Analysis of decision-making options in complex technical system design

V Nemtinov¹, A Zazulya², V Kapustin² and Y Nemtinova³, ⁴
¹Department of Computer-integrated Systems in Mechanical Engineering, Tambov State Technical University, 106 Sovetskaya Street, 392000, Tambov, Russian Federation
²Department of Agroengineering, Tambov State Technical University, 106 Sovetskaya Street, 392000, Tambov, Russian Federation
³Department of «Economic Security and Quality, Tambov State Technical University, 106 Sovetskaya Street, 392000, Tambov, Russian Federation
⁴Department of Management, Marketing and Advertising, Tambov State University named after G.R. Derzhavin, 33, Internatsionalnaya Street, 392000, Tambov, Russian Federation

¹E-mail: jnemtinova@hotmail.com

Abstract. In this article, we present a scheme of sequential analysis and elimination of variants that does not use the idea of step-by-step decision making and can be implemented for analysis of engineering solutions at the stage of manufacturing preparation. This scheme uses the methodology of sequential analysis and screening of options both by constraints and by the objective function without constructing initial parts of each variant and their further development. We have also developed a software product for the automated information system that implements the proposed optimal decision making scheme, which includes an automated selection of: metal grade, type and method of producing a blank depending on the type of hardening for engineering products. The system has been tested on the example of units included in the shaper-vulcanizers.

1. Introduction

A specific feature of complex technical systems is that many problems solved at various stages belong to the class of discrete programming problems. In this case, the search for optimal solutions is carried out both by one criterion and by a combination of criteria. In cases where the set of solutions is small (not more than \(10^3 – 10^4\) options), given the speed of modern computers, a desired solution can be found using the method of exhaustive search of options. However, with an increase in the number of options, this becomes problematic even when using the latest models. Therefore, there is a need to build a general procedural scheme, which could be used to find the optimal solution. The basis of this scheme is the method of sequential design, analysis and screening of variants, based on generalization of the main ideas of the theory of sequential statistical decisions by A. Wald [1].

When implementing this method, a decision-making process is represented as a multi-stage structure resembling the structure of a complex experiment. Each step is associated with checking the availability of certain properties of a subset of options and leads either to a direct reduction of the initial set of options, or prepares the possibility of such a reduction in the future. At the same time, at
the stage of task formalization, it is necessary to indicate those distinctive properties that a desired variant should possess. Then it is needed to identify as many signs as possible to establish that this option is not a desired one. Among these signs, the most easily checked and inherent to as many options as possible are chosen. After that, the choice of a numerical solution scheme consists in selecting a rational order of checking of those signs, which allows screening out non-competitive options and finding the optimal one. One of the rules for eliminating undesirable variants is based on the principle of monotonic recursiveness [2-5]. Based on this principle, step-by-step design algorithms were built for solving various discrete optimization problems [6-9].

From the standpoint of formal logic, the scheme of sequential analysis of variants can be reduced to the following sequence of repetitive transformations:
- splitting the set of solutions into several subsets, each of which has additional specific properties;
- using these properties to search for logical contradictions in the description of individual subsets;
- excluding those subsets of solutions which containing logical contradictions in their description.

At the same time, the method of sequential development, analysis and selection of options is constructed in a way which allows to eliminate unprofitable (unpromising) initial parts of options before they are fully constructed as soon as this feature can be detected [10-12]. Since filtering out the unpromising initial parts of the variants also eliminates their continuations, there is a significant efficiency in the computational procedure, and it is becoming even more significant as more specific properties are used for construction of analysis and dropout operators.

Along with the well-known advantages, step-by-step design algorithms have certain disadvantages. As a rule, they impose excessive demands on the RAM of personal computers; as the number of constraints grows, the volume of computational operations for choosing an optimal solution increases dramatically.

At the same time, the methodology of sequential analysis of variants allows to construct general schemes for solving discrete optimization problems [13–15]. If the idea of step-by-step problem solving within the method of sequential analysis and sifting out options is abandoned, there is no need to memorize sets of “denominated” partial solutions at each step which ought to be developed at further stages, thus saving PC memory, as these algorithms work with the whole set of possible solutions at each step.

Taking into account the aforementioned discussion, let us consider one of the possible schemes of sequential analysis and screening of variants, which does not use the idea of step-by-step design of solutions and can be used in analysis of engineering solutions to the problems of manufacturing preparation of engineering production.

2. Procedure for analyzing engineering solutions for complex systems
In the proposed scheme for analysis of engineering solutions, we use the methodology of sequential analysis and screening of options by eliminating unpromising elements, both by constraints and by the objective function without constructing the initial parts of options and their further development. We present the proposed method for the problem of discrete optimization in the following statement.

Let \( Z(Q(X)) \) be the problem of minimizing a function \( F \) on a finite set \( Q(X) \), that is, the task of finding

\[
x^* = \arg \min_{x \in Q(X)} F(x),
\]

where the set \( Q(X) \) is given as follows:

\[
d_l(x) \leq d_l^*, \quad l = 1, m;
\]

\[
d_l(x) \geq d_l^*, \quad l = m + 1, M;
\]

\[
x \in X = \prod_{j=1}^{n} W_j;
\]
where \( W_j = \{ w_{j(1)}, \ldots, w_{j(k_j)}, \ldots, w_{j(K_j)} \} \) \( j = 1, n; \) \( W_j \) is \( K_j < \infty; \) \( |X|^n = \prod_{j=1}^{n} K_j; F, d_l \) - arbitrary functions of a discrete argument; \( d_l^* \) - given numbers.

A solution is valid if it satisfies conditions (2) - (4).

The basis of the considered method for solving the problem (1) - (4) is the procedure \( \Omega \) of sequential screening of variable values \( w_{j(k_j)} \in W_j \), that is, elements of possible solutions to the problem \( x = (w_{l(k_1)}, \ldots, w_{j(k_j)}, \ldots, w_{m(n_n)}) \in X \). An integrated diagram of the procedure for decision options analysis is shown in figure 1. The procedure \( \Omega \) consists of two procedures \( \Omega_1 \) and \( \Omega_2 \); the procedure \( \Omega_1 \), in its turn, consists of \( M \) “elementary” procedures \( \Omega^{(l)}_1 \) \((l = 1, M)\), each of which consists in eliminating the elements \( w_j = w_{j(k_j)}, \) \( k_j \in J_j = \{1, \ldots, K_j\} \), \( j = 1, n \) by the \( l \)-th constraining, satisfying the inequality

\[
d_l^\prime \left( w_{l(k_1)}^{l(k_1)}, w_{2(k_2)}, \ldots, w_{j-l(k_j-l)}, w_{j(k_j)}, w_{j+1(k_j+1)}, \ldots, w_{m(n_n)} \right) > d_l^*,
\]

where

\[
x^{l(k_j)} = \left( w_{l(k_1)}^{l(k_1)}, w_{2(k_2)}, \ldots, w_{j-l(k_j-l)}, w_{j(k_j)}, w_{j+1(k_j+1)}, \ldots, w_{m(n_n)} \right) \equiv \arg \min_{x \in \left( X \setminus W_j \right) \cup \left\{ w_{j(k_j)} \right\}} d_l(x),
\]

if \( l = 1, m \), or the inequality

\[
d_l^\prime \left( w_{l(k_1)}^{l(k_1)}, w_{2(k_2)}, \ldots, w_{j-l(k_j-l)}, w_{j(k_j)}, w_{j+1(k_j+1)}, \ldots, w_{m(n_n)} \right) < d_l^*,
\]

where

\[
x^{l(k_j)} = \left( w_{l(k_1)}^{l(k_1)}, w_{2(k_2)}, \ldots, w_{j-l(k_j-l)}, w_{j(k_j)}, w_{j+1(k_j+1)}, \ldots, w_{m(n_n)} \right) \equiv \arg \max_{x \in \left( X \setminus W_j \right) \cup \left\{ w_{j(k_j)} \right\}} d_l(x)
\]

if \( l = m+1, M \). It should be noted that the variant \( x^{l(k_j)} \), described by the relations (6) and (8) provides the optimum of the function \( d_l(x) \) with a fixed element \( w_{j(k_j)} \) for the set \( W_j \). If the variant \( x^{l(k_j)} \) is not unique, then in the relations (5) and (7) any of them is taken.

Let's rewrite conditions (5) and (7) with allowance for (6) and (8) respectively in the form:

\[
d_l^\prime \left( x^{l(k_j)} \setminus W_j, w_{j(k_j)} \right) > d_l^*, \quad l = 1, m
\]

\[
d_l^\prime \left( x^{l(k_j)} \setminus W_j, w_{j(k_j)} \right) < d_l^*, \quad l = m+1, M
\]

We denote the set of elements from \( W_j = W_j^{(l)} \), remaining after applying the procedure \( \Omega_1 \) через \( W_j^{(l)} \). Then, after applying the procedure \( \Omega_1 \) we get a “truncated” set of possible options.
Figure 1. An integrated scheme of the procedure for analyzing decision options in the design of complex systems.

\[ X^{(t')} = \emptyset \]

| \[ X^{(t')} \neq \emptyset \]

where \( X = X^{(0)} \supseteq X^{(1)} \). Next, we apply the procedure \( \Omega_1 \) again to the set \( X^{(t)} \) and get \( X^{(2)} \) and so on until we get \( X^{(t+1)} = X^{(t)} \) at some \( t+1 \) step. This condition will be considered the final one for the end of application of the procedure \( \Omega_2 \). When applying the procedure \( \Omega_1 \) to the problem \( Z(\tilde{Q}(X)) \) three cases are possible: 1) \( X^{(t)} = \emptyset \). This means that the task is invalid.

2) \( X^{(t)} \neq \emptyset \) and the set \( X^{(t)} \) is small enough \( \left| X^{(t)} \right| \sim 10^3 - 10^4 \). Applying the procedure \( \Omega_2 \) leads to a significant reduction in the set of options for solving the problem, and then it can further be solved by a complete exhaustive search on the set \( X^{(t)} \).

3) \( X^{(t)} \neq \emptyset \) and the set \( X^{(t)} \) is large enough in terms of the time spent on implementation of a complete exhaustive search on computers and contains valid solutions. In this case, one should apply the procedure \( \Omega_2 \) to the problem \( Z(\tilde{Q}(X^{(t)})) \) which is to replace the original task with a sequence of tasks \( Z^s(\tilde{Q}(X^{(t,s)})) \) \( s = 1, 2, ... \), that have the form:

\[ x^s = \arg \min_{x \in Q(X^{(t,s-1)})} F(x), \]  

where the set of permissible variants of the problem \( \tilde{Q}(X^{(t,s-1)}) \) is determined from the relations:
and constraints (2) – (3).

When considering the problem $Z^1(\bar{Q}(X^{(i)}))$ any number from the interval $[\min F(x), \max F(x)]$ can be taken for $F_1^*$. The streamline of the procedure for finding the optimal solution to the problem we set $F_1^* \equiv \left( \frac{\min F(x) + \max F(x)}{2} \right)$. For this task, we apply the procedure $\Omega_1$, which consists of eliminating the elements $w_{j(k)} \in X^{(i)}$ by the constraint $F(x) \leq F_1^*$.

The procedure $\Omega_1$ is again applied to the set of remaining variants and the procedure continues according to the scheme described above.

In cases, when after applying the procedure $\Omega_1$ an empty set of options is obtained, the problem $Z^1(\bar{Q}(X^{(i)}))$ is solved with the constraint $F(x) > F_1^*$.

If, as a result of problem solving, the set of remaining options is sufficiently large, then one should proceed to solving the problem $Z^2(\bar{Q}(X^{(i)}))$ and $F_2^* \equiv \left( \frac{\min F(x) + F_1^*}{2} \right)$ is used as a constraint.

The condition for the end of $\Omega$ procedures is reduction of the set of options to the quantity of $10^3$ – $10^4$. Next, an optimal solution to the problem $Z(\bar{Q}(X))$ is found by the method of exhaustive search of variants.

Approbation of the proposed procedure for finding the optimal solution is implemented for the problem of synthesis of technological processes for manufacturing of engineering products (metal products). Based on specifics of technological design of this class of production systems, all output variables are divided into three categories. The first category includes output variables for which all their possible values are used when forming a set of solution options.

The second category combines output variables for which only those values that fall into the neighborhood of the “optimistic” values of the local criterion are used when forming a set of solution options. This neighborhood is determined by the following rule: $F^h \cdot r \leq F^{opt}_h$, $r < 1$, $h = 1, 2, ..., H$, where $r$ is the coefficient specified by the decision maker for the neighborhood of “optimistic” values of the local criterion $F$; $F^h$ - the value of the criterion for the $h$ - th version of output variables; $H$ - the set of their permissible values.

The third category includes the least significant output variables for which only one value of the output variable is used when forming a set of solution options.

When designing technological processes, division into categories is carried out by the decision maker in the process of forming a set of solutions to the problem. Let us consider an example of automated selection of metal grade, type and method of production and type of a workpiece depending on the type of hardening for metal products at the stage of technological preparation of manufacturing. The first category includes output variables: type of blank production, metal grade, method of blank production, type of hardening treatment; the second - type of hardening treatment, type of a workpiece; and the third - auxiliary materials for carrying out the method of blank production.

3. Results and discussion
As a result, using the proposed procedure for problem solving on the example of one simple detail, such as a gear, appears to be approximately 3 times faster than the traditional procedure. Given the
fact that the composition of a complex product (for example, a shaper-vulcanizer) includes more than 500 parts, there is a significant reduction in decision-making time. Together with this, the qualifications and experience of designers and technologists involved in the development of complex engineering products and technological preparation of its production are actively used.

Conclusion
Based on the research results the following conclusions are made: a generalized procedural model of decision support for design of technological processes was developed for a class of technical systems characterized by taking into account importance and categorization of output variables for further analysis and uses either all their values, or only those that fall into the “optimistic” neighborhood of values of the local criterion, or single values - for the least significant variables; a software for an automated information system was created, which includes a software package of automated selection of: metal grade, type and method of blank manufacturing depending on the type of hardening for engineering products.

The system was tested on the example of structural units included of the shapers-vulcanizers.

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