Efficient engineering approach to communication satellite design

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Abstract. Choosing the efficient options of communication satellites (CS) requires the computer-aided design and researching complex and super-complex technical systems; satellite systems are among them. Therefore, organising space vehicle design process reveals a clear tendency to its automation that is specific for both routine, stand-alone technical feature of designing process, and the intellectual aspects of design.

1. Introduction

Developing approaches of efficient design is necessary under the conditions of stiff competition in the international market; it is also necessary to develop methodology permitting to perform multi-criteria evaluation of efficiency of design options at the early stages of life cycle. The methodological approach under development is based on applying poly-structure space vehicle conception as complex technical systems and mathematical models of analyzing efficient options to develop a decision-making support system (MDSS), further development of computer-aided design system (CAD) [1, 2, 3]

The main goals to develop methodology of efficient design are to reduce terms and costs taking into account the design quality, efficiency in utilizing onboard assets, satellite output characteristics. We could determine two absolutely different approaches to design automation. The first applied approach is connected with direct automation of various routine operations while designing: using computer-assisted patterns, prototypes, unifying data communications. Within this approach we create a database, where we locate all data obtained within the process of designing various space vehicles. The specialists – designers perform the designing procedures and place the outcomes in the database. The results from one department to a different one are transmitted with outputting the necessary data (documents, images and others) in a formalized view. The data structure from the database, their contents and form is determined by interconnect protocol. Advantages in time is discounted due to complicating satellite systems, increasing in number of requirements and sharp increasing in time to the design decision making procedures [1, 4].

We need to computerize the design procedures, computerize the analysis of various options to construct space vehicles, computerize the selection of the most suitable option, and automate modeling the chosen options permitting to make evaluation of dynamic characteristics of design alternatives. The listed assignments are the essence of the second approach. They impose on the necessity to develop
MDSS for the design. There could be an individual decision-making support system for each design stage including the stage of ground experimental method [2, 3, 7].

Complicating communication satellite requires sharp increase of data volume; the information should be processed at the stage of ground experimental method. It has an effect on program-methodical documentation to the ground experiments that is automatically formed by data included into MDSS of the previous design stages [2].

Analyzing tendencies of complex technical systems allows to state some requirements to construct the contemporary computer-aided design system [1, 3]. Communication satellite CAD has to facilitate:

1) Processes of selecting and analyzing options of constructing space vehicles at all stages of design and ground experiments together with computer-aided issue of documentation at all stages;

2) computer-aided generation of the design outcomes at every stage and possibility to access to the outcomes at further stages;

3) an ability to adjust previously made decisions on data obtained during next stages, as well as prevent from considering options not generated by the software at any design stage;

4) an ability to enlarge a model and figure base to evaluate options.

Applying poly-structural description together with highlightening various structure types includes analysis and synthesis of interstructural interconnections (meta-structure). Depending on the research goals to the relations of meta-structural interconnections there could be various content interpretations. While generating and selecting design decisions, it is viable to interpret the relation as consequence of structures in generation and selection of the designed subsystem options as well as relationship between model parameters describing different structures [1, 3].

Poly-structural conception develops presuppositions to applying formalized methods to describe a space vehicle, to simulate an operating mode, and to organize design management [2, 4, 5].

The specific features in design determine the main types of space vehicle structures and formation of interstructural interconnections; it means the design stages belonging to the original data, resources, design time and others [1, 3].

At the early stages of the life cycle (releasing feasibility assessments), when the main design goal is the evaluation of the possibility to design a satellite, it is viable to use the following main constructs: functional ones, technical specifications, design-layout parameters, economical and time parameters. Meta-structural interconnections are on figure 1. The given structures are in the order, as they are viable to generate when a space vehicle option is selected at the stage of the primary design [2, 4].

One and the same design stage can relate to several options of poly-structural conception, therefore, while researching, there is an assignment to select its variant rationally. However, formal state of a selection task faces the difficulties in evaluating various options according to the qualitative or quantitative parameters (figure 1).

![Figure 1. State of evaluating various.](image-url)
Analysis of formal computer-aided simulations at different design stages shows that in most cases they result in the tasks of multi-criteria pseudo-Boolean optimization [5, 6]; at the late stage they are associated with applying simulators [2].

Therefore, it is proposed to use a two-level simulator of decision making to determine a communication satellite design image at the primary stages of a life cycle [1]. For this purpose we introduce a Boolean variable:

\[ x_{ij} = \begin{cases} 1, & \text{if } i\text{-th board system is chosen in } j\text{-th option of its construction} \\ 0, & \text{in the opposite case} \end{cases} \]

where: 
- \( i \) - is an index of on-board system number; 
- \( j_i \) - is an index of \( i\)-th board system in \( j\)-th option of its construction 

\( \{ x_{ij} \} \) — a set of alternative options of on-board systems;

Therefore, a simulator to select an efficient option of a space vehicle is a task of multi-criteria Boolean optimization.

Solving the problem of forming Pareto set including all possible construction options, if other options do not dominate over according to the criteria to be applied, the head designer of a space vehicle should meet the following restrictions [1, 2]:

\[ M_{CS} \leq M_{LS}; \]
\[ V_{CS} \leq V_{APB}; \]
\[ E_{CS} \leq E_{PSS}; \]
\[ |X_{BT}| \leq |X_{BT LS}|, |Y_{BT}| \leq |Y_{BT LS}|, |Z_{BT}| \leq |Z_{BT LS}|; \]
\[ |I_{xx}| \leq |I_{xx LS}|, |I_{yy}| \leq |I_{yy LS}|, |I_{zz}| \leq |I_{zz LS}|; \]
\[ T_{AL} \geq T_{AL RP}, K_{G CS} \geq K_{G CS RP}, \gamma_{CS} \geq \gamma_{CS RP}; \]
\[ C_{R&D and OPERATION} \leq C_{R&D and OPERATION}; \]
\[ C_{DRD} \leq C_{DRD}; \]
\[ T_{LAUNCH} \leq T_{LAUNCH}; \]
\[ T_{R&D} \leq T_{RP}; T_{R&D} \leq T_{R&D}; \]
\[ E_{CS} > 0; E_{CS/R} > 0, E_{EB} > 0; \]
\[ \forall i = 1, \sum_{j=1}^{J} x_{ij} = 1; \]

where:
- \( E_{CS}^c \) - is a criterion of a mission effectiveness of a communication satellite according to its cost; 
- \( C_r \) - relative cost of a communication satellite; 
- \( E_{CS}^m \) - specific mission effectiveness of a communication satellite; 
- \( E_{CS}^M \) - is a criterion of mission effectiveness of a CS according to mass; 
- \( E_{EB}^C \) - is economic benefit value for the whole life cycle of CS from its operation; 
- \( M_{CS} \) - is total mass of a communication satellite \( M_{CS} = \sum_{i=1}^{C} M_i; \)
- \( R_{LV} \) - available opportunities of launch vehicles, applied for launching communication satellites to a transfer orbit; 
- \( V_{CS} \) - CS volume at launch position \( V_{CS} = \sum_{i=1}^{C} V_i; \)
V_{APB} - internal volume of assembly-protection block incorporated into launch vehicles, used to locate CS in the underfaring volume;

\[ E_{CS} - \text{energy consumption of CS} \quad E_{CS} = \sum_{i=1}^{N} E_i; \]

\[ E_{PSS} - \text{available performance of electric power supply system of a communication satellite}; \]

\[ T_{AL, CS, \gamma} - \text{active life, coefficient of readiness, probability of faultless operation of a developed CS and data broadcasting relatively}; \]

\[ T_{AL, CS, \gamma}^{RP}, C_{R CS}, \gamma_{CS}^{RP} - \text{active life, coefficient of readiness, probability of faultless operation of a developed CS and data broadcasting relatively, definite requests for proposals for a CS design and development}; \]

\[ C_{CDR} - \text{design cost level of board data-relay duct for the developed CS}; \]

\[ C_{CDR}^{T} - \text{design cost level of board data-relay duct for the alternative CS, developed by tender or operating satellites within various civilian satellite communication systems}; \]

\[ C_{R&D and OPERATION} - \text{research and development (R&D) design cost and communication satellite operation, and data broadcasting}; \]

\[ C_{R&D and OPERATION}^{T} - \text{research and development (R&D) design cost and alternative communication satellite operation, and data broadcasting; satellites developed by tender or operating satellites}; \]

\[ C_{R&D and OPERATION}^{RP} - \text{the limitation to the research and development (R&D) design cost and CS operation, and data broadcasting, available in the request for proposal}; \]

\[ T_{R&D} - \text{R&D duration to design CS and data broadcasting} \quad T_{k & d} = \sum_{k=1}^{l} T_i; \]

\[ T_{\text{s}} - \text{duration of R&D stages to design CS and data broadcasting}; \]

\[ T_{R P} - \text{R&D duration to design CS and data broadcasting, the definite request of proposal to design CS}; \]

\[ T_{R&D}^{T} - \text{R&D duration to design alternative CS and data broadcasting, satellites are developed by tender or operating satellites}; \]

\[ T_{\text{LAUNCH}} - \text{the general duration, characterizing the work duration to design CS and data broadcasting up to its launch and bringing a satellite into operation on a transfer orbit}; \]

\[ T_{\text{LAUNCH}}^{T} - \text{the general duration, characterizing the work duration to design alternative CS and data broadcasting developed by tender within other civilian communication satellite system up to their launch and bringing into operation on a transfer orbit}; \]

\[ p_{ji} - \text{probability of faultless operation of } i\text{-th board satellite system in } j\text{-th CS option}; \]

\[ T_{ji} - \text{duration of } i\text{-th R & D sub-stage to design CS in its } j\text{-th option}. \]

To make a decision selection of a decision rule or verification is the most significant during the efficient design.

Due to the proposed methodology the decision rules are constructed as resulting preference pattern (RPP): Pareto-like, lexicographic, based on acceptability and majority principles.

Advanced design is to develop combined RPP that presents determined combinations of the RPP presented before and their modifications.

Based on the decision rule we develop a man-machine procedure (MMP) of decision making, it is a designer tool (DT) to select or verify the alternatives. MMP is realized interactively in the dialogue form between MD and a computer [1, 2]. Computer analyses the current decision making situation for iteration; MD introduces the information about additional preferences using different modes. The main condition for MMP efficiency is its accuracy in considering MD as a making decision agent, taking into account their psychological features. Man-machine procedures of constricting a RPP core have shown good results, where a core is a set of non-dominated design versions of the given RPP [2]. The efficiency of the procedures is determined due to the fact that, for iteration, they involve detailed research of the core features by computer; the result of such research is clear and accessible for MD activity.
Due to the research, on the base of general and specific efficiency indexes, we have developed a generalized hierarchical model to select an efficient option to design a CS, computer models to select efficient options to design on-board systems. During the early design stages, we used discrete models with Boolean variables. As a result a model to select an efficient version is a task of multi-criteria Boolean optimization of generalized and specific efficiency indexes if the head designer of CS follows some restrictions [1].

The performed computer models, criteria, algorithms and methodology of design have been tested and demonstrated their efficiency while designing communication satellites, developed at JSC “Integrated satellite systems” named after academic M.F. Reshetnev [2].

CS CAD is realized with the developed methodology; CAD uses the data included into decision-making support system (MDSS) of the previous design stages, allowing to computerize generation and analysis of various options to design and select the most comfortable option out of the existing.

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