Morphological methods for design of modular systems (a survey)

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The article addresses morphological approaches to design of modular systems. The following methods are briefly described: (i) basic version of morphological analysis (MA), (ii) modification of MA as method of closeness to ideal point(s), (iii) reducing of MA to linear programming, (iv) multiple choice problem, (v) quadratic assignment problem, (vi) Pareto-based MA (i.e., revelation of Pareto-efficient solutions), (vii) Hierarchical Morphological Multicriteria Design (HMMD) approach, and (viii) Hierarchical Morphological Multicriteria Design (HMMD) approach based on fuzzy estimates. The above-mentioned methods are illustrated by schemes, models, and illustrative examples. An additional realistic example (design of GSM network) is presented to illustrate main considered methods.

Keywords: System design, Morphological design, Modular systems, Configuration, Composition, Synthesis, Combinatorial optimization, Decision making

1. Introduction

Morphological analysis (MA) was firstly suggested by F. Zwicky in 1943 for design of aerospace systems. Morphological analysis is a well-known general powerful method to synthesis of modular systems in various domains (e.g., [3], [26], [33], [66], [77]). MA is based on divide and conquer technique. A hierarchical structure of the designed system is a basis for usage of the method. The following basic partitioning techniques can be used to obtain the required system hierarchical model: (a) partitioning by system component/parts, (b) partitioning by system functions, (c) partitioning by system properties/attributes, and (d) integrated techniques. In this article, system hierarchy of system components (parts, subsystems) is considered as a basic one. This case corresponds to modular systems which are widely used in many domains of engineering, information technology, and management (e.g., [4], [24], [32], [33], [36], [62], [75]). Many years the usage of morphological analysis in system design was very limited by the reason that the method leads to a very large combinatorial domain of possible solutions. On the other hand, contemporary computer systems can solve very complex computational problems and hierarchical system models can be used as a basis for partitioning/decomposition solving frameworks. Recent trends in the study, usage, and modification/extension of morphological analysis may be considered as the following: (1) hierarchical systems modeling, (2) optimization models, (3) multicriteria decision making, and (4) taking into account uncertainty (i.e., probabilistic and/or fuzzy estimates).

In the article, the following system design methods are briefly described: (i) basic morphological analysis (as morphological generation of admissible composite solutions), (ii) modification of MA as method of closeness to ideal point(s), (iii) reducing of morphological analysis to optimization model as linear programming, (iv) multiple choice problem, (v) quadratic assignment problem, (vi) multicriteria analysis of morphological decisions with revelation of Pareto-efficient solutions, (vii) Hierarchical Morphological Multicriteria Design (HMMD) approach, and (viii) version of Hierarchical Morphological Multicriteria Design (HMMD) approach based on fuzzy estimates. The above-mentioned methods are illustrated by solving schemes, mathematical models, and illustrative numerical examples. Preliminary materials (a description of the morphological methods and an example for GSM network) were published in [41], [50].

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2. Basic Configuration Problem

Generally, morphological system design approaches are targeted to design of system configuration as a selection of alternatives for system parts (e.g., [39]). Fig. 1 illustrates this problem. Here a composite (modular) system consists of $m$ system parts: \{P(1), ..., P(i), ..., P(m)\}. For each system part (i.e., $\forall$ $i = 1, m$) there are corresponding alternatives \{X^i_1, X^i_2, ..., X^i_{q_i}\}, where $q_i$ is the number of alternatives for part $i$. Thus, the problem is:

Select an alternative for each system part while taking into account some local and/or global objectives/preferences and constraints.

Evidently, the objective/preferences and constraints are based on (correspond to) quality of the selected alternatives and quality of compatibility among the selected alternatives. In [39], some other system configuration problems are described as well (e.g., reconfiguration, selection and allocation).

![Fig. 1. System configuration problem (selection)](image)

3. Morphological Design Approaches

Our basic list of morphological design approaches consists of the following: (1) the basic version of morphological analysis (MA) (e.g., [7], [10], [26], [66], [77]); (2) the modification of morphological analysis as searching for an admissible (by compatibility) element combination (one representative from each morphological class, i.e., a set of alternatives for system part/component) that is the closest to a combination consisting of the best elements (at each morphological class) (e.g., [3], [13]); (3) modification of morphological analysis via reducing to linear programming (MA&linear programming) [29]; (4) modification of morphological analysis via reducing to multiple choice problem (MCP) or multicriteria multiple choice problem (e.g., [56], [70]); (5) modification of morphological analysis via reducing to quadratic assignment problem (QAP) (e.g., [11], [39]); (6) the multicriteria modification of morphological analysis as follows (Pareto-based MA): (a) searching for all admissible (by compatibility) elements combinations (one representative from each morphological class), (b) evaluation of the found combinations upon a set of criteria, and (c) selection of the Pareto-efficient solutions (e.g., [14], [18]); (7) hierarchical morphological multicriteria design (HMMD) approach ([33], [36]); and (8) version of hierarchical morphological multicriteria design approach with probabilistic and/or fuzzy estimates (HMMD&uncertainty) [33]. Table 1 contains some properties of the approaches above.

![Table 1. Description of approaches](image)
3.1. Morphological Analysis

The MA approach consists of the following stages:

Stage 1. Building a system structure as a set of system parts/components.

Stage 2. Generation of design alternatives (DAs) for each system part (i.e., a morphological class).

Stage 3. Binary assessment of compatibility for each DAs pair (one DA from one morphological class, other DA from another morphological class). Value of compatibility 1 corresponds to compatibility of two corresponding DAs, value 0 corresponds to incompatibility.

Stage 4. Generation of all admissible compositions (one DA for each system part) while taking into account compatibility for each two DAs in the composition obtained.

The method above is an enumerative one. Fig. 2 illustrates MA (binary compatibility estimates are depicted in Table 2).

| $S_1 = X_2^1 \ast \ldots \ast X_3^1 \ast \ldots \ast X_5^m$ |
| $P(1)$ | $X_1^1$ | $X_2^1$ | $X_3^1$ | $X_4^1$ | $X_5^1$ |
| $P(i)$ | $X_1^m$ | $X_2^m$ | $X_3^m$ | $X_4^m$ | $X_5^m$ |
| $P(m)$ |

Here the following morphological classes are examined: (a) morphological class 1: $\{X_1^1, X_2^1, X_3^1, X_4^1, X_5^1\}$, (b) morphological class 2: $\{X_1^i, X_2^i, X_3^i, X_4^i, X_5^i\}$, and (c) morphological class $m$: $\{X_1^m, X_2^m, X_3^m\}$. Further a simplified case is considered for three system parts (and corresponding morphological classes). The result (admissible) solution (composition or composite design alternative) is: $S_1 = X_2^1 \ast \ldots \ast X_3^1 \ast \ldots \ast X_5^m$.

3.2. Method of Closeness to Ideal Point

First, modification of MA as method of closeness to ideal point was suggested (e.g., [3], [13]). Illustration for method of closeness to ideal point is shown in Fig. 3 (binary compatibility estimates are contained in Table 3).

| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |
| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |
| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |
| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |
| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |
| $X_1^1$ | $X_1^m$ | $X_2^1$ | $X_2^m$ | $X_3^1$ | $X_3^m$ |

Here for each system part (from the corresponding morphological class) the best design alternatives (as an ideal) are selected (e.g., by expert judgment). In the illustrative example (Fig. 3), the ideal design alternatives are: $X_1^1, X_3^1,$ and $X_3^m$. Thus, the ideal point (i.e., solution) is: $S_0 = X_2^1 \ast \ldots \ast X_3^1 \ast \ldots \ast X_3^m$. Unfortunately, this solution $S_0$ is inadmissible (by compatibility). Admissible solutions are the following: $S_1 = X_2^1 \ast \ldots \ast X_3^1 \ast \ldots \ast X_5^m$ and $S_2 = X_5^1 \ast \ldots \ast X_3^1 \ast \ldots \ast X_3^m$. 

Fig. 3. Illustration for MA with ideal point
Let $\rho(S', S'')$ be a proximity (e.g., by elements) for two composite design alternatives $S', S'' \in \{S\}$. Then it is reasonable to search for the following solution $S^* \in \{S^o\} \subseteq \{S\}$ ($\{S^o\}$ is a set of admissible solutions): $S^* = \arg \min_{S \in \{S^o\}} \rho(S, S_o)$. Clearly, in the illustrative example solution $S_2 = X_1^* \ast \ldots \ast X_3^* \ast \ldots X_m^*$ is more close to ideal solution $S_o$ (i.e., $\rho(S_2, S_o) \leq \rho(S_1, S_o)$). Generally, various versions of proximity (as real functions, vectors, etc.) can be examined (e.g., [27], [60]).

### 3.3. Pareto-Based Morphological Approach

An integrated method (MA and multicriteria decision making, an enumerative method) was suggested as follows (e.g., [4]):

**Stage 1.** Usage of basic MA to get a set of admissible compositions.

**Stage 2.** Generation of criteria for evaluation of the admissible compositions.

**Stage 3.** Evaluation of admissible compositions upon criteria and selection of Pareto-efficient solutions.

Fig. 4 illustrates Pareto-based MA. Concurrently, binary compatibility estimates are depicted in Table 4. Further, the solutions have to be evaluated upon criteria and Pareto-efficient solution(s) will be selected. It is important to note that the estimate vector for each DA can contain estimates of compatibility as well. Pareto-based morphological approach was used by several students during the author’s course (instead of HMMD) ([37], [40], [43]).

#### 4. Here admissible solutions are the following:

Where $x_i = 1$ if item $i$ is selected, $c_i$ is a value ("utility") for item $i$, and $a_i$ is a weight (or resource required). Often nonnegative coefficients are assumed. The problem is NP-hard ([19], [60]) and can be solved by enumerative methods (e.g., Branch-and-Bound, dynamic programming), approximate schemes with a limited relative error (e.g., [27], [60]). In multiple choice problem (e.g., [60]), the items are divided into groups and we select element(s) from each group while taking into account a total resource constraint (or constraints). Here each element has two indices: $(i, j)$, where $i$ corresponds to number of group and $j$ corresponds to number of item in the group. In the case of multicriteria description, each element (i.e., $(i, j)$) has vector profit: $c_{i,j} = (c_{i,j}^1, \ldots, c_{i,j}^r, \ldots, c_{i,j}^t)$. and multicriteria multiple choice problem is ([50]):

### 4.4. Linear Programming

In [29], MA is reduced to linear programming. Here constraints imposed on the solution are reduced to a set of inequalities of Boolean variables and quality criterion for the solution as an additive function is used. In this case, well-known methods for linear programming problems can be used.

### 5.5. Multiple Choice Problem

The basic knapsack problem is (e.g., [19], [27], [60]):

$$\max \sum_{i=1}^{m} c_i x_i \quad s.t. \sum_{i=1}^{m} a_i x_i \leq b, \quad x_i \in \{0,1\}, \quad i = 1, m,$$

where $x_i = 1$ if item $i$ is selected, $c_i$ is a value ("utility") for item $i$, and $a_i$ is a weight (or resource required). Often nonnegative coefficients are assumed. The problem is NP-hard ([19], [60]) and can be solved by enumerative methods (e.g., Branch-and-Bound, dynamic programming), approximate schemes with a limited relative error (e.g., [27], [60]). In multiple choice problem (e.g., [60]), the items are divided into groups and we select element(s) from each group while taking into account a total resource constraint (or constraints). Here each element has two indices: $(i, j)$, where $i$ corresponds to number of group and $j$ corresponds to number of item in the group. In the case of multicriteria description, each element (i.e., $(i, j)$) has vector profit: $c_{i,j} = (c_{i,j}^1, \ldots, c_{i,j}^r, \ldots, c_{i,j}^t)$. and multicriteria multiple choice problem is ([50]):

$$\max \sum_{i=1}^{m} \sum_{j=1}^{q_i} c_{i,j} x_{ij}, \quad \forall \xi = 1, r \quad s.t. \sum_{i=1}^{m} \sum_{j=1}^{q_i} a_{i,j} x_{ij} \leq b, \quad \sum_{j=1}^{q_i} x_{ij} = 1 \quad \forall i = 1, m, \quad x_{ij} \in \{0,1\}.$$
For this problem formulation, it is reasonable to search for Pareto-efficient solutions. This design approach was used for design and redesign/improvement of applied systems (software, hardware, communication) ([44], [50], [70]). Here the following solving schemes can be used [50]: (i) enumerative algorithm based on dynamic programming, (ii) heuristic based on preliminary multicriteria ranking of elements to get their priorities and step-by-step packing the knapsack (i.e., greedy approach), (iii) multicriteria ranking of elements to get their ordinal priorities and usage of approximate solving scheme (as for knapsack) based on discrete space of system excellence (as later in HMMD).

3.6. Quadratic Assignment Problem

Assignment/allocation problems are widely used in many domains (e.g., [11], [19], [63]). Simple assignment problem involves nonnegative correspondence matrix \( Y = [c_{i,j}] \) \((i = 1, n; j = 1, n)\) where \(c_{i,j}\) is a profit ('utility') to assign element \(i\) to position \(j\). The problem is (e.g., [19]):

Find assignment \(\pi = (\pi(1), \ldots, \pi(i), \ldots, \pi(n))\) of elements \(i = 1, n\) to positions \(\pi(i)\) which corresponds to a total effectiveness: \(\sum_{i=1}^{n} c_{i,\pi(i)} \rightarrow \max\).

More complicated well-known model as quadratic assignment problem (QAP) includes interconnection between elements of different groups (each group corresponds to a certain position) (e.g., [11], [33], [63]). Let a nonnegative value \(d(i, j, k, j_2)\) be a profit of compatibility between item \(j_1\) in group \(J_l\) and item \(j_2\) in group \(J_k\). Also, this value of compatibility is added to the objective function. QAP may be considered as a version of MA. Thus, QAP can be formulated as follows:

\[
\begin{align*}
\max & \sum_{i=1}^{m} \sum_{j=1}^{n} c_{i,j}x_{i,j} + \sum_{l<k} \sum_{j_1=1}^{m} \sum_{j_2=1}^{n} d(l, j_1, k, j_2) x_{l,j_1} x_{k,j_2}, \quad l = 1, m, \quad k = 1, m; \\
\text{s.t.} & \quad \sum_{i=1}^{m} \sum_{j=1}^{n} a_{i,j} x_{i,j} \leq b, \quad \sum_{j=1}^{n} x_{i,j} \leq 1 \quad \forall i = 1, m, \quad x_{i,j} \in \{0, 1\}.
\end{align*}
\]

QAP is NP-hard. Enumerative methods (e.g., branch-and-bound) or heuristics (e.g., greedy algorithms, tabu search, genetic algorithms) are usually used for the problem. In the case of multicriteria assignment problem, the objective function is transformed into a vector function, i.e., \(c_{i,j} \Rightarrow \bar{c}_{i,j} = (c_{i,j}^1, \ldots, c_{i,j}^k, \ldots, c_{i,j}^r)\) and the vector objective function is, for example:

\[
(\sum_{i=1}^{m} \sum_{j=1}^{n} c_{i,j}^1 x_{i,j}, \ldots, \sum_{i=1}^{m} \sum_{j=1}^{n} c_{i,j}^k x_{i,j}, \ldots, \sum_{i=1}^{m} \sum_{j=1}^{n} c_{i,j}^r x_{i,j}).
\]

Here Pareto-efficient solutions are usually searched for.

3.7. Hierarchical Morphological Multicriteria Design

A basic description of Hierarchical Morphological Multicriteria Design (HMMD) is contained in ([33], [36], [39]). The assumptions of HMMD are the following: (a) a tree-like structure of the system; (b) a composite estimate for system quality that integrates components (subsystems, parts) qualities and qualities of interconnections (hereinafter referred as 'IC') across subsystems; (c) monotonic criteria for the system and its components; and (d) quality of system components and IC are evaluated on the basis of coordinated ordinal scales. The designations are: (1) design alternatives (DAs) for nodes of the model; (2) priorities of DAs \(P(i)\); (3) monotonic criteria for each pair of DAs \((w = 0, k; \ l \ corresponds \ to \ the \ best \ level)\); (3) ordinal compatibility estimates for each pair of DAs \((w = 0, k; \ l \ corresponds \ to \ the \ best \ level)\). The basic phases of HMMD are:

Phase 1. Design of the tree-like system model (a preliminary phase).

Phase 2. Generating DAs for leaf nodes of the system model.

Phase 3. Hierarchical selection and composing of DAs into composite DAs for the corresponding higher level of the system hierarchy (morphological clique problem).

Phase 4. Analysis and improvement of the resultant composite DAs (decisions).

Let \(S\) be a system consisting of \(m\) parts (components): \(P(1), P(2), \ldots, P(m)\) (Fig. 1). A set of DAs is generated for each system part above. The problem is:

Find composite design alternative \(S = S(1) \ast \ldots \ast S(i) \ast \ldots \ast S(m)\) of DAs (one representative design alternative \(S(i)\) for each system component/part \(P(i), i = 1, m\)) with non-zero IC estimates between the selected design alternatives.
A discrete space of the system quality is based on the following vector (Fig. 5): \( N(S) = (w(S); n(S)) \), where \( w(S) \) is the minimum of pairwise compatibility between DAs which correspond to different system components (i.e., \( \forall P_j \), and \( P_j, 1 \leq j_1 \neq j_2 \leq m \) in \( S \), \( n(S) = (n_1, ..., n_r, ..., n_k) \), where \( n_r \) is the number of DAs of the \( r \)th quality in \( S \) (\( \sum_{r=1}^{k} n_r = m \)). Here composite solutions (composite DAs) are searched for which are nondominated by \( N(S) \) (i.e., Pareto-efficient solutions) (Fig. 5).

In (33, 36), the described combinatorial problem is called morphological clique problem, this problem is NP-hard (because a more simple its subproblem is NP hard [28]). Generally, the following layers of system excellence can be considered (e.g., [33]): (i) ideal point; (ii) Pareto-efficient points; (iii) a neighborhood of Pareto-efficient DAs (e.g., a composite decision of this set can be transformed into a Pareto-efficient point on the basis of an improvement action(s)). Clearly, the compatibility component of vector \( N(S) \) can be considered on the basis of a poset-like scale too (as \( n(S) \)). In this case, the discrete space of system excellence will be an analogical lattice (34, 36).

Fig. 6 and Fig. 7 illustrate HMMD (by a numerical example for a system consisting of three parts \( S = X \setminus Y \setminus Z \)). Priorities of DAs are shown in Fig. 6 in parentheses and are depicted in Fig. 7. Table 5 contains compatibility estimates (they are pointed out in Fig. 7 too). In the example, composite decisions are (Pareto-efficient solutions) (Fig. 5, Fig. 6, Fig. 7, Fig. 8): \( S_1 = X_2 \setminus Y_2 \setminus Z_2 \), \( N(S_1) = (1; 2, 1, 0) \); \( S_2 = X_1 \setminus Y_2 \setminus Z_2 \), \( N(S_2) = (2; 1, 2, 0) \); \( S_3 = X_1 \setminus Y_1 \setminus Z_3 \), \( N(S_3) = (3; 0, 2, 1) \).

HMMD method was used to design various modular systems (e.g., packaged software, communication networks, security system, web-hosting system, car, telemetric system, test inputs in system testing, concrete technology, immunoassay technology, management for smart home, sensor node) (33, 35, 36, 38, 41, 45, 46, 48, 49, 51, 52, 55, 56). In addition, HMMD was used in modular system improvement processes (33, 35, 36, 42, 47, 57).

| Lattice: \( w = 1 \) | Lattice: \( w = 2 \) | Lattice: \( w = 3 \) |
|---------------------|---------------------|---------------------|
| \( < 3, 0, 0 > \)  | \( < 3, 0, 0 > \)  | \( < 3, 0, 0 > \)  |
| \( N(S_1) \)       | \( N(S_2) \)       | \( N(S_3) \)       |
| \( < 2, 1, 0 > \)  | \( < 2, 1, 0 > \)  | \( < 0, 1, 2 > \)  |
| \( < 2, 0, 1 > \)  | \( < 1, 2, 0 > \)  | \( < 0, 1, 2 > \)  |
| \( < 0, 1, 2 > \)  | \( < 0, 1, 2 > \)  | \( \)  |
| \( < 0, 0, 3 > \)  | \( < 0, 0, 3 > \)  | \( < 0, 0, 3 > \)  |

Fig. 5. Space of system quality (3 system parts, 3 levels of element quality)

| \( S = X \setminus Y \setminus Z \) | \( S_1 = X_2 \setminus Y_2 \setminus Z_2 \) | \( S_2 = X_1 \setminus Y_2 \setminus Z_2 \) |
|-----------------------------------|-----------------------------------|-----------------------------------|
| \( X \) | \( Y \) | \( Z \) |
| \( X_1(2) \) | \( Y_1(3) \) | \( Z_1(1) \) |
| \( X_2(1) \) | \( Y_2(2) \) | \( Z_2(1) \) |
| \( X_3(2) \) | \( Y_3(1) \) | \( Z_3(2) \) |

Fig. 6. Example of composition

| \( S = X \setminus Y \setminus Z \) | \( S_1 = X_2 \setminus Y_2 \setminus Z_2 \) | \( S_2 = X_1 \setminus Y_2 \setminus Z_2 \) |
|-----------------------------------|-----------------------------------|-----------------------------------|
| \( Z_1 \) | \( Z_2 \) | \( Z_1 \) |
| \( X_1(2) \) | \( Y_1(3) \) | \( Z_1(1) \) |
| \( X_2(1) \) | \( Y_2(2) \) | \( Z_2(1) \) |
| \( X_3(2) \) | \( Y_3(1) \) | \( Z_3(2) \) |

Fig. 7. Concentric presentation

| Table 5. Compatibility |
|------------------------|
| \( Y_1 \) | \( Y_2 \) | \( Z_1 \) | \( Z_2 \) |
| \( X_1 \) | 3 | 2 | 0 | 2 | 3 |
| \( X_2 \) | 0 | 3 | 0 | 1 | 0 |
| \( X_3 \) | 0 | 0 | 0 | 0 | 1 |
| \( Y_1 \) | 0 | 0 | 3 | 0 |
| \( Y_2 \) | 0 | 2 | 0 | 0 |
∀ { and Table 8 presents realistic aggregated compatibility { and realistic aggregated priorities { alternatives (r membership function of priority 3.8. Morphological Multicriteria Design (Uncertainty).

Here a brief description of the approach is presented (by a simplified example). Fuzzy estimates for DAs or/and IC are considered. The following designations are used: (1) i is an index corresponding to the design alternative; (2) µr(i) is a membership function of priority r(i) ∈ {1, 2, 3}, we consider the following set: µl(i), l = 1,...,3 (l corresponds to value of priority); and (3) µw(i1, i2) is a membership function of compatibility w(i1, i2) between alternatives i1 and i2, we use the following set: {µk(i1, i2), k = 0,...,3} (k corresponds to value of pairwise compatibility). Thus, let µw(i1, i2) be the following vector (i.e., pairwise compatibility vector): (µk(i1, i2), µk(i1, i2), µk(i1, i2), µk(i1, i2)).

Thus, the following relationships over the set of DAs can be obtained (by fuzzy priorities): (a) A1 > A2; (b) B1 > B2; and (c) C1 and C2 are non-comparable. Now it is reasonable to examine the following cases:

Case 1: deterministic (aggregated) estimates of priorities for DAs {rα(i)} and deterministic (aggregated) estimates of compatibility for IC {wα(i1, i2)} (a basic case).

Case 2: estimates of DAs are aggregated (deterministic) {rα(i)}, and estimates of compatibility are fuzzy {µw(i1, i2)}, ∀(i1, i2).

Case 3: estimates of DAs are fuzzy {µl(i)} ∀i and estimates of IC are aggregated (deterministic) {wα(i1, i2)}, ∀(i1, i2).

Case 4: estimates of DAs are fuzzy {µl(i)} ∀i and estimates of compatibility are fuzzy {µw(i1, i2)}, ∀(i1, i2).

Thus, the following relationships over the set of DAs can be obtained (by fuzzy priorities): (a) A1 > A2; (b) B1 > B2; and (c) C1 and C2 are non-comparable. Now it is reasonable to examine the following cases:

Case 1: deterministic (aggregated) estimates of priorities for DAs {rα(i)} and deterministic (aggregated) estimates of compatibility for IC {wα(i1, i2)} (a basic case).

Case 2: estimates of DAs are aggregated (deterministic) {rα(i)}, and estimates of compatibility are fuzzy {µw(i1, i2)}, ∀(i1, i2).

Case 3: estimates of DAs are fuzzy {µl(i)} ∀i and estimates of IC are aggregated (deterministic) {wα(i1, i2)}, ∀(i1, i2).

Case 4: estimates of DAs are fuzzy {µl(i)} ∀i and estimates of compatibility are fuzzy {µw(i1, i2)}, ∀(i1, i2).

The ideal point

\[ w = 1 \]

\[ w = 2 \]

\[ w = 3 \]

Fig. 8. Illustration for space of quality

3.8. Morphological Multicriteria Design (Uncertainty)

The version of HMMD under uncertainty has been suggested in [33]. Here a brief description of the approach is presented (by a simplified example). Fuzzy estimates for DAs or/and IC are considered. The following designations are used: (1) i is an index corresponding to the design alternative; (2) µr(i) is a membership function of priority r(i) ∈ {1, 2, 3}, we consider the following set: µl(i), l = 1,...,3 (l corresponds to value of priority); and (3) µw(i1, i2) is a membership function of compatibility w(i1, i2) between alternatives i1 and i2, we use the following set: {µk(i1, i2), k = 0,...,3} (k corresponds to value of pairwise compatibility). Thus, let µw(i1, i2) be the following vector (i.e., pairwise compatibility vector): (µk(i1, i2), µk(i1, i2), µk(i1, i2), µk(i1, i2)).

Now let rα(i) and wα(i1, i2) be aggregated estimates for design alternative i, and for a pair of design alternatives (i1, i2) accordingly.

Here a basic system example is depicted in Fig. 9. Table 6 contains normalized fuzzy priorities \{µl(i)\} and realistic aggregated priorities \{rα(i)\}. Table 7 contain normalized fuzzy compatibility \{µw(i1, i2)\}, and Table 8 presents realistic aggregated compatibility \{wα(i1, i2)\}.

Table 6. Fuzzy priorities

| DAs i | µl1(i) | µl2(i) | µl3(i) | rα(i) |
|-------|--------|--------|--------|------|
| A1    | 1.00   | 0.00   | 0.00   | 1    |
| A2    | 0.00   | 0.05   | 0.95   | 3    |
| B1    | 0.15   | 0.65   | 0.20   | 2    |
| B2    | 0.85   | 0.15   | 0.00   | 1    |
| C1    | 1.00   | 0.00   | 0.00   | 1    |
| C2    | 0.00   | 1.00   | 0.00   | 2    |

Fig. 9. Example of system
Fig. 10 illustrates the cases above (top index of composite DAs corresponds to the case).

Clearly, that main solving method is based on two stages: (1) generation of feasible composite decisions; and (2) selection of Pareto-efficient decisions. Unfortunately, it is reasonable to point out the following two significant features of our synthesis problem with fuzzy estimates: (a) complexity of corresponding combinatorial problems is increasing because a number of analyzed composite decisions is more than in deterministic case; and (b) it is necessary to construct a preference rule to select the best fuzzy decision(s).

4. Design Examples for GSM Network

In recent two decades, the significance of GSM network has been increased (e.g., [12], [20], [22], [58], [61], [64], [74]). Thus, there exists a need of the design and maintenance of this kind of communication systems. Here a numerical example for design of GSM network (a modification of an example from [50]) is used to illustrate and to compare several MA-based methods: basic MA, method of closeness to ideal point, Pareto-based MA, multiple choice problem, and HMMD.
4.1. Initial Example

The general tree-like simplified model of GSM network is as follows (Fig. 11, the developers of DAs are pointed out in parentheses):

0. GSM network \( S = A \ast B \).
1. Switching SubSystem SSS (\( A = M \ast L \)).
   1.1. Mobile Switching Center/Visitors Location Register MSC/VLR \( M : M_1 \) (Motorola), \( M_2 \) (Alcatel), \( M_3 \) (Huawei), \( M_4 \) (Siemens), and \( M_5 \) (Ericsson).
   1.2. Home Location Register/Authentification Center HLR/AC \( L : L_1 \) (Motorola), \( L_2 \) (Ericsson), \( L_3 \) (Alcatel), and \( L_4 \) (Motorola).
2. Base Station SubSystem BSS (\( B = V \ast U \ast T \)).
   2.1. Base Station Controller BSC \( V : V_1 \) (Motorola), \( V_2 \) (Ericsson), \( V_3 \) (Alcatel), \( V_4 \) (Huawei), \( V_5 \) (Nokia), and \( V_6 \) (Siemens).
   2.2. Base Transceiver Station BTS \( U : U_1 \) (Motorola), \( U_2 \) (Ericsson), \( U_3 \) (Alcatel), \( U_4 \) (Huawei), and \( U_5 \) (Nokia).
   2.3. Transceivers TRx \( T : T_1 \) (Alcatel), \( T_2 \) (Ericsson), \( T_3 \) (Motorola), \( T_4 \) (Huawei), and \( T_5 \) (Siemens).

Note an initial set of possible composite decisions contained 3000 combinations (\( 5 \times 4 \times 6 \times 5 \times 5 \)).

\[
\text{GSM network } S = A \ast B = (M \ast L) \ast (V \ast U \ast T)
\]

Fig. 11. General simplified structure of GSM network

Let us consider criteria for system components as follows (weights of criteria are pointed out in parentheses):

1. \( M \): maximal number of datapathes (1000 pathes) \( (C_{m_1}, 0.2) \); maximal capacity VLR (100000 subscribers) \( (C_{m_2}, 0.2) \); price index \( (100000/\text{price(USD)}) \) \( (C_{m_3}, 0.2) \); power consumption \( (1/\text{power consumption(kWt)}) \) \( (C_{m_4}, 0.2) \); and number of communication and signaling interfaces \( (C_{m_5}, 0.2) \).
2. \( L \): maximal number of subscribers (100000 subscribers) \( (C_{l_1}, 0.25) \); volume of service provided \( (C_{l_2}, 0.25) \); reliability (scale \([1, ..., 10]\)) \( (C_{l_3}, 0.25) \); and integratability (scale \([1, ..., 10]\)) \( (C_{l_4}, 0.25) \).
3. \( V \): price index \( (100000/\text{cost(USD)}) \) \( (C_{v_1}, 0.25) \); maximal number of BTS \( (C_{v_2}, 0.25) \); handover quality \( (C_{v_3}, 0.25) \); and throughput \( (C_{v_4}, 0.25) \).
4. \( U \): maximal number of TRx \( (C_{u_1}, 0.25) \); capacity \( (C_{u_2}, 0.25) \); price index \( (100000/\text{cost(USD)}) \) \( (C_{u_3}, 0.25) \); and reliability (scale \([1, ..., 10]\)) \( (C_{u_4}, 0.25) \).
5. \( T \): maximum power-carrying capacity \( (C_{t_1}, 0.3) \); throughput \( (C_{t_2}, 0.2) \); price index \( (100000/\text{cost(USD)}) \) \( (C_{t_3}, 0.25) \); and reliability (scale \([1, ..., 10]\)) \( (C_{t_4}, 0.25) \).

Tables 9, 10, 11, 12, and 13 contain estimates of DAs upon criteria above (data from catalogues, expert judgment) and their resultant priorities (the priorities are based on multicriteria ranking by an outranking technique \[\text{\textit{[67]}}\]). Compatibility estimates are contained in Tables 14 and 15 (expert judgment).

| Table 9. Estimates for \( M \) |
|-----------------------------|
| Criteria        | Priority \( r \) |
| \( C_{m_1} \) | \( C_{m_2} \) | \( C_{m_3} \) | \( C_{m_4} \) | \( C_{m_5} \) | \( r \) |
| \( M_1 \)     | 3.7       | 8.6       | 6         | 5.1      | 4         | 2 |
| \( M_2 \)     | 4.0       | 11        | 8         | 7        | 5         | 3 |
| \( M_3 \)     | 4.1       | 10        | 9         | 7        | 4         | 3 |
| \( M_4 \)     | 3.2       | 7         | 5         | 6        | 3         | 1 |
| \( M_5 \)     | 3.5       | 8.7       | 6.2       | 5        | 4         | 2 |
Table 10. Estimates for L

| DAs | Criteria | Priority r |
|-----|----------|------------|
|     | C_{t1}  | C_{t2} | C_{t3} | C_{t4} |     |
| L_1 | 9      | 7 | 7 | 7 | 8 | 1 |
| L_2 | 10     | 4 | 9 | 8 | 1 |
| L_3 | 12     | 8 | 10| 10| 2 |
| L_4 | 9      | 5 | 8 | 8 | 1 |

Table 11. Estimates for V

| DAs | Criteria | Priority r |
|-----|----------|------------|
|     | C_{v1}  | C_{v2} | C_{v3} | C_{v4} |     |
| V_1 | 6      | 4 | 3 | 4 | 1 |
| V_2 | 7      | 5 | 7 | 7 | 2 |
| V_3 | 9      | 7 | 10| 7 | 3 |
| V_4 | 7      | 5 | 8 | 6 | 2 |
| V_5 | 6      | 3 | 4 | 4 | 1 |

Table 12. Estimates for U

| DAs | Criteria | Priority r |
|-----|----------|------------|
|     | C_{u1}  | C_{u2} | C_{u3} | C_{u4} |     |
| U_1 | 2      | 7 | 5 | 8 | 1 |
| U_2 | 4      | 10| 6 | 10| 3 |
| U_3 | 3      | 9 | 6 | 10| 2 |
| U_4 | 3      | 6 | 3 | 7 | 1 |
| U_5 | 3      | 10| 6 | 9 | 2 |

Table 15. Compatibility

| L_1 | L_2 | L_3 | L_4 |
|-----|-----|-----|-----|
| M_1 | 3   | 2   | 0   | 3 |
| M_2 | 2   | 3   | 2   | 0 |
| M_3 | 0   | 2   | 3   | 2 |
| M_4 | 2   | 3   | 3   | 3 |
| M_5 | 3   | 3   | 0   | 3 |

Table 13. Estimates for T

| DAs | Criteria | Priority r |
|-----|----------|------------|
|     | C_{t1}  | C_{t2} | C_{t3} | C_{t4} |     |
| T_1 | 9      | 7 | 10 | 7 | 3 |
| T_2 | 6      | 4 | 3  | 4 | 1 |
| T_3 | 7      | 5 | 7  | 7 | 2 |
| T_4 | 7      | 5 | 8  | 6 | 2 |
| T_5 | 6      | 3 | 4  | 4 | 1 |

Table 14. Compatibility

| L_1 | L_2 | L_3 | L_4 |
|-----|-----|-----|-----|
| U_1 | 2   | 0   | 2   | 3 |
| U_2 | 0   | 2   | 0   | 3 |
| U_3 | 0   | 2   | 0   | 3 |
| U_4 | 0   | 3   | 0   | 0 |
| U_5 | 3   | 0   | 2   | 2 |

4.2. Morphological Analysis

In the case of basic MA, binary compatibility estimates are used. To decrease the dimension of the considered numerical example, the following version of MA is examined. Let us consider more strong requirements to compatibility: (Tables 16 and 17): (i) new compatibility estimate equals 1 if the old estimate was equal 3, (ii) new compatibility estimate equals 1 if the old estimate was equal 0 or 1 or 2. Clearly, here we can get some negative results, for example: (a) admissible solutions are absent, (b) some sufficiently good solutions (e.g., solutions with one/two compatibility estimate at the only admissible/good levels as 1 or 2) will be lost. As a result, the following admissible DAs can be analyzed:

(1) nine DAs for A: A_1 = M_1 * L_1, A_2 = M_1 * L_4, A_3 = M_2 * L_2, A_4 = M_3 * L_3, A_5 = M_4 * L_2, A_6 = M_4 * L_3, A_7 = M_5 * L_1, A_8 = M_5 * L_2, and A_9 = M_5 * L_4;

(2) two DAs for B: B_1 = U_1 * U_5 * T_1, B_2 = U_2 * U_2 * T_4, B_3 = U_3 * U_3 * T_4, B_4 = V_3 * U_2 * T_4, and B_5 = V_3 * U_3 * T_4;

and the resultant composite DAs are: S_1 = A_1 * B_1, S_2 = A_2 * B_1, S_3 = A_3 * B_1, S_4 = A_4 * B_1, S_5 = A_5 * B_1, S_6 = A_5 * B_1, S_7 = A_7 * B_1, S_8 = A_8 * B_1, S_9 = A_9 * B_1; S_{10} = A_1 * B_2, S_{11} = A_2 * B_2, S_{12} = A_3 * B_2, S_{13} = A_4 * B_2, S_{14} = A_5 * B_2, S_{15} = A_6 * B_2, S_{16} = A_7 * B_2, S_{17} = A_8 * B_2, S_{18} = A_9 * B_2; S_{19} = A_1 * B_3, S_{20} = A_2 * B_3, S_{21} = A_3 * B_3, S_{22} = A_4 * B_3, S_{23} = A_5 * B_3, S_{24} = A_6 * B_3, S_{25} = A_7 * B_3, S_{26} = A_8 * B_3, S_{27} = A_9 * B_3, S_{28} = A_1 * B_4, S_{29} = A_2 * B_4, S_{30} = A_3 * B_4, S_{31} = A_4 * B_4, S_{32} = A_5 * B_4, S_{33} = A_6 * B_4, S_{34} = A_7 * B_4, S_{35} = A_8 * B_4, S_{36} = A_9 * B_4; S_{37} = A_1 * B_5, S_{38} = A_2 * B_5, S_{39} = A_3 * B_5, S_{40} = A_4 * B_5, S_{41} = A_5 * B_5, S_{42} = A_6 * B_5, S_{43} = A_7 * B_5, S_{44} = A_8 * B_5, and S_{45} = A_9 * B_5.
Finally, the next step has to consist in selection of the best solution.

Table 16. Compatibility

| L1 | L2 | L3 | L4 |
|----|----|----|----|
| M₁ | 1  | 0  | 1  |
| M₂ | 0  | 1  | 0  |
| M₃ | 0  | 0  | 1  |
| M₄ | 0  | 1  | 1  |
| M₅ | 1  | 1  | 0  | 1 |

Table 17. Compatibility

| U₂  | U₅  | T₁  | T₂  | T₃  | T₄  | T₅  |
|-----|-----|-----|-----|-----|-----|-----|
| V₁  | 0  | 0  | 0  | 1  | 1  | 0  | 0  |
| V₂  | 1  | 1  | 1  | 0  | 0  | 0  | 1  |
| V₃  | 1  | 1  | 1  | 0  | 0  | 0  | 1  |
| V₄  | 1  | 0  | 0  | 1  | 0  | 0  | 0  |
| V₅  | 1  | 0  | 0  | 0  | 0  | 0  | 0  |
| V₆  | 0  | 1  | 0  | 1  | 0  | 1  | 0  |
| U₁  | 0  | 0  | 1  | 0  |
| U₂  | 0  | 0  | 1  | 0  |
| U₃  | 0  | 0  | 1  | 0  |
| U₄  | 0  | 1  | 1  | 0  |
| U₅  | 1  | 0  | 0  | 0  |

4.3. Method of Closeness to Ideal Point

Here the initial set of admissible solutions corresponds to the solution set that was obtained in previous case (i.e., basic MA). Evidently, this approach depended on the kind of the proximity between the ideal point \( S' \) and examined solutions.

First of all, let us consider estimate vector for each admissible solution (basic estimates are contained in Tables 9, 10, 11, 12, and 13):

\[
\bar{z} = (z_M \bigcup z_L \bigcup z_U \bigcup z_T) = (z_{m1}, z_{m2}, z_{m3}, z_{m4}, z_{m5}, z_{l1}, z_{l2}, z_{l3}, z_{l4}, z_{c1}, z_{c2}, z_{c3}, z_{c4}, z_{u1}, z_{u2}, z_{u3}, z_{t1}, z_{t2}, z_{t3}, z_{t4}).
\]

On the other hand, it may be reasonable to consider a simplified version of the estimate vector as follows: \( \hat{z} = (r_M, r_L, r_U, r_T) \), where \( r_M, r_L, r_U, r_T \) are the priorities of DAs which are obtained for local DAs (for \( M \), for \( L \), for \( V \), for \( U \), and for \( T \); Table 9, Table 10, Table 11, Table 12, Table 13). To simplify the considered example, the second case of the estimate vector is used. Thus, the resultant vector estimates (i.e., \( \{\hat{z}\} \)) for examined 45 admissible solutions are contained in Tables 18 and 19. Evidently, it is reasonable to consider the estimate vector for the ideal solution as follows: \( \hat{z}_I = (1, 1, 1, 1, 1) \). Now let us use a simplified proximity function between ideal solution \( I \) and design alternative DA as follows (i.e., metric like \( l^2 \)):

\[
\rho(I, DA) = \sqrt{\sum_{k \in \{M, L, V, U, T\}} (z_k(I) - z_k(\hat{DA}))^2}.
\]

The resultant proximity is presented in Tables 18 and 19. Finally, the best composite design alternative (by the minimal proximity) is: \( S'_6 = S_{27} = A_9 \ast B_3 = M_5 \ast L_4 \ast V_2 \ast U_3 \ast T_4 \) (\( \rho = 1.7321 \)). Several composite DAs are very close to the best one, for example:

\[
S'_1 = S_{19} = A_1 \ast B_3 = M_1 \ast L_1 \ast V_2 \ast U_3 \ast T_4 \ (\rho = 2.0), \quad S'_2 = S_{20} = A_2 \ast B_3 = M_1 \ast L_4 \ast V_2 \ast U_3 \ast T_4 \ (\rho = 2.0), \quad S'_3 = S_{24} = A_6 \ast B_3 = M_4 \ast L_2 \ast V_3 \ast U_3 \ast T_4 \ (\rho = 2.0), \quad S'_4 = S_{25} = A_3 \ast B_3 = M_5 \ast L_1 \ast V_2 \ast U_4 \ast T_4 \ (\rho = 2.0), \quad S'_5 = S_{26} = A_8 \ast B_3 = M_5 \ast L_2 \ast V_3 \ast U_2 \ast T_4 \ (\rho = 2.0), \quad S'_6 = S_{27} = A_9 \ast B_3 = M_5 \ast L_4 \ast V_2 \ast U_3 \ast T_4 \ (\rho = 2.0).
\]

It may be reasonable to point out several prospective directions for the improvement of this method:

1. consideration of special types of proximity between solutions and the ideal point (e.g., ordinal proximity, vector-like proximity etc.);
2. usage of special expert judgment interactive procedures for the assessment of the proximity;
3. consideration of a set of ideal points (the set can be generated by domain expert(s)); and
4. design of special support visualization tools which will aid domain expert(s) in his/her (their) activity (i.e., generation of the ideal point and assessment of proximity).

In addition let us list the basic approaches to generation of the ideal point(s):
1. consideration of design alternative with the estimate vector in which each component equals the best value of the design alternatives estimates (by the corresponding criterion, i.e., minimum or maximum);
2. consideration of design alternative with the estimate vector in which each component equals the best value of the corresponding criterion scale (i.e., minimum or maximum);
3. expert judgment based generation design alternative(s);
4. projection of expert judgment based design alternatives into convex shell of the set of Pareto-efficient points; etc.

| DAs   | \( \vec{z} \) | Closeness to ideal point | Membership of Pareto-set |
|-------|----------------|--------------------------|--------------------------|
| \( S_1 \) | (2, 1, 1, 2, 3) | 2.4495 | No |
| \( S_2 \) | (2, 1, 1, 2, 3) | 2.4495 | No |
| \( S_3 \) | (3, 1, 1, 2, 3) | 3.0 | No |
| \( S_4 \) | (3, 2, 1, 2, 3) | 3.1623 | No |
| \( S_5 \) | (1, 1, 1, 2, 3) | 2.2361 | Yes |
| \( S_6 \) | (1, 2, 1, 2, 3) | 2.4495 | No |
| \( S_7 \) | (2, 1, 1, 2, 3) | 2.4495 | No |
| \( S_8 \) | (2, 1, 1, 2, 3) | 2.4495 | No |
| \( S_9 \) | (2, 1, 1, 2, 3) | 2.4495 | No |
| \( S_{10} \) | (2, 1, 2, 3, 2) | 2.6458 | No |
| \( S_{11} \) | (2, 1, 2, 3, 2) | 2.6458 | No |
| \( S_{12} \) | (3, 1, 2, 3, 2) | 3.1623 | No |
| \( S_{13} \) | (3, 2, 2, 3, 2) | 3.3166 | No |
| \( S_{14} \) | (1, 1, 2, 3, 2) | 2.4495 | No |
| \( S_{15} \) | (1, 2, 2, 3, 2) | 2.6458 | No |
| \( S_{16} \) | (2, 1, 2, 3, 2) | 2.6458 | No |
| \( S_{17} \) | (2, 1, 2, 3, 2) | 2.6458 | No |
| \( S_{18} \) | (2, 1, 2, 3, 2) | 2.6458 | No |
| \( S_{19} \) | (2, 1, 2, 2, 2) | 2.0 | No |
| \( S_{20} \) | (2, 1, 2, 2, 2) | 2.0 | No |
| \( S_{21} \) | (3, 1, 2, 2, 2) | 2.6458 | No |
| \( S_{22} \) | (3, 2, 2, 2, 2) | 2.8284 | No |
| \( S_{23} \) | (1, 1, 2, 2, 2) | 1.7321 | Yes |

Table 19. Estimates of admissible solutions

| DAs   | \( \vec{z} \) | Closeness to ideal point | Membership of Pareto-set |
|-------|----------------|--------------------------|--------------------------|
| \( S_{24} \) | (1, 2, 2, 2, 2) | 2.0 | No |
| \( S_{25} \) | (2, 1, 2, 2, 2) | 2.0 | No |
| \( S_{26} \) | (2, 1, 2, 2, 2) | 2.0 | No |
| \( S_{27} \) | (2, 1, 2, 2, 2) | 2.0 | No |
| \( S_{28} \) | (2, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{29} \) | (2, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{30} \) | (3, 1, 3, 3, 2) | 3.6056 | No |
| \( S_{31} \) | (3, 2, 3, 3, 2) | 3.7417 | No |
| \( S_{32} \) | (1, 1, 3, 3, 2) | 3.0 | No |
| \( S_{33} \) | (1, 2, 3, 3, 2) | 3.1623 | No |
| \( S_{34} \) | (2, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{35} \) | (2, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{36} \) | (2, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{37} \) | (2, 1, 3, 3, 2) | 2.6458 | No |
| \( S_{38} \) | (2, 1, 3, 3, 2) | 2.6458 | No |
| \( S_{39} \) | (3, 1, 3, 3, 2) | 3.1623 | No |
| \( S_{40} \) | (3, 2, 3, 3, 2) | 3.3166 | No |
| \( S_{41} \) | (1, 1, 3, 3, 2) | 2.4495 | No |
| \( S_{42} \) | (1, 2, 3, 3, 2) | 2.6458 | No |
| \( S_{43} \) | (2, 1, 3, 3, 2) | 2.658 | No |
| \( S_{44} \) | (2, 1, 3, 2, 2) | 2.6458 | No |
| \( S_{45} \) | (2, 1, 3, 2, 2) | 2.6458 | No |

4.4. Pareto-based Morphological Analysis

Here the initial set of admissible solutions corresponds to the previous case of basic MA. Two approaches can be used for multicriteria assessment of admissible solutions:

1. Basic method: selection of Pareto-efficient solutions over the set of admissible composite solutions on the basis of usage of the initial set of criteria for assessment of each admissible composite DAs;
2. Two-stage method:
   (i) assessment of initial components by the corresponding criteria and ranking of the alternative components to get an ordinal priority for each component,
   (ii) selection of Pareto-efficient solutions over the set of admissible composite solutions on the basis of usage of the vector estimates which integrate priorities of solution components above. The results of the Pareto-based MA are presented in Tables 18 and 19, i.e., the resultant (Pareto-efficient) DAs are: (i) \( S_i^p = S_5 = A_5 \ast B_1 = M_4 \ast L_2 \ast V_1 \ast U_5 \ast T_1 \) and (ii) \( S_i^p = S_23 = A_5 \ast B_3 = M_4 \ast L_2 \ast V_2 \ast U_3 \ast T_4 \).

4.5. Multiple Choice Problem

Multiple choice problem with 5 groups of elements (i.e., for \( M, L, V, U, T \)) is examined (Fig. 12). Evidently, here it is reasonable to examine multicriteria multiple choice problem. In the example, a simplified problem solving approach is considered (Table 20):

(i) a simple greedy heuristic based on element priorities is used;
(ii) for each element (i.e., \( i, j \)) 'profit' is computed as follows: \( c_{i,j} = 4 - r_{i,j} \);
(iii) for each element (i.e., \( i, j \)) a required resource is computed as follows: \( a_{i,j} = 11 - z_{i,j} \) where \( z_{i,j} \)
equals: (a) for $M$: the estimate upon criterion $C_{m3}$ (Table 9), (b) for $L$: 1.0, (c) for $V$: the estimate upon criterion $C_{v1}$ (Table 11), (d) for $U$: the estimate upon criterion $C_{u3}$ (Table 12), and (e) for $T$: the estimate upon criterion $C_{mt3}$ (Table 13).

\[ S = M \times L \times V \times U \times T \]

| No. $(i, j)$ | DAs | Priority $r$ | Resource requirement $a_{i,j}$ | $c_{i,j}/a_{i,j}$ | Selection (constraint: $\leq 14$) | Selection (constraint: $\leq 15$) |
|--------------|-----|--------------|-------------------------------|-----------------|-------------------------------|-------------------------------|
| (1, 1)       | $M_1$ | 2            | 5.0                           | 0.4             | No                            | No                            |
| (1, 2)       | $M_2$ | 3            | 3.0                           | 0.33            | No                            | No                            |
| (1, 3)       | $M_3$ | 3            | 2.0                           | 0.5             | No                            | No                            |
| (1, 4)       | $M_4$ | 1            | 6.0                           | 0.5             | Yes                           | Yes                           |
| (1, 5)       | $M_5$ | 2            | 4.8                           | 0.38            | No                            | No                            |
| (2, 1)       | $L_1$ | 1            | 1.0                           | 3.0             | Yes                           | Yes                           |
| (2, 2)       | $L_2$ | 1            | 1.0                           | 3.0             | No                            | No                            |
| (2, 3)       | $L_3$ | 2            | 1.0                           | 2.0             | No                            | No                            |
| (2, 4)       | $L_4$ | 1            | 1.0                           | 3.0             | No                            | No                            |
| (3, 1)       | $V_1$ | 1            | 5.0                           | 0.6             | No                            | No                            |
| (3, 2)       | $V_2$ | 2            | 4.0                           | 0.5             | No                            | No                            |
| (3, 3)       | $V_3$ | 3            | 2.0                           | 0.5             | No                            | No                            |
| (3, 4)       | $V_4$ | 2            | 4.0                           | 0.5             | No                            | No                            |
| (3, 5)       | $V_5$ | 1            | 5.0                           | 0.6             | No                            | No                            |
| (3, 6)       | $V_6$ | 3            | 1.0                           | 1.0             | Yes                           | Yes                           |
| (4, 1)       | $U_1$ | 1            | 6.0                           | 0.5             | No                            | Yes                           |
| (4, 2)       | $U_2$ | 3            | 5.0                           | 0.2             | No                            | No                            |
| (4, 3)       | $U_3$ | 2            | 5.0                           | 0.4             | Yes                           | No                            |
| (4, 4)       | $U_4$ | 3            | 8.0                           | 0.39            | No                            | No                            |
| (4, 5)       | $U_5$ | 2            | 5.0                           | 0.4             | No                            | No                            |
| (5, 1)       | $T_1$ | 3            | 1.0                           | 1.0             | Yes                           | Yes                           |
| (5, 2)       | $T_2$ | 1            | 8.0                           | 0.39            | No                            | No                            |
| (5, 3)       | $T_3$ | 2            | 4.0                           | 0.5             | No                            | No                            |
| (5, 4)       | $T_4$ | 2            | 3.0                           | 0.66            | No                            | No                            |
| (5, 5)       | $T_5$ | 1            | 7.0                           | 0.42            | No                            | No                            |

Thus, the following simplified one-objective problem is considered:

\[
\max \sum_{i=1}^{5} \sum_{j=1}^{5} c_{ij}x_{ij} \quad \text{s.t.} \quad \sum_{i=1}^{5} \sum_{j=1}^{5} a_{ij}x_{ij} \leq b, \quad \sum_{j=1}^{5} x_{ij} = 1 \quad \forall i = 1,5, \quad x_{ij} \in \{0, 1\},
\]

where $q_1 = 5$, $q_2 = 4$, $q_3 = 6$, $q_4 = 5$, $q_5 = 5$. After the usage of the greedy heuristic, the following composite DAs are obtained (Table 20):

1. resource constraint $b = 14$: $S^C_1 = M_4 \times L_1 \times V_6 \times U_3 \times T_1$,
2. resource constraint $b = 15$: $S^C_2 = M_4 \times L_1 \times V_6 \times U_1 \times T_1$.  

---

Fig. 12. Designed GSM network (priorities of DAs are shown in parentheses)

Table 20. Example for multiple choice problem
4.6. Hierarchical Morphological Design

A preliminary example for HMMD was presented in [50] (Fig. 13). For system part A, we get the following Pareto-efficient composite DAs: (1) \( A_1 = M_4 \ast L_2, \ N(A_1) = (3; 2, 0, 0) \); (2) \( A_2 = M_4 \ast L_4, \ N(A_2) = (3; 2, 0, 0) \). For system part \( B \), we get the following Pareto-efficient composite DAs: (1) \( B_1 = V_5 \ast U_1 \ast T_5, \ N(B_1) = (2; 3, 0, 0) \); (2) \( B_2 = V_5 \ast U_4 \ast T_2, \ N(B_2) = (2; 3, 0, 0) \); (3) \( B_3 = V_1 \ast U_5 \ast T_1, \ N(B_3) = (3; 1, 1, 1) \), and (4) \( B_4 = V_2 \ast U_3 \ast T_4, \ N(B_4) = (3; 0, 3, 0) \). Fig. 14 illustrates system quality for \( B \).

\[
S = A \ast B = (M \ast L) \ast (V \ast U \ast T)
\]

\[
S_1 = A_1 \ast B_1 = (M_4 \ast L_2) \ast (V_5 \ast U_1 \ast T_5)
\]

\[
S_2 = A_1 \ast B_2 = (M_4 \ast L_2) \ast (V_5 \ast U_4 \ast T_2)
\]

\[
S_3 = A_1 \ast B_3 = (M_4 \ast L_2) \ast (V_1 \ast U_5 \ast T_1)
\]

\[
S_4 = A_2 \ast B_1 = (M_4 \ast L_4) \ast (V_5 \ast U_1 \ast T_5)
\]

\[
S_5 = A_2 \ast B_2 = (M_4 \ast L_4) \ast (V_5 \ast U_4 \ast T_2)
\]

\[
S_6 = A_2 \ast B_3 = (M_4 \ast L_4) \ast (V_1 \ast U_5 \ast T_1)
\]

\[
S_7 = A_1 \ast B_4 = (M_4 \ast L_2) \ast (V_2 \ast U_3 \ast T_4)
\]

\[
S_8 = A_2 \ast B_4 = (M_4 \ast L_4) \ast (V_2 \ast U_3 \ast T_4)
\]

SSS \( A = M \ast L \)

BSS \( B = V \ast U \ast T \)

\[
A_1 = M_4 \ast L_2
\]

\[
A_2 = M_4 \ast L_4
\]

\[
M \quad L
\]

MSC/ HLR/ VLR

AC

V1(1)

BSC

BTS

TRx

V2(2)

U1(1)

T1(3)

V3(3)

U3(2)

T3(2)

V5(1)

U5(2)

T5(1)

V6(3)

Fig. 13. Designed GSM network (priorities of DAs are shown in parentheses)

\[
N(B_1), N(B_2)
\]

The ideal point

\[
N(B_3), N(B_4)
\]

\[
w = 1
\]

\[
w = 2
\]

\[
w = 3
\]

Fig. 14. Space of system quality for \( B \)

Now it is possible to combine the resultant composite DAs as follows (Fig. 13):

1. \( S_1^H = A_1 \ast B_1 = (M_4 \ast L_2) \ast (V_5 \ast U_1 \ast T_5) \);
2. \( S_2^H = A_1 \ast B_2 = (M_4 \ast L_2) \ast (V_5 \ast U_4 \ast T_2) \);
3. \( S_3^H = A_1 \ast B_3 = (M_4 \ast L_2) \ast (V_1 \ast U_5 \ast T_1) \);
4. \( S_4^H = A_2 \ast B_1 = (M_4 \ast L_4) \ast (V_5 \ast U_1 \ast T_5) \);
5. \( S_5^H = A_2 \ast B_2 = (M_4 \ast L_4) \ast (V_5 \ast U_4 \ast T_2) \);
6. \( S_6^H = A_2 \ast B_3 = (M_4 \ast L_4) \ast (V_1 \ast U_5 \ast T_1) \);
7. \( S_7^H = A_1 \ast B_4 = (M_4 \ast L_2) \ast (V_2 \ast U_3 \ast T_4) \);
8. \( S_8^H = A_2 \ast B_4 = (M_4 \ast L_4) \ast (V_2 \ast U_3 \ast T_4) \).
Finally, it is reasonable to integrate quality vectors for components A and B to obtain the following quality vectors: \( N(S_1^H) = (2; 5, 0, 0) \), \( N(S_2^H) = (2; 5, 0, 0) \), \( N(S_3^H) = (3; 3, 1, 1) \), \( N(S_4^H) = (2; 5, 0, 0) \), \( N(S_5^H) = (3; 3, 1, 1) \), and \( N(S_6^H) = (3; 3, 1, 1) \). The obtained eight resultant composite decisions can be analyzed to select the best decision (e.g., additional multicriteria analysis, expert judgment).

4.7. Brief Comparison and Discussion of Methods

Note, 45 resultant solutions were obtained by basic MA. Table 21 integrates resultant composite solutions for four methods: (1) ideal point method (the best solution and six close solutions), (2) Pareto-based method (two solutions), (3) multiple choice problem (two solutions), (4) HMMD (eight solutions).

| Method                  | Resultant composite DAs | Quality vector (HMMD) |
|------------------------|-------------------------|-----------------------|
| 1. Ideal-point method  | \( S_1^f = M_4 \ast L_2 \ast V_2 \ast U_3 \ast T_4 \) | (3; 2, 3, 0)          |
|                        | \( S_2^f = M_1 \ast L_1 \ast V_2 \ast U_3 \ast T_4 \) | (3; 1, 3, 1)          |
|                        | \( S_3^f = M_1 \ast L_4 \ast V_2 \ast U_3 \ast T_4 \) | (3; 1, 4, 0)          |
|                        | \( S_4^f = M_4 \ast L_3 \ast V_2 \ast U_3 \ast T_4 \) | (3; 1, 4, 0)          |
|                        | \( S_5^f = M_2 \ast L_1 \ast V_2 \ast U_3 \ast T_4 \) | (3; 1, 4, 0)          |
|                        | \( S_6^f = M_5 \ast L_4 \ast V_2 \ast U_3 \ast T_4 \) | (3; 1, 4, 0)          |
| 2. Pareto-based MA     | \( S_1^P = M_4 \ast L_2 \ast V_1 \ast U_5 \ast T_1 \) | (3; 3, 1, 1)          |
|                        | \( S_2^P = M_4 \ast L_2 \ast V_2 \ast U_3 \ast T_4 \) | (3; 2, 3, 0)          |
| 3. Multiple choice problem | \( S_1^C = M_4 \ast L_1 \ast V_6 \ast U_3 \ast T_1 \) | (0; 2, 1, 2)          |
|                        | \( S_2^C = M_4 \ast L_1 \ast V_6 \ast U_1 \ast T_1 \) | (0; 3, 0, 2)          |
| 4. HMMD                | \( S_1^H = M_4 \ast L_2 \ast V_5 \ast U_1 \ast T_3 \) | (2; 5, 0, 0)          |
|                        | \( S_2^H = M_4 \ast L_2 \ast V_5 \ast U_4 \ast T_2 \) | (2; 5, 0, 0)          |
|                        | \( S_3^H = M_4 \ast L_2 \ast V_1 \ast U_5 \ast T_3 \) | (3; 3, 1, 1)          |
|                        | \( S_4^H = M_4 \ast L_1 \ast V_5 \ast U_1 \ast T_3 \) | (2; 5, 0, 0)          |
|                        | \( S_5^H = M_4 \ast L_1 \ast V_5 \ast U_4 \ast T_2 \) | (3; 3, 1, 0)          |
|                        | \( S_6^H = M_4 \ast L_1 \ast V_1 \ast U_5 \ast T_3 \) | (3; 3, 1, 1)          |
|                        | \( S_7^H = M_4 \ast L_2 \ast V_2 \ast U_3 \ast T_4 \) | (3; 2, 3, 0)          |
|                        | \( S_8^H = M_4 \ast L_2 \ast V_2 \ast U_3 \ast T_4 \) | (3; 2, 3, 0)          |

Now let us discuss the obtained solutions (Table 21):

1. In the case of the first three methods (MA, ideal point method, and Pareto-based method), compatibility estimates at level 3 were used to combine solutions. Thus cardinality of the combinatorial space of admissible solutions was decreased (for the examples) and the resultant solution set does not involve solutions with compatibility estimates at level 2 and 1. In the other case, cardinality of the admissible solution set can be very high. High cardinality of the admissible solution set will lead to very high computational complexity (MA, ideal point method, Pareto-based method) and participation of domain expert(s) at the first method stage (i.e., generation of admissible solutions) will not be possible.

2. In the case of MA, a sufficiently large and rich set of admissible solutions was obtained: 45. Note, this solution set covers solutions sets for other methods (i.e., ideal-point method, Pareto-based method, HMMD). At the same time, the problem is: *to analyze this large solution set.*

3. In the case of ideal point method, only solution \( S_1^f \) belongs to the set of Pareto-efficient solutions. The set of considered solutions \( \{ S_1^f, S_2^f, S_3^f, S_4^f, S_5^f, S_6^f \} \), which are close to the above-mentioned solution, is not sufficiently good by elements. At the same time, some good solutions are lost, for example: \( S_3^H, S_5^H, S_6^H, S_8^H \).

4. In the case of Pareto-based method, many good solutions are lost, for example: \( S_6^H, S_6^H, S_8^H \), etc.

5. In the case of multiple choice problem, compatibility estimates are not examined. As a result, all obtained solutions are inadmissible. It can be reasonable to extend this kind of optimization models by additional logical constraints which will formalize the compatibility requirements. But it may lead to
complicated models.

6. In the case of HMMD, the set of solutions is sufficiently rich and not very large at the same time (eight solutions).

Table 22 contains an additional qualitative author’s comparison of the examined methods. Here computational complexity is depended on enumerative computing and analysis of all admissible combinatorial solutions (i.e., admissible combinations). In the case of HMMD, the usage of hierarchical system structure decreases complexity of the computing process. In the case of Pareto-based MA, an analysis of Pareto-efficient solutions will required additional enumerative computing. Finally, column ”Usefulness for expert(s)” (Table 22) corresponds to the following: (i) possibility to include the domain(s) expert(s) or/and decision maker(s) into the solving process (i.e., to include cognitive man-machine procedures into the design framework), (ii) understandability of the used design method to domain(s) expert(s) and/or decision maker(s).

Table 22. Qualitative comparison of used methods

| Method                      | Computational complexity | Taking into account compatibility | Usefulness for selection of the best solutions | Usefulness for expert(s) |
|-----------------------------|--------------------------|-----------------------------------|----------------------------------------------|--------------------------|
| 1.MA                        | High                     | Yes, binary                       | Hard                                         | Hard                     |
| 2.Ideal-point method        | High                     | Yes, binary                       | Easy                                         | Good                     |
| 3.Pareto-based MA           | High                     | Yes, binary                       | Medium, analysis of Pareto-efficient solutions| Good                     |
| 4.Multiple choice problem   | Low/Medium               | None                              | Easy                                         | Medium                   |
| 5.HMMD                      | Low/Medium               | Yes, ordinal                      | Easy                                         | Good                     |

Generally, the selection of the certain kind of the morphological method for a designed system has to be based on the following: (a) a type of the examined system class (structure, complexity of component interaction, etc.); (b) structure and complexity of the examined representative of the system class; (c) existence of an experienced design team; (d) possibility to implement some assessment procedures (for assessment of DAs and/or compatibility); (e) possibility to use computational recourses (e.g., computing environment, power software, computing personnel), and (f) possibility to use qualified domain(s) experts and/or decision makers.

5. Towards Other Approaches

Generally, hierarchical design approaches are often based on a hierarchical model of the designed system and ‘Bottom-Up’ framework (Fig. 15). The list of some hierarchical design approaches, which are close to MA-based approaches and based on the framework above, is the following: (1) hierarchical design frameworks (e.g., [30], [69]); (2) structural synthesis of technical systems based on MA, cluster analysis, and parametric optimization [65]; (3) HTN (hierarchical task network) planning (e.g., [15]); (4) hierarchical decision making in design and manufacturing (e.g., [5], [6], [8], [23], [31]); and (5) linguistic geometry approach (e.g., [72]).

Here it is reasonable to point out some non-linear programming models which are targeted to modular system design as well. First, modular design of series and series-parallel information processing from the viewpoint of reliable software design while taking into account a total budget (i.e., multi-version software design) was investigated in ([1], [2], [9]). The authors suggested several generalizations of knapsack problem with non-linear objective function. Thus, the following kind of the optimization model for reliable modular software design can be examined (a basic case) [9]:

\[
\max \prod_{i=1}^{m} (1 - \prod_{j=1}^{q_i} (1 - p_{ij}x_{ij})) \quad s.t. \quad \sum_{j=1}^{q_i} x_{ij} \leq b_i, \quad \sum_{j=1}^{q_i} x_{ij} \geq 1 \ \forall i = 1, m, \quad x_{ij} \in \{0,1\},
\]

where \( p_{ij} \) is a reliability estimate of software module version \((i, j)\) (i.e., version \( j \) for module \( i \)), \( d_{ij} \) is a cost of software module version \((i, j)\). Fig. 16 illustrates the design problem above. Evidently, the obtained models are complicated ones and heuristics or enumerative techniques are used for the solving
process ([1], [2], [9]). In [76], the problems above are considered regarding the usage of multi-objective genetic algorithms. Second, design problems in chemical engineering systems require often examination of integer and continuous variables at the same time and, as a result, non-linear mixed integer programming models are formulated and used (e.g., [17], [21]).

In addition, it is reasonable to point out constraint-based approaches (e.g., [16], [59], [73]) including composite constraint satisfaction problems and AI-based solving approaches (e.g., [68], [71]).

6. Conclusions

In the article, several MA-based system design approaches were described. Generally, it can be very useful and prospective to extend studies in the examination and usage of the MA based approaches in engineering, computer science, and management. For example, the following significant applied domains may be pointed out: (i) usage of morphological methods in allocation (layout, positioning) problems (e.g., [33], [39]); (ii) usage of morphological methods in combinatorial evolution and forecasting of modular systems (e.g., [47], [53]). The future research directions can include the following:

1. continuation of the analysis, evaluation, comparison of MA-based system design methods;
2. consideration of uncertainty in all modifications of MA;
3. extension of "method of closeness to ideal point" while taking into account the following: (i) a set of ideal points, (ii) various kinds of proximity (e.g., functions, vector functions);
4. analysis, investigation, and modification of morphological methods based on multiple choice problem and its generalizations including special constraints for system elements compatibility;
5. design and investigation of special computer-aided systems based on morphological approaches;
6. investigation of special versions of morphological approaches which involve experts into a solving process (i.e., interactive approaches);
7. investigation of dynamical versions of morphological approaches while taking into account changes of system requirements;
8. usage of morphological system design methods for integration of heterogeneous networks;
9. usage of morphological system design methods in embedded systems for configuration and reconfiguration (including online mode) of hardware and/or software;
10. generation of engineering benchmarks for evaluation and analysis of MA-based system design methods; and
11. usage of MA and its modifications in engineering, IT/CS, and mathematical education (e.g., [37], [40], [43], [49], [51], [52], [55], [56]).

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