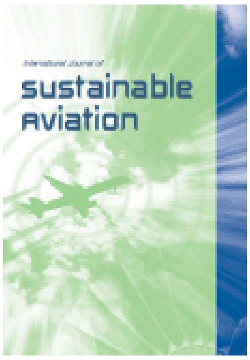

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Optimisation-based development process for small-sized UAS

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Abstract: This article presents the optimisation-based development process used to develop an advanced configuration BWB UAS within the framework of the Hungarian PIACI-KFI project. The article introduces the project, and the business application-based determination of the design requirements. An overview of past and state-of-the art aircraft design processes is discussed, and the importance of optimisation and process drivers as integral parts of such systems is highlighted. Finally, the design stages of the conceptual level UAS designs are described and discussed. At each stage, the four stages process includes an optimisation process driver as an integral component, generating a large set of potential designs. From the design dataset the Pareto optimal points were identified, and results selected by the project consortium. The outcome of the design process were 2 connected designs: a development prototype under EU Open Category, and the final production version which can achieve the project's business goals.

Keywords: conceptual design; multidisciplinary optimisation; UAS design.

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1 Introduction

Unmanned aircraft systems (UAS) are aircraft (and their supporting systems), where, as the name suggests, there are no pilots on board. In everyday language these aircraft are often referred to as drones. They can be operated by a remote pilot or function at varying levels of autonomy. The market for unmanned vehicles is a dynamically growing, young industry. By 2021 Goldman Sachs (Poponak et al., 2016) predicted USD 100 billion as market size, with an estimated continual growth between 16–24% up to 2028 (MarketsandMarkets, 2021; Research and Markets, 2021). This tremendous value can only be unlocked when the correct value generating activity is identified, and appropriate vehicles are used. As such, there is a great benefit in integrating business factors into the design of UAS, to ensure that the designed aircraft can be optimised to best accomplish the mission it was selected to perform. This paper presents part of the research work performed in the Hungarian national project titled: 'Development of multi-purpose fixed-wing drone based on innovative solutions and the creation of necessary competencies'. In this project, based on an initial prototype UAS, first market opportunities and possible business cases were investigated, then improvement directions were identified to develop an upgraded version of the UAS, which can be used to achieve the predicted business goals of the project.

This article is organised as follows. First, the background, business case and requirements definition for the UAS design is presented. In the following chapter, a brief introduction to aircraft design process is provided. In the next chapter, application of the methodology and the specific implementation of the optimisation-based UAS development process are presented, following with the discussion of the resulting UAS design. Finally, the conclusions and the impact of the developed methodology on the project are presented.

2 Background of the UAS development activity

As it was mentioned, the article presents the results from the Hungarian national project, in the future referenced as the PIACI-KFI project. The aim of the project is to develop

UAS, which have the potential to be used (or sold) as part of a financially viable business, for which the identification of valid business cases is also part of the project. In addition, the project also includes the development of core skills and know-how related to small UAS design and manufacturing, including novel, additive manufacturing processes.

Figure 1 Initial prototype UAS being prepared for test flights (see online version for colours)

The project started with an initial UAS prototype that was used for further developments. The UAS is a BWB (blended wing body) type aircraft, with an estimated maximum take-off mass of 20 kg. The capabilities of this UAS were investigated with engineering analysis and physical tests; one of such test setups is shown in Figure 1. As the project is aimed at further developing this initial configuration, the business case investigation was based on this prototype configuration.

In the project the following steps were performed related to the business case investigation:

- Identification of UAV applications: over 800 UAS-based service offerings were investigated and analysed. The information was compiled into a database, recording the category of the application, the details of application, the type of UAV used, the nationality of the service provider, the company providing the service, and some additional description and references. Figure 2 shows the distribution of application categories identified and the configuration of UAVs used for the services.

- Comparison to similar UAVs: over 60 similar size (sub 25 kg) fixed wing UAS were identified, and the prototype's capabilities compared using multiple factors such as wingspan, MTOM, range, endurance, cruise speed and so on. The prototype UAS was placed in the lower-middle range of the available capabilities, identifying the most important directions of improvement compared to competing UAS. Figure 3 shows the results of this comparison. Note that no data was available on the ceiling (maximum flight altitude) capability of the prototype UAS.

Figure 2 Distribution of application categories and UAV types used from the drone applications database (see online version for colours)

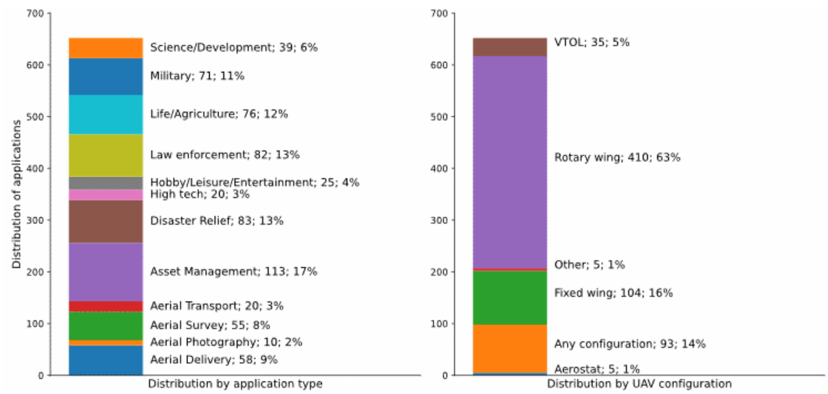
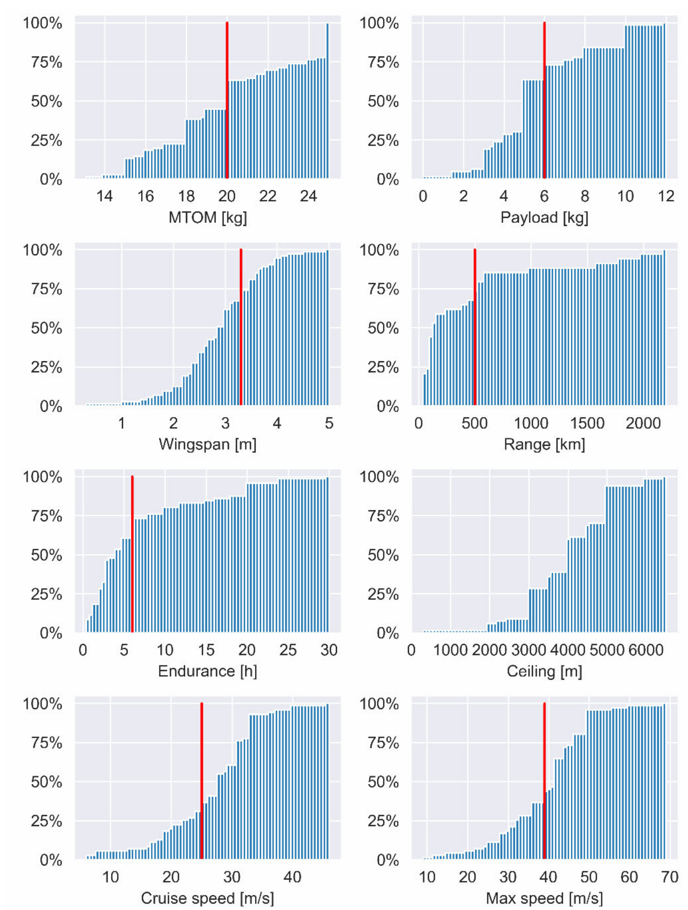


Figure 3 Performance comparison of prototype UAV with similar class UAVs (see online version for colours)



Note: Red line represents the prototype UAV.

- The possible business activity types related to the prototype UAS were collected and scored based on business viability. The activities covered a broad range, starting from complete UAV sales, through data collection services, education/training provider and so on. A total of 22 different activities were investigated. The scoring criteria included 8 factors, which were analysed in a Hungarian industry specific context. Table 1 shows the summary of the business analysis activities, presenting the business models, scoring criteria, the individual and total scores for each.

Table 1 Business activity analysis scoring summary

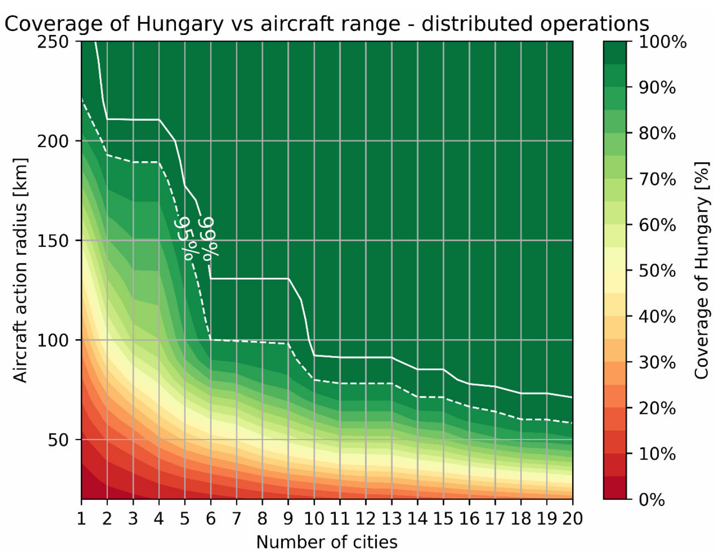
Business category	*Profitability*	*Market size*	*Competition*	*Barriers to entry*	*Simple technology*	*Skill availability*	*Investment*	*Customer independence*	*Total*
Aircraft sales	2.5	2.3	1.0	2.3	2.5	4.0	3.0	4.3	21.8
Airframe sales	2.5	1.5	1.3	2.3	3.0	4.0	3.3	4.3	22.0
Systems sales	3.5	3.3	1.5	2.3	2.0	4.5	3.3	4.0	24.3
Equipment sales	4.0	3.5	1.8	3.0	3.8	4.5	4.0	4.3	28.8
Control systems development	2.8	3.3	1.8	2.5	2.3	3.8	3.3	3.8	23.3
Aircraft rental	3.0	2.8	2.5	2.3	3.5	4.3	3.0	2.5	23.8
Airframe rental	2.0	1.3	3.5	2.0	3.3	3.8	2.8	1.8	20.3
Systems rental	2.5	2.5	3.0	2.0	2.3	3.8	2.3	1.8	20.0
Equipment rental	2.3	2.3	3.3	2.3	3.5	4.0	3.3	1.8	22.5
Raw data capture service	3.5	3.5	1.5	2.8	3.8	3.5	3.3	1.8	23.5
Processed data service	4.0	3.8	2.5	2.0	3.5	3.0	3.0	1.8	23.5
Asset management	3.5	2.8	3.5	3.0	2.5	2.5	2.0	2.8	22.5
Business software development	4.3	3.5	1.8	2.8	2.3	4.3	2.8	3.3	24.8
Comprehensive services	4.0	3.5	3.5	3.5	1.8	2.8	1.8	2.0	22.8
Support services	3.3	3.5	2.8	2.8	3.5	4.5	3.8	1.8	25.8
‘One stop shop’	3.8	3.3	4.0	3.3	2.3	2.5	2.3	2.5	23.8
UAV insurance	3.8	4.3	2.8	3.0	3.3	4.0	3.7	3.3	28.0
UAV financing	4.0	3.0	2.0	3.5	4.5	5.0	2.0	3.5	27.5
Training provider	3.3	3.3	2.3	3.3	4.5	4.3	4.3	3.8	28.8
Remote programming	2.8	2.3	3.8	2.0	3.5	4.3	4.5	1.7	24.7
Events organisation	1.8	2.3	2.8	3.0	4.5	4.0	2.5	3.3	24.0
Connected services	1.7	3.0	2.7	2.7	4.7	4.7	2.7	4.0	26.0

Based on the business case identification it was concluded that the most promising candidate was the offering of inspection services for large, linear infrastructure at national level. In Hungary, there are over 250,000 km of linear infrastructure available which includes road networks, railways, gas and oil pipelines, electric networks, and rivers. Developing a fixed wing UAS-based service, that could inspect these infrastructure elements represent a business case with high potential.

Based on the identified business case and the location of infrastructure and potential airfields in Hungary, an optimisation-based process was used to evaluate the UAS's required performance as a function of the number and placement of operational bases. The process involved performing a sequence of shorter optimisation loops. For each loop, the algorithm identified the most appropriate cities from where the UAS could be operated, and what coverage of Hungary could be achieved using the given number of cities (operational bases) and a given UAS action radius. As such the objective of each optimisation is to maximise the area covered by the UAS, and the input variable is the list of cities, from which 'n' should be chosen, and this is performed for 'n' between 1 and 20, and 1–250 km UAS action radius. Apart from the finite list of cities, there are no additional constraints defined for the process. Following this approach, for each number of cities and UAS operational radius, the achievable maximum coverage of the country's area could be enumerated.

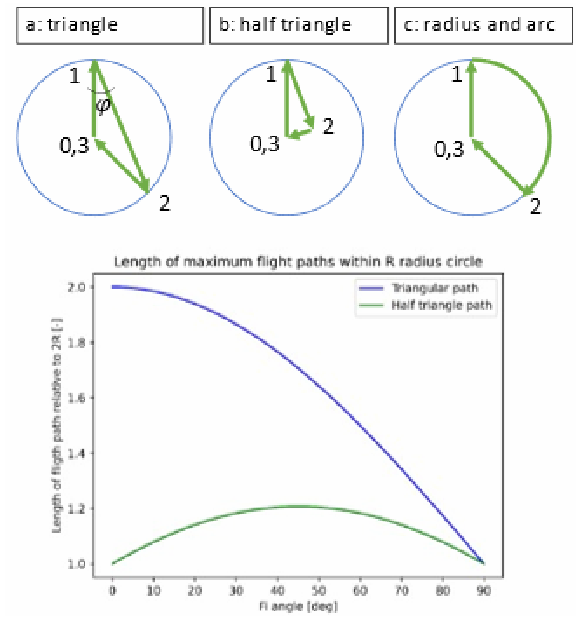
Figure 4 shows the results of this analysis. From these results, when given a desired coverage, for example 99% of the country's area, the Pareto-optimal set of ground requirements (number of cities) and aircraft requirements (action radius) could be identified. Following the white solid line in Figure 4, representing the 99% example, it can be seen that the requirements towards the UAS can be lowered when more operating bases are established in the appropriate cities, however, a clear breaking point can be identified at six operating bases. Above this, adding more bases does not significantly reduce the requirements on the UAS.

Figure 4 Achievable coverage of Hungary vs. the number of operating bases (cities) (see online version for colours)



Based on this it was shown that a minimum action radius of about 130 km would be required to achieve 99% coverage, considering radial flights from the operating bases. To inspect linear infrastructure, depending on the specific layout in a given area, 2x–8x of this distance is required for efficient inspection capability. This comes from a high-level geometric analysis, which is graphically presented in Figure 5.

Figure 5 Possible geometric layout of linear infrastructure (see online version for colours)



Essentially a section of linear infrastructure to be inspected within a circle can be laid out in 3 possible ways.

- complete triangle which is essentially a chord in the circle
- half triangle, which is a half chord
- section of arc (up to complete circle).

Any layout of linear infrastructure can be broken down into sections that are completely or at least partially correspond to the above 3 cases and as such the geometric cases can be considered as the longest route possible. If the aircraft is able to complete these, then it is able to complete any inspection task. Based on these routes (and the simple radial out and in mission), simple mathematical calculations give the maximum flight range required to follow:

- radial: 2R
- triangle: 4R
- half triangle: 2.42R
- arc: up to half circle: 5.14R
- arc: complete circle: 8.28R.

Based on these numbers, the range requirements towards the UAS need to be decided on a business/operational basis. It can be clearly seen that inspection along the circumference of the circular area poses the highest demand. Whether it is important to complete the inspection in one mission, comes down to business considerations. For example, when inspecting road surface quality, it can be perfectly acceptable to return to base and complete the mission in two or more segments. Also note, these figures do not include the necessary reserves for the mission, it is purely operational range. In the case of the project presented as there were no operational constraints or time requirements defined, it was decided that a 2.5R range is acceptable, corresponding to slightly more than the ‘b’ (half triangle) case, or about 28° of arc at maximum radius.

Based on the above identified business goals, and the investigated sensor systems, the following requirements were defined towards the UAS:

- range: 250 km
- cruise speed: 12 m/s
- payload: 7 kg
- MTOM: 25 kg
- completely electric propulsion
- BVLOS capability
- capability for catapult launch and parachute recovery and landing gear-based operations as well.

Some of the requirements identified were constrained by the EU drone regulations (European Union Aviation Safety Agency, 2022). It was the intention, that at least for the initial phases of development, it is desirable that the UAS can be operated under the EU Open Category. To develop into a full-service offering, because of the BVLOS capability it is very likely, that at least the EU Special Category operations would be required. However, at the time of writing the article, there is still uncertainty how this could be practically achieved.

Based on the above identified requirements, the initial prototype UAS was further developed in the project, using the optimisation-based conceptual design process, which will be presented in the following chapters.

3 Brief introduction to the aircraft design process

Aircraft design is a unique field of science in itself. Many of the modern engineering tools (such as CATIA) and methods (such as MDAO) were originally developed in connection with aircraft design. While the nomenclature and sometimes the number of steps could differ between organisations, generally the aircraft design process can be represented by the following steps:

1. requirements analysis
2. conceptual design
3. preliminary design

4 detailed design

5 manufacturing, testing, and certification.

Conceptual design is arguably the most important step in the development process of a new (or modified) aircraft, as this step can determine up to 60–80% of the finished product's cost and performance. As it is often said, even the best engineering cannot fix a flawed concept.

In aircraft conceptual design there are many established theories and methods, among them Howe (2000), Raymer (2006), Roskam (2003), Torenbeek (1976), Stinton (2001), Corke (2002) and Jenkinson (1999). These methods can be considered the classic, textbook-based tools, which are widely taught and used even today. These methodologies primarily deal with classic subsonic aircraft design (although they do include supersonic vehicles, for example Raymer's methodology goes up to Mach 4). As such many specialised methodologies are available for a given very specific classes of aerospace vehicles, for example space transportation systems (Hammond, 2001) or solar powered aircraft (Noth, 2008). Specifically, for UAS while there are complete design methodologies published, such as Austin (2010) or Cai et al. (2011), however as of today none of them could be identified as the definite textbook like the above-mentioned classic tools. Design of UAS is not fundamentally different from larger aircraft, however due to the size differences many aspects need to be dealt with differently (especially for micro and nano size UAS), which information is often not fully available even in the published design methodologies. It is likely that in the future design methods and experience will consolidate and the above-mentioned list of classic textbooks can be expanded with the definitive UAS design books. For a detailed review of the various classification approaches and published design methods, the reader should refer to the review article of (Hassanalian and Abdelkefi, 2017)

Usually except for the simplest of design tasks, calculator and paper-based implementations of these methods are not used anymore. Most design activities are done using some form of computerised design environments. The first of these environments were General Dynamic's SYNAC and Boeing's CPDS, followed by most of the big aerospace players. Tools with published information today include the Piano, NASA FLOPS, VSP and Open VSP, the APD software from Pacelab, MICADO, CEASIOM, PASS, AGILE just to mention a few. Some of these are commercially available software implementing a design methodology and sometimes containing validated data (for example Piano). Some of them are collaborative efforts between university and industry players (AGILE) and there are open-source options (Open VSP). There are also tools that are only available to use within an organisation, such as the GENUS design tool of Cranfield University, where the original version was developed with the contribution of one of the authors (Smith et al., 2019).

These design environments are the software implementation of one or multiple design methodologies at various levels of fidelity. NASA (Robinson and Martin, 2008) defined 0–5 levels of fidelity for conceptual design, which range from simple parametric definition to full-scale 3D representation of the aircraft and its internals. The appropriate level of fidelity needs to be chosen based on the task and hand, the available tools and based on the resource (time, computational power, cost) constraints.

In addition to the design engineering tools, most methodologies today include some form of numerical design process, some form of optimisation, sensitivity analysis or similar. While these tools are available in most, some environments (such as GENUS) were designed with optimisation as a core element of the software tool's capability, as an integral, inseparable part of the design process itself. Developing tool kits in such way can fully utilise the tremendous computing power available in today's computers.

As it was mentioned, in terms of UAV design, there are no canonical textbooks or methods universally accepted such as Roskam, Raymer or the others mentioned above. The usual approach is the adaptation of the classic aircraft design processes to the smaller sizes, usually by assuming the appropriate constants in the different methodologies. Recent examples of designs without optimisation include high performance UAVs, (Varsha and Somashekar, 2018), VTOL capable UAV (Dündar et al., 2020), turboprop powered high-altitude UAV (Dinç, 2020), tailsitter UAV (Domitran and Babac, 2023) even hybrid UAV-UUV designs (Papadopoulos et al., 2022). There are examples of optimisation included in the process, such as the works of El Adawy et al. (2023). Generally, most optimisation tools are used as a monolithic problem definition a single instance of aircraft design is set up, and the optimiser is used to find design improvement suggestions. In this paper the aim is to develop the methodology to use optimisation as an integral tool that can be utilised multiple times during the design process to aid the exploration of the design space and progress the maturity of the UAV concept throughout the design space.

4.1 Design tool introduction

The design tool used is an in-development modular software package written in python. The software implements design tools of various levels of fidelity, both analytical and numeric calculations tools are available. Various design process tools, such as optimisers (gradient-based and evolutionary) are also integrated in a modular fashion. Low fidelity estimation methods mostly implement Howe's methodology, while the parametrisation of the aircraft and design process tools were developed based on the PhD research of Sziroczák (2016). As of today, detailed publication of the design software's capabilities is not publicly available yet.

4.2 Design areas addressed

In the PIACI-KFI project, the UAS design task concentrate on the improvement of the initial UAS prototype based on the identified requirements and business goals. In order to develop a viable conceptual level design, nine essential areas of aircraft design are addressed in the project. These areas are the following:

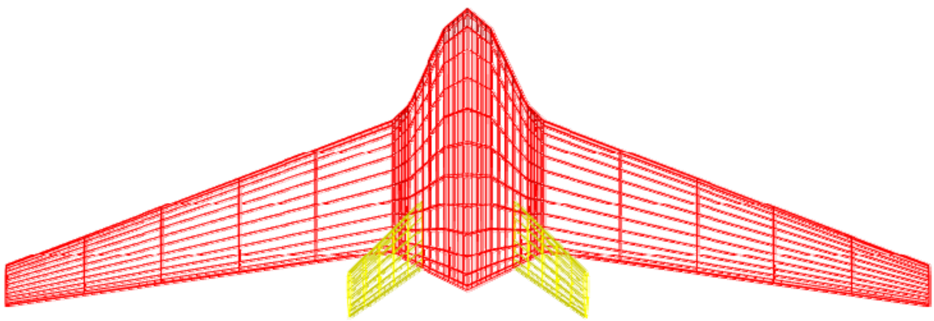
- geometry
- mission
- propulsion specification
- mass breakdown
- aerodynamics
- propulsion
- packaging and CG

- performance
- stability and control.

In the following parts of the chapter, the design activities are discussed based on these areas.

The geometry definition of the aircraft is based on the BWB shape of the initial prototype UAS. During the design the external geometry of the aircraft was represented in a fully parametric way. In order to simplify the development of the improved prototype, it was decided to keep the internal (body) sections of the UAS unmodified, so that most of the propulsion, payload and battery systems could be integrated without major modifications to these systems. The initial shape of the UAS is shown in Figure 6.

Figure 6 UAS concept design geometry representation (see online version for colours)



The lifting surface was divided into sections, and the outer sections were parametrised with continuous real parameters, for each section these are:

- section properties: length, sweep, dihedral
- cross-section properties: incidence (twist), chord length.

In this project due to the time constraints, it was decided that no arbitrary shape aerodynamic optimisation is to be performed, and as such a list of applicable aerofoils were selected. The list of aerofoils was selected based on a set of automated 2D analyses performed on a database of over 100 aerofoils. The aerofoil coordinates were sourced from airfoiltools.com (Airfoiltools.com, 2023). The 2D analysis was performed using the XFOIL open-source software, by scripting the pre-processing, execution and postprocessing of aerofoil data (Drela, 2013). From the results of this investigation, a set of aerofoils with their most important characteristics were compiled, which is shown in Table 2.

The ranking of individual characteristics is based on their applicability to this specific application. It can be seen that there is no single aerofoil with dominating performance, rather each choice represents a compromise solution. The usage of these aerofoils was taken as category variables that were not used as inputs for the optimisation process, rather each option was individually investigated, and a separate optimisation loop was performed for each.

Table 2 List of selected potential aerofoils ranked based on different characteristics

Name	*CL max*		*Cm @CL max*		*L/D max*		*CL optimal*	*Cm @CL optimal*		*Vs/Vc (clopt)*	
	Value	*Rank*	*Value*	*Rank*	*Value*	*Rank*		*Value*	*Rank*	*Value*	*Rank*
e421	1.9339	5	–0.1208	5	62.7	7	1.2909	–0.1762	5	0.67	2
e422	1.8148	6	–0.0839	4	60.0	11	1.2609	–0.1182	4	0.69	3
e423	2.0015	4	–0.1812	8	73.4	4	1.8942	–0.2161	9	0.95	10
fx63137	1.6961	8	–0.1265	7	90.7	2	1.4960	–0.1830	6	0.88	8
fx63137sm	1.7785	7	–0.1248	6	91.5	1	1.4619	–0.1876	7	0.82	6
FX74 CL5 140	2.0199	3	–0.2158	11	64.8	6	2.0199	–0.2158	8	1.00	11
nlf0115	1.2959	10	0.0160	2	60.9	9	0.8335	–0.0313	2	0.64	1
s1223	2.2925	1	–0.2152	10	74.0	3	1.6155	–0.2717	11	0.70	4
s1223rtl	2.2190	2	–0.1992	9	60.1	10	1.6466	–0.2475	10	0.74	5
s2027	1.3529	9	–0.0243	3	69.4	5	1.1522	–0.0520	3	0.85	7
MT profile	1.1315	11	0.0202	1	61.5	8	1.0381	0.0126	1	0.92	9

The mission definition for the UAS is a simple fixed wing aircraft mission, broken down into individual segments of take-off, climb, cruise, descent, and landing. Due to the light weight of the UAS it is assumed that taxiing is not necessarily performed under the UAS's own power. The catapult launch/parachute recovery is deemed as a mission of secondary importance, as due to the assisted take-off and the lack of landing gears, the achievable range of the aircraft will be superior to the landing gear version. The parachute is present on both configurations due to its possible use in emergency landing situations.

The propulsion specification defines a BLDC motor and propeller-based propulsion system. The following list describes the components of the propulsion system.

- Motor: Plettenberg Dinator 30/4 with added gearbox
  - a rated power 1,900 W at 10,000 maximum RPM
  - b mass 0.425 kg.
- Propeller: 18 × 10 Graupner CAM folding carbon fibre propeller.
- Battery: custom developed 8S LiPo battery pack
  - a nominal voltage 34.8 V
  - b 1.415 kg mass
  - c 297 Wh/kg energy density
  - d 12 Ah capacity
  - e minimum SOC of 30%.

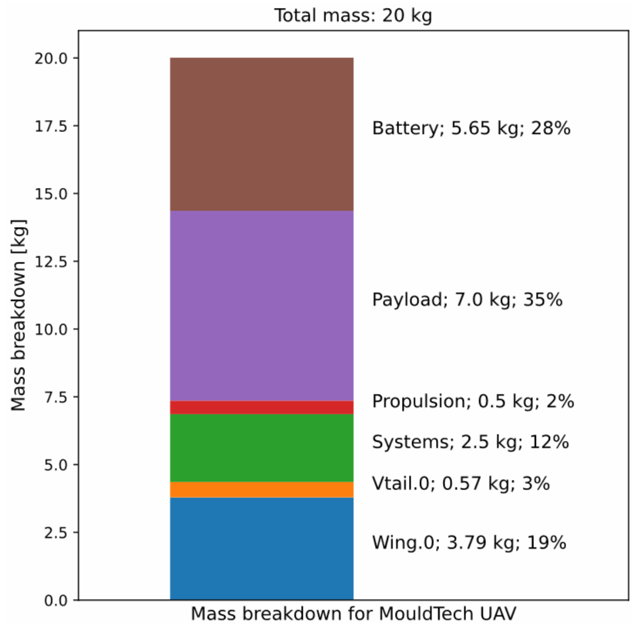
It was decided to develop the new UAS using this exact same propulsion system as these components are readily available. Note that based on wind tunnel tests and numerical analysis performed in the project, it was recommended to use a propeller with larger diameter and preferably in a non-folding configuration. For the conceptual studies, a simple electric motor and propeller model were used, while the batteries were represented with constant efficiency and nominal voltage. The propulsion logic is also straightforward, the model provides the energy use associated with the required power from the propulsion system.

Mass breakdown is estimated based on a hybrid method of using known component masses when available (motor, battery, parachute, etc.), and the rest were estimated using Howe's mass estimation methodology with the appropriate design factors considered for a small size UAS. Figure 7 shows a typical mass breakdown chart generated for a single instance of the UAS design. In this project the 'systems', 'propulsion' and 'payload' components were represented with a fixed mass, as those components were selected and are independent of the UAS size. The structural components, 'wing.0' and 'vtail.0' were estimated using Howe's mass breakdown equations. As the mass breakdown is controlled by the MTOM, after estimating all component masses except the batteries, the difference between the sum of components and MTOM is assumed to be filled with battery packs. This way a convergent mass breakdown is always guaranteed, providing better conditions for the numerical optimisation processes.

Aerodynamic characteristics of the design are estimated using two methods, depending on the stage of the design process.

When at the initial steps the overall shape is of question, the aerodynamic prediction method of Howe is used, which is a low fidelity, parametric approach based on the equivalent wing shape of the configuration. Howe's methodology is empirical equations based, which were coded in Python.

Figure 7 Example mass breakdown graph for a single instance of UAS design (see online version for colours)

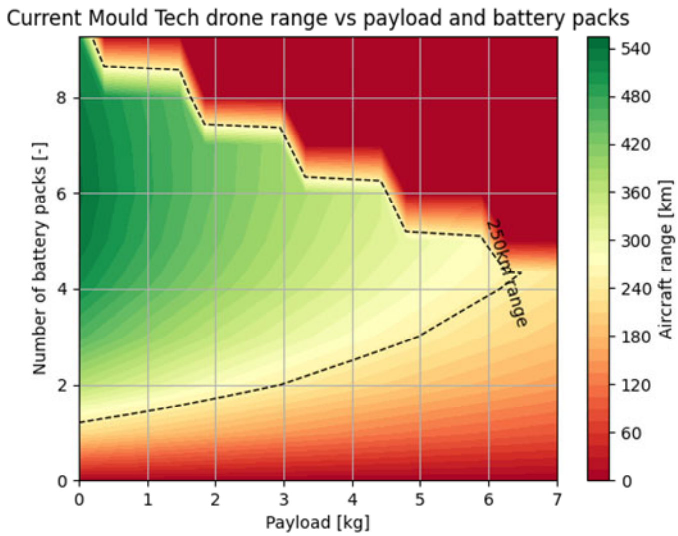


When selecting aerofoils and optimising the smaller details, a python wrapper-based implementation of PanAir is used, with additional viscous correction based on the wetted area of the aircraft. The PanAir code was modified to allow memory-based input/output operations as opposed to the default input/output file and single execution-based operation. The PanAir source code was compiled and linked into a .dll file and a python wrapper was generated to interface with the rest of the design program. The current version of this code does not allow the use of the full capability of PanAir, but it enables the evaluation of basic aerodynamics coefficients for simple shapes, such as a BWB aircraft. The viscous correction uses Howe's equations based on the wetted area of the aircraft.

Packaging and CG definition was not rigorously evaluated during the design process, the CG was estimated based on the known CG location of the initial prototype UAS. As it was the specific intention not to alter the centre (body) section of the UAS, which contains the highest proportion of mass (refer to Figure 7), it is a valid assumption, to use the known CG as the basis of the modified version. Connected to the CG position, stability of the UAS was evaluated based on the static margin method, based on the estimated CG, and calculated neutral point. Being an unmanned aircraft with active control, it is not debatable what the acceptable margins for stability are, however it was decided that static stability is desirable, but the margin should be kept low to reduce trim drag losses. The stability of the final design configurations was evaluated offline after the design using a set of higher fidelity tools.

Performance of the aircraft was calculated in segments following the mission definition, with a modified form of the Breguet range equation adapted to purely electric configuration. The equations used were developed by the authors and were published before (Sziroczák et al., 2020). Of key interest are the range and endurance characteristics of the aircraft. In a configuration like this small UAS it is also possible to trade payload mass with battery packs to achieve even higher range. As such it is important to identify that in addition to the nominal 250 km range with 7 kg payload scenario, what other performance points the UAS can reach, similarly to the ferry range of large aircraft. Figure 8 shows an example set of results when fully evaluating the capabilities of one instance of design.

Figure 8 Achievable aircraft range as a function of payload mass and number of on-board battery packs (see online version for colours)



It has to be further noted, that the requirements specify an unusually low cruise speed (12 m/s) which was based on the chosen sensors (camera) payload package. This imposes conflicting design direction regarding stall speed and range.

4.3 Optimisation-based design steps

The design space of the improved UAS design is explored following a multi-step procedure, each integrating optimisation tools into the process. The full procedure used can be described as the following:

1 semi-idealised geometry (simplified aerofoils) exploration, to determine general configuration and promising directions

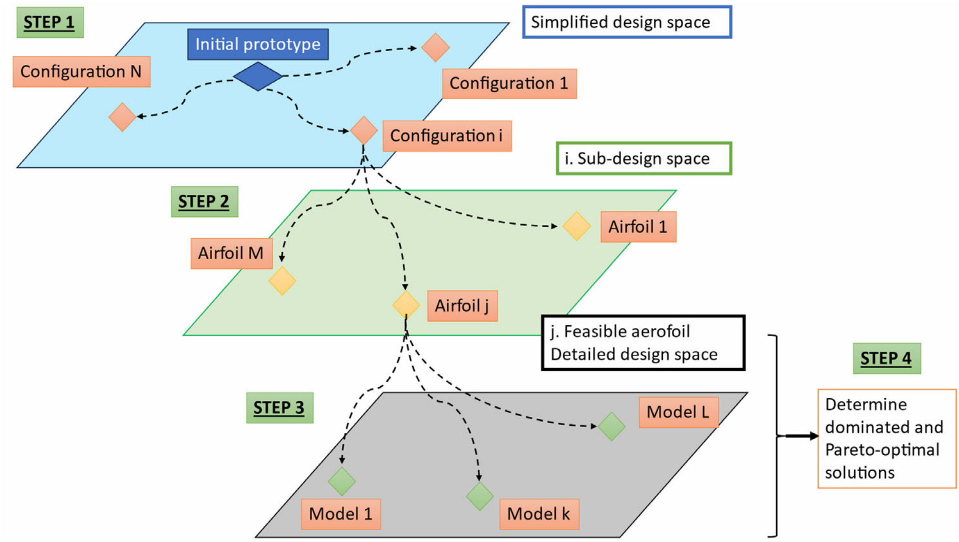
2 aerofoil selection sensitivity studies

3 in-detail further optimisation of promising concepts

4 determination of Pareto-optimal solutions.

Figure 9 shows the graphic representation of the procedure. In the following the steps area described in more detail, giving examples of the design studies performed.

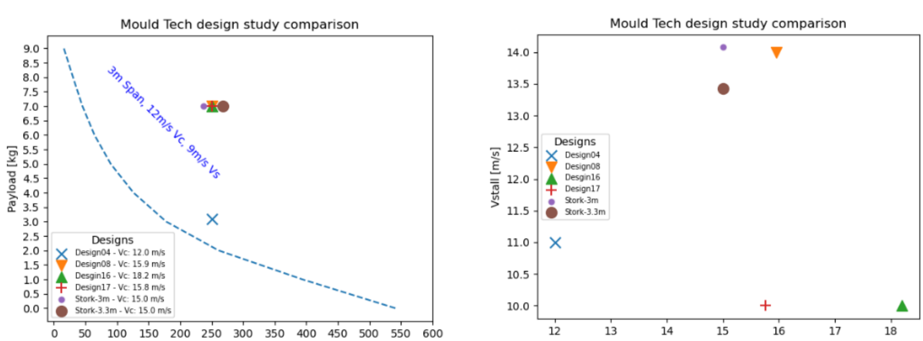
Figure 9 Graphic representation of the workflow procedure (see online version for colours)



In the first step, the general design space exploration of the UAS concept is performed. The main aim of this step is to identify the limitations and the possible solution directions to achieve the (highly conflicting) requirements defined in the project. In this step low fidelity design methods were used, and a set of optimisation tasks were performed, setting the objective function to various aspects of the design, including minimal mass, wingspan, stall speed, maximal range, endurance, just to name a few.

The outputs not currently set as the objective function were included as constraints, investigating different possible scenarios. Results of this initial study are shown in Figure 10.

Figure 10 Results of initial design space exploration (see online version for colours)



A typical configuration investigation example would be the following. Note that only the key factors are listed, other more general inputs, such as normal load factor or ceiling are omitted.

Configuration number 3:

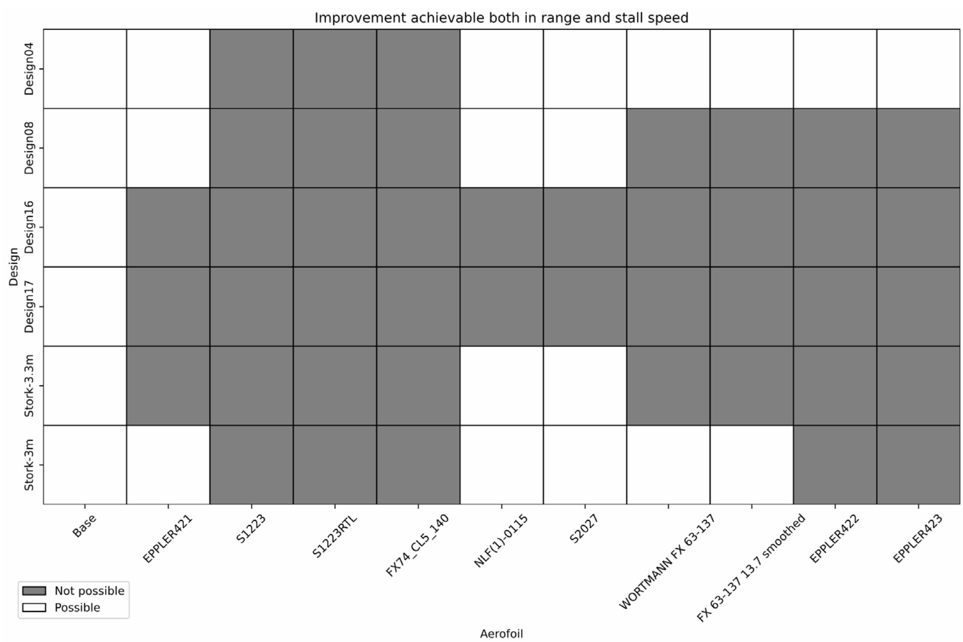
- Description: configuration #3 investigates an option with 3 m limited wingspan, in order to allow simpler operations under EASA Open. The aim is to investigate the maximum payload capacity achievable under the given constraints.
- Objective: maximise payload capacity.
- Constraints:
  - a at most 25 kg
  - b at least 250 km range
  - c at most 10 m/s stall speed
  - d 12 m/s cruise speed
  - e at most 3 m wingspan
  - f at least 67 litre fuselage useful volume.
- Optimiser variables:
  - a Wing section geometry: span, chords, sweep, twist, incidence, dihedral angle, thickness
  - b Fuselage section geometry: width, length, thickness

The outcome of the optimisation process in this case shows, the maximum achievable payload is 2.53 kg, which is very low, when compared to the requirements defined at the end of Section 2: Background of the UAS development activity. As such, this configuration is not appropriate to achieve the requirements, and cannot be developed into the production UAS. However, it was decided to further explore the sub 3 m wingspan design space in this project, as it would allow the design of a 'development version' of the UAV that can be operated more flexibly under the EU legislation.

Based on the results and the example shown, it can be seen that the designs proposed are unable to meet all requirements simultaneously. This is mainly due to the fact, that the relatively high range and payload capacity are in direct conflict with the low cruise speed, which also imposes an even stricter constraint on the stall speed to enable safe operations. The EU drone regulations also provide strict constraints on the design space, as in order to operate in the Open Category, MTOM must be below 25 kg, and wingspan must be 3 m or less. Based on the exploration four possible design directions were proposed, along with a 2-step development approach; a smaller, sub 3 m wingspan development version of the UAS should be produced, which can be used for development activities under the EU Open Category, which greatly simplifies these operations. In addition, a larger, but still sub 25 kg production version of the UAS should be developed, that will be used to provide the linear infrastructure inspection services in the future. Both aircraft share the same body geometry, so systems and payload integration into both aircraft is simple.

In the second stage of the design process, a series of investigations were performed on the design directions identified in stage 1, by varying the aerofoil geometries of the UAS concept, based on the promising potential options (see Table 2 for details). For each design direction and aerofoil combination an optimisation loop was run, to determine the maximum achievable benefits using the specific aerofoil. It needs to be noted, that the parameters in these loops were kept to the minimum (only vary the wing section geometry), due to the large number of design points that had to be investigated. The designs were evaluated based on two key outputs, stall speed and range, as these were the two most constraining aspects identified in stage 1 of the design. The results of this analysis are summarised in Figure 11.

Figure 11 Results of aerofoil studies, determining possible improvement in both range and stall speed



As it can be seen, there are only a few configuration and aerofoil combinations where both the stall speed and range characteristics can be simultaneously improved. Based on these results, more detailed UAS designs were produced with detailed representation of the aerofoil selection.

In the third stage of the design process the viable configuration and aerofoil configurations were further analysed. In this stage multiple optimisation loops were performed for each design point. Each separate optimisation loop had different design variables, constraints and objective functions (for example minimum mass or maximum range, etc.) defined, similarly to stage 1, to come up with a broad range of possible designs. In addition to the parameters in stage 1, stage 3 uses a broader range of geometric parameters, for example the blend radius between the fuselage and wing section, and other similar 'higher detail' inputs.

For example, 'Design 04B' is a result of an optimisation process, where the objective was to maximise the achievable range, while setting the payload to 3 kg, cruise speed to

12 m/s and uses the Eppler 422 aerofoil. The optimisation process suggests that the achievable range in this configuration, obeying all the imposed constraints is 86 km.

Figure 12 Results of optimisation based detailed design investigations (see online version for colours)

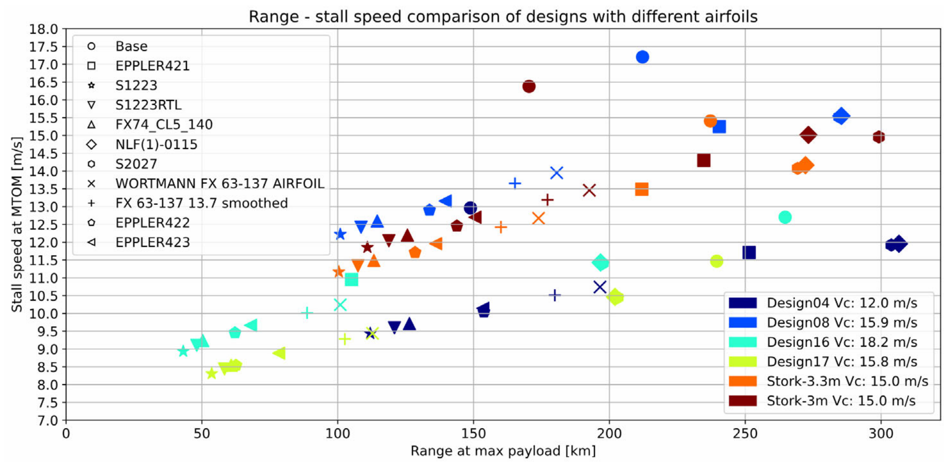


Figure 12 shows the summary of the design activities performed in the third stage. Each colour and glyph coded point represents the result of an optimisation run of a single instance of UAS design. As it can be seen, there are a wide range of possibilities in the shown stall speed-range design space. An ideal optimum design would be as far to the bottom-right of the graph as possible. It can be seen, that opposing to this, all designs are more-or-less following an upward sloping trendline. As such it can be concluded that a compromise must be made.

Following up, in the fourth and final stage of the design process, Pareto-optimal sets from the design points including those shown in Figure 12, were extracted and presented to the wider project consortium. As the points on a Pareto set all represent non-dominated solutions, it was decided that the project leader, with support from the other consortium members need to provide further input into the design selection process, considering additional, not necessarily classic aircraft design related aspects and constraints, such as the available manufacturing technologies, tooling, space, concept of operations, and so on. Based on this, two concepts, 4B and 17B were decided as the development directions in the project, the first as a development prototype for sensors and operations testing, and the second as the final production version aircraft for the future service. These two concepts were taken forward to the preliminary and detailed level design stages and the development prototype further into the manufacturing step. Rigorous testing and verification of the performance characteristics are scheduled as the follow up activities of the PIACI-KFI project.

5 Discussion

The manuscript showed the design methodology used to improve the design of an existing BWB UAV. Starting off with the requirements analysis, the business possibilities and operational concept investigation was included as part of the analysis. The approach helped to identify which business areas are the most promising, and what can be achieved by improving the UAS design, but it needs to be noted that the decision in this project is not purely based on the results of the technical analysis. The overall business strategy, including other projects, applications and available market was also considered by the project leader, when deciding on the requirements to which the UAV is designed.

The modules used in the UAV design process followed the common approach of adapting an existing aircraft design methodology (predominantly Howe's) to work with the specific task of UAV design. As the design task was a concept development, and not a clean sheet design, some approaches were modified to reuse existing components, for example the systems and propulsion groups.

The novelty of the presented methodology is the flexible introduction of optimisation procedures into the aircraft design process. In classic approaches, a design process is often treated as a single optimisation problem, and the user sets up the whole process accordingly. The approach presented here uses optimisation integrated as one of the 'ordinary' tools used in a design process. As such, multiple, different optimisation-based subproblems were solved to investigate the design space and come up with a design improvement suggestion for the BWB UAS under development in this project.

The design approach presented in this manuscript was quasi-validated by the development of the improved version of the BWB UAS, showing the potential in the optimisation-based approach. However, there are still challenges that require further research. Apart from the technical side to expand the software's capability to handle additional classes of aircraft there are usability challenges to solve. Currently, setting up the optimisation process requires manual coding, which is a limit on the productivity of the process. Also, it represents an issue regarding verification and trusting the results, as obviously, coding allows the user to override or change the otherwise validated parts of the program. As such further research focuses on setting up the process and streamlining the design workflow. As a longer-term goal, existing in vision only today, the integration of AI tools into the design process description will be investigated.

6 Conclusions

This article presented the optimisation-based development process used to develop an advanced configuration of a BWB UAS. The article briefly presented the PIACI-KFI project, its goals, and the determined business application, based on which a set of requirements could be developed for the improved design of the UAS. The aircraft design process was also introduced, highlighting the past solutions and the state-of-the-art tools in use today. The importance of including optimisation or other design drivers as an integral part of the design environments were also discussed. Finally, the article presented the process, where the optimisation-based aircraft development process was implemented. The individual steps of the design process were detailed, and the results acquired discussed. In the PIACI-KFI project due to the conflicting requirements a large number of different configurations were evaluated, and the output of the design process was summarised as the Pareto set of the different concepts, primarily considering range and stall speed as the two key output variables. From the Pareto set, two different instances of design were selected; one to be used as a development prototype, which can be operated under the EU Open Category, thereby greatly simplifying the development operations. The second concept selected is a full-size production version of the UAS, which is to be developed to be used for the future linear infrastructure inspection service.

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Nomenclature

BVLOS	Beyond visual line of sight.
BWB	Blended wing body.
CG	Centre of gravity.
MDAO	Multi-disciplinary analysis optimisation.
MTOM	Maximum take-off mass.
SOC	State of charge.
UAS	Unmanned aerial systems.
UAV	Unmanned aerial vehicle.