that is shown in the figure 5 shows the parallel coordinates plot for the figures of merit indexed by sets also shown in table 2. In the current version of the tool, the parallel coordinates package used is *HiPlot*[9]. In this work, *degree of hybridisation* (DOH) is defined as the fraction of the required power supplied by the electrical powerchain [5]. By observing this plots, for instance, one can affirm that with a linearly decreasing DOH for climb have lower emissions than those with linearly increasing DOH.

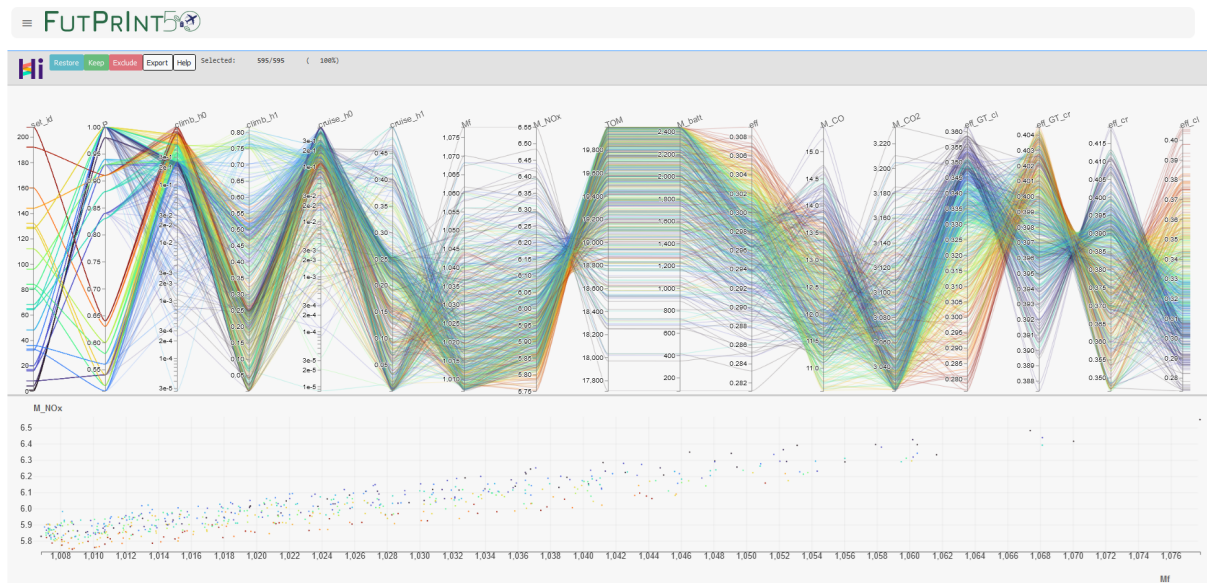


Figure 5: Interactive Parallel Coordinates and Scatter Plot

3. Future work

The visualisation tool described in this work is under development. Future work is going to focus on the second layer (see figure 2), that is, in the implementation of some uncertainty quantification and sensitivity analysis features with the goal of assisting informed decision-making and supporting technology forecasting and road-mapping activities. For a reconstructed probabilistic model f :

$$\tilde{y}_1, \dots, \tilde{y}_i = f(\tilde{x}_1, \dots, \tilde{x}_n) \quad (3)$$

The aim is to answer questions, such as:

- How the technology uncertainties modelled by parameters a affect the outputs a (uncertainty propagation problem)
- What is the sensitivity of the outputs a and its uncertainties to a given input, for instance, the battery power density? (technology forecasting problem)

The inverse problem also has practical use:

$$\tilde{x}_1, \dots, \tilde{x}_i = F(\tilde{y}_1, \dots, \tilde{y}_n) \quad (4)$$

4. Conclusion

An interactive tool designed to facilitate studies of probabilistic set-based multidisciplinary design optimisation has been presented. The originality of this work is complementary to the probabilistic set-based methodology introduced by Spinelli et al. [5]. New methodologies often encounter resistance to be incorporated to the design workflow. To address this issue, an interactive interface was designed to guide the user through the steps of the design methodology and to provide an easy way to high-dimensional visualisation, leveraging the interactivity between parallel coordinates and scatter plots, to assist the informative decision-making process. In addition to that, this tool is easily extendable to additional research codes without much effort from the user. In our illustrative case study, decision-makers are able to interactively explore the hybrid-electric propulsion design space while considering the impact on the figures of merit from expected improvements in the coming years of key enabling technologies. This interactive exploration is possible due to the use of parallel coordinates. Parallel coordinates are a widely used visualization technique for multivariate data and high-dimensional geometry that maps subsets of $\mathbb{R}^n$ into $\mathbb{R}^2$. Parallel coordinates also allow users to interact with the data in many ways, such as using colour sets and scatter plots. This allows designers to explore and synthesize multiple alternative solutions, effectively expanding the conventional design space to both the system and the subsystem levels. In this way, the feasibility of hybrid-electric aircraft can be studied from a systems perspective maintaining the connection with more detailed trade-off studies of components of the sub-systems. Hence, research codes integrated into an easy-to-use web visualisation tool can assist top management to make decisions, without the need for specialized computational and mathematical knowledge.

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