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STRUCTURAL ANALYSIS AND SYNTHESIS FOR CONCEPTUAL DESIGN IN AEROSPACE

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Abstract. This proposed project presents a structural synthesis approach in conceptual design. One of the key stages in design process is the conceptual design phase. Conceptual design is considered to be the most difficult phase of engineering design, with success dependent to a great extent on the expertise of the designer. The structural synthesis is a powerful means of research in conceptual design. The offered procedure of the synthesis engineering solution (ES) is a development of the morphological methods.
The approach allows:
- Generate effectively the morphological array and by means of a measure of similarity to carry out the clusterization and to choose the best alternatives.
- Organize a search for promising ES.
- Solve the problem of reduction the dimensionality of morphological sets of variants by their clustering and therefore to reduce the labor input at search for the new technical solutions.

1. INTRODUCTION - CONCEPTUAL ENGINEERING DESIGN

This proposed project presents a structural synthesis approach in conceptual design. One of the key stages in design process is the conceptual design phase. Conceptual design is considered to be the most difficult phase of engineering design, with success dependent to a great extent on the expertise of the designer. Automation of some aspects of this phase would be of immense practical benefit [1].
During this phase, the designer must devise an initial design that incorporates ‘‘working principles’’ or physical solutions to all the ‘‘essential’’ features of the problem, and which has been evaluated to be acceptable and feasible [2]. This 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’’ [3].
Conceptual design is a fundamental and indispensable forerunner to further detailed design. Not only is it well known that the design concept is the overwhelming factor influencing the product life-cycle cost and level of innovation; but an excellent detailed design based upon a poor and inappropriate concept can never compensate for the inadequacy of that concept. This is echoed by Miles and Moore [18]: 'Usually, in comparison to the overall costs of a scheme, the design costs are a relatively small part; and yet they have a fundamental bearing on the overall cost, durability, serviceability and utility of the product. To put it simply, a poor design results in a poor product . . . '
Conceptual design is an early phase in the design process, which involves the generation of solution concepts to satisfy the functional requirements of a design problem. There can be more than one solution to a problem; this means that there is scope for producing improved designs if one could explore a solution space larger than is possible at present [4].
As shown in Fig. 1, design uncertainty is largest for entirely original designs and decreases during design [5].

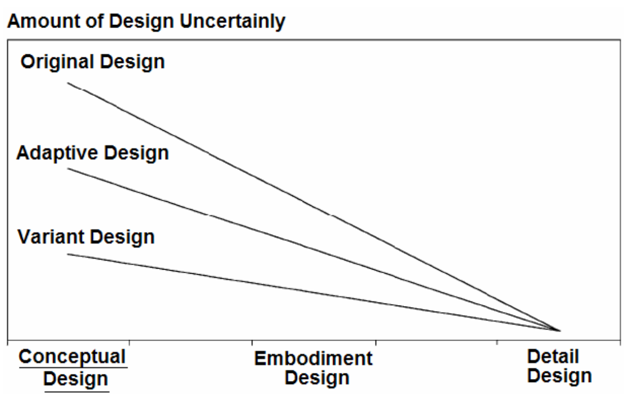

Figure1: Decreasing design uncertainty through product design process

The project costs are minimal on a conceptual design stage, but importance of accepted solutions is maximal. Therefore the conceptual design is the basic phase of designing process (Fig.2).

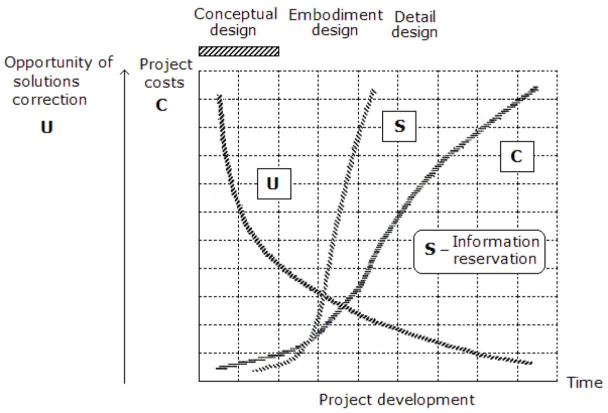

Figure 2: Dependence of cost, information and solutions correction at various project stages

2. IMPORTANCE OF STRUCTURAL SYNTHESIS

For creation of competitive products in Aerospace it is typically necessary to synthesize from 50 up to 150 new engineering solutions [6]. In [7] 3 levels of optimization are examined at creation of new engineering solutions (ES). First level is understood as a choice of managing technical idea or a principle of the projected system function. Second level of optimization is search of alternatives to the optimized structure and third level - definition of the best values of characteristics for the chosen structure.

Performance characteristics of projected systems at the third level of optimization can be improved on the average of 10-15% (Fig. 3). At level 1 and 2 characteristics are improved on the average of 30-35 %, and sometimes more. The higher the level of optimization, the more is the effect of optimization. In engineering practice there is usually no way allowing the choice of an optimum engineering solution based on conditions of the technical project at once.

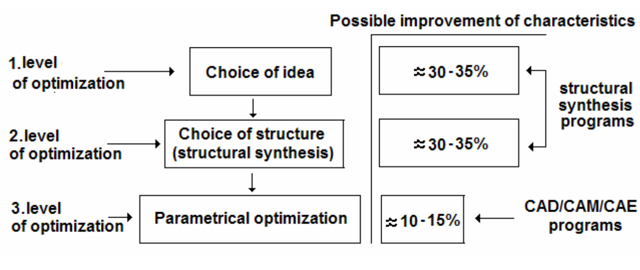

Figure 3: 3 levels of ESs-optimization

It is possible to divide the conceptual design process (Fig. 4) into 2 stages [8]. After statement of problem at 1st stage rational composition and the structure of system (qualitative characteristics) are chosen, and at 2nd stage parametrical optimization with the fixed composition and structure (quantitative characteristics) is carried out. Problems of parametrical optimization are given in to formalization and are well investigated.

At the same time problems encountered in 1st stage are difficult to formalize, and for their solution there is only a small group of methods. The problem is that a mistake in choice of ES can not be further corrected. Therefore it is necessary to analyze, as far as possible, all real variants which number can run up to several thousands. And accordingly, at the acceptance of the basic problem solutions there is a considerable excess of the information volume on potential variants of a choice in comparison with what the designer is able to process operatively [9].

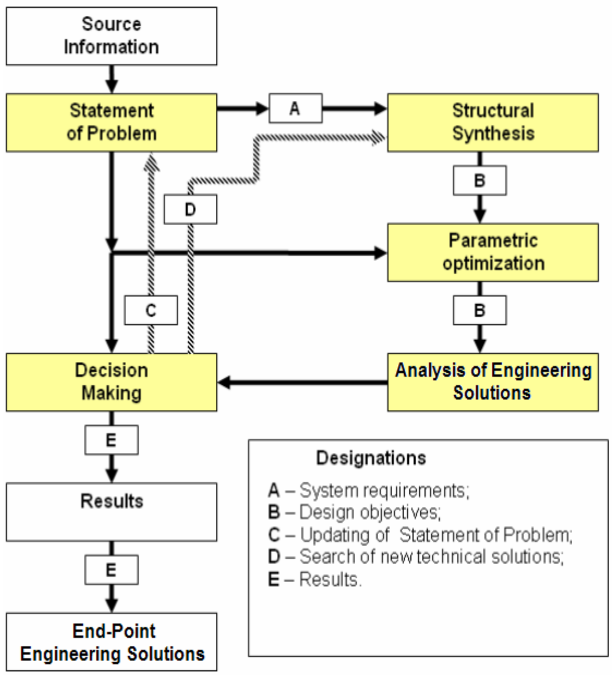

Figure 4: Macro-model of conceptual design process

Subject of search in structural synthesis is achievement of some compromise levels for lines of inconsistent criteria. The sequence of computing operations for finding of an optimum algorithm for the design calculation is displayed by objective function. This function does not correspond to the basic requirements of theoretical methods of optimization (including genetic algorithms).

The objective function is discontinuous, exists in operator notation, it is not based on analytic forms, is not differentiable, not unimodal, not separable and also not additive. It is impossible to model analytically a hyper surface of objective functions and to predict their change on an increment of variables. Instead of step-by-step promotion in space of attributes area-scanning searches with use of clusters seem to be more efficient.

3. MORPHOLOGICAL AND HEURISTIC APPROACH TO STRUCTURAL SYNTHESIS

For the problems decision of structural synthesis there are two groups of methods - morphological and heuristic. Heuristic approaches yield unstable results and are subjective.
For structural synthesis the morphological method can be effectively used. It consists of construction of the morphological table, filling it by the possible alternative variants and of a choice of the best solution combinations from all clusters.
Morphological analysis (or General Morphological Analysis) is a method developed by Fritz Zwicky for exploring all the possible solutions to a multi-dimensional, non-quantified problem complex [10, 11, 12]. 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 U.S.A and Europe in the field of future studies, engineering system analysis and strategy modeling [Odrin, 1998; Coyle et al., 1994; Rhyne 1995; Levin, 1997,2007; Ritchey 1997, 2003, 2006; Stenström & Ritchey 1999; Akimov, 2005].
The basic problem of morphological methods is the so-called "damnation of dimension", which means, that rapid generation of an enormous set of variants is relatively simple, but the selection of the best variants is very difficult. [13].
The disadvantages of morphological methods are

- the labor-intensive selection of a choice from set of variants and
- the impossibility of search and analysis of all possible variants.

In order to reduce the morphological array, efficient methods for the structural synthesis have been developed [13].

4. THE METHODOLOGY FOR STRUCTURAL SYNTHESIS OF ENGINEERING SYSTEMS

The methodology is developed for elimination of imperfection - structural synthesis of engineering systems (SSES). The methodology is grounded on:

- classification theory,
- system and cluster analysis,
- morphological analysis,
- combinatorial logic,
- theories of designing of complex systems and
- optimization theory.

The list of SSES stages is as follows:
(1) Specification of requirements of a designed system;
(2) Creation of the morphological table;
The group of the basic characteristics is singled out in the object. Depending on a kind of a problem the essential characteristics {P}, i.e. able to affect the problem solution, are chosen from the array of characteristics {Pp}.

$$\{P\} <= \{Pp\}$$

The choice is the informal moment. For example, the array of characteristics {P} can be revealed from the formulas of inventions. For each characteristic the elements are chosen, i.e. the possible variants of its execution or realization. Arranging them among themselves, it is possible to get the array of various solutions (variants).
The total number of variants equals:

$$N = A1 * A2 *...* Ai *... * An,$$

Where Ai (i=1, n) - the number of values of 1,2... n the appropriate characteristic elements. The morphological table (Fig. 5) contains 100800 potential variants.
(3) Composition of additional matrices (criteria, basic variants, existing systems, etc.);
The basic complexities on the way of choosing the solution are determined by two circumstances: complexity of formalization of a problem and the great amount of various requirements, criteria and restrictions. The criterion is a similarity of the purpose, its approximation, model. At the transition from the purposes to criteria, the last are considered as quantitative models of the qualitative purposes. The definition of the criterion value for the given alternative is, in essence, the indirect identification of its appropriateness as a means for the purpose achievement.
Henceforth each element of the morphological table is compared with the appropriate value of the criterion on which the estimation will be made. The

weighting coefficients are given to criteria depending on the purpose [7].

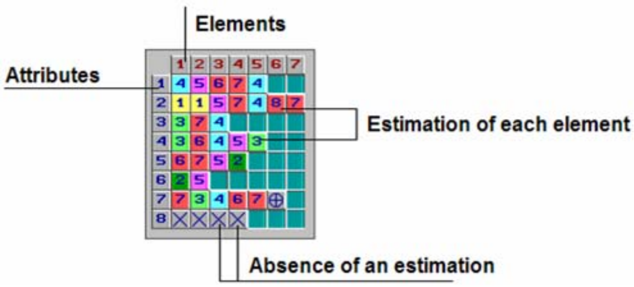

Figure 5: Morphological table

(4) Generation of ESs;
At the next stage the generation of variants, their estimation, initial selection are carried out and some array of rational variants {R} for the subsequent analysis is formed. Each new generated variant is compared with the previous one from the array {R}. If it is at the higher level it is registered in the array {R}, if at the worse level it is rejected.
(5) Cluster analysis;
Henceforth the clusterization of the variants using the entered measure of similarity is carried out. The process of clusterization is considered as the search of a "natural" grouping of objects. The designer can choose the necessary degree of decomposition the initial array to clusters. The area of research is narrowed to several clusters (Fig. 6) which are further investigated.

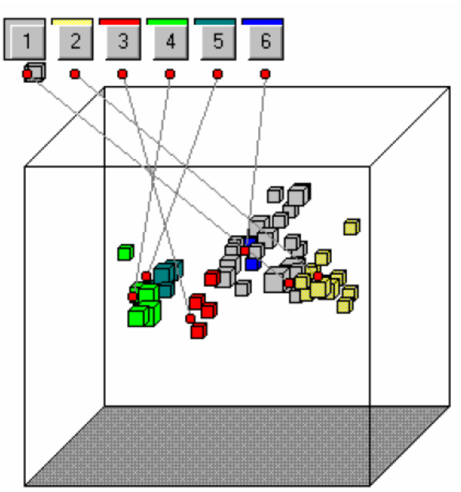

Figure 6: Grouping the variants in clusters

(6) Analysis and choice of the optimum solution;
Comparing variants, the best solutions which success is the most probable are being defined. The degree of the found alternatives novelty (Fig.7) is introduced.

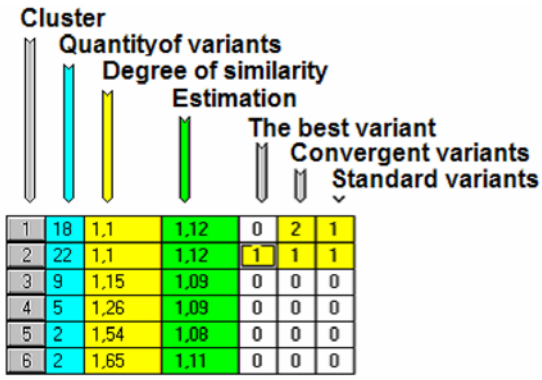

Figure 7: The analysis of clusters and variants

(7) Parametrical optimization.
After choosing some number of variants the parametrical optimization and the final choice are made.

Note that the following applications of SSES are published: [13,14,15]. Various technical systems covering aerospace, power, new physical effects [16], ecological and medical areas were investigated by means of that method (Fig.8). Exemplary, brief results of two engineering solutions are presented: Advanced reentry vehicles and high-altitude stratospheric platforms.

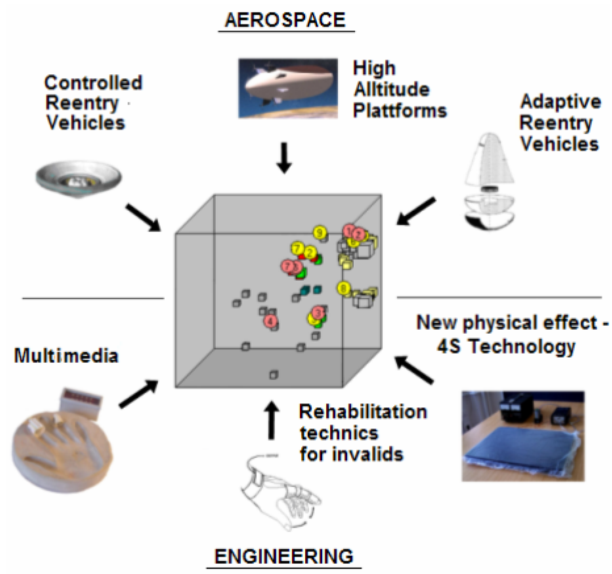

Figure 8: SSES-methodology scopes use

All the reentry vehicles variants are analyzed according to the degree of similarity. According to the procedures results the set of pre-optimal clusters (variants) is formed (Fig.9). The best variants are included into the final table. At the end the process involves a design of structural ESs schemes («white boxes»). They consist of element models and structural models. The procedure was used to solve the problem of search for the new construction and arranging schemes of the reentry vehicles. The modification of the focal object method and inverse approach were used to form the initial set of elements. The number of variants is 451584 [17].

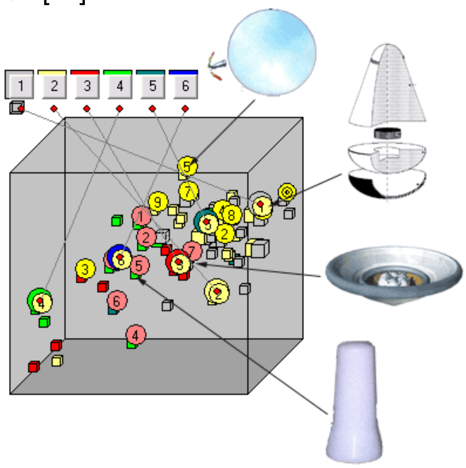

Figure 9: Morphological field of the advanced reentry vehicles (2004)

By means of the method also an analysis and synthesis of long endurance **stratospheric platforms** has been conducted. The total number of possible alternatives equaled to 5180, and for the analysis 123 variants located in 7 clusters (Fig 10) were chosen. As a result some perspective systems, among which was the universal one [18, 19, 20] were synthesized.

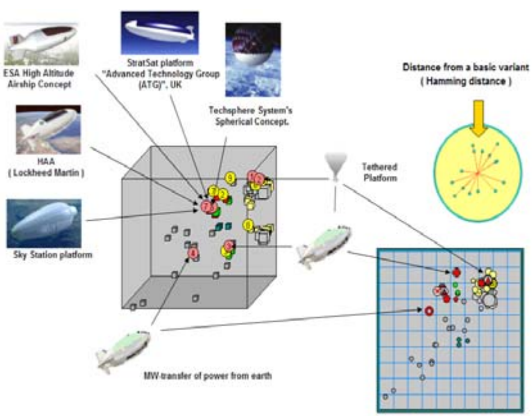

Figure 10: Morphological field of the high altitudes Platforms (2007)

5. CONCLUSIONS

The structural synthesis is a powerful means of research in various fields of knowledge. The offered procedure of the synthesis ES is a development of the morphological methods.

The approach allows:

- Generate effectively the morphological array and by means of a measure of similarity to carry out the clusterization and to choose the best alternatives.
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References

1. S. Potter, S.J. Culley, M.J. Darlington, P. K. Chawdhry: Automatic conceptual design using experience-derived heuristics. Research in Engineering Design. Volume 14, Number 3. Springer, London. 2003. P.131-144.
2. G. Pahl, W. Beitz: Engineering design – a systematic approach. Springer, Berlin Heidelberg New York, 2nd edn. 1996.
3. M. French: Conceptual design for engineers. Springer, Berlin Heidelberg New York, 2nd edn. 1985.
4. Chakrabarti and T. P. Bligh: An Approach to Functional Synthesis of Solutions in Mechanical Conceptual Design. Part I: Introduction and Knowledge Representation Engineering Design Centre. UK Research in Engineering Design. Department of Engineering, University of Cambridge. P. 127-141. 1994.
5. P. Fitch, J. S. Cooper: Life-cycle modeling for adaptive and variant design. Part 1: Methodology Research in Engineering Design. P. 216–228. 2005.
6. Golubev, A. Samarin: Aircraft design. Moscow, Machinistroenie, 1991.
7. A. Polovinkin: Algorithms of design solutions optimization – Energy. Moscow. 1976.
8. D. Rakov: Direct and return tasks of structural synthesis by new technical decisions search. Information technologies in designing and development. N2. P. 42-49. 2007.
9. S. V. Akimov: Introduction in morphological methods of research and modeling of knowledge of a subject domain. VNIIPI. 2003.

10. F. Zwicky: Discovery, Invention, Research through the Morphological Approach. McMillan. New York. 1969.
11. M. Sh. Levin: Towards Combinatorial Analysis, Adaptation, and Planning of Human-Computer Systems. Applied Intelligence, 16(3), P. 235-247, 2002.
12. M.Sh. Levin: Composite Systems Decisions. Springer, London. 2006.
13. D. Rakov: Morphological Synthesis Method of the Search for Promising Technical Systems. IEEE Aerospace and Electronic Systems magazine, N12, P. 3-8. Seattle, 1996.
14. D. Rakov: Structural Synthesis und Analysis for innovative engineering systems. 29. International symposium IGIP-2000 „Unique and Excellent“, Leuchtturm-Verlag, HTA Biel-Bienne, Switzerland. P. 388 - 395. 2000.
15. D. Rakov: Super Light Reentry Vehicles. Space Technology Oxford. Special Issue on “Advanced Reentry Vehicles”. ST2428, Volume 24. Part 4. P.237-243. 2005.
16. D. Rakov, J. Thorbeck: High Sound Proofing Ability of Porous Materials under Stress Using 4S Technology. First CEAS European Air and Space Conference "Century Perspectives", Paper Nr. CEAS-2007-469, Berlin, S. 849 - 852. September 2007.
17. D. Rakov: Super Light Reentry Vehicles. Space Technology Oxford. Special Issue on “Advanced Reentry Vehicles”. ST2428, Volume 24, Part 4. P.237-243. 2005.
18. D. Rakov: Die stratosphärischen Luftschiffe. DGLR-Kongress, Band 1. DGLR-2004-150. Dresden. S. 691 - 695. 2004.
19. D. Rakov, J. Thorbeck, F. Böhm: Vergleich von verschiedenen Konzepten für aerostatische stratosphärischen Plattformen. DGLR-Kongress, Stuttgart. S. 1217 -1224. 2002.
20. D. Rakov, J. Thorbeck: High Altitude Platforms. DGLR Workshop X, Luftfahrzeuge leichter als Luft, - Leichtbau im Rahmen der leichter-als-Luft-Technologie. TU München. Juni 2007.