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Complex engineering systems: rational choice of evolutionary projects

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Abstract

This article is devoted to several actual problems of complex engineering system design and development. The main subject is how to choose most rational project for system future evolution from various proposed one. Fuzzy forecasting approach seems to be mostly fruitful solution to overcome these problems. A new technique for realizing this approach via fuzzy shaping of system's acceptability domain is considered. As example several useful yield results of the approach practical implementation achieved by choosing the best improving project for the real complex engineering system are established. Some perspective directions for future project development exploration based on fuzzy forecasting approach are briefly discussed.

Keywords: acceptability domain; borderline drifting simulation; decision making; design technical requirements; fuzzy forecasting technique; performance quality measures; rational development project; survivability reserves; system life cycle.

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Introduction

One of the fundamental and most complicated problem has to be solved by contemporary engineering is to design, to construct and to develop various type of complex engineering systems (CES) as reliable and survivable as it possible [1-3]. On this understanding CES's evolutionary projects may be either progressive (evolvable) or negative and regressive (degradable) during whole system's exploitation process. In the light of these facts various CES's design problems connected with well-founded choosing of most rational project for complex system evolution and future development ways from various proposed are very actual, important and perspective.

Nowadays, as one of the most important system design and development task may be considered a very difficult problem of the complex system survivability assurance during a long exploitation process. Functional survivability assurance of CES (performability) is an essential, complicated and very troublesome part of the general problem [4]. Originally, CES's performability is usually determined by threshold values of performance quality measures destined to evaluate how successfully our system will carry out all prescribed functions during its life cycle. But CES's successive realization of all initially specified design tasks and functions indicates that all primary system mission goals will be eventually achieved.

From most important performability working measures and characteristics specified CES exploitation process, first of all it ought to be remarked the next ones:

- key performance factors (KPF) of CES;
- quality of service (QoS) for functions execution processes;
- several technical, economic and ergonomic specifications.

Evidently most of these appreciable CES's metrics have quantitative nature. Hence, there is an urgent necessity to develop some innovative approach to KPF forecasting and appraisement based on multifunctional complex aggregated criteria for quantitative as well as for qualitative estimation and investigation of system's key functional characteristics. Practical implementation of such aggregative approach will allow CES's designers effectively and adequately analyze situations with various system conditions during whole system's life cycle (SLC). To realize such approach to CES's design and development process first of all it's necessary to determine what basic criteria have to be employed in the system acceptability evaluation.

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I. METHODS

A. *Performability domain of evolvable/degradable CES*

Let's firstly formulate and refine some definitions about acceptability domain of CES. Let we have CES which must works under some conditions and restrictions in the all course of time SLC. System design targets of the CES are traditionally formulated as Performance quantity/quality measures (PQ^2M) which have to meet various technical requirements. As usual these PQ^2M are originally postulated in the form of basic design options in CES's Design Technical Brief (DTB).

Previously in [5] for estimation of CES performability it was proposed to use only quantitative KPF measures, based on design technical requirements (DTR), specified in DTB for main design characteristics of CES to be developed. In accordance with these requirements performance quality of CES is defined by set of the system's destination indices (SDI) $\boldsymbol{Q} = \{q_1 \dots q_L\}$, which must be stayed on preliminary technical limitations predetermined by experts. Usually such specifications are represented in CES's DTB as general DTR in the form of design constraints (DC) such as:

$$q_j \geq q_j^{TT} \quad \text{and/or} \quad q_j \leq q_j^{TT}, \quad j = \overline{1, L} \quad . \qquad (1)$$

Here the set of system desirable technical characteristics $q_j^{TT}, \quad j = \overline{1, L}$ represents originally formulated by designers quantitative boundary properties and borderlines of performance conditions for L quantitative KPF only.

To explore system survivability and appreciate degradable level of CES it was proposed to use normalized metrics (performability reserves) $z_j(\boldsymbol{X}), \; j = \overline{1, L}$ in following form

$$z_j(\boldsymbol{X}) = a_j \frac{q_j(\boldsymbol{X}) - q_j^{TT}}{q_j^{TT}}, \quad j = \overline{1, l} \qquad (2)$$

for DC in the form $q_j \geq q_j^{TT}$ and/or

$$z_j(\boldsymbol{X}) = a_j \frac{q_j^{TT} - q_j(\boldsymbol{X})}{q_j^{TT}}, \quad j = \overline{l+1, L} \qquad (3)$$

for DC in the form $q_j \leq q_j^{TT}$,

where a_j – some weighted coefficients, which describe significance degree of j-th KPF in aggregate estimation of the system operational capability; $\boldsymbol{X}$ – vector of the system's internal parameters, directly influencing on KPF value.

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Thus, quantitative estimation of CES performability and working efficiency may be executed on the base of metrics, characterized system progressive evolution or degradation on certain period of its life cycle. Recently in [6] it was proposed to define as criterion that our system will operate just within performability domain (System Performability Area - SPA) fulfillment to the next condition:

$$\min_{j} \quad z_j(\boldsymbol{X}) \geq 0, \quad j = \overline{1, L} \quad . \qquad (4)$$

Unfortunately, in attempts to solve problem (4) for real complex IT-systems we have been faced with many hardly overcoming problems not only connected with awful volume of computational tasks, but with existence in PQ^2M not only quantitative but qualitative specifications, which are very essential and not having yet any numerical measurements.

B. Qualitative evaluation of CES development level

Solving of this problem it is reasonable to realize on the base of analyses alternative projects of CES evolution ways via fuzzy forecasting. This approach seems to be very fruitful for prediction of configuration shape for CES's acceptability domain with primarily shaping of corresponding fuzzy visual images of SPA. But first of all we are interested in shaping and investigation of System Acceptability Domain (SAD), which represents an enclosed region in a space of system parameters (named acceptability reserves). Within the borderlines of this region all design specifications, restrictions, conditions and requirements either quantitative or qualitative ones are successfully satisfied. And moreover, all prescribed system functions and performance quantity/quality measures are in feasible ranges and may be realized in practice.

To implement this approach really and to organize rational exploration of SPA's configuration it seems to be reasonable and fruitful to apply a modified fuzzy forecasting approach to CES's evolution process investigation [7-9]. It is based on multifunctional aggregate criteria for CES's level of development estimation, which includes all partial criteria for system level of development estimation. This vector comprises several metrics for evaluation system stability and in fact level of development in physical and intellectual sense. Earlier proposed multidimensional aggregate vector for CES's level of development estimation was defined as [10]:

$$\mathbf{HVC} = \{\mathbf{PDC}, \mathbf{IDC}\},$$

where $\mathbf{PDC} = \{PDI, SPD\}$, $\mathbf{IDC} = \{IDI, SID\}$ - aggregate vector criteria for physical and intelligence development.

Basic elements (components) of these aggregate vector criteria are:

- *PDI*, *IDI*- indexes of physical and intelligence development respectively;
- *SPD*, *SID*- stability coefficients of physical and intelligence development.

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The creation of two variants of pairwise comparison matrix is carried out for states S_0 (initial) and S_{rat} (final) on partial criteria groups (PCG) for local priorities calculations, which are necessary for system indexes of development computation. On the base of these local priorities we may define minimum and maximum values for development indexes as follows:

$$PDI_{\min} = 1{,}25(GPP_{\min}(S_{rat}) - GPP_{\min}(S_0)) \text{ ,}$$

$$PDI_{\max} = 1{,}25(GPP_{\max}(S_{rat}) - GPP_{\max}(S_0)) \text{ ,}$$

$$IDI_{\min} = 1{,}25(GPI_{\min}(S_{rat}) - GPI_{\min}(S_0)) \text{ ,}$$

$$IDI_{\max} = 1{,}25(GPI_{\max}(S_{rat}) - GPI_{\max}(S_0)) \text{ ,}$$

$GPP_{\min}(S_{rat}), GPP_{\min}(S_0)$, $GPP_{\max}(S_{rat}), GPP_{\max}(S_0)$ - are minimum and maximum values of global priorities of system states S_0 and S_{rat} in physical criteria's group respectively;

$GPI_{\min}(S_{rat}), GPI_{\min}(S_0)$, $GPI_{\max}(S_{rat}), GPI_{\max}(S_0)$ - are minimum and maximum values for global priorities of system states S_0, S_{rat} in intelligence criteria's group respectively.

Formulas for CES local and global priorities evaluation applied to partial criteria groups of physical and intelligence levels of development were previously established in [9].

C. *CES's development trend fuzzy identification*

After ranging of alternatives and intermediate decision obtaining it will be necessary to determine basic development process trend of CES. It is reasonable to realize such process via fuzzy classification by specifying values of membership function to main development type of certain trend directions: progressive, regressive, intellectual, physical or neutral. First of all it is necessary to define dominated type of these trends: physical or intellectual. It may be done in accordance with some special expert evaluation approach which was previously established in [11]. It should be noted that as provided by this technique required trend forecasting has to be based on mutual expert decision as convolution of fuzzy estimation values obtained from individual expert judgments for PCG [11-13].

D. *Economic factors in CES development projects choise*

Let's discuss the problem of CES project choosing from economic point of view [14]. Let we have N alternative projects as development ways for CES. Let each project from initial set $A = \{A_i \text{ , } i \in \{1,2,\ldots,N\}\}$ meets all resource limitations.

Each project $A_i \in A$ is defined by cortege

$$(k_i, \triangle c_i, \; t_i^{(p)}) \text{ ,}$$

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where k_i - project realization financial expenditure required; Δc_i - exploitation expenditure after project implementation; $t_i^{(p)}$ - temporal resources (project duration cycle).

Let define CES exploitation stage duration as $t_i^{(e)}$, whole SLC duration as T_0. Then total expenditure for project $A_i, i \in A$ realization will be

$$C_{T_0}(A_i) = k_i + \Delta c_i t_i^{(e)} = k_i + \Delta c_i (T_0 - t_i^{(p)}) .$$

It's necessary to find most preferable project $A_{rat} \in A$ from point of view of minimizing total expenditure during life cycle period T_0. Mathematically we have next problem:

$$A_{rat} = \mathbf{arg}\left\{\mathbf{min}\, C_{T_0}(A_i), i = \overline{1, N}, B(A_i) \in B(S_{rat})\right\} ,$$

where $B(A_i)$ - position in multicriteria space, matching S_i, as a system final state after project A_i realization.

II. Results

A. *Main stages of the Technique*

Let's consider several essential features of the innovative technique for SAD shaping and exploration. Main stages of proposed technique based on fuzzy analysis may be presented as follows.

1. Specification of partial criteria vector (PCV) groups to estimate physical and intelligence levels of CES development.
2. The choice of estimation scale intensity for several criteria properties of analyzed CES's states after implementation of respective development projects.
3. Specification of importance coefficients (weights) for respective PCV.
4. Obtaining of PCV for CES current state S_0 and its transformation to normalized values with applying of generalized Harrington desirability function (HDF).
5. Obtaining of interval estimates PCV to define rational state of CES S_{rat} and its transforming to normalized values via using generalized HDF.
6. Obtaining of dual-variant pairwise comparison matrix (PCM) for system states S_0 and S_{rat} on PVG by calculation of its elements as a ratio of respective estimates normalized values, using herewith minimum and maximum values of interval's estimations for state S_{rat}.

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7. An estimation of CES's development level and shaping of" acceptability domain" in the space of indexes of physical and intelligence development, defined by minimum and maximum values of respective development indexes.
8. Calculations of estimates on PCV for alternatives and their transforming to normalized values by using of HDF.
9. Calculation of PCM for state s_0 and system conditions after realization alternative development projects for CES $S_i, \overline{i=1,N},$ by calculations of its elements as a ratio of respective normalized values in PCV.
10. Evaluation of development levels for alternatives CES's projects and definition of it positions in the space of indexes of physical and intelligence development.
11. An investigation of the acceptability domain configuration via presence within it some points of alternative variants mapping. If such points exist we organize the set of perspective ones by choosing most respective decisions and go to stage 12, otherwise – to stage 13.
12. Ranking of perspective alternatives in order of increasing total expenditure and choosing of most preferable one.
13. Informal general qualitative analysis of alternative CES development ways by expert judgment method, optionally system targets refinement and ultimate decision making.

Obtaining values of criteria's properties in qualitative partial criteria of physical and intelligence development for analyzed states of CES designation is performed in ninth gradation primary scale. Transforming primary values on quantitative and qualitative partial criteria to normalized values of secondary scale is carried out by using the proposed technique, which is based on Harrington scale and generalized HDF implementation [11, 14].

III. DISCUSSION

A. *CES's Evolutionary Trend Fuzzy Identificaton*

How we can practically exploit the technique described in previous section? Firstly, it's necessary to define the qualitative trend of system's future development. Such trend may be either positive and progressive (evolvable) or negative and regressive (degradable). Such qualitative forecasting is based on expert estimation technique.

Obtainment of PVG-estimates to determine rational state of CES after future development stage S_{rat} is carried out by expert judgment method. Thus, as a results we have fuzzy estimates for criteria properties, described by membership functions: $\mu_{\tilde{y}}(y_i)=1, \quad y_i \in Y_{\tilde{y}}$, where $Y_{\tilde{y}}$ - fuzzy universum media for $\tilde{y}$.

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Appraisal of correspondence of alternative variants of CES development with predicted rational state S_{rat} is carried out in the space of indexes of physical and intelligence development. Obviously in general case "system goal domain" represents polygone such as

$$B(S_{rat}) = [PDI_{\min}, PDI_{\max}] \times [IDI_{\min}, IDI_{\max}].$$

For normalizing of qualitative variables and functions let's use next estimation for qualitative acceptability reserves

$$z_j = \mathbf{exp}(-\mathbf{exp}(-q_{ij})), \quad i = \overline{1, N}, \quad j = \overline{1, K},$$

where q_{ij} - intermediate estimations, defined via corresponded preliminary values in initial scale y_{ij};

K - criteria total number (qualitative and quantitative).

Conversion from original estimation scale to normalized values is carried out by applying an average and borderline values of numerical intervals in Harrington scale. Then values z_j for quantitative criteria group may be re-specified in correspondence with Table 1.

To calculate qualitative criteria q_{ij} are used next relationships, formulated for those one need to be maximized:

$$q_{ij} = \begin{cases} 0.35\dfrac{(y_{ij} - y_j^*)}{(y_{1j}^* - y_j^*)} - 0.83, & y_{ij} \in [y_j^*, y_{1j}^*] \quad , \\ 0.24\dfrac{(y_{ij} - y_{1j}^*)}{(y_{2j}^* - y_{1j}^*)} - 0.48, & y_{ij} \in (y_{1j}^*, y_{2j}^*], \\ 0.246\dfrac{(y_{ij} - y_{2j}^*)}{(y_{3j}^* - y_{2j}^*)} - 0.24, & y_{ij} \in (y_{2j}^*, y_{3j}^*], \\ 0.37\dfrac{(y_{ij} - y_{3j}^*)}{(y_{4j}^* - y_{3j}^*)} + 0.06, & y_{ij} \in (y_{3j}^*, y_{4j}^*], \\ 0.394\dfrac{(y_{ij} - y_{4j}^*)}{(y_{5j}^* - y_{4j}^*)} + 0.376, & y_{ij} \in (y_{4j}^*, y_{5j}^*], \\ 0.3\dfrac{(y_{ij} - y_{5j}^*)}{(y_{6j}^* - y_{5j}^*)} + 0.77, & y_{ij} \in (y_{5j}^*, y_{6j}^*], \\ 0.43\dfrac{(y_{ij} - y_{6j}^*)}{(y_{7j}^* - y_{61j}^*)} + 1.07, & y_{ij} \in (y_{6j}^*, y_{7j}^*], \\ 0.75\dfrac{(y_{ij} - y_{7j}^*)}{(y_j^{**} - y_{7j}^*)} + 1.5, & y_{ij} \in (y_{7j}^*, y_j^{**}], \end{cases}$$

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where y_j^*, y_j^{**} - subjectively the worst and the best values for *j*-th partial criterion (PC);

$y_{kj}^*, k=\overline{1,7},$ - upper borderlines of intervals values of *j*-th criterion, corresponded to linguistic variable values "very low", "low", "average", "above average", "good", "very good", "high". It should be noted, that to value "very high" corresponds to half-open interval $(y_{7j}, y_j^{**}]$.

Table 1 –Correspondence between values of original estimation scale and their normalized values

Value y_{ij}	1	2	3	4	5	6	7	8	9
Value z_j	0,1	0,2	0,28	0,37	0,5	0,63	0,71	0,8	0,9

It may be reasonable to proceed from quantitative scale to initial verbal scale comprised nine grades and hereinafter to employ relationships for qualitative criteria to calculate values of quantitative measures z_j. Evidently, that by using proposed approach of normalized criteria evaluation all elements in pairwise comparison matrix on PCG will in interval from 1 to 9. An essential difference from applying Saaty scale is that, in our case elements of pairwise comparison matrix may have arbitrary values from aforementioned diapason.

And finally as a general condition that complex system development trend will be progressive and stable let demand:

$$\min_j \quad z_j(\mathbf{X}) \geq 0.25, \quad j=\overline{1,K} \quad . \qquad (5)$$

Evidently for well-controlled system evolutionary process all intermediate states along desirable development trajectory must satisfy these requirements. Thus for complex system with progressive evolutionary trend its configuration of SAD will be expandable.

B. CES's Acceptability Domain Fuzzy Shaping Example

We carried out several experiments to apply the technique proposed to fuzzy shaping of acceptability domain for real complex IT-system. As a result of our investigation attempts some patterns of SAD visual fuzzy images in **Z**-space for real CES are established in Fig.1. Each dimension in multidirectional **Z**-space of SAD corresponds to one of the system acceptability reserves $\mathbf{z}_j$ with normalized value in range from 0 to 1. In general case for many complex systems their SAD shapes are represented as non-convex polygone.

Visual SAD-shape established as image No1 corresponds to worst-case development project and may be considered as an initial variant for rational choosing of evolution way for investigated CES. Although this

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project belongs to stable but nearly negative progressive forecasting trend, it is still quite acceptable for realization, because it completely satisfies to conditions (1-5) and as consequence it SAD fuzzy shape is not empty. So it may be considered as basic feasible solution for the primary problem of system design and development.

Both others alternative projects which seem to be much more preferable and perspective, obviously they are much more expensive. But these projects as we see from their established visual SAD-shapes in a much greater degree are corresponded to system mission requirements, because their acceptability reserves are essentially large. But the decision what project from these two alternatives is more acceptable is a final and essential problem of our research.

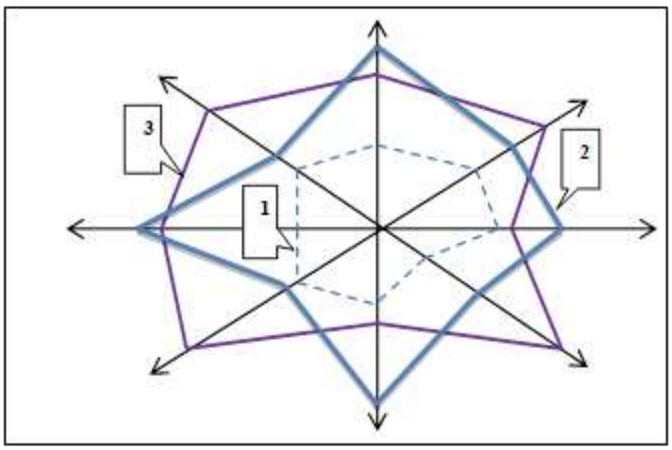

Fig. 1. Examples of a SAD fuzzy shapes in **Z**-space

IV. FINAL REPORT

So in our case an established feasible region (acceptability domain) represents multidimensional polytope in normalized multicriteria **Z**-space of CES. The problem is how to choose most acceptable and satisfactory configuration for this domain from point of view of system ultimate goals in design, creation, exploitation and development. Evidently, that consistence of CES development processes may be determined comparatively by its convergence to predicted desirable trajectory of system development as a most reasonable template. And as a several perspective patterns we should take into account all possible alternatives from perspective **P**-set.

Let all criteria in normalized **Z**-space $z_j,\ j=\overline{1,K}$ of CES are arranged in the order of decreasing of its importance in a clockwise sense beginning from vertical ordinate axis as it is shown on Fig.1. Thus, each non-even-numerical direction in normalized **Z**-space is more preferable than following even-numerical direction. Due to such suggestion in result of SAD-shape configuration analysis we shall come to conclusion that project 2 is much more preferable than project 3. Indeed SAD-shape of project 2 has essential preferences in all non-

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even directions while SAD of project 3 has some preferences only along subsidiary even-numerical axes. Thus project 2 may be considered as ultimate decision for the main original problem of evolutionary project choice.

Otherwise, from economical point of view formal rule for rational choice of CES's development project as an object for practical implementation may be described as follows:

$$A_{rat} = \mathbf{arg}\left\{\mathbf{min}\, C_{T_0}\,\mathbf{(}A_i\mathbf{)}, i = \overline{1, N}, A_i \in P\right\} .$$

Ultimate reasonable decision about development project approval and implementation may be made by CES design authorities or top-crew of decision takers.

V. CONCLUSION

It should be noted that if the set of perspective alternative projects will be empty its necessary to make final decision on the base of SAD visual analysis with regard of decision taker chief personal opinion, but also taking into account various economic factors. Another way is that CES developers must modify original project specifications.

Main issues for further research will be next:

- How expert judgments validity may be strengthened;
- How to improve existing fuzzy shape of SAD after final project choosing by CES primary goals refinement.

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