International Journal on Emerging Technologies **10**(2a): 137-140(2019)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Fuzzy Forecast Approach to Estimation of Complex Engineering System's Acceptability

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(Received 05 May 2019, Revised 16 July 2019 Accepted 25 July 2019)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: In this paper one of the most actual problem of complex engineering system design and development is discussed. The problem is how to explore and to estimate complex systems possibilities to be reliable and survivable during all its future life cycle. Fuzzy forecasting approach based on group-expertise procedure seems to be most convenient solution to overcome this problem. The new technique to realize worst-case analysis of complex system's evolution behavior via fuzzy shaping of its acceptability domain is considered. For detailed investigation of acceptability domain evolution way we use composite aggregative criteria for quantitative as well as for qualitative estimation of complex system's key performance characteristics. As a result of fuzzy forecasting and domain borderline shaping via group-expertise we hope to be entirely convinced that within the system acceptability domain all design specifications, all constructive restrictions and requirements either quantitative or qualitative are successfully satisfied. In conclusion perspective directions for system survivability and acceptability worst-case analysis based on fuzzy forecasting group-expertise procedure are observed.

Keywords: acceptability domain; borderline drift simulation; fuzzy forecasting; group-expertise procedure; performability reserves; performance quality measures; system life cycle; worst-case analysis

I. INTRODUCTION

One of the most important and 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 [1-5]. During system's exploitation process CES's evolution may be either progressive (evolvable) or negative and regressive (degradable). In this way numerous CES's design problems connected with well-founded worst-case analysis of the complex system evolution and future development trends are very actual and extremely interesting.

Nowadays, a system's dependability assurance during an overall exploitation period may be considered as one of the important constituent of CES's worst-case design and development process. Functional survivability assurance of CES (performability) is an essential, indefeasible and troublesome part of the general problem [6-9]. Originally, CES's performability is 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. And CES's successive realization of all initially specified design functions indicates that all primary system mission goals will be eventually achieved.

Many significant CES's metrics have quantitative nature. But some notable performance metrics (NPM) are qualitative. Hence, there is an urgent necessity to develop some innovative approach to NPM forecasting and appraisement based on multifunctional complex aggregative criteria for quantitative as well as for qualitative estimation and investigation of system's substantial characteristics. Practical implementation of this comprehensive approach will allow CES's designers effectively and adequately analyze situations with various system conditions during whole System's Life Cycle (SLC). To realize this idea in CES's design and development process an approach is proposed hereafter which may be employed for the system worst-case acceptability evaluation.

II. METHODS

System's Acceptability Domain: Fuzzy Bounds

A. Performability Domain of Evolvable/Degradable CES

As a rule CES must works under serious conditions and restrictions at the all duration of SLC. System design targets of the CES are traditionally formulated as a set of performance quantity/quality measures (PQ2M) which have to meet various technical requirements. As usual these PQ2M are originally postulated in the form of basic design options in CES's Design Technical Brief (DTB).

In [10,11] for estimation of CES performability it was proposed to use only quantitative NPM measures, based on Design Technical Requirements (DTR), specified in DTB for main design characteristics of CES has to be developed. In accordance with these requirements performance quality of CES is defined by set of the system's destination indices (SDI) Q = {q1… qJ}, which have to be located within correspondent technical bounds predetermined by very skilled design experts. Usually such specifications are represented in CES's DTB as general DTR in the form of design constraints (DC).

Quantitative estimation of CES perform ability and working efficiency may be executed on the base of various metrics, characterized system progressive evolution or degradation on certain period of its life cycle. In [13] it was proposed to define as the global criterion that complex system will operate just within precisely restricted performability domain its fulfillment to the next condition:

$$\min_{j} \quad z_j(X) \geq 0, \ j = \overline{1, J} \qquad (1)$$

where z_j – certain normalized performability quantitative reserve, corresponded to j-th NPM in aggregated estimation of the system operational capability; X – vector of the system's internal parameters, directly influencing on NPM value; and J – quantitative NPM number.

Unfortunately, in attempts to solve problem (1) for real complex IT-systems we faced with many hardly overcoming problems related not only with awful volume of computational tasks, but also with existence in PQ2M not merely quantitative but qualitative specifications, which are very substantial and haven't any numerical measurements.

B. Qualitative Evaluation of CES Characteristics

Solution 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 it. But first of all we are interested in shaping and investigation of System Acceptability Domain (SAD), which represents an enclosed region in a normalized space of system parameters Z(X), defined as 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 SAD's configuration it seems to be reasonable and fruitful to apply a modified fuzzy forecasting approach to CES's evolution process investigation [12-14]. It is based on aggregative criteria for CES's level of development estimation, which includes some partial criteria for system characteristics evaluation. This criteria vector comprises several metrics for assessment of system stability and its level of development in physical and intellectual sense.

C. SAD's Fuzzy Borderline Drift Simulation

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 or neutral. First of all it is necessary to define dominated type of these trends. It may be done in accordance with some individual or group expert's evaluation approach which was previously established in [10]. It should be noted that as provided by proposed technique required trend forecasting is based on mutual group-expertise procedure as convolution of fuzzy estimation values obtained from collective experts judgments [11]. Time series data mining may be also useful in this case. But from the point of view of worst-case analysis first of all we are interested in investigation of the pessimistic trends in SAD's fuzzy borderlines drift during their positions simulation [12].

D. System's Acceptability: Worst-Case Analysis

Hereinafter in our fuzzy forecasting technique, we employ heuristic algorithm for Membership Function (MF) realization and embodiment presented in [16]. In this regard MF for fuzzy variable values, approximately equal to K, is represented by

$$\mu_K(u) = e^{-\alpha(K-u)^2}, u \in U,$$

where U – universum media for u (in general case the set of all real numbers);

α – some predetermined MF fuzzy parameter.

Value of α may be defined as

$$\alpha = \frac{-4\ln 0.5}{(\beta(K))^2},$$

in this case $\beta(K)$ – is the distance between argument values for $\mu_K(u)$, where MF meaning is equal to 0.5.

Then expression for fuzzy variable MF may be defined as

$$\mu_K(u) = e^{4\ln 0,5((K-u)/\beta(K))^2}, u \in U$$

The procedure for making forecasts in the form of a fuzzy number is based on Saaty's hierarchy analyses method [17]. A detailed description of the fuzzy prediction method based on a group examination procedure is presented in [18]. Specification of the expert's competence coefficients (weights) vector E as described in [19, 20].

Described fuzzy forecasting technique may be very useful for system's development trend identification on the base of well-defined prognoses of quantitative acceptability reserves.

Obtainment of expert group's prognoses in qualitative form for system's acceptability domain shaping may be performed subsequently in accordance of seven or ninth gradation scale. In this case primary values transforming to normalized values of secondary scale may be carried out by using Harrington scale and Harrington Desirability Function (HDF) [21].

E. SAD: Fuzzy Forecasting and Shaping

First of all for SAD's shaping it's necessary to know the previously determined trend of system's development. This trend may be either progressive (evolvable) or regressive (degradable). Furthermore, system's development trend may be neutral (or stable). Then qualitative worst-case forecasting process may be successfully introduced by instrumentality of established above group-expertise procedure with the utilization of certain specific modification.

Obtainment of PCM-elements estimations to determine worst-case bounds of SAD after prognostic development stage is carried out by group-expert judgment method. Thus, as a result we receive fuzzy estimations for qualitative criteria properties, described by correspondent MF.

Appraisal of correspondence of alternative variants of CES development with earlier predicted trend is carried out in the space of indexes of its physical and intelligence development. Left borderline bounds of fuzzy forecasted normalized values of acceptability reserves will correspond to worst-case SAD's shape.

For normalizing CES's qualitative variable values let's use next estimation for qualitative acceptability reserves

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

where q_{ij} – intermediate estimations of PQ2M, defined via corresponded preliminary values in initial scale y_{ij} ;

K – total criteria number (qualitative and quantitative).

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

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

$$q_{ij}=\begin{cases} 0.35\dfrac{(y_{ij}-y_j^*)}{(y_{1j}^*-y_j^*)}-0.83, & y_{ij}\in[y_j^*,y_{1j}^*] \quad , \\ 0.24\dfrac{(y_{ij}-y_{1j}^*)}{(y_{2j}^*-y_{1j}^*)}-0.48, & y_{ij}\in(y_{1j}^*,y_{2j}^*], \\ 0.246\dfrac{(y_{ij}-y_{2j}^*)}{(y_{3j}^*-y_{2j}^*)}-0.24, & y_{ij}\in(y_{2j}^*,y_{3j}^*], \\ 0.37\dfrac{(y_{ij}-y_{3j}^*)}{(y_{4j}^*-y_{3j}^*)}+0.006, & y_{ij}\in(y_{3j}^*,y_{4j}^*], \\ 0.394\dfrac{(y_{ij}-y_{4j}^*)}{(y_{5j}^*-y_{4j}^*)}+0.376, & y_{ij}\in(y_{4j}^*,y_{5j}^*], \\ 0.3\dfrac{(y_{ij}-y_{5j}^*)}{(y_{6j}^*-y_{5j}^*)}+0.77, & y_{ij}\in(y_{5j}^*,y_{6j}^*], \\ 0.43\dfrac{(y_{ij}-y_{6j}^*)}{(y_{7j}^*-y_{61j}^*)}+1.07, & y_{ij}\in(y_{6j}^*,y_{7j}^*], \\ 0.75\dfrac{(y_{ij}-y_{7j}^*)}{(y_j^{**}-y_{7j}^*)}+1.5, & y_{ij}\in(y_{7j}^*,y_j^{**}], \end{cases}$$

To determine/estimate qualitative criteria values q_{ij} let's use next relationships, formulated for those acceptability criteria, that need to be maximized:

Where y_j^*, y_j^{**} – the worst-case and the best-case group-expertise values for j-th partial criterion respectively;

$y_{kj}^*, \rightleftharpoons k=\overline{1,7},$ – right 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 optimistic value "very high" corresponds to half-open subinterval $(y_{7j}, y_j^{**}]$.

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 reserves z_j. Evidently, that by using proposed approach of normalized criteria evaluation all elements in pairwise comparison matrix on PCM will in interval from 1 to 9. An essential difference from Saaty scale is that, in our case elements of pairwise comparison matrix may have arbitrary values from aforementioned diapason.

Finally, as the general condition that CES acceptability domain will be adequate in worst-case sense let's demand:

$$\min_j \; z_j(X) \geq 0.25, \quad j=\overline{1,K} \qquad (2)$$

For well-controlled evolutionary process all intermediate states along desirable development trajectory must satisfy these requirements. But for systems with regressive evolutionary trend theirs SAD configuration will be volume-reduced.

III. RESULTSAND DISCUSSION

We carried out several experiments to apply the proposed technique to fuzzy shaping of acceptability domain for real complex IT-system. As a result of our investigation some patterns of SAD visual fuzzy images in Z-space for real CES were obtained.

Several received SAD-shapes corresponded to worst-case system development project may be considered as an initial variant for rational choosing of evolution way for investigated CES. Although some analyzed projects belong to stable but nearly regressive forecasting trend, they are still quite acceptable for realization, because they completely satisfy to acceptability condition (2) and as consequence their SAD shapes are not empty. So they would be considered as basic feasible solutions for the rational choice of CES development.

As usual system acceptability domain represents polytope in normalized multi-criteria Z-space of CES. The next problem will be how to choose most acceptable and satisfactory configuration for this domain from worst-case point of view. Evidently, that consistence of CES development processes may be determined comparatively by its convergence to predicted desirable trajectory of system elaboration as a most reasonable template. And as a several perspective patterns we should take into account all possible alternatives from progressive trend.

If 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, then each non-even-numerical direction in normalized Z-space will be more preferable than following even-numerical direction. Due to such suggestion in result of SAD-shape configuration analysis we shall receive final conclusion what shape is much more preferable. Indeed if SAD-shape of certain project may have essential preferences in all non-even directions while SAD-shapes of other projects may have some advantages along subsidiary even-numerical axes then ultimate decision about concrete system development way will be evident.

IV. SUMMARY

It is proposed to carry out the solution of the problem of evaluating the performance of complex technical systems on the basis of a comprehensive analysis of the worst condition of their functional survivability field. Fuzzy forecasting of evolutionary processes of the formation and development of complex systems based on methods and technologies of group expertise seems justified and productive. The questions posed in the article are relevant, especially in light of the need for research and selection of the most promising options for development of modern large-scale engineering systems with a sufficiently long period of operation. The practical significance of the results of the study in our opinion is not in doubt.

V. CONCLUSIONS

It should be noted that if the set of degradable alternatives will be empty its necessary to make final decision on the base of SAD visual analysis with regard of expert group's chief individual opinion about worst alternatives which belong to "stable" development trend.

Main issues for further research and development will be:

- Strengthening of expert group prognoses validity;
- Fuzzy neural networks application to support described technique practical realization;
- Improving of existing fuzzy shape of SAD after final evaluation of acceptability reserves.

ACKNOWLEDGEMENTS

The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. This work was supported by the Russian Federation Ministry of Education and Science, project No. 8.6141.2017/8.9.

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