ANALYSIS AND SYNTHESIS OF AIRCRAFT CONFIGURATIONS DURING CONCEPTUAL DESIGN USING AN ADVANCED MORPHOLOGICAL APPROACH

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Abstract

This paper presents an advanced morphological approach supporting designers and developers in their search, synthesis and analysis of new engineering solutions of new aircraft configurations during the Conceptual Design Phase. The process covers the analysis of the underlying problem structure as well as the appropriate synthesis and modelling during the Conceptual Design Phase. The specifics of structural synthesis consist of the discreteness of variables, the presence of conditionally logical limitations and the need to work with multiple conflicting criteria. The purposeful variation of characteristic values for configuration variants improves the initial ones. Key objective is to find a solution space of configurations with the potential to fulfil the top level aircraft requirements. Implementation and usage of cluster analysis, set theory, set of rules allows to identify the clusters of innovative aircraft configurations combining high performance potential with robustness regarding requirement changes and design uncertainties. Case studies verify the significant potential of the proposed approach compared to present methods.

Keywords

conceptual design phase, solution space, new engineering solutions, morphological matrix, UAV modelling, folding wings

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1. INTRODUCTION

Within the three phases of aircraft design (Conceptual, Preliminary and Detailed), the Conceptual Design Phase is the most challenging one: a high number of complex decisions regarding aircraft configuration (e.g. wing-fuselage arrangement, propulsion group, materials) have to be taken with a long-term and irreversible impact. Most of the decisions have a binary character (e.g. position of engines, empennage, wing-folding). As little detailed information is available at the beginning, a robust solution space has to be found prior to the Preliminary and Detailed Design Phase. Even modern Mixed-Integer Programming (MIP) Solvers are not able to provide adequate solutions in this generally non-convex solution space.

Therefore, the Conceptual Design Phase is the fundamental and indispensable forerunner of the more detailed design phases. It is well known that the right design concept is the key factor influencing the majority of product life-cycle cost and defining the level of product innovation. However, an excellent detailed design based upon a poor and inappropriate design concept can never compensate the shortcomings of that concept.

It is the objective of this paper to present a methodology to systematically identify a robust solution space using the advanced morphological approach as a numerical technique for the systematic synthesis of new aircraft configurations. The specific problem to be solved in this paper demonstrating the application of this approach is to determine a solution space of configurations fulfilling the top level aircraft requirements for manned and unmanned complex energy-efficient flight systems with reduced environmental impact, i.e. reduced fuel consumption, flight noise and better energy efficiency. The best possible solution space results from a selection among clusters of potential solutions taking into consideration their sensitivities to parameter variations (i.e. uncertainty) and their resilience to changes of discrete sets of parameters.

The presented advanced morphological approach includes the analysis of the underlying problem structure of the technical problem as well as the appropriate synthesis and parametric modelling and multi-disciplinary optimization during conceptual design phase. The specifics of structural synthesis processes allow to consider the discreteness of variables, the presence of conditionally logical limitations and the need to work with multiple conflict criteria. The purposeful variation of characteristic values of configuration variants improves the initial ones. Implementation and usage of cluster analysis, set theory and set of rules allows to identify the clusters of innovative aircraft configurations combining high performance potential with robustness regarding requirement changes.

Key objective is to find a solution space of configurations with the potential to fulfil the top level aircraft requirements. In this paper new tools for the investigations of the complex flight systems, in particular the energetic and environment aspects, are introduced.

As the Conceptual Design Phase is the phase of the design process “that makes the greatest demands on the designer, and where there is the most scope for striking improvements and where the most important decisions are taken” [1], automation and “intellectualization” of some

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aspects of this phase would be of immense practical benefit [2,3]. During this phase, the designer must devise an initial design which (a) incorporates ''working principles'' or physical solutions for all required ''essential'' features of the problem and which (b) has been evaluated to be acceptable and feasible [4].

The Conceptual Design Phase involves the generation of solutions, of engineering concepts and of design principles to satisfy the functional requirements for a given design problem. As more than only one solution of a problem exists, improved designs can be identified within the defined design space if the set of potential Engineering Solution (ES) can be enlarged compared to present possibilities [5]. As shown in Fig. 1 the largest information uncertainty exists during the concept phase and then decreases towards the development phase. The accumulated project costs are minimal at the concept stage, but the impact of engineering solutions decided during this phase is maximal. Computer Aided Innovation (CAI), which can be considered as part of knowledge-based engineering supports identification and evaluation of ES during conceptual design [3,6,7].

The more variants of ES are analyzed, the higher are the quality of the study and the confidence to achieve the project requirements and objectives. For this reason, the choice and the consideration of alternative variants is the main task of the design process.

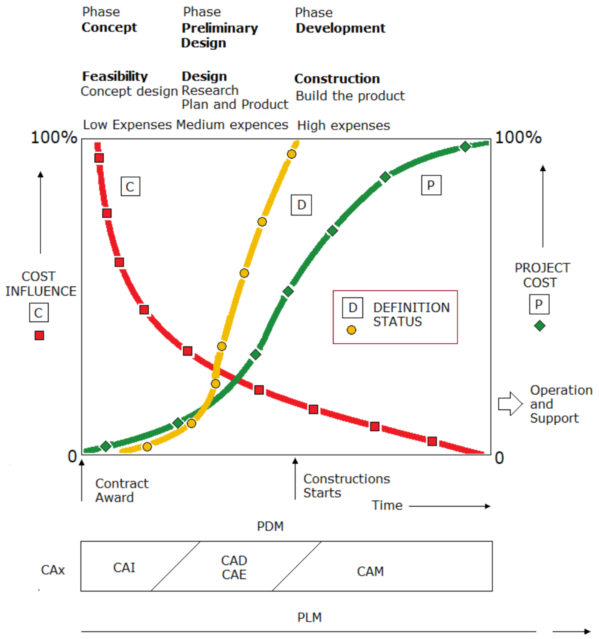


FIG. 1. Change in project cost, cost influence and uncertainty of information during project execution

2. STRUCTURAL AND PARAMETRIC SYNTHESIS

Problems like the finding of optimal ES is part of systems theory. Systems theory is the interdisciplinary study of systems. Each system is delineated by its spatial and temporal boundaries, surrounded and influenced by its environment, described by its structure and purpose or nature and expressed in its functioning. In terms of its effects, a system can be more than the sum of its parts if it expresses synergy or emergent behavior [8].

The design of a system (device, process) is a set of two main tasks: the definition of (a) the structure (structural synthesis) and (b) of parameter range for the synthesized structure (parametric synthesis or parametric optimization) (Fig.2).

The solution strategies for these two tasks are different. The parametric synthesis task is usually reduced to determine solutions satisfying the metric criteria, making them formally resolved. In contrast, the task of structural synthesis is absolutely different and cannot be generally allocated to the class of formally solvable problems. The structural synthesis result is the choice of the rational structure of the object (i.e. ES). This requires to work with uncertain structural connections, non-metrical attributes of the structure elements and quality criteria. The objective function of a structural synthesis does not correspond to the main requirements of usual optimization methods because (1) it is discontinuous or cannot always be determined; (2) it exists in operator notation; (3) it is not based on analytical expressions; (4) it is not differentiable, not unimodal, not separable, and not additive [8]. The solution of the structural synthesis task is the main and exclusive subject of the researcher´s creative activity.

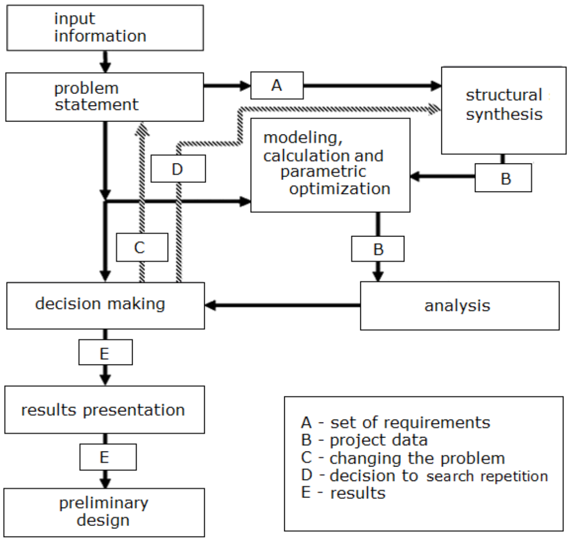


FIG. 2. Macro description of the design process

The specifics of structural synthesis tasks consist of the discreteness of variables and presence of conditionally logical limitations. In addition, we need to work with multiple conflicting criteria. The essence of a research project consists in the purposeful alteration of characteristic values for variants improving the initial ones. The very notion of "the best" in project tasks is undefined and vague, since a number of criteria are not quantifiable and/or conflict with each other. The main difficulty during the search for the design of an ES is the uncertainty of the results due to incomplete information on evaluation criteria [9]. At present, there are many methods to search and synthesize engineering solutions, including structural analysis for the realization of scientific and technical ideas [10]. The most common method among the discursive techniques is the morphological analysis [11,12]. By frequency of use, morphological methods are the first among ranks of discursive approaches. Thus, according to statistics compiled in 2009, the total number of companies using the morphology one is more than 40 percent, while regular use is done by more than 20 percent [13]. Morphological synthesis is regarded as a methodology to streamline the problem to be solved. Whereas morphological analysis is a method (developed by F. Zwicky) to explore all possible solutions of a multi-dimensional, non-quantified problem complex [14]. Zwicky applied this method to such diverse tasks as the classification of astrophysical objects and the development of jet and rocket propulsion systems. More recently, morphological analysis has been extended and applied by a number of researchers in the USA and Europe in the field of future studies, engineering system analysis and strategy modeling [12]. Today, the morphological approach serves as a standard when new systems are being designed. At present, there are many methods to search and synthesize solutions based on the morphological analysis in a variety of physical and engineering areas. The power of the resulting morphological set can reach millions of possible solutions. In general, classic morphologic models are inappropriate for large complex studies, e.g. in flight systems optimization. Some of the major problems of application of classical methods of morphological analysis are: poor access to support software which can address the combinatorial explosion generated by multi-parameter problem spaces inherent in the use of morphological analysis; insufficiently flexible processes that address users' operational constraints; seen to be overly generic, disguising identification of specific application areas of interest [14].

3. METHODOLOGICAL BACKGROUND

The advanced morphological approach (AMA) is based on [15-18]. The proposed approach shall be explained with a generic set {T, Z, W, V, O, L, M, N, K, C, P}, arbitrarily defined by one or more experts and shown in Table 1, column "Task Definitions" [19]. The selectable options can and must not represent completely all possibilities for each task.

In the proposed AMA method, conceptual design is conducted in 10 steps (Fig. 3): synthesis of the morphological matrix (1), definition of a system of criteria (2), weighting of options (3) and selection of reference variants (4), generation (5) and selection of variants (6) using estimates of each variant and comparison with others, clustering of variants based on similarity measure and creation the solution space (7), analysis of clusters and solutions (8), analysis of the design risk, variants and selection (9), synthesis of anticipation models, parametric modeling and optimization stage (10).

	Task	Task Definition
T	Formulation of the problem	t1 - synthesize and choose the best ES t2 - reverse ES search
Z	Solution level	z1 - choice the best function z2 - choose the best structure
W	Criteria	w1- vector criterion w2 - scalar criterion
V	Additional information	v1-no v2- well-known or existing solutions v3 - cross-consistency matrix
O	Measurement	o1 - point scale
L	System investigations	l1 - integrated system l2 - the study of the subsystems
M	Variants assess	m1 - variants assessment in general, after the synthesis of the parts m2 - evaluation of individual subsystems bevor to synthesis
N	Variants generating	n1 - loop through all variants n2 - loop through all variants with choice n3 - random selection n4 - random selection with choice
K	Clustering method	k1 - Hamming distance k2 - L1-norm
C	Target function	c1– additive c2 – multiplicative
P	Number of levels of the system under consideration	p1 - one p2–two and more

Table 1. Sequence of tasks

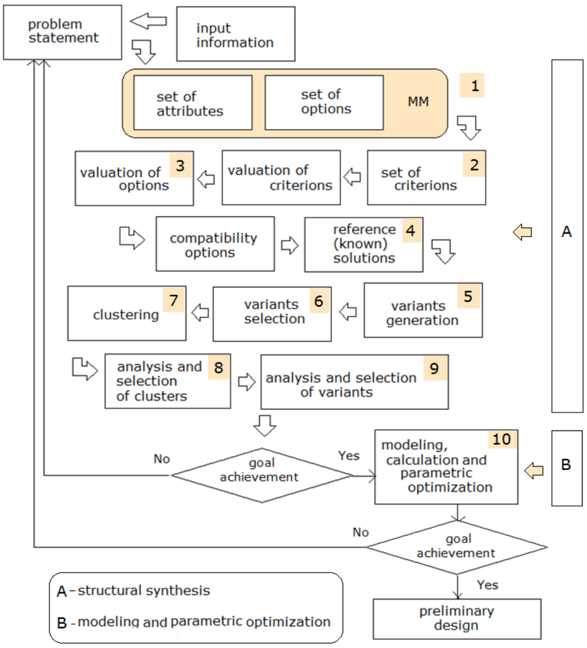


FIG. 3. AMA block diagram

While the process will be explained in detail in chapter 4 and 5, two aspects shall be highlighted in advance: In step (7) the clustering of variants takes place as shown in Figure 4.

Clusters can be generated by grouping solutions e.g. having a nearly similar Hamming distance. The Hamming distance between two variants with same set of attributes is defined as the number of options at which the corresponding symbols are different. It is also used as a measure of likeness or similarity [20]. If reference variants, i.e. realized ES with known options for the criteria as defined in the morphological matrix, are included they can be used as starting points for clusters.

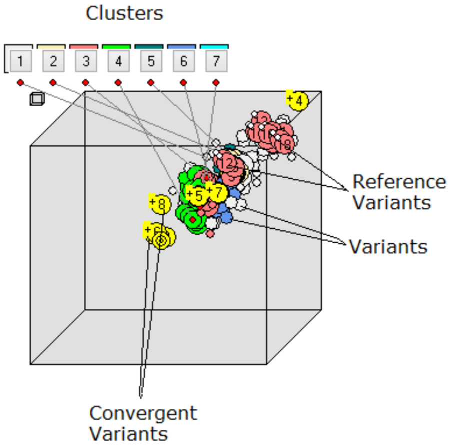


FIG. 4. Clustering of variants and the solution space

This approach for cluster creation shown in Fig. 5 identifies in the neighborhood of a reference ES additional promising ES as part of the generated ES.

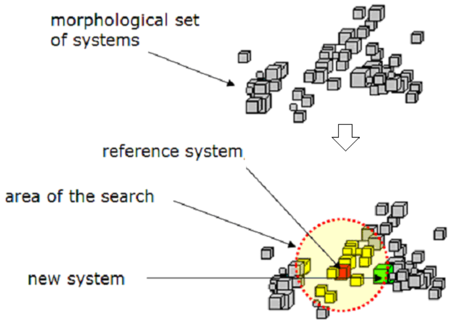


FIG. 5. The sequence of finding new ES

To illustrate this approach, two ES in Aerospace have been synthesized and studied.

4. AMA FOR A STRATOSPHERIC UAS

The number of potential roles for unmanned aircraft systems (UAS) is legion, especially in the civil field. The demands defined by the customer lead to system requirements which determine principally the shape, size, performance and costs of the air vehicle, but also of the overall UAS operating system. Some of the more important parameters involved, beginning with the air vehicle, are briefly discussed below [3,21].

The studied UAS shall have a performance potential to fulfil the following mission (Top Level Aircraft Requirements):

- UAS with civil mission (e.g. observation, research, communication node, etc.)
- Flight altitude: 12-20 km (above Jetstream)
- Long flight in the stratosphere (as long as possible on station; ideal: >1 Week)
- No range requirement – defined position to be hold within area of 4 km^2
- Max. 10 m/s wind during climb – no Jetstream – max. 10 m/s wind on position for 4h/day flight time
- Payload 1kg, constant 50W electric power consumption.

Task definition

In order to solve the problem, the given set of subtasks arbitrarily was selected in Table 1 by means of the problem-oriented engineering judgement:

$$\{t_1, z_1, w_1, v_2, o_1, l_1, m_1, n_2, k_1, c_1, p_1\}$$

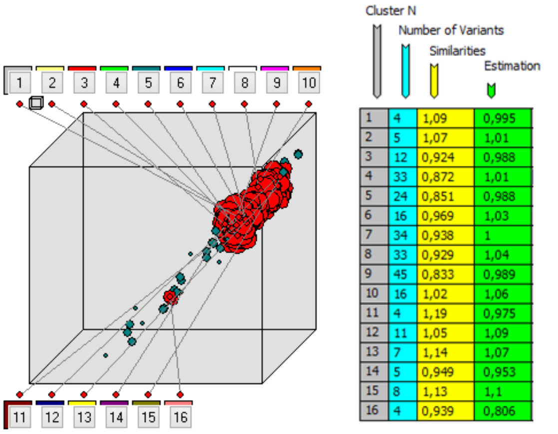
The proposed morphological matrix and the criterion table of this ES are given in Table 2 and Table 3. The complete morphological matrix contains $3 \cdot 2 \cdot 4 \cdot 3 \cdot 4 \cdot 3 \cdot 3 \cdot 2 \cdot 3 \cdot 2 \cdot 2 \cdot 2 \cdot 2$ = 248,832 potential UAS variants. First, 12,000 variants are generated using random search (RS). This method does not require the gradient of the problem to be optimized, and RS can hence be used on functions that are not continuous or differentiable. For all variants, the average estimation and the average measure of similarity are calculated. This estimation is based on an assessment of each ES by an Expert Panel. These quantitative assessment results are normalized to “1” (as average) making it possible to evaluate the clusters and individual options. 256 potential “best” variants are identified by the expert panel based on engineering judgement of the attribute options (~2% of the 12,000). The selected variants are grouped using Hamming distance k1 into 16 clusters (Fig.7). The solution space contains also the 15 reference variants of built flight systems (Fig.8).

	Criteria	Comments
1	UAS System Cost	Estimated cost of complete system (Ground Support & UAS)
2	Cost per Mission	Cost per mission/flight incl. Cost for fuel/energy, operators, etc.
3	Total Weight /Mission Flight Time	This is a technical key performance indicator for a long endurance mission: How much weight including stored energy does it take to fulfil a mission
4	Emissions	Emissions like CO_2, etc. and noise
5	Reliability	
6	Energy Efficiency	
7	Speed (Wind and time for climb)	Capability of UAS to reach mission altitude and endure wind
8	Flight duration	Time of UAS to stay on the predefined position (time for climb/descent excluded)
9	Safety (flight in the stratosphere)	Safe operation including hazards from fuel, tethers, electromagnetic waves etc.

Table 2: Criterion table

Category	**P_x**	**Attribute (descriptors)**	**Option P_x^1**	**Option P_x^2**	**Option P_x^3**	**Option P_x^4**
Lift	1	Lift	aerodynamic	thrust	aerostatic	
Thrust	2	Thrust	coupled to Lift Generation	independent from Lift Generation		
Energy Storage	3	Internal Energy storage	non	chemical, reversible (e.g. LiPo battery)	chemical, irreversible (e.g. fuel tank)	mechanic (e.g. fly-wheel)
Energy supply	4	External Energy Supply	non	continuous (e.g. solar, microwave)	interrupted, discontinuous (e.g. tank)	
Power generation	5	Engines	electric	internal combustion (e.g. diesel engine)	gas turbine	reaction engine (e.g. rocket motor)
	6	Engines	single engine	twin engines	more than 2 engines	
Flight control	7	Flight height control	aerodynamic (e.g. elevators)	Changing of thrust	aerostatic	
	8	Flight directional control	aerodynamic (e.g. rudder)	Thrust imbalance (e.g. two engine		
Fuselage	9	Fuselage	no	one fuselage	twin-boom	
Geometric Characteristics Wing	10	increasing the wing area	no	yes		
	11	Wing area control	no	yes (e.g. to maximize solar radiation usage)		
Flight guidance	12	Trajectory	constant height	changing height		
	13	Guidance	remote controlled	autonomous		

Table 3: Morphological Matrix



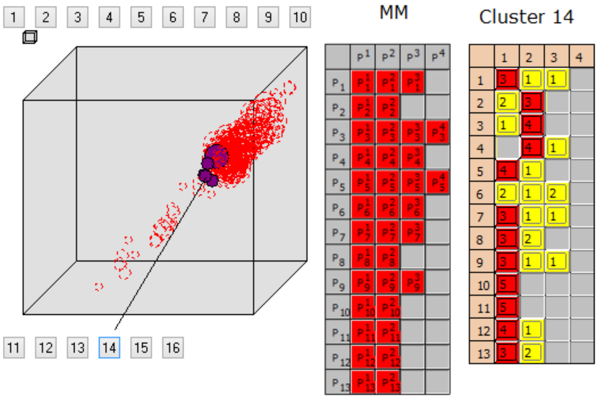
Cluster N	Number of Variants	Similarities	Estimation
1	4	1,09	0,995
2	5	1,07	1,01
3	12	0,924	0,988
4	33	0,872	1,01
5	24	0,851	0,988
6	16	0,969	1,03
7	34	0,938	1
8	33	0,929	1,04
9	45	0,833	0,989
10	16	1,02	1,06
11	4	1,19	0,975
12	11	1,05	1,09
13	7	1,14	1,07
14	5	0,949	0,953
15	8	1,13	1,1
16	4	0,939	0,806

FIG. 7. Solutions space with 16 Clusters with their values of relative estimations and similarities

FIG. 8. The reference variants in the solutions space

After the cluster analysis, we can draw the following conclusions:

- Many variants have incompatible options (e.g., P_4^2 und P_5^2in Table 3 - continuous external energy supply (e.g. solar, microwave) with simultaneous using internal combustion (e.g. diesel engine) or in the case of today's knowledge impossible implementation (Cluster 7,8,13, 15 and 16, with options combination, P_3^1 und P_4^1 - simultaneous absence energy storage and external energy) state.
- Under the reference variants, the highest relative measure has the configuration Sharp [22] (estimation - 1,02) and the configurations of Solar Eagle (1,00), Helios (0,95), Solar Impulse (0,95). The worst configuration is Stratosphere Rotor Platform (0,58) [23].
- Better reference variant (Variant 32) is located in Cluster 4. Without microwave energy supply for the aerodynamic configuration (Cluster 4) or helicopter configuration (Cluster 5) with power supply cable corresponds to technical UAS solutions.
- Many of the generated and selected variants and clusters have hybrid properties (Attributes P_1 and P_2).
- In Cluster 14 aerodynamic P_1^1 are electric P_5^1 UAS with energy storage on board P32 with external power supply P_4^2 with aerodynamic P_8^1 or thrust controls P_8^2(Fig.9).



	P^1	P^2	P^3	P^4
P_1	P_1^1	P_1^2	P_1^3	
P_2	P_2^1	P_2^2		
P_3	P_3^1	P_3^2	P_3^3	P_3^4
P_4	P_4^1	P_4^2	P_4^3	
P_5	P_5^1	P_5^2	P_5^3	P_5^4
P_6	P_6^1	P_6^2	P_6^3	
P_7	P_7^1	P_7^2	P_7^3	
P_8	P_8^1	P_8^2		
P_9	P_9^1	P_9^2	P_9^3	
P_{10}	P_{10}^1	P_{10}^2		
P_{11}	P_{11}^1	P_{11}^2		
P_{12}	P_{12}^1	P_{12}^2		
P_{13}	P_{13}^1	P_{13}^2		

	1	2	3	4
1	3	1	1	
2	2	3		
3	1	4		
4		4	1	
5	4	1		
6	2	1	2	
7	3	1	1	
8	3	2		
9	3	1	1	
10	5			
11	5			
12	4	1		
13	3	2		

FIG. 9. Cluster 14 in the solutions space and variants

The cluster analysis identifies four areas to be of interest for further investigations:

1. Aerodynamic configurations with energy storage on board as well as external power supply and with aerodynamic or thrust vector flight control
2. Investigations of hybrid (lift) UAS
3. Aerodynamic configurations or helicopter
4. Configurations with power supply by cable

After the stage of structural synthesis and analysis (Fig 2 and 3), modeling and parametric calculations of the selected ES's were carried out applying the program „Lane“ (Fig. 10) [24]. The software enables aircraft designers to work on a fast modeling and simulation solution. The research and modeling components are based on mathematical models and techniques for analysis, simulation, and evaluation of flying qualities. The fast modeling helps to reduce mistakes and the need for rework and significantly reduces the time required for the predesign cycle.

Program Lane calculates the complete range of performance parameters over a user-specified range of ballistic and aerodynamic variables and provides the user with useful quick-look (evaluate) functions for the examination of a wide variety of data (e.g. thrust, fuel flow, lift, drag, etc.). Lane provides a powerful framework to support the iterative process of unconventional aircraft pre-design (electrical airplanes, hybrids etc.

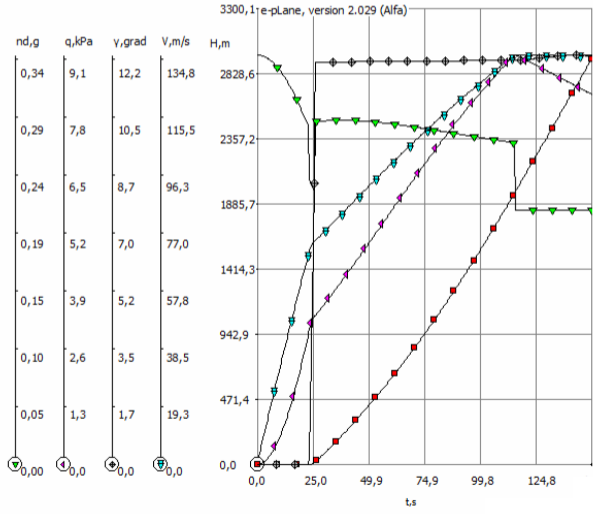


FIG. 10. Screenshot of Lane program

5 AMA FOR FLIGHT SYSTEM CONFIGURATIONS WITH FOLDING WINGS (PROBLEM STATEMENT)

Possible aircraft configurations with folded wings are investigated. A morphological matrix is constructed containing 27648 potentials (Table 4) and reference variants. Among the reference variants are configurations proposed by Boeing and Airbus. Upon analysis, the following conclusions about prospective lines of investigation in these field can be drawn:

Possible purposes of configurations use:

- improving the aerodynamic performance (lift-to-drag ratio, lift-induced drag) of aircraft systems
- reduced fuel consumption,
- reduced noise
- reducing environmental impact
- increased strength characteristics
- weight reduction

Control–

- roll control
- rotation control
- pitch control
- control of mass center
- control of the pressure center
- longitudinal and transverse stabilization

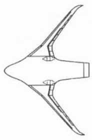
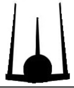
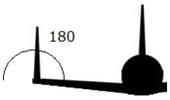
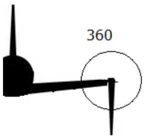
Attribute **(descriptors)**	**Option P_X^1**	**Option P_X^2**	**Option P_X^3**	**Option P_X^4**
Concept	Blended Wing Body (BWB) 	Conventional 		FW 
Wing Folding	2 positions (up/down)	more as 2 positions		
Wings Part	Up to 30% 	30-70% 	more than 70% and all wing 	
Folding Parts	2 	3 		
Energy for unfolding	Internal (electro, hydro, memory alloys)	external environment (Lift)	Combination	
The connection with main wing				
Design	(non closed?) system 	rigid (closed?) system (fuselage) 	rigid (closed?) system (tail) 	Prandtl Plane Configuration 
Symmetry of the configuration	Symmetrical 	Not symmetrical 	Combination	
Control (primarily)	Lift	Pitch 	Roll 	Combination 
Rotation	180 Grad 	180 Grad 		

Table 4: Morphological Matrix „ Configurations with folding wings “

The intention is to study morphing configurations using the properties of the environment (i.e. energy from the surrounding airflow). It is assumed that this will lead to an increase in the energy efficiency of the studied systems, to an increase in reliability and to completely new configurations (Fig.10, 11).

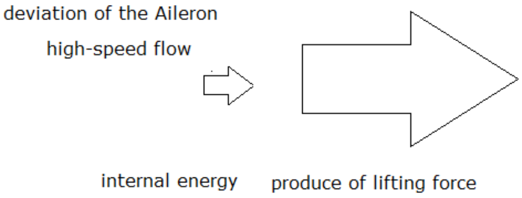


FIG. 10. The use of energy from the external environment

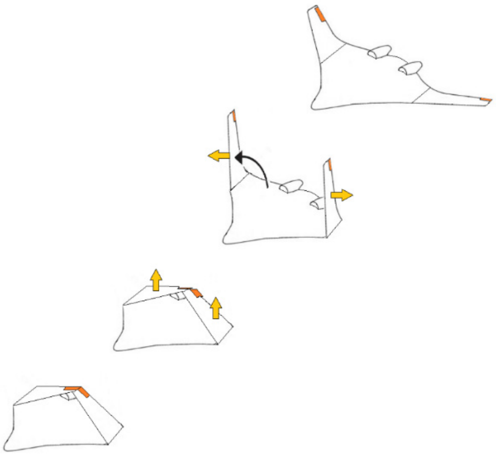


FIG. 11. The use of velocity head during flight for morphing

5. CONCLUSION

The methods to generalize the process of designing the “best” aircraft configuration on a conceptual level lead to the conclusion that a lot of experience is necessary to solve problems during the creation of new systems.

Existing approaches and techniques are applicable mainly for solving parametric modeling and optimization and cannot be used for structural synthesis. They allow to identify the problem and formulate the purpose and objectives of the investigations.

To improve the quality and efficiency of work in the creation of new systems, a new advanced morphological approach of structural analysis and synthesis of structural solutions in aerospace activity is proposed. It allows to search for new engineering solutions during the conceptual design phase, to form clusters of options, to generate a set of pre-optimal options, to choose the most rational variants and to compare them.

The AMA is based on classical morphological approach, system and cluster analysis. The structural synthesis determines hereinafter the parametric methods and optimization.

As the approach has a generic character, it is possible to apply it systematically in order to identify robust solutions for complex engineering challenges.

A major aim of the presented approach is the systematic expansion of a number of potential solutions of engineering problems, their clustering and the efficient selection during the solution space synthesis in order to increase the number of possible innovative solutions in the engineering design. The technique, demonstrated in two case studies, testifies the power of the approach for generating design concepts.

In addition, the proposed approach clarifies and arranges the structuration of the decision task. The validity of decision-making increases and a multitude of variants, among which the selection is carried out, is broadened. This enables the improvement of the quality of developed engineering systems.

As explained, the AMA method depends on expert votes and judgements. When several experts are involved, their vote follows a statistic distribution which can be used to include probabilistic approaches into the AMA to define new rules for clustering based on the vote’s uncertainties and to include these uncertainties within the whole AMA process.

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