Multistage Global Search Using Various Scalarization Schemes in Multicriteria Optimization Problems

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Abstract. In this paper, an approach, in which the decision making problems are reduced to solving the multicriteria time-consuming global optimization problems is proposed. The developed approach includes various methods of scalarization of the vector criteria, the dimensionality reduction with the use of the Peano space-filling curves and the efficient global search algorithms. In the course of computations, the optimization problem statements and the applied methods of the criteria scalarization can be altered in order to achieve more complete compliance to available requirements to the optimality. The overcoming of the computational complexity of the developed approach is provided by means of the reuse of the whole search information obtained in the course of computations. The performed numerical experiments have confirmed the reuse of the search information to allow reducing essentially the amount of computations for solving the global optimization problems.

Keywords: Decision making, multicriteria optimization, criteria scalarization, global optimization with nonlinear constraints, numerical experiment

1   Introduction

The multicriteria optimization (MCO) problems, which are used as the statements of the decision making problems often are the field of extensive research - see, for example, the monographs [1-3] and the reviews of the scientific and applied results in this area [4,5].

Usually, the finding of the effective (non-dominated) decisions, in which the improvement of the values with respect to any criteria cannot be achieved without the worsening of the values with respect to other criteria is understood as the solution of a MCO problem. In the most general case, when solving the MCO problems, it can appear to be necessary to obtain a complete set of the effective decisions (the Pareto set). However, the finding of all effective decisions may require a considerable amount of computations, and the set of obtained decisions may appear to be quite large. As a result, the approaches that obtain the more limited set of effective decisions are applied wider. Among such approaches, there are various kinds of the criteria convolutions, the lexicographic optimization methods, the algorithms of searching the best approximation to the given prototypes, etc. All methods mentioned above

allow accounting for the specific features of the MCO problems being solved and satisfy the requirements to the optimality from the decision maker.

The present work is devoted to the solving of the MCO problems, which are used for the description of the complex decision making problems, in which the criteria of efficiency may have a complex multiextremal form, and the determining of the values of the criteria and constraints may require a large amount of computations. Also, is assumed that in the course of computations it is possible to change the statement, the methods, and the parameters of solving the MCO problem that results in the necessity of the multiple solving of the global optimization problems.

The practical use of this approach implies the overcoming of a considerable computational complexity of the decision making problems that can be provided by means of the use of highly efficient global optimization methods and the complete utilization of the search information obtained in the course of computations.

In the present paper, the results of investigations on the generalization of the decision making problem statements [6,7] and on the development of the highly efficient global optimization methods utilizing the whole search information obtained in the course of computations [8-10] are presented.

Further structure of the paper is as follows. In Section 2, the statement of the decision making problems based on multistage multicriteria global search are presented. In Section 3, a general scheme of the criteria scalarization is proposed. In Section 4, the search information obtained in the course of computations is considered. In Section 5, an efficient algorithm for solving the time-consuming global optimization problems with the nonlinear constraints is presented. Section 6 contains the results of numerical experiments confirming the developed approach to be promising. In Conclusion, the obtained results are discussed and possible main directions of further research are outlined.

2   Multistage multicriteria optimization problem statement

For the formal description of the process of solving the complex decision making problems, the following generalized two-phase scheme is proposed.

1. In the most general form, a decision making problem is defined by means of a vector function of characteristics

$$w(y) = \big(w_1(y), w_2(y), \ldots, w_M(y)\big), \; y \in D \tag{1}$$

where $y = (y_1, y_2, \ldots, y_N)$ is the *vector of varied parameters* and $D \subset R^N$ is the search domain, which is usually an N-dimensional hypercube

$$D = \{y \in R^N : a_i \le y_i \le b_i, 1 \le i \le N\} \tag{2}$$

for given vectors a and b.

It is supposed, that the values of characteristics $w(y)$ are non-negative, and the decreasing of these ones corresponds to the increasing of the efficiency of the chosen decisions. Also, it is supposed that the characteristics $w_j(y), 1 \le j \le M$, may be mul-

tiextremal, and the determining of their values may require large enough amount of computations. Besides, the characteristics $w_j(y), 1 \leq j \leq M$, are supposed to satisfy the Lipschitz condition

$$|w_i(y_1) - w_i(y_2)| \leq L_i\|y_1 - y_2\|,\ 1 \leq i \leq M \tag{3}$$

where L_i is the Lipschitz constant for the characteristic $w_j(y)$, $1 \leq j \leq M$, and $\|*\|$ denotes the Euclidean norm in R^N.

2. Then, a MCO problem is formulated on the basis of the statement considered above. For this purpose, a vector criterion of efficiency is selected among the characteristics $w_j(y), 1 \leq j \leq M$, from (1)

$$f(y) = \big(f_1(y), f_2(y), \dots, f_s(y)\big),\ f_j(y) = w_{i_j}(y),\ 1 \leq j \leq s,\ 1 \leq i_j \leq M \tag{4}$$

and the vector function of constraints

$$g(y) = \big(g_1(y), g_2(y), \dots, g_m(y)\big),\ g_l(y) = w_{i_l}(y) - q_l,\ 1 \leq j \leq m, 1 \leq i_l \leq M \tag{5}$$

where $q_l > 0, 1 \leq l \leq m$, are the allowances on the feasible values of characteristics $w_j(y),\ 1 \leq j \leq M$.

The efficiency criteria and constraints formulated in such a way allow defining a multicriteria optimization problem

$$P: f(y) \to min,\ y \in Q \tag{6}$$

where Q is the feasible search domain

$$Q = \{\, y \in D : g(y) \leq 0 \,\}. \tag{7}$$

In development of this scheme of the MCO problem statement, further an opportunity of simultaneous formulation of several MCO problems

$$\mathbb{P}_t = \{\, P_1, P_1, \dots, P_t \,\}, \tag{8}$$

will be allowed, the set of which can be varied in the course of computations by means of adding new or by removing already existing optimization problems.

In general, the proposed scheme of the optimal decision search process (1) - (8) defines a new class of the optimization problems – the multistage multicriteria global optimization (MMGO) problems.

3 Reduction of the multistage multicriteria search to the scalar one-dimensional global optimization problems

One of the approaches to solving the MCO problems used wider consist in the scalarization of the vector criterion into some general scalar criterion of efficiency that allows using a wide set of already existing optimization methods for solving the global optimization problems. Among the possible scalarization methods, there are, for ex-

ample, the weighted sum method, the compromise programming method, the weighted minimax method, and many other methods – see, for example, [2,3].

In the general form, the statement of the global optimization problems generated as a result the MCO problem criteria scalarization can be represented as follows:

$$\min \varphi(y) = F(\alpha, y), \ g(y) \leq 0, \ y \in D, \tag{9}$$

where F is the scalar objective function, α is the vector of parameters of the applied criteria scalarization method, $g(y)$ are the constraints of the MCO problem from (6), and D is the search domain from (2).

Particular forms of the function $F(\alpha, y)$ are defined by the criteria scalarization methods applied. For example, the following scalarization methods are possible.

1. In the case of equal importance of the criteria f_i, $1 \leq i \leq s$, the minimax convolution scheme (MMC) [3] can be applied:

$$F^1(\lambda, y) = \max(\lambda_i f_i(y), 1 \leq i \leq s), \tag{10}$$

$$\lambda = (\lambda_1, \lambda_2, \dots, \lambda_s) \in \Lambda \subset R^s \colon \sum_{i=1}^{s} \lambda_i = 1, \lambda_i \geq 0, 1 \leq i \leq s.$$

2. In the case of arrangement of the criteria in importance, the method of successive concessions (MSC) [2,3] can be used. In this case the scalar objective function F can set as follows

$$\min F^2(\lambda, y) = f_s(y), f_i(y) \leq f_i^{min} + \delta_i \left(f_i^{max} - f_i^{min} \right), \tag{11}$$

$$1 \leq i < s, g(y) \leq 0, y \in D,$$

where f_i^{min}, f_i^{max}, are the minimum and maximum values of the criteria $f_1(y)$, $1 \leq i < s$, in the domain D respectively, and $0 \leq \delta_i \leq 1$, $1 \leq i < s$, are the concessions with respect to each criterion. As before, the values of concessions $0 \leq \delta_i \leq 1$, $1 \leq i < s$, can be varied in the course of computations. The quantities f_i^{min}, f_i^{max}, $1 \leq i < s$, the values of which may be unknown *a priori*, can be replaced by the minimum and maximum estimates of the criteria values computed using the available search information.

3. In the case of availability of any estimates of the criteria values of the required decision (for example, based on an ideal decision or on any existing prototype) the MCO problem solution may consist in finding an effective decision the most completely matching given values of optimality (the reference point method, RPM). Such a problem can be formulated in the form of a scalar optimization problem

$$\min F^3(\lambda, y) = \frac{1}{s} \sum_{i=1}^{s} \theta_i (f_i(y) - f_i^*)^2, g(y) \leq 0, y \in D \tag{12}$$

where the objective function $F^3(\lambda, y)$ is the standard deviation of the decision $y \in D$ from the sought ideal decision, and the quantities $0 \leq \theta_i \leq 1, 1 \leq i < s$, are the magnitudes of importance of approximations with respect to each particular variable $y_i, 1 \leq i \leq N$.

Within the framework of the developed approach, it is possible to change the used scalarization methods (10)-(12) and/or altering the parameters of convolutions λ,

δ and θ. Such variations expand the set of the MCO problems $\mathbb{P}$ from (8) necessary for solving the initial decision making problem into a wider set of the scalar global optimization problems (9)

$$\mathbb{F}_T = \{ F_i(\alpha_i, y): 1 \leq i \leq T \}, \tag{13}$$

in which each problem $P \in \mathbb{P}$ from (8) can correspond to several global optimization problems (9).

In the developed approach, one more step of converting the problems being solved $F(\lambda, y)$ from (9) is applied, namely the dimensionality reduction is performed with the use of the Peano space-filling curves (evolvents) $y(x)$ providing an unambiguous mapping of the interval $[0,1]$ onto an N-dimensional hypercube D [11, 12]. As a result of such reduction, the multidimensional global optimization problem (9) is reduced to a one-dimensional problem:

$$F(\alpha, y(x^*)) = \min \{ F(\alpha, y(x)) : g(y(x)) \leq 0, x \in [0,1] \}. \tag{14}$$

The dimensionality reduction allows applying many well known highly efficient one-dimensional global optimization algorithms for solving the problems (9) (after performing necessary generalization) – see, for example, [11-15].

4   Computational complexity reduction of the multistage multicriteria search on the basis of the reuse of the search information

The numerical solving of the global optimization problems (9) is usually implemented by the successive computing the values of characteristics $w(y)$ at the points y^i, $0 \leq i \leq k$, of the search domain D [11,14]. The data obtained as a result of computations can be represented in the form of the matrix of the search information

$$\Omega_k = \left\{ \left(y^i, w^i = w(y^i) \right)^T : 1 \leq i \leq k \right\}. \tag{15}$$

As a result of scalarization (9) and the use of the dimensionality reduction (14), the set Ω_k from (15) can be transformed into the form of the matrix of the search state

$$A_k = \{ (x_i, z_i, g_i, l_i)^T : 1 \leq i \leq k \}, \tag{16}$$

where x_i, $1 \leq i \leq k$, are the reduced points of the executed global search iterations, z_i, g_i, $1 \leq i \leq k$, are the values of the scalar criterion and constraints of current optimization problem $F(\alpha, y(x))$ at these points, and l_i, $1 \leq i \leq k$, are the indices of global search iterations, in which the points x_i, $1 \leq i \leq k$, were computed.

The availability of the set Ω_k from (15) allows reducing the results of all preceding computations z_i, $1 \leq i \leq k$ in the matrix A_k to the values of the next optimization problem $F(\alpha, y(x))$ from (9) without any repeated time-consuming computations of the values of $w(y)$ from (1), i. e.

$$w_i \xrightarrow{\alpha,P} (z_i, g_i), \ 1 \leq i \leq k, \ \forall \alpha, \ P \in \mathbb{P} \tag{17}$$

The reuse of the search information can provide a gradual decreasing of the amount of computations when solving every next optimization problem down to the execution of few iterations only to find the next effective decisions.

5   Efficient solving the multistage multicriteria optimization problems with nonlinear constraints

Within the framework of developed approach, the efficient method was applied for solving the global optimization problems the nonlinear constraints [11]. The essence of the approach is the constructing of a problem with some aggregated unconstrained objective function, the solving of which leads to the solution of the initial problem (9) – more detailed description of the approach will be given below.

Let us introduced a simpler notation for the reduced problems (9) as

$$\min\{g_{m+1}(x): g_i\big(y(x)\big) \leq 0, 1 \leq i \leq m, x \in [0,1]\}. \tag{18}$$

$$g_{m+1}(x) = F\big(\lambda, y(x)\big).$$

The problem (18) can be considered in the statement of partial computability when each function $g_j(y)$, $1 \leq j \leq m+1$ is defined and computable in certain sub-interval $\Delta_j \subset [0,1]$ only where

$$\Delta_1 = [0,1], \ \Delta_{j+1} = \big\{ x \in \Delta_j : g_j\big(y(x)\big) \leq 0 \big\}, \ 1 \leq j \leq m. \tag{19}$$

Taking into account the conditions (19), the objective function of the problem (18) can be represented in the form

$$\varphi(x^*) = \min \big\{ g_{m+1}\big(y(x)\big): x \in \Delta_{m+1} \big\}, \tag{20}$$

on the basis of which the problem (18) can be transform to the problem of minimizing the aggregated function

$$\min \big\{ \Phi\big(y(x)\big) = g_\nu\big(y(x)\big), \ \nu = \nu(x), \ x \in [0,1] \big\}, \tag{21}$$

$$1 \leq \nu = \nu(x) \leq m+1, \ g_\nu\big(y(x)\big) > 0, \ g_j\big(y(x)\big) \leq 0, \ 1 \leq j \leq \nu - 1/$$

The index $\nu = \nu(x)$, $1 \leq \nu \leq m+1$ defines the first violated constraint at the point x in successive calculation of constraints.

Within the framework of the developed approach, the algorithm of global constrained optimization (AGCO), which is considered in details in [11] is applied for solving the global unconstrained problems (21).

6   Results of numerical experiments

The numerical experiments have been carried out using the computational nodes of Lobachevsky supercomputer at Nizhni Novgorod State University. The peak performance of the supercomputer was 573 Tflops, each computational node was equipped with Intel Sandy Bridge E5-2660 processor 2.2 GHz, 64 Gb RAM.

Within the framework of the present paper, the construction of a numerical approximation (PDA) of the Pareto domain (PD) was understood as a solution of a MCO problem. In order to evaluate the efficiency of constructing the *PDA*, two main indicators applied widely were used: The completeness of coverage of the Pareto domain (hypervolume index, HV) and the uniformity of distribution of the numerical estimates of the effective decisions (distribution uniformity index, DU) [10]. The higher values of the index *HV* and the lower values of the index *DU* corresponds to the better approximation.

Within the executed experiments, the two-dimensional bi-criterial MCO problems were used, the criteria of which were defined with the use of the family of multiextremal functions [11]. The functions of this family are defined as follows

$$f(y_1, y_2) = -(AB + AC)^{\frac{1}{2}},$$
$$AB = \left(\sum_{i=1}^{7}\sum_{j=1}^{7}\left[A_{ij}a_{ij}(y_1, y_2) + B_{ij}b_{ij}(y_1, y_2)\right]\right)^2, \tag{22}$$
$$CD = \left(\sum_{i=1}^{7}\sum_{j=1}^{7}\left[C_{ij}a_{ij}(y_1, y_2) - D_{ij}b_{ij}(y_1, y_2)\right]\right)^2,$$

where the expressions

$$a_{ij}(y_1, y_2) = sin(\pi i y_1) sin(\pi j y_2), b_{ij}(y_1, y_2) = cos(\pi i y_1) cos(\pi j y_2)$$

are defined in the area $0 \leq y_1, y_2 \leq 1$, and the parameters $-1 \leq A_{ij}, B_{ij}, C_{ij}, D_{ij} \leq 1$ are the independent random numbers distributed uniformly in the same interval.

The initial series of the numerical experiments was performed to evaluate the positive effect (the reducing of the number of the executed iterations) due to the reuse of the search information obtained in the course of computations (see Section 4). When conducting the experiments, the AGCO algorithm was applied sequentially with all scalarization methods considered in Section 3: the minimax convolution of the criteria (10), the method of successive concessions (11), and the reference point method (12). For each method mentioned above, 50 subproblems with various values of the parameters λ, δ and θ correspondingly have been solved. In order to evaluate the indicator HV of the completeness of the PDA approximation, the reference point (-4,-4) was used. For the AGCO algorithms, the reliability parameter $r = 2.3$ was used; the accuracy in the stopping condition was set as $\varepsilon = 0.01$.

The results of performed experiments are presented in Table 1. The column "Iters" contains the total number of iterations (the number of computations of the criteria values) required for solving the problem (22). The column "PDA" shows the number of the obtained effective decisions in the PDA. In the first part of the table (columns 2-5), the results of solving all subproblems without the use of the search information

are shown. In the second part (columns 6-9) the results of solving the same subproblems but with the use of the whole search information obtained in the course of computations (i. e. when solving every next subproblem, the search information obtained when solving all preceding subproblems was utilized) are presented. In the column "S", the speedup obtained as a result of reducing the number of the global search iterations (the number of the computed criteria values) required to solve all 50 subproblems due to the reuse of the search information is shown.

The results of experiments presented in Table 1 demonstrate the reduction of the number of the executed iterations of the AGCO algorithm more than 9 times. At that, the indicator HV takes almost the same values independently on the usage of the search information. However, the indicator DU was better notably (except the method of successive concessions) at the computations without the use of the search information (similar remark can be expressed on the number of effective decisions in the PDA as well) – most likely, this effect is manifested due to essentially less number of the executed iterations when using the search information. One can note also that the reference point method has some advantage in the efficiency indicators (the number of points in PDA, indicators HV and DU). However, this method inferior the use of the minimax convolutions in the number of iterations required to solve all 50 subproblems essentially.

Table 1. Efficiency of the reuse of the search information
in solving the problem (22) using various criteria scalarization methods

Scalarization method	Search information								S
	Not used				Used				
	Iters	PDA	HV	DU	Iters	PDA	HV	DU	
MMC (10)	9124	152	53.4	0.64	922	44	52.7	0.91	9.9
MSC (11)	12802	88	52.8	1.16	1402	40	52.4	1.09	9.1
RPM (12)	12881	240	53.6	0.51	1323	56	53.0	0.83	9.7

In the last experiment, solving a test MCO problem has been conducted when applied criteria scalarization methods altered in the course of computations with a complete use of the search information. In this experiment, at the first stage of computations, the minimax criteria convolution was used in solving three subproblems (10) with the convolution coefficients (1,0), (0.5,0.5), and (0,1), correspondingly. At the second stage, the scalarization method was changed to the reference point method (12), where the estimate (-14,-7) was used as the reference point with the weighting coefficients (0.5,0.5). And finally, at the third stage, the method of successive concessions (11) was applied with the concession with respect to the first criterion $\delta = 0.5$.

The results of performed experiments are given in Table 2. The column "Total iters" contains the total number of executed global search iterations whereas the column "New iters" shows the points of iterations executed at particular stage of solving the problem only. As follows from the results presented in Table 2, the number of the global search iterations executed at separate stages of solving the MCO problem reduced continuously (from 304 down to 35), and the reuse of the search information

provides the opportunity of dynamic altering the criteria scalarization methods applied in the course of computations efficiently.

Table 2. Results of solving the problem (22) with altering the criteria scalarization methods in the course of computations

Stage of computations, criteria scalarization method	Total iters	New iters	PDA
1. MMC (10), three subproblems	304	304	14
2. RPM (12)	402	98	19
3. MSC (11)	437	35	24

The PDA approximations of Pareto set obtained at the sequentially completed stages are shown in Fig. 1.
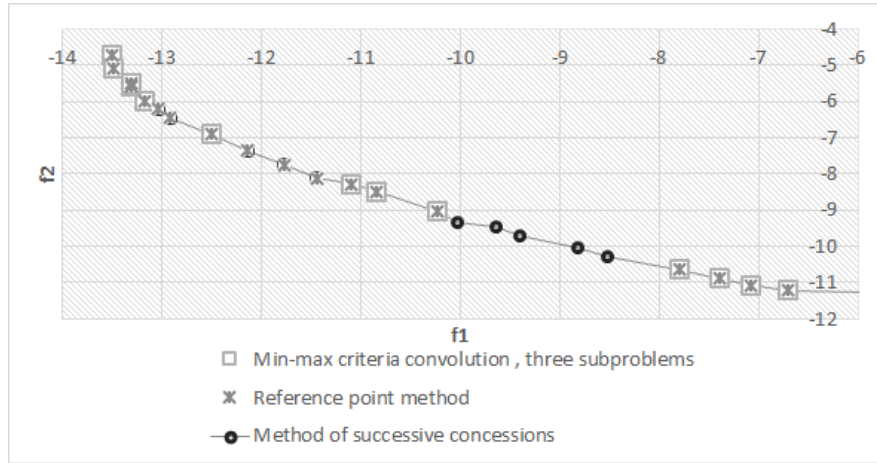

Fig. 1. Approximations of the Pareto set *PDA* obtained at the sequentially completed stages of computations

Conclusion

An approach is proposed to transform the decision making problems to the multistage multicriteria time-consuming global optimization problems. As a key property of the proposed approach it is supposed that the optimization problem statements and the applied methods of the criteria scalarization can be changed in the course of computations. The computational complexity is reduced by means of the reuse of the computed search information. The performed numerical experiments have confirmed the developed approach is promising.

In further investigations it is intended to execute the numerical experiments on solving the problems for a larger quantity of efficiency criteria and for larger dimensionality. Parallel computations can be considered as well.

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