Creation of innovative concepts in Aerospace based on the Morphological Approach

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Abstract. The development of innovative aircraft configurations can be an important contribution to achieve the emission reduction goals set for the aviation industry. However, current common aircraft conceptual design processes only allow the consideration of a limited number of initial configurations thus leaving possibly more efficient solutions out of scope. A significantly wider range of aircraft configurations can be taken into account by applying the Morphological Analysis. After a brief presentation of its historical background and actual applications in other domains, this article focuses on the use of this method and its benefits in aerospace. The summary and comparison of several applications in the field of aircraft design show that these still require a higher level of formalisation and robustness. For this purpose, the main steps required to integrate morphological analysis into the aircraft conceptual design phase based on the Advanced Morphological Approach are identified. These are the definition of the morphological matrix along with the evaluation criteria, the obtaining of option evaluations, filtering the impossible solutions and exploration of the solution space.

1. Introduction

The advancing climate change urges a significantly higher level of energy efficiency in the upcoming aircraft generations. Ambitious emission reduction goals are set for the aviation industry for the year 2050 by the European Commission [1]. A report shows that even an optimistic scenario for the integration of new technologies into airline fleets might not be enough to fulfil aviation's contribution to the Paris Agreement on climate change from 2015 [2].

These conditions underline the need for a cardinal technological breakthrough in the next aircraft generations. Bardenhagen and Rakov [3] underline that the decisions made during the early phases of conceptual design such as defining the aircraft configuration have a significant influence on the project cost. Furthermore, a design modification at a later stage causes delays and additional costs. However, the generation of initial aircraft concepts is still driven mostly by brainstorming [4]. Therefore, the variety of ideas to be considered is significantly limited by the designer's imagination, possibly leaving more efficient solutions out of scope. Such challenges could be addressed by developing Computer Aided Innovation (CAI) tools for idea management purposes, which are described in [5]. These can be classified as tools for idea generation, collection, evaluation, classification and analysis. However, there is a certain lack of common industry software for idea generation [6]. This gap could be filled by implementing the Morphological Analysis (MA). This formalised problem-structuring method [7] allows an exhaustive exploration of the possible solutions for multi-dimensional, multi-criteria and non-quantifiable problems [3, 8]. After decomposing the system into relevant (sub-)functional attributes, alternative options are defined for each attribute. All possible combinations of these options for the total set of attributes represent the problem solution space. The intuitive character and the ability of the MA to address abstract and non-quantifiable tasks has led to its application in numerous fields from engineering to policy analysis [9].

To a larger extent, three major applications of the MA are known in aircraft conceptual design, among which is the Advanced Morphological Approach [3]. However, the purpose and the application conditions of the MA vary among these works. The objective of the current article is to identify the benefit of the MA for aircraft conceptual design and outline the further challenges and development steps for the integration of the MA in the domain based on the Advanced Morphological Approach.

2. Challenges of the conceptual design phase

The design of a device (system, process) comprises a set of two main tasks: the definition of (a) the structure (structural synthesis) itself and (b) of the parameter range for the synthesised structure (parametric synthesis). Parametric synthesis tasks are usually reduced to the determination of solutions satisfying the metric criteria, making them formally resolved. The task of structural synthesis is absolutely different as it cannot be generally allocated to the class of formally solvable problems. The result of structural synthesis is the choice of the rational structure of the object. Structural synthesis requires working 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 optimisation methods because it can be discontinuous, in operator notation, not based on analytical expression, non-differentiable, not unimodal, not separable, or not additive [3, 10].

The main difficulty of the conceptual design of innovative systems is the significant uncertainty of information. Psychological reasons also play a role in the search process. So, a person is able to work simultaneously with 5 to 7 variable parameters. In addition, a person has an inherent desire to improve the design solution by simultaneously varying one parameter with fixed values of other parameters. But the dimension of the tasks when searching for configurations is tens and hundreds of different parameters.

One of our conclusions is that it is necessary to fundamentally abandon the search for strictly optimal variants. We propose to focus on the synthesis of a certain number of rational variants that are close to the theoretical best in terms of the values of the criteria.

3. The Morphological Analysis

The challenges of structural synthesis during conceptual design can be addressed by the Morphological Analysis (MA) which was developed by the Swiss astrophysicist Fritz Zwicky [11, 12]. It was designed as a problem-structuring technique to seek the total set of possible solutions for multidimensional, multicriterial, non-quantifiable problems under uncertainty conditions.

3.1. Summary of the method

In order to achieve this, the problem is decomposed and defined as a morphological matrix, the cross-consistency assessment handles impossible solutions and finally, the solution space is generated.

(i) **Problem decomposition - morphological matrix (MM)** - First, the product to be designed is decomposed into functional, sub-functional or other characteristic attributes [8, 11, 14]. Their quantity defines the dimension of the problem. Each attribute is then assigned

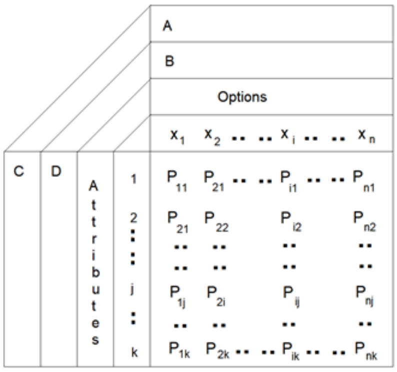

Figure 1. Matrix of qualitative-morphological attributes. Source: [10]

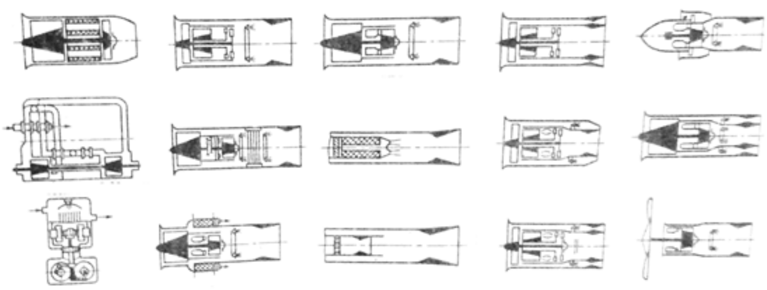

Figure 2. Structural and schematic diagrams of combined engines for various types of energy exchange. Source: [13]

a number of discrete options able to fulfil the attribute's purpose. The options of the same attribute cannot be combined, meaning that a potential problem solution may include only one option per attribute. In the case of engineering solutions, those are very often technological options but could also involve operational and other aspects. The attributes and their options are represented in a Morphological Matrix (MM), the general layout of which is depicted in figure 1.

(ii) **Cross-consistency assessment (CCA)** - The issue with the possibly overwhelming amount of generated solutions from the MM can be partially addressed by conducting a cross-consistency assessment (CCA) [8]. This involves the definition of the cross-consistency matrix (CCM), which aims to identify impossible combinations of options. The matrix includes pair-wise comparisons of all technological options of different attributes and marks the incompatible ones.

(iii) **Solution space generation** - The entire set of solutions is generated by permuting the technological options for all attributes. One obtains the solution space by subtracting the impossible solutions obtained through the CCM from the entire solution set.

3.2. Historical applications

The MA developer Fritz Zwicky has demonstrated its vast applicability in multiple fields, such as design of telescopes, observation and experimentation with celestial phenomena, as well as law and justice in the Space Age [8, 15].

An extensive overview of the variety of MA applications is given by Ritchey and Àlvarez in [8]. Naturally, the abstract character of the approach has allowed its use in domains such as Future Studies and Scenario Development, Technological Forecasting, Management science, Policy analysis and Organisational design, Security, Safety and Defence studies, as well as Creativity, Innovation and Knowledge Management. However, the MA has also found application in problems from technical fields such as Engineering and Product Design as well as Design Theory and Architecture, which cannot be addressed by conventional approaches. An example is given by Kapustyan and Makhotenko in [16], where they use a System-Morphological Approach for the design of nuclear technologies. The authors propose a combinatorial concept for working with the options. They describe the basics of the mathematical apparatus of calculations used to solve optimisation problems in design.

In 1942, Zwicky was involved in the early stages of rocket research and development in Aerojet Engineering Corporation. Using the morphological box method, the scientist managed to generate a significant number of original solutions in rocket engineering in a short time [17]. He developed and justified several of the first jet engines and received more than 50 patents. In the future, he justified and improved the methods of MA.

Kurziner considers the application of a morphological approach to the systematisation of jet engines. The power of the morphological set leaves 108000 variants [13]. To reduce the set, the author suggests excluding incompatible options. He also notes that the traditional hierarchical method of classification, in contrast to the morphological one, cannot provide all possible variants of engines. Examples of synthesised combined engines are shown in figure 2.

4. Applications of the Morphological Analysis in aerospace conceptual design

The following section outlines the usage of MA in aircraft conceptual design. Three such major applications are known so far: the Advanced Morphological Approach (AMA) by Bardenhagen and Rakov [3], the Technology Identification, Evaluation and Selection (TIES) method Mavris and Kirby [18], as well as the computerised optimisation framework for the MM in aircraft conceptual design by Ölvander et al. [19] (in the following: the Computational Optimisation Framework or COF). Thereby, the focus will lie on the AMA. This is followed by a methodological comparison of the approaches.

4.1. The Advanced Morphological Approach

The Advanced Morphological Approach (AMA) proposed by Bardenhagen and Rakov [3] aims to serve as an aid to the designer of aircraft concepts by suggesting a significantly wider range of potential problem solutions. The method uses MA in the context of structural synthesis, striving to find a limited set of promising solutions for given Top-Level Requirements (TLR). The AMA is based on the classical MA, system and cluster analysis. The focus here lies in involving innovative technologies for future designs, thus handling the lack of statistical data by using qualitative option evaluations. Meanwhile, the AMA not only strives to identify a single optimal aircraft concept for a given mission, but also aims to intuitively explore and analyse the solution space. Additionally, it integrates the creation of the MM and CCM, the considerations of existing aircraft configurations as reference solutions, as well as the clustering of the solution space. The AMA is not limited to applications in Aerospace and could be used for structural synthesis in many other domains [3].

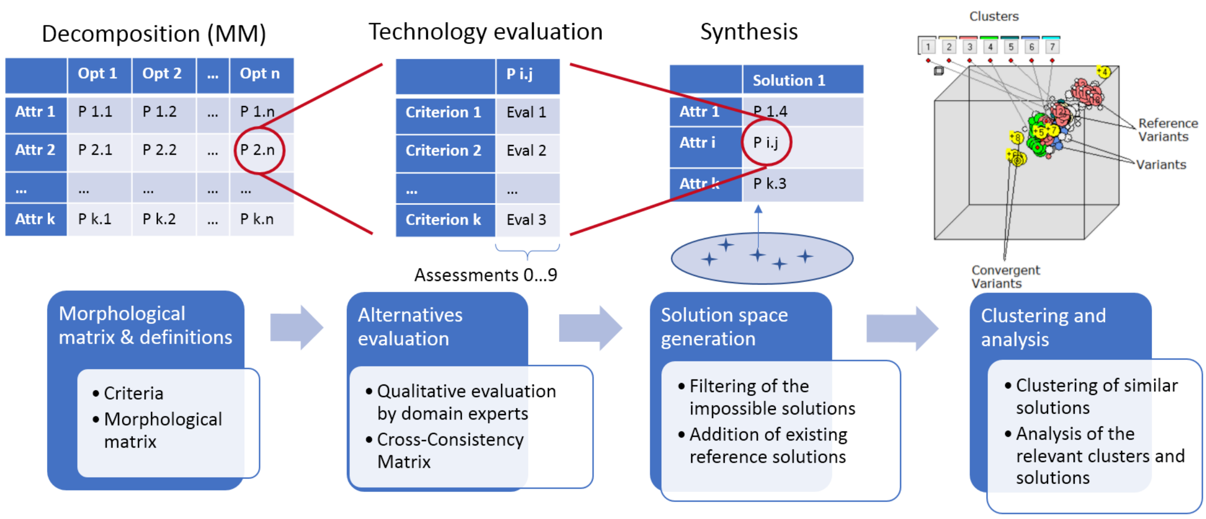

Figure 3. Steps of the Advanced Morphological Approach.

The AMA methodology can be summarised with the following steps (figure 3). 1) **Problem statement definition**: In the case of conceptual aircraft design, the problem statement can be defined through the TLR for a given flight mission. Typically, this includes requirements on flight altitude, range, payload type and mass, and further aspects; 2) **Synthesis of the morphological matrix**, 3) **Definition of a system of criteria**; 4) **Evaluation of the technological options**: All technological options of each attribute are evaluated regarding the criteria defined earlier. The evaluations are made on a qualitative scale from 1 (worst option) to 9 (best option). For prospective technologies with little to no information on their performance, the opinion of a group of experts from the respective domains can be sought; 5) **Selection of reference solutions**: A number of existing solutions (aircraft) which fulfil the TLR are chosen to be used in the further analysis. These are decomposed according to the morphological matrix and are scored based on the evaluations of the technological options they possess; 6) **Generation of the solution space**; 7) **Clustering**: The solution space is clustered into groups of similar aircraft configurations. The process uses distance criteria such as the Hamming distance which equals the number of different technological options in their attributes; 8) **Analysis and selection of solutions**; 9) **Synthesis of anticipation models, parametric modelling and optimisation stage**

Bardenhagen and Rakov [3] demonstrated the AMA on the conceptual design of a stratospheric UAS with a civil mission, required to hold position within an area of 4 km at an altitude between 12 and 20 km.

4.2. Technology Identification, Evaluation and Selection method

The Technology Identification, Evaluation and Selection (TIES) method developed by Mavris and Kirby [18] serves as a "comprehensive, structured and robust methodology for decision-making in the early phases of aircraft design" [18]. As such, it aims to facilitate the impact assessment of different technologies and thus allow for an easier project resource allocation. For this purpose, the authors introduce the Overall Measure of Value (OMV) in terms of technical feasibility and economic viability. The goal of this approach is to evaluate the OMV for a certain configuration and find the optimal mix of technologies to maximise the OMV.

The approach starts by quantifying the OMV for a baseline configuration by mapping qualitative customer or societal requirements in terms of performance- and economic-based requirements (e.g. operating costs, weight, approach speet, etc.). These were defined as percentage reductions from present day predictions towards a more efficient aircraft instead of absolute values. The next step involves the sizing and economic analysis of the baseline with an external software. If the resulting reductions do not fulfil the required percentages, a MM is used to generate new aircraft configurations. The method also uses CCA, a Technology Impact Matrix, Pugh Matrix and the TOPSIS method to evaluate and rank the technological options.

4.3. A computerised optimisation framework for the morphological matrix in aircraft conceptual design

In [19] Ölvander et al. present "a formal mathematical framework for the use of the morphological matrix in a computerised conceptual design framework" [19] and demonstrate it on use cases in aircraft conceptual design. The uniqueness of this method is the application of a quantified MM in order to provide as much deterministic data about a solution alternative in the early conceptual design stage as possible. In this case, the alternative technological options of the attributes or sub-systems are represented by mathematical models or functions aiming to determine their approximated characteristics such as weight, cost or power consumption. According to [19], "every potential sub-solution is described either with physical or statistical equations, or a combination of these".

Option incompatibilities or other combinational constraints are also mathematically modelled. The MM is used as a special model feature which aims to increase the automation of the conceptual design phase. The authors note that the objective function of the optimisation problem can vary depending on the goal and usually represents a non-linear programming problem difficult to be solved. The presented use cases use binary and integer representations to solve the problems. The discussed work [19] demonstrates the functionality of the framework on two use case scenarios: the conceptual design of an Unmanned Aerial Vehicle with More Electric Aircraft technologies and the design of an aircraft fuel system.

4.4. Comparison of the available Morphological Analysis applications in aircraft conceptual design

Although not particularly numerous to date, the available applications of the morphological analysis in aircraft conceptual design exhibit differences. At this point, a comparison among the previously introduced methods is conducted in order to identify common structures. According to the categorisation scheme of Kohn and Hussig [5], one could classify the methods into the idea management categories. The integration of MMs automatically places all methods into its idea generation sub-category. The idea collection aspect is represented only partially in AMA and COF. While the AMA additionally collects ideas as existing reference aircraft concept solutions, the COF uses given quantitative information about technological options as elements of the MM. Idea classification implies the clustering of the ideas into groups of similar solutions, which is done in a direct way only by the AMA. Finally, all three approaches evaluate the generated solutions according to the defined criteria - either in a qualitative or quantitative way.

A comparison of the mentioned MA integration methods is shown in figure 4. Apart from

	AMA	TIES	COF
Benefit	Detailed designer aid with visualisations	Impact assessment of technologies	Quantitative subsystem design
Demonstrated system level of application	Aircraft concept (system level)	Aircraft concept (system level)	Component concept (subsystem level)
Time of technology deployment	← Further future	Near future	Present time
Data availability	None		Detailed →
Data sources	Expert judgements	Literature, statistics	Vendors, Catalogues, etc. →
Data type	Qualitative		Quantitative →
Design starting point	Blank sheet	Baseline reference concept	Blank sheet
Solution space exploration	Clustering	Quantitative comparison of alternative metrics	none

Figure 4. A comparison of the AMA, TIES and COF methods.

the common aim to identify an optimal product configuration, the methods are beneficial to the designer in different ways. The TIES method and COF are dedicated to more specialised purposes such as the impact assessment of technologies to prioritise their development, as well as the quantitative design of sub-systems. In the same time, the AMA was presented as a more general tool for structural synthesis by offering better decision-making support through visualisations and further aid. The AMA and TIES have been demonstrated on system level problems such as the conceptual design of aircraft configurations, while the COF was applied rather in sub-system design (e.g. actuation, fuel and electric power systems).

Worth noting is also the relationship between the innovation level of the technological options from the MM and the data used to evaluate these. The integration of existing technologies allows the use of available exact data directly from component documentation, which was done within the COF. In contrast, the AMA and the TIES method are oriented rather towards perspective future technologies integrated in designs to be deployed in the further future. The lack of information on such systems implies the increased use of qualitative data obtained from domain experts, statistical and probabilistic approximations. The approaches can also be distinguished by their design starting point - whether the process starts from a blank sheet or the evaluations are referred to a preliminary defined baseline configuration.

5. Benefits and improvement possibilities for the application of the Morphological Analysis in aircraft conceptual design

The conducted analysis of the AMA, the TIES method and the COF allows to outline the benefits from using the MA in aircraft conceptual design. These are the significant expansion of the solution space available to the designer, the increased objectivity of the decision-making process, the improved deployment of the multidisciplinary knowledge in the design process, as well as an structuring and enhanced robustness when handling unknown data for innovative concepts.

In the context of the presented applications, the AMA positions itself as a design aid tool aiming to cover all subcategories of the idea management classification. The approach focuses on the conceptual design of future concepts involving innovative technologies. The lack of statistical data on these implies the use of qualitative data, which should be acquired from domain experts. Another accent of the method lies in the thorough exploration of the solution space by offering the designer an overview of promising problem solutions. In order to achieve these targets, it is necessary to further increase the robustness of the methodology and address a list of challenges. In the following, the main objectives of the next AMA development phase are identified along with suggestions to tackle these.

- **Improved problem structuring** - Complex problems need a well-structured system decomposition and interpretable evaluations of their sub-elements, as well as criteria weighting. Such approach would require the integration of hierarchical Multi-Attribute Decision-Making methods such as the Analytic Hierarchy Process.
- **Multidisciplinary expert judgement elicitation** - According to Cooke [20], the scientific conduction of expert judgement elicitations should be structured and comply with the principles of Scrutability/Accountability (reproducibility of results), Empirical Control, Neutrality (true expert opinions) and Fairness (no prejudgement of the experts) [21]. In this context, it is necessary to define an appropriate Structured Expert Judgement (SEJ) process adapted to aerospace design with the use of MA.
- **Handling uncertainties** - The uncertainties should be accounted for during the technology evaluation by the experts, the following judgement aggregation and the solution clustering. Considering the qualitative nature of the evaluations, the probabilistic assessments appear less appropriate due to lack of deterministic values. A possible way to tackle uncertainties would be to use fuzzy numbers and fuzzy logic, thus reducing the information loss throughout the process.

6. Conclusion

The MA is able to help fill the gap of lacking tools for idea generation in aircraft conceptual design and further domains. Particularly, the MM can contribute to the structured expansion of the problem solution space, which is limited for the designer and still suboptimal to address the requirements for new aircraft generations. Its extension, the Advanced Morphological Approach, aims to cover the whole spectrum of idea management, namely by offering the designer solution evaluation, classification and visualisation. However, the conducted comparison of the three MA applications in aircraft conceptual design shows limited standardisation and robustness of the methods in regard to innovative technologies and scarce amount of data. In this context, the AMA shows a significant potential to increase the objectivity of the decision-making in early conceptual design by improving the integration of multidisciplinary knowledge as well as by offering structuring and modelling of uncertain data for new technologies. This could be achieved by developing a methodology for Structured Expert Judgement elicitations specifically for the use in product (aircraft) conceptual design with MA.

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