IMPROVEMENT AND TESTING OF THE ADVANCED MORPHOLOGICAL APPROACH IN THE DOMAIN OF CONCEPTUAL AIRCRAFT DESIGN

V.T. Todorov*, D. Rakov†, A. Bardenhagen*

* Technische Universität Berlin, Institute of Aeronautics and Astronautics, Chair of Aircraft Design and Aerostructures, 10587 Berlin, Germany

† Russian Academy of Sciences, Blagonravov Mechanical Engineering Research Institute (IMASH), 101990 Moscow, Russia

Abstract

This article discusses the progress of the refinement and testing of the Advanced Morphological Approach (AMA) in the conceptual design of aircraft. Unconventional aircraft configurations can be considered as a potential way to address the current challenges in the aviation domain to reduce emissions and increase efficiency. Taking into account the lack of idea generation methods for innovative aircraft concepts, the AMA as presented in previous work allows to decompose the system into functional and/or characteristic attributes and their corresponding sets of technological alternatives. The subsequent synthesis and clustering of potential solution configurations helps to derive a limited set of optimal aircraft concepts. The first part of this paper summarizes the recent developments of the AMA such as handling of uncertainties through fuzzy numbers and hierarchical structuring of the problem definition with the Fuzzy Analytic Hierarchy Process. Ultimately, the results of a first test use case for a flight vehicle conceptual design problem using the AMA's current state and involving a group of experts are presented and discussed. The suggested approach considers to a larger extent the cognitive and professional bias during expert evaluations. It offers a more robust and intuitive formulation and solution of abstract conceptual design problems lacking historical data to lean on.

Keywords

conceptual design; Advanced Morphological Approach; Morphological Analysis; expert judgment elicitation

1. INTRODUCTION

The challenges that the aviation industry currently faces possess a multifaceted character. Firstly, a great importance is attributed to the achievement of the emission reduction and efficiency improvement goals for the upcoming airplane generations. Secondly, the application of sustainable aircraft is sought to be expanded for less common and unconventional missions such as transportation, search and rescue (SAR) flights in areas with complex terrain or Urban Air Mobility. However, addressing these goals simultaneously might be a lengthy process requiring not only the integration of prominent technological innovations, but also the introduction of disruptive aircraft concepts. Such problem statements often represent complex tasks unable to be defined as an integral optimization problem due to their complicated multi-dimensional and multi-disciplinary nature [1, 2]. Furthermore, the lack of experimental data on certain promising technologies could lead to significant uncertainties when studying the design trade-offs. These challenges require the application of a novel tool for the efficient selection of innovative aircraft concepts. It has been shown that innovative ideas for new efficient aircraft configurations can be generated and analyzed by using the Advanced Morphological Approach (AMA) on the example of a stratospheric unmanned aerial vehicle [1]. On a global scale, this method fulfills and integrates a set of idea management tasks including structured and transparent idea generation, evaluation and classification for product design purposes [3]. In addition, its focus lies even further in the design of complex engineering solutions such as new aircraft generations.

Currently, the AMA is being enhanced in order to address its identified challenges such as the lack of uncertainty consideration, detailed solution space analysis and the formal definition of qualitative technology evaluation [4].

These evaluations represent one of the main building blocks of the AMA and aim to qualitatively assess technology alternatives for the upcoming aircraft generations which lack deterministic test data. Such assessments can be obtained from structured expert judgment elicitation (SEJE) in the form of expert workshops. In this context, a first expert workshop has been conducted for the testing purpose of the current AMA enhancement state. The present paper describes the concept and the results of this initial expert workshop.

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After a brief review of the AMA theory, the workshop methodology will be described by outlining its main components: use case definition, problem hierarchy structure, uncertainty modeling approach and questionnaire design. Subsequently, the post-processing of the obtained data will be explained, followed by the final results. Finally, these will be critically commented and improvement proposals will be drawn.

1.1. Objectives, main hypothesis and limitations

The current work can be positioned as a smaller part of a much wider project aiming to enhance the AMA regarding multiple aspects. In particular, it is intended as a practical kick-off implementation of the first workshop development stage. In general, SEJE methods such as the Classical Model by Cooke [5] or the IDEA protocol (Investigate, Discuss, Estimate, Aggregate) [6] comprise multiple stages, e.g. individual evaluations, discussion, expert calibration, etc. The global objective is to develop a full-scale SEJE methodology adapted for the purpose of the project which should fulfill all typical SEJE requirements. However, obtaining final results on a given design problem statement is not the primary purpose of the current work. The main objectives of the paper can be summarized as follows:

- Testing of the first stage of a typical SEJE method, namely solely individual expert evaluations, adapted to the AMA and aircraft design;
- Testing of the developed software for the purpose;
- Feedback from the experts on their experience and the methods applied;
- Derivation of improvement proposals and suggestions for further development;
- Obtaining initial results for later studies and method development.

In this context, certain limitations within the workflow have been intentionally defined in order to focus on these main objectives. The limitations will be mentioned throughout the paper.

The workshop and the post-processing workflow are based on qualitative technology assessment and aim to study the main hypothesis that qualitative expert knowledge is suitable for global conceptual design problems due to the lacking statistical data on innovative technologies.

Subsequently, the challenge this workshop needs to overcome is to make subjective opinions a scientific basis for the conceptual design of complex engineering systems such as aircraft.

1.2. Morphological Analysis

At the core of AMA lies the Morphological Analysis (MA), which is dedicated to structure the problem by decomposing it into functional and/or characteristic attributes. Each of these is assigned a number of alternative technological options (referred to as simply "options" in the following) able to fulfill the attribute's purpose. The attributes and the options are summarized in a morphological matrix (MM) by defining its rows and columns respectively. The MA was developed in the mid-20th century by Fritz Zwicky [7] and applied in multiple fields such as engineering and product design, design theory and architecture, technological forecasting, management science and knowledge management [8]. Ultimately, such problem structuring allows to derive a solution space defined by all possible option combinations for different attributes. However, the continuous extension of the MM results in voluminous multidimensional solution spaces which may often be hard to explore.

1.3. The Advanced Morphological Approach

Seeking for a universal method aiming to evaluate and analyze the solution space, Bardenhagen and Rakov [1] extended the MA to the AMA. After the definition of the MM, the AMA integrates qualitative assessments of the options on a scale from 1 to 9 for a set of predefined criteria. These assessments are obtained from professional opinions of one or more domain experts, further referred to as decision-makers (DMs). The generated solutions from the MM bear the evaluations of their selected options and are positioned in the solution space according to the weighted and accumulated criteria scores. In a next step, the solution space is organized by grouping similar solutions/configurations into clusters (clustering). The current work focuses on the step involving assessment of innovative technological options to implement in the upcoming aircraft generations. A more detailed overview of the AMA can be found in reference [1].

2. METHODOLOGY OF THE FIRST WORKSHOP TEST RUN

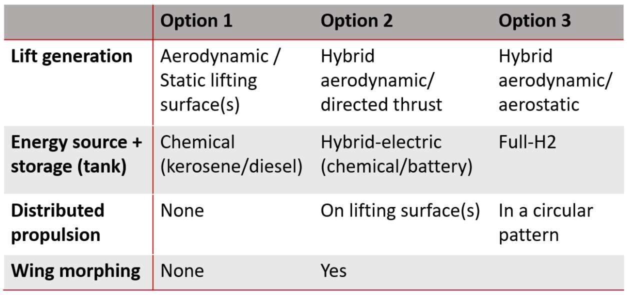
This section will address the main components of the workshop concept, namely the definition of the use case, the problem structuring into a hierarchy by applying the Analytical Hierarchy Process, the uncertainty modeling with fuzzy numbers, and the questionnaire design. A significant part of the theory is based on previous work found in reference [4].

2.1. Use case definition

The use case selected for the first workshop is a conceptual design task for a new generation of a multifunctional SAR aircraft. This choice has been made for multiple reasons.

Firstly, to enable aircraft conceptual design on a global scale instead of focusing on a particular sub-system. Avoiding to demand specialized knowledge on niche technologies from the DMs aims at a) inviting a wider involvement of participants from various professional backgrounds and b) focusing on the methodology testing and analysis rather than on obtaining final results in a particular (sub-)discipline.

Secondly, a SAR mission extends the requirements of a simple transport flight and allows the exploration of unconventional technology combinations.



	Option 1	Option 2	Option 3
Lift generation	Aerodynamic / Static lifting surface(s)	Hybrid aerodynamic/ directed thrust	Hybrid aerodynamic/ aerostatic
Energy source + storage (tank)	Chemical (kerosene/diesel)	Hybrid-electric (chemical/battery)	Full-H2
Distributed propulsion	None	On lifting surface(s)	In a circular pattern
Wing morphing	None	Yes	

FIG 1. Morphological matrix for the conceptual design of a next generation multi-functional SAR aircraft

Top-Level Aircraft Requirements

The Top-Level Aircraft Requirements (TLARs) for the SAR aircraft have been defined as follows:

- Mission: transport/deployment/retrieving capabilities in remote and/or high mountain areas
- Short takeoff and landing distances, low-speed flight and hover capabilities are considered as an advantage
- Payload: 1 ton/ 5 passengers / medical equipment / equivalent cargo mass
- Range: 200 km
- Altitude: 0-5 km
- Flight conditions: stormy weather, wind gusts, heavy rain.

Morphological Matrix

Based on these TLARs, the attributes and options of the MM have been selected as shown in Fig. 1. By considering the conceptual aircraft design on a global system scale, the attributes reflect some of the main aircraft functions, namely: lift generation, energy source (including the corresponding storage possibility, e.g. fuel tank or battery), along with prominent innovative aspects such as the integration of distributed propulsion or wing morphing. Obviously, the selected attributes and their corresponding technological options by no means represent an exhaustive set of all available alternatives and/or necessary components needed to be considered for the final concept definition. Since the main purpose of the present work is methodology testing, the priority was the workshop conduction, while holding it within reasonable time limits rather than covering full-scale conceptual design. Therefore, only main aircraft functionalities have been taken into account while focusing on prominent disruptive technologies.

Evaluation criteria

The defined technological alternatives should be compared according to a set of pre-defined criteria. For the current workshop, the following criteria have been selected:

- Mission performance
- CO_2 and NO_x emissions
- Direct Operating Cost (DOC)

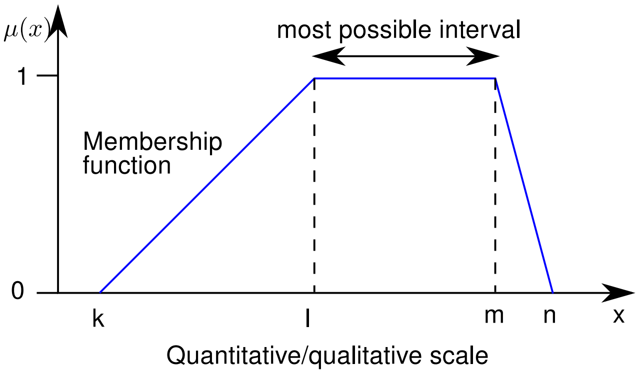


FIG 2. A general example of a trapezoidal fuzzy number. Adapted from [4]

The general label "mission performance" encompasses all aspects contributing to the effective fulfillment of the TLARs, as well as the increasing of overall aircraft efficiency such as increase in aerodynamic qualities or weight reduction, etc.

In general, the solution scores in the AMA are calculated by obtaining the weighted sum of the separate option scores regarding the criteria and the criteria weights. For the purpose of simplicity and the main objectives outlined in section 1.1, the current use case prioritizes the criteria equally without assigning different weights.

2.2. Uncertainty modeling

The conducted workshop aims to obtain and combine the knowledge from experts with heterogeneous professional backgrounds. When dealing with subjective opinions however, one faces information containing uncertainty regardless of the DM's level of expertise. In such situations, it is necessary first to identify the type of uncertainty relevant for the conditions and subsequently select an appropriate modeling approach for this uncertainty.

Previously conducted work [4] has already analyzed these challenges and suggests using the concept of trapezoidal fuzzy numbers for uncertainty capturing within this particular type of expert workshops. A general example of a trapezoidal fuzzy number is given in Fig. 2. Such an approach allows to place a vague linguistic statement onto a quantitative or qualitative scale (x-axis) in the form of a membership function. This representation assigns each scale value (x-axis) a grade of membership to the linguistic statement in the interval $[0, 1]$ (y-axis), 0 meaning a complete lack of affiliation to the linguistic statement and 1 being full membership [9].

2.3. Problem hierarchy structure

In order to capture the multiple dimensions of the problem statement in aircraft conceptual design, the Analytical Hierarchy Process (AHP) by Saaty [10] is used. This approach implies the structuring of the problem statement in multiple hierarchy levels. The benefits and integration possibilities of AHP in

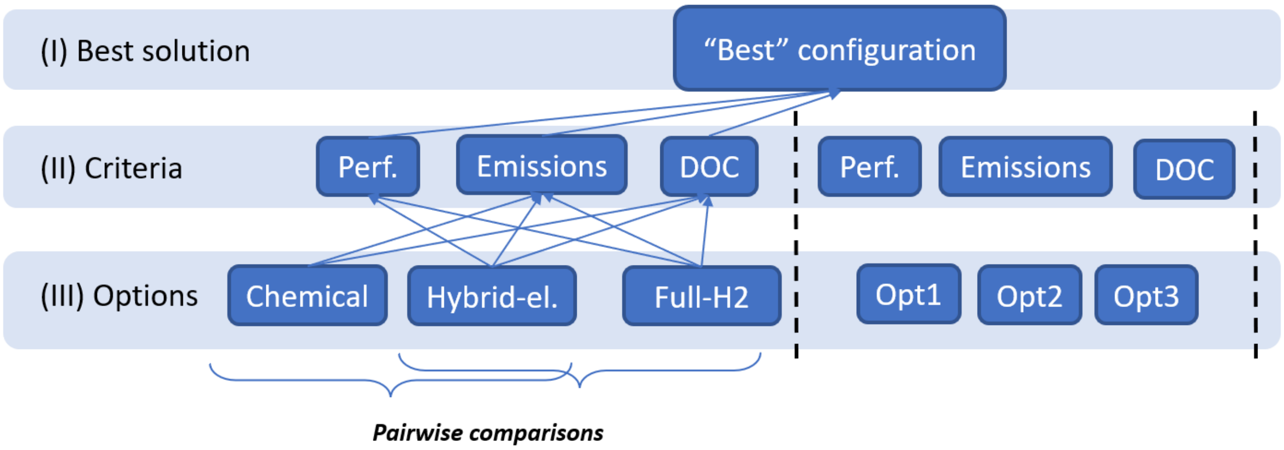


FIG 3. **Hierarchy structure for the conceptual design of a new generation SAR aircraft within the current workshop.**

the AMA methodology have been outlined in reference [4]. Based on these, a hierarchy for the current problem definition is proposed, which is shown in Fig. 3.

Three hierarchy levels have been defined, where a single evaluation represents a pairwise comparison of elements from the same level according to one element of the level above. The hierarchy shown here positions the technological options from the MM in the bottom level (level III). These are compared according to the pre-defined criteria in level II. Finally, one should assess the importance of the criteria for the current mission in order to obtain the "best" or "optimal" configuration, designated as the ultimate goal in level I. Taking for instance the energy source attribute from the MM, one would conduct separate pairwise comparisons among the chemical, hybrid-electric and full-H2 energy source options according to the criteria Mission Performance, Emissions and DOC. This would be repeated for each MM attribute.

These pairwise comparisons for all elements and criteria are the ones obtained from the DMs during the workshop. These are fed to the AHP algorithm which will calculate the weights of each element according to any other element of the levels above.

In order to represent the option comparisons as fuzzy numbers, the Fuzzy Analytical Hierarchy Process (FAHP) is applied - an extension of the classical AHP. Instead of real (crisp) numbers, it uses fuzzy numbers as comparison inputs and calculates the element weights as fuzzy numbers as well. The detailed method can be found in references [11, 12].

2.4. Questionnaire design

During the workshop, the DMs were required to input their pairwise comparisons (defined in the previous subsection) in the form of trapezoidal fuzzy numbers. Reference [4] suggests the implementation of fuzzy evaluations in such technology assessment workshops under consideration of the FAHP. However, it gives only an example to evaluate the superiority of a given option over another. This approach has been further refined to allow the assessment of the superiority or inferiority of a certain option in a single diagram. A sample task can be seen in Fig. 4. The DM is asked to evaluate the conventional aircraft configuration (main option) regarding Operating Empty Weight (OEW) in reference to the configurations a) canard; b) twin-fuselage; c) blended-wing-body (BWB) (reference options). The fuzzy trapezoidal evaluations should be placed on a qualitative axis, where the positive values are interpreted as follows: 1 - equal; 3 - weak superiority; 5 - strong superiority; 7 - significant superiority; 9 absolute superiority/dominance [4]. The values on the negative side bear the same grades, meaning however inferiority of the main option against the reference one(s). The answer can be interpreted as follows: the expert assesses the conventional aircraft configuration according to OEW criterion as a) equal (1) to intermediately superior (4) to the canard configuration; b) strongly (5) to significantly (8) superior to the twin-fuselage and c) weakly (-3) to significantly(-7) inferior to the BWB concept.

For each evaluation representing the comparison of two options in regard to a single criterion, the DMs were asked to enter the four significant points defining the unsteady corners of the trapezoidal fuzzy number. In addition, they were encouraged to write their reasons for the entered evaluation in the form of bullet points. According to [13, 14], justifications influence the evaluations and can contribute to debiasing of the judgment.

2.5. Workshop concept

Five experts from the aircraft design and aerostructures domains took part in this first workshop. It was initiated with an introductory presentation, explaining the context, objectives and giving instructions for the workshop. As stated in the current objectives (subsection 1.1), this workshop focuses on a single part of a SEJE, namely on individual evaluations. Hence, its main part was dedicated to the individual assessment of the option comparisons regarding the criteria without any interaction among the DMs. For this purpose, a specialized software platform had been de-

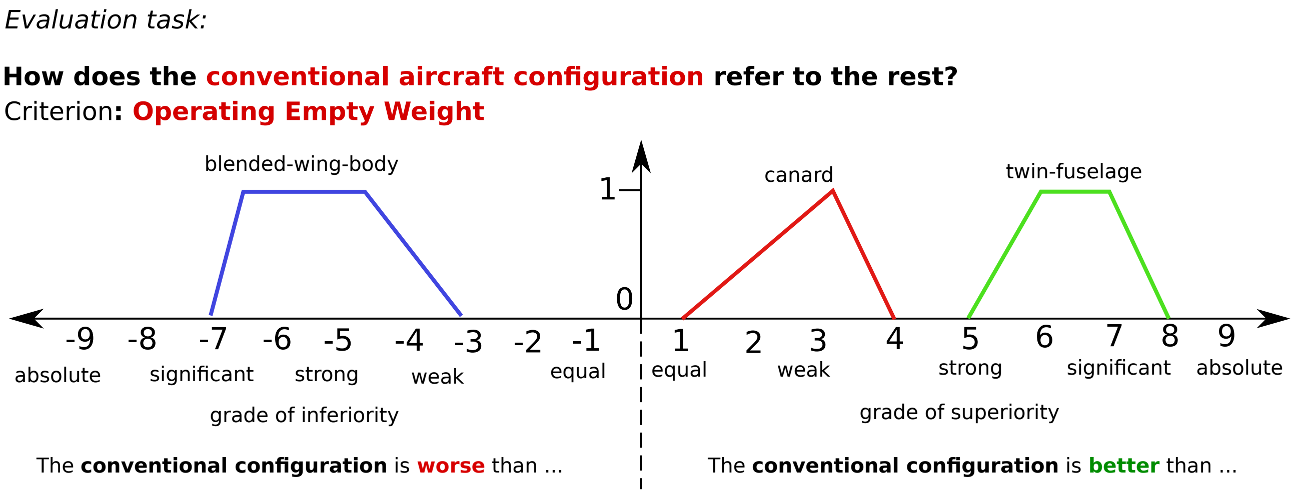


FIG 4. A sample option comparison question

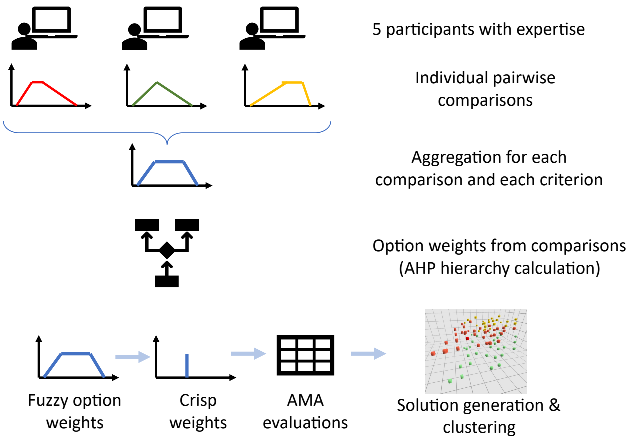


FIG 5. Post-processing data flow

veloped, which consisted of a front-end with an established user interface (UI), and a back-end, performing the necessary operations to store the evaluations in a proper format for their further use. In the UI, the DMs were entering their evaluations and justifications in an interactive way as defined in the questionnaire design subsection 2.4.

During the individual evaluations, no consultations among the participants were allowed. Finally, they were asked for feedback on their user experience and on the methodology by encouraging improvement suggestions.

2.6. Post-processing of the raw results

The evaluations obtained from the DMs are in the form of fuzzy numbers. The further steps aim to obtain a solution space based on these assessments by using the AMA. In order to achieve a smooth integration of the workshop raw results into the workflow, these have underwent several steps of post-processing. These are depicted in Fig. 5 and described in the following:

1) **Data cleaning**

   The raw workshop results represent fuzzy numbers which contain certain errors. Although the introductory presentation contained instructions on the correct input of the four significant points for the trapezoidal fuzzy evaluations, one could still observe inconsistencies in the raw data. However, it was still possible to comprehend the logical implications of the incorrect entries unambiguously. A specially developed workflow was dedicated to the automatic detection and correction of various input inconsistencies while preserving the logical meaning of the evaluations. Typical encountered errors were for example:
   - Reverse order of the significant points of the trapezoidal fuzzy evaluations;
   - Fuzzy numbers going from the negative to the positive side of the evaluation diagram, which was then treated as equal importance of both technology options;
   - Significant points placed within the interval $[0, 10]$ instead of the allowed $[1, 9]$.

   The conduction of such an extended data cleaning has indicated the necessity to make the workshop instruction more explicit and to improve the user input validation in the software UI, which at that point had not been introduced to a wide extent.

2) **Evaluation aggregation**

   During the workshop, five experts entered their pairwise fuzzy comparisons for all MM options according to each criterion. In order to use these as AMA input, it was necessary to obtain their aggregated evaluations. Reference [15] summarized two types of aggregation for such elicitation - behavioral and mathematical. Since the current workshop did not involve participant discussions and a direct opinion exchange as such, no behavioral aggregation has been conducted for the present work. Instead, the fuzzy evaluations have been combined only mathematically. As references [4] and [16] point out, it is necessary to conduct a dedicated study to identify the most appropriate approach for mathematical aggregation. Since the current work aims mainly to test the workshop methodology, only the geometric

mean of the fuzzy evaluations will be considered here. The geometric mean calculation for fuzzy numbers is described in [16].
In addition, one should acknowledge the varying level of participants' expertise in different disciplines. This influences the validity of their evaluations and is typically addressed by assigning the DMs appropriate weights [15]. In the current work, the experts' evaluations were prioritized equally, leaving the investigation of appropriate DM weighting as a subject of further studies.

3) **Option weights**
After obtaining the aggregated option comparisons, these are used as input to the FAHP algorithm by Buckley described in [12]. This yields the weights for each single option according to each criterion as visualized in the hierarchy structure in Fig. 3.
4) **Defuzzification**
The option weights resulting from the FAHP also represent fuzzy numbers. However, the current version of the AMA software accepts crisp (real) numbers as input. For this purpose, the option weights have been transformed from fuzzy to crisp numbers, the process being called "defuzzification". Reference [16] has outlined different defuzzification methods and suggests the centroid method as one of the most common and straightforward methods used in the literature [16, 17]. It envisages the derivation of the crisp number by finding the center of gravity of the shape formed by fuzzy membership function and the x-axis [16]. This approach has been applied in the post-processing section for the current workshop, resulting in crisp numbers for all option weights.
5) **AMA application**
At this point, the AMA software was used to generate the solution space.

3. RESULTS

After having conducted the workshop and its post-processing, the AMA software yielded a generated solution space (visualized in Fig. 6) with the following characteristics:

- Dimensions - the diagram dimensions correspond to the three evaluation criteria - mission performance (red axis), CO_2, NO_x emissions (green axis) and DOC (blue axis);
- Size - the total of 54 solutions were generated, resulting from the exhaustive combination of all options. No inconsistent options have been detected;
- Clustering - performed with the K-Means method for the optimal amount of eight clusters.

Further position of a solution along a given axis means increasing advantage - e.g. further position along the DOC axis means better/lower DOC.
The current version of the AMA software yields multiple visualizations and opportunities to analyze the solution space. These can be summarized as the overview of all clusters, the identification of the global and local optima, and trend analysis for the dominance of certain options in different solution space areas and the location of existing reference configurations in the solution space.

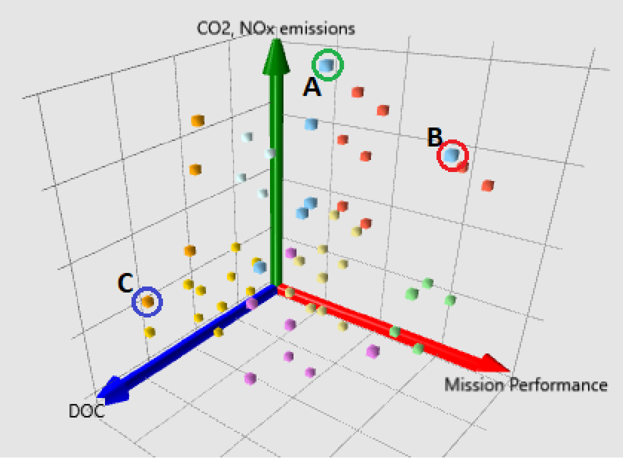


FIG 6. The generated solution space. Different colors represent the eight clusters. The optimal configurations according to the different criteria are marked with the letters A, B and C.

3.1. Cluster overview

Optimal number of clusters

The K-Means method used for the clustering requires the number of clusters as an input parameter. The optimal number of eight clusters has been found by applying the so called "elbow method", which shows the variation of the summed squared distances between the points and the cluster centers [18].

Cluster metrics

The overview of the eight clusters with their corresponding metrics is shown in Tab. 1. Some metrics are based on the total score of each solution, representing the weighted sum of the scores of the selected options according to each criteria. The table columns are described in the following:

- Max. norm. sol. score - the maximum value of the cluster solution scores referred to the average solution score in the entire solution space. Indicates the score of the "best" solution within the cluster compared to the whole solution space.
- Score std. dev. - the standard deviation of the total solution scores within the cluster. Indicates the numerical compactness of the cluster based on the total scores.
- Rel. Hamming distance - the average Hamming distance within the cluster relative to the average Hamming distance of the whole solution space. Represents the qualitative cluster compactness, based on the variation of the selected technological options.

According to the overview, cluster number four (in cyan) yields the highest score of all metrics com-

Cluster ID & color	Sol. count	Max. norm. sol. score	Avg. norm. score	Score std. dev.	Rel. Hamming distance
1 🟨	10	1,00	0,90	0,90	0,73
2 🟥	8	1,07	1,03	0,56	0,70
3 🟩	5	1,11	1,00	0,87	0,57
4 🟦	6	1,21	1,16	0,63	0,68
5 🟪	7	1,13	1,03	1,15	0,83
6 ⬜	4	1,01	0,97	0,61	0,54
7 🟫	10	0,99	0,93	0,63	0,88
8 🟧	4	1,15	1,09	0,62	0,54

TAB 1. Clusters overview

Attribute	**Selected option**
Lift generation	Hybrid aerodynamic & aerostatic (A) /Hybrid aerodynamic & directed thrust (B)
Energy source	Full-H2
Distributed propulsion	None
Wing morphing	Yes

TAB 2. Selected options for global maxima A and B

bined. Not only does it contain the solution with the highest normalized total score of 1,21 (slightly more than 20 percent above the average of all solutions), but also exhibits the highest average normalized solution score among all clusters - 1,16. However, it does not represent the most compact cluster, as seen from the solution score standard deviation (0,63) and the relative Hamming distance (0,68). This is still the cluster containing the most remote solutions from the coordinate system origin (longest radius vector and highest scores).
Worst metric scores are assigned to cluster with ID 1 (in yellow), having the lowest average cluster score of 0,90 (10% lower than the entire space average). In the same time, the highest score shown by its solutions amounts to merely the average of the entire solution space, corresponding to a normalized solution score of 1,00. Accordingly, this cluster is located closest to the coordinate system origin.

3.2. Global extrema

Global maxima

In the context of the generated solution space, the global maximum is defined as the solution with the highest total score in the entire solution space. This condition is fulfilled by two configurations (optima A and B) in the current generated solution space, which are assigned to cluster with ID 4. Their scores and selected options are outlined in Tables 2, 3 and 4.

Criterion	**Solution score**
Mission performance	18,09
CO2 & NOx emissions	23,64
DOC	17,10
Total	**58,83**
Total ref. to sol. space	**1,21**

TAB 3. Scores for global maximum A

Criterion	**Solution score**
Mission performance	21,73
CO2 & NOx emissions	21,11
DOC	15,80
Total	**58,64**
Total ref. to sol. space	**1,21**

TAB 4. Scores for global maximum B

The availability of two global maxima is due to the minor score trade-off between the mission performance and emissions criteria. The only difference in these configurations is the hybridization of the lift generation with a static lifting surface combined either with aerostat(s) or a vertical component of directed thrust. Apart from that, both optima use solely hydrogen as energy source, morphing wings and no distributed propulsion.

Global minima

There also exist two solutions with approximately equal lowest score of roughly 17% below the solution space average, both placed in cluster with ID 1. These implement static lifting surface(s), hybrid-electric propulsion, no wing morphing and distributed propulsion either on lifting surface(s) or in a circular pattern.

3.3. Local maxima

The local maxima represent solutions which exhibit maximal scores according to (at least) one criterion or diagram axis. The local maxima for the mission performance and emissions criteria correspond to the global maxima marked as solution A and B in Fig. 6 and described in Tab. 2, 3 and 4.
The local maximum with the highest DOC (marked as solution C in Fig. 6) would integrate hybrid aerodynamic and aerostatic lift generation, full-H2 energy source, morphing wings but no distributed propulsion. Its total score lies however roughly 7% over the solution space average.

3.4. Trend analysis

The visualizations within the AMA software allow to observe the distribution of applied technological op-

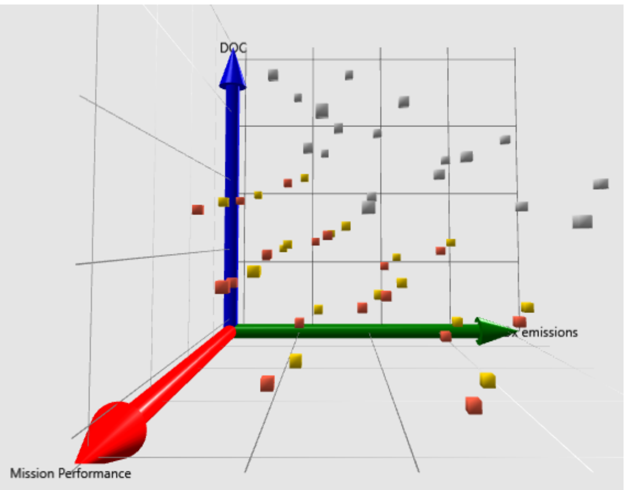


FIG 7. **Option distribution for the distributed propulsion attribute. Gray - none; red - circular pattern; yellow - on lifting surface (aligned positions).**

tions in the solution space. Fig. 7 shows the options positioning of the distributed propulsion attribute.

Roughly half of the solution space volume contains solutions without distributed propulsion (in gray). It is apparent that its absence results in lower DOC. This was justified by the participants with increased system complexity and therefore rising maintenance costs. Some solutions without distributed propulsion also exhibit higher mission performance and lower emissions, being justified by lower system complexity and therefore reduced weight.

As for the distributed propulsion placed linearly on lifting surface(s) or in a circular pattern, the influence of these options on the solution DOC score can be considered negligible. The circular placement shows however a minor mission performance advantage and comparable emission disadvantage in reference to the linear configuration.

Similarly, one can consider the option distribution for the energy source attribute shown in Fig. 8. From this perspective, one can distinguish three roughly homogeneous layers with apparent nonlinear boundaries. As expected, the layer transition happens along the emissions criterion axis with decreasing involvement of chemical fuel (from fully chemical through hybrid-electric to fully hydrogen).

3.5. Reference configurations

The location of existing configurations or ideas in the solution space serves as an additional reference anchor for the assessment of potential solutions or the reduction of the solution set. Since the current problem states the design of a SAR aircraft, two configurations suitable for this mission have been selected based on an overview of typical SAR aircraft [21] and other prospective configurations. These are the conventional transport aircraft Airbus C-295 as well as the Bell Boeing V-22 Osprey with static lifting surfaces and directed thrust.

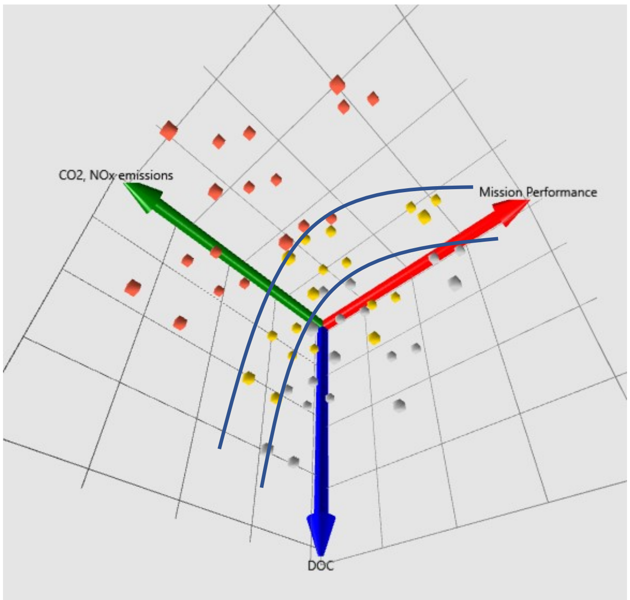


FIG 8. **Option distribution for the energy source attribute. Gray - chemical (kerosene/diesel); red - full-H2; yellow - hybrid-electric (chemical & battery).**

In this case however, one notices the missing typical aircraft used for SAR purposes - the conventional helicopter as a reference solution. The reason for this is the lacking lift generation option implementing only directed thrust (not hybridized with static lifting surfaces). It was intentionally left out of scope in order to reduce the number of comparisons and hold the workshop duration within reasonable limits - in favor of the methodology testing objective.

The chosen existing aircraft are defined in the AMA workflow as "reference solutions" by selecting their implemented MM options. Ultimately, these are shown in the solution space visualization, as presented in Fig. 9. One can observe that these solution points exhibit relatively low scores according to some criteria in reference to most generated configurations. Since the character of the evaluations and the scores is purely qualitative and relative, this should by no means be interpreted as a weak assessment of the existing aircraft. The reason for this location of the reference configuration within the solution space is due to the fact that these are compared with innovative and potentially more efficient technologies. Nevertheless, the DOC scores of the Airbus C-295 and the V-22 Osprey approach the solution space maximum value.

3.6. Participant feedback

One of the main outcomes of the current workshop is the DMs' feedback, which is a vital asset for the further method development and refinement. It can be summarized in the following points:

- **Ambiguous option comparisons**
  Some of the options were encompassing a wider spectrum of implementation possibilities. This led

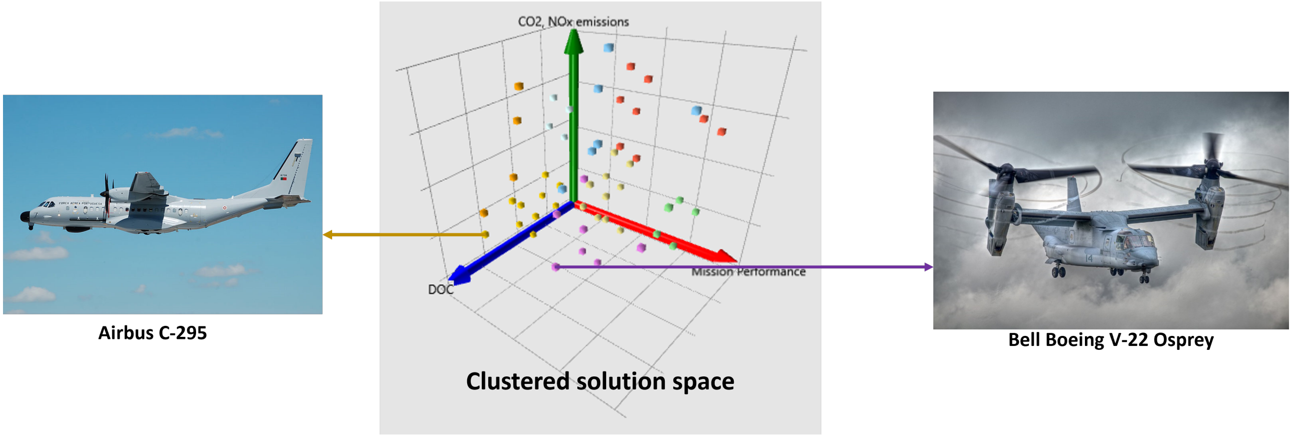


FIG 9. Location of the reference configurations in the solution space. Sources of aircraft photos: [19, 20]

to a certain confusion among the experts, since the general expectation was to assess concrete technologies. A typical example is the fully-hydrogen energy source and the corresponding hydrogen tank from the MM. It was unclear whether a) the hydrogen medium is liquid or gaseous and b) whether a gas turbine/combustion chamber or a fuel cell should be used to convert the chemical energy. On the one hand, the idea was to give the DMs freedom to explore the available possibilities and to enter their expert judgment in the form of a fuzzy number which would incorporate the whole range of implementations and uncertainties. On the other hand, it is fully comprehensible that such a formulation brings additional parameters into consideration and therefore increases the complexity of the task.

- **Option dependencies**
  Another type of ambiguity was faced when a given comparison depended on a selected option from another attribute for a more precise judgment. For example, in order to compare the hybrid aerodynamic/directed thrust and the hybrid aerodynamic/aerostatic lift generation options regarding emissions, it would be necessary to know the grade of kerosene, electricity or hydrogen involvement as an energy source.
  Initially, the given question formulation implied the uncoupled consideration of a given attribute from the rest of the aircraft system. However, the workshop still revealed a lack of precision in the definition of the attributes and options in the MM.
- **Amount of evaluations**
  The participants pointed out the large amount of evaluations to conduct. For the MM presented in Fig. 1, the amount of pairwise comparisons to obtain for the three defined criteria amounts to 28. However, the developed questionnaire included not only the unique pairwise comparisons but also the reciprocal ones (e.g. both following questions were asked: a) "What is the superiority/inferiority of technology A over technology B?" and b) "What is the superiority/inferiority of technology B over technology A?"). The initial idea behind that concept was to let the DMs correct their evaluations in case they come up with additional arguments for a better evaluation at a later point. Instead, it turned out that there was almost no demand to correct the evaluations in such manner. This prolonged the workshop additionally and brought confusion by showing the same pair of options a second time.
- **Layout of the evaluation diagram**
  The diagram on which the DMs placed their comparisons as trapezoidal fuzzy numbers (Fig. 4) was often found to be time-consuming to comprehend. In particular, with progressing elapsed time, it was taking more effort to understand which option pair was to be evaluated, which option should be evaluated as a main one and which as a reference, and accordingly, which option's advantages should be considered on the positive side of the scale and which on the negative.

4. CONCLUSION

The present paper has demonstrated the application of the enhanced AMA and SEJE methodology for the conceptual design of a new generation SAR aircraft. As a result, the main objectives have been achieved, namely a) the testing of the individual evaluations (first) step of a specially developed full-scale SEJE approach for qualitative technology assessment and b) the extraction of participant feedback and initial workshop results for the further method development and refinement.

In the problem definition step, a MM has been defined, which included innovative technological options for the system attributes lift generation, energy source, distributed propulsion and wing morphing. Within the workshop, these options were compared according to the criteria mission performance, CO_2/NO_x emissions, and DOC. The DMs entered their comparisons in the form of trapezoidal fuzzy numbers along with justifications in order to capture uncertainty and reduce bias. Subsequently, the raw results were cleaned and the evaluations of different experts were aggregated and then fed to the FAHP algorithm. The resulting weights of each option served as input to the AMA method, which generated a solution space with 54 solutions grouped in eight clusters. The current AMA software capabilities allowed the visualization and description of a cluster overview with cluster metrics, detailed information on each solution and the identification of global and local extrema. Furthermore, a visualization of option domination trends in the solution space has been demonstrated, which shows the distribution of applied options in the solution space. In order to compare the generated configurations with existing aircraft or ideas, three reference solutions have been located in the solution space.

Since many innovative technologies under consideration lack extended test/statistical data, a full-scale data-based validation of the results cannot be conducted. Instead, the relative positioning of the solutions and their selected options can be qualitatively verified. The results have confirmed the expected influence of the innovative technologies and correspond to the justifications of the experts. For example, lower kerosene involvement in the energy source mix lead to an advantage regarding CO_2/NO_x emissions and morphing wings allow for better performance, however also to higher system complexity hence to increased DOC (maintenance). This is an initial and rough verification of the results, pointing out the necessity for improved solution space analysis, which has been intentionally left out of scope for the current paper.

Apart from a valuable input for further method development and refinement, the expert feedback also represents a validation source for the workshop concept and conduction. The main aspects pointed out refer to question ambiguity and questionnaire layout. A significant improvement potential has been identified in the problem statement. A more explicit definition of the options and the reduction of additional parameters is required, which over-complicate the evaluation tasks and hence reduce the quality of the answers.

Additional improvement opportunities have been identified for the UI as well. Further studies need to improve the layout of the evaluation diagram where the fuzzy comparisons are placed. Additionally, a better compactness of the evaluation workflow should be assured by reducing the workshop length and at the same time preserve the amount of obtained information.

In a next step, the full-scale SEJE for the use with the AMA should be further developed. This includes the conceptualization and testing of discussions among experts. Additionally, different evaluation aggregation methods should be studied and a proper expert judgment weighting considering the different expertise domains and levels of the DMs should be derived. As the analysis of the generated solution space was rather qualitative in this work, it is necessary to elaborate a more detailed solution space exploration aiming to reveal additional findings.

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Contact address:

vladislav.t.todorov@tu-berlin.de

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