INFORMATICA, 2005, Vol. 16, No. 2, 213–240

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Hierarchical Decision Making Framework for Evaluation and Improvement of Composite Systems (Example for Building)

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Received: June 2004

Abstract. The article describes a hierarchical decision making framework for the evaluation and improvement/redesign of composite systems. The framework is based on Hierarchical Morphological Multicriteria Design (HMMD) and corresponding morphological clique problem which realize “partitioning/synthesis macroheuristic”. The system evaluation process consists in hierarchical integration of expert judgment (as ordinal estimates): a method of integration tables or the above-mentioned morphological approach. As a result, ordinal multi-state classification is realized. The system improvement/redesign process is examined as the selection and planning of redesign operations while taking into account operations attributes (e.g., required resources, effectiveness) and binary relations (*equivalence*, *complementarity*, *precedence*) on the operation sets. For modeling the system improvement process several combinatorial optimization models are used (knapsack problem, multiple choice problem, etc.) including HMMD.

The suggested approach is illustrated by realistic numerical example for two-floor building. This applied problem is examined from the viewpoint of earthquake engineering.

Key words: engineering design, system analysis, composite systems, evaluation, improvement, multicriteria decision making, combinatorial optimization, morphological analysis, macroheuristic, civil engineering, earthquake engineering.

1. Introduction

1.1. *Evaluation and Improvement of Composite Systems*

Design, evaluation, and improvement/redesign of complex systems involve a wide range of tasks and cover all stages of products/systems life cycles (Aiello *et al.*, 2002; Buede, 1999; Dixon, 1987; Finger and Dixon, 1989; Hazelrigg, 1996; Hubka and Eder, 1988; Kusiak, 1999; Otto and Wood, 2000; Pahl and Beitz, 1996; Ulrich and Eppinger, 1999).

It is reasonable to point out the following main contemporary technological tendencies in the engineering of complex systems and products:

1. Consideration of the system design processes on the basis of hierarchical decision making technology (Hazelrigg, 1996; Hubka and Eder, 1988; Kuppuraju *et al.*, 1985; Levin, 1998).

2. Examination of several system/product generations including: (1) system analysis on the basis of new customer needs; (2) revelation of bottlenecks in existing systems; (3) improvement/redesign of the system while taking into account new needs, e.g., socio-technological needs, environmental needs (Berman *et al.*, 1994; Bertero, 1992; Beskow and Ritzen, 2000; Chakravarti, 1999; Davidovici, 1993; Dixon and Colton, 2000; Du Bois *et al.*, 1989; Engelhardt, 2000; Fogliatto and Albin, 2001; Forster *et al.*, 1995; Fothergill *et al.*, 1995; Gunasekaran *et al.*, 1994; Hameri and Nihtila, 1998; Knosala and Pedrycz, 1992; Levin, 1998; Levin and Danieli, 2000; Marino, 1997; Miyasato *et al.*, 1986; Ozer, 1999; Soebarto and Williamson, 2001; Stumptuer and Wotawa, 2001; Tenner and Detoro, 1996; Ulrich and Eppinger, 1999; Yerramareddy and Lu, 1993; Zakarian and Kusiak, 2001).

3. Usage of a modular approach as modular engineering, modular design (Baldwin and Clark, 2000; Ericsson and Erixon, 2000; Ganza, 1999; Hamlin and Sanderson, 1998; Huang and Kusiak, 1998; Hop, 1988; Hutchings, 1996; Jones, 1981; Kamrani and Salhieh, 2000; Levin, 1998). This trend is based on several reasons as follows:

1. Many systems and products are composite ones (e.g., in car industry, in aerospace industry). As a result, modular approach is very prospective from the viewpoints of life cycle engineering and product platform design (Ericsson and Erixon, 2000; Gonzalez–Zugasti *et al.*, 2000; Kusiak, 1999; Simpson *et al.*, 2001),

2. Modular system structure is very good basis to the use of many hierarchical decision making frameworks (including the use and acquisition of expert information) for the system analysis and design (Hubka and Eder, 1988; Levin, 1998; Stumptuer and Wotawa, 2001; Yerramareddy and Lu, 1993).

4. Study of the system evaluation and improvement/redesign problems (Aiello *et al.*, 2002; Berman *et al.*, 1994; Beskow and Ritzen, 2000; Bowman *et al.*, 2000 Chakravarti, 1999; Dixon, 1987; Dixon and Colton, 2000; Engelhardt, 2000, Forster *et al.*, 1995; Fothergill *et al.*, 1995; Gunasekaran *et al.*, 1994; Hameri and Nihtila, 1998; Kusiak, 1999; Levin, 1998; Otto and Wood, 2000; Ozer, 1999; Soebarto and Williamsson, 2001; Tenner and Detoro, 1996; Yerramareddy and Lu, 1993; Zakarian and Kusiak, 2001).

Our article focuses on the above-mentioned two problems: (1) system evaluation and (2) system redesign/improvement. In the case of composite multidisciplinary systems, these problems are complicated and involve the following: (i) various system parts (for the system components), (ii) a crucial role of experts and their experience, (iii) a fundamental on the basis of previous situations and previous solved problems; and (iv) the coordination of the above-mentioned efforts (i.e., evaluation processes for system components, coordination of experts, analysis and usage of previous results, etc.). On the other words, it is necessary to take into account several "dimensions" of the problem solving process as follows: (a) system components and their interconnection; (b) time; (c) kinds of possible solving procedures (e.g., expert judgment, models, simulation); (d) kinds of information support, e.g., design case studies, some special engineering spaces and their combinations, engineering history data bases, knowledge bases; (d) coordination of the procedures and information into a resultant solving process. Moreover, different research methods can be used for different system components and for different parts of the problem solving process. The problem of integration of local decisions for system components/for local situations into a global decision plays a central role and requires special approaches.

In our article, two basic parts are contained: (a) the system evaluation process that is based on a hierarchical decision making procedure including our special attention to integration of local ordinal estimates into a global evaluation results; (b) the system improvement process that is considered from the viewpoint of operation management including the usage of support combinatorial models and a hierarchical decision making procedure. Our material is an addition to an existing set of corresponding approaches. The issues of the analysis and comparison of various methods for the above-mentioned two problems and selection of the best method for a certain applied design situation require special studies and are not examined here.

In the article, Hierarchical Morphological Multicriteria Design (HMMD) (Levin, 1998) is used as a basic approach to evaluate and to redesign the examined system. The approach realizes “partitioning/synthesis macroheuristic”. Concurrently, other combinatorial models are briefly described: hierarchical integration of ordinal information and several combinatorial optimization problems for the system improvement/ redesign, e.g., knapsack problem, multiple choice problem, multicriteria ranking. Thus, our system evaluation part consists in hierarchical integration of expert judgment as ordinal estimates on the basis of the following: (i) integration tables (Glotov and Paveljev, 1984) and (ii) morphological approach (Levin, 1998; Levin, 2001). This is close to diagnosing some tree-structured systems (Stumptuer and Wotawa, 2001). The above-mentioned approaches lead to ordinal multi-state classification decisions which are used in many domains, for example: in control of financial risk (Agarwal *et al.*, 2001); in medical diagnostics (Du Bois *et al.*, 1989; Larichev *et al.*, 1991); in quality analysis (Belkin and Levin, 1990); and in ordinal decision making/management (Cook and Kress, 1992).

It is reasonable to point out the basic kinds of the improvement/redesign problem (Levin, 1998):

Problem 1: Find the best improvement plan to reach a required level for the resultant system while taking into account the following: (i) results as a quality level for the resultant system and (ii) required resources (a set of admissible improvement actions).

Problem 2: Find the best level for the resultant system(s) while taking into account the following: (i) admissible limited resources (a set of admissible improvement actions) and (ii) some constraints for the improvement plan.

Here the improvement/redesign part is examined from the viewpoint of operations management including the following components: (a) a set of redesign operations; (b) some binary relations on the operations set above (e.g., *equivalence*, *nonequivalence*, *complementarity*, *noncomplementarity*, *precedence*); and (c) multiple criteria description of the operations. As a result, our improvement/redesign activity consists in a modular design of the system improvement plan on the basis of interconnected redesign operations. This approach is close to traditional planning in manufacturing.

Our system evaluation and improvement framework is oriented to and illustrated by a realistic numerical example for the evaluation and redesign of a two-floor building from the viewpoint of earthquake engineering.

1.2. *Evaluation and Improvement of Buildings*

The article addresses a framework of the system analysis, evaluation, and improvement/redesign for a certain applied domain: buildings from the viewpoint of earthquake engineering (Table 1) (Cheng and Wang, 1996; Hu *et al.*, 1996; Jonsson, 2000; Kramer, 1995; Lagorio, 1990; Levin and Danieli, 2000; Marino, 1997; Naeim, 1989; Renhorn, 1999; Wakabayashi, 1984). In recent years, the significance of this application is increasing. Our paper does not address risk management (Hessami, 1999), post-earthquake restoration and reconstruction (Kozin and Zhou, 1988), damage diagnosis of concrete structures using artificial intelligence techniques (e.g., neural networks) (Chao and Cheng, 1996; Tsa and Hsu, 2001), optimal and multiple criteria land use analysis and planning (Fischer *et al.*, 1996; Yewlett, 2001), probabilistic approaches to seismic risk analysis (Budnitz *et al.*, 1998; Lindell and Perry, 1997), simulation techniques (Fishman, 1996; Hon *et al.*, 2000; Sobol, 1994), stochastic approaches to preventive maintenance (Gertsbakh, 2000; Usher *et al.*, 1998), and economical issues of seismic design (Warshavsky *et al.*, 1996). We consider a building as a composite (decomposable, modular) system. Some methodological issues for the design and redesign of buildings (mainly on

Table 1

Some bibliography sources in earthquake engineering and building design

Topics	Sources
1. Design management and design framework	Austin *et al.*, 1999; Baldwin *et al.*, 1999
2. Earthquake engineering and seismic design (general)	Arnold and Reitherman, 1982; Hu *et al.*, 1996; Naeim, 1989; Wakabayashi, 1996
3. Description of earthquakes and regions	Flood *et al.*, 1998; Kramer, 1995
4. Modeling of earthquake situations	Flood *et al.*, 1998
5. Economical issues of seismic design	Warshavsky *et al.*, 1996
6. Evaluation and assessment of buildings and damage	Budnitz *et al.*, 1998; Chao and Cheng, 1996; Kanda and Shah, 1997; Marino, 1997; Miyasato *et al.*, 1986; Neap, 2001; Renhorn, 1999; Soebarto and Williamson, 2001; Tsa and Hsu, 2001
7. Strengthening and improvement of buildings	Bertero, 1992; Cheng and Wang, 1996; Davidovici, 1993; Marino, 1997
8. Description of requirements to seismic design	Hu *et al.*, 1996; Marino, 1997; Wakabayashi, 1984
9. Seismic stability of auxiliary elements	Lagorio, 1990
10. Configuration of buildings	Arnold and Reitherman, 1982; Baglivo and Graber, 1983; Park, 2000

the basis of special languages) have been described in (Austin *et al.*, 1999; Baldwin *et al.*, 1999; Hien *et al.*, 2000).

Note some evaluation models for new products and systems are considered in (Fogliatto and Albin, 2001; Ozer, 1999; Soebarto and Williamson, 2001), special signal flow graphs are used for evaluation of design process alternatives in (Isaksson *et al.*, 2000), fuzzy sets approach is applied for evaluation of design alternatives in (Knosala and Pedrycz, 1992).

Four basic redesign problems for buildings can be formulated on the basis of the following two dimensions:

(1) *architectural requirements* or *requirements of earthquake engineering* and

(2) *redesign of a building project* or *redesign of an existing building*.

Evaluation problems can be considered as follows:

(1) evaluation of a building or a project;

(2) evaluation of a real building after earthquake.

In the article, the following parts of the redesign scheme are proposed: (a) schemes for evaluation of buildings/projects; (b) a basic set of improvement/redsign actions (operations); (c) basic requirements for buildings; and (d) multicriteria description and binary relations (*equivalence*, *complementarity*, and *precedence*) for improvement actions; and (e) combinatorial problem formulations and solving schemes for the evaluation and redesign processes. A preliminary compressed version of our research was published in (Levin and Danieli, 2000).

Note our material leads to a hybrid approach that integrates decision making techniques and ordinal expert judgment as a special knowledge base. Some approaches to earthquake engineering on the basis of traditional artificial intelligence methods are described in (Miyasato *et al.*, 1986). A numerical illustrative example illustrates the redesign framework for a building project.

In addition, it is reasonable to point out our material is an integrated effort of two specialists: Mark Sh. Levin (hierarchical schemes for the system analysis, evaluation and design/redesign; multicriteria decision making; combinatorial optimization: Sections 1.1, 2, 3.1, 3.2, 4.4) and Moshe A. Danieli (multi-year experience in the design and redesign of buildings from the viewpoint of earthquake engineering). As a result, Sections 1.2, 3.3, 3.4, 4.1, 4.2, 4.3 are joint ones.

2. Two Hierarchical Approaches

Hierarchical approaches for organization and management of engineering information on complex systems are basic ones (Kuppuraju *et al.*, 1985; Levin, 1998; Wong and Sriram, 1993). In this section, we will describe two hierarchical methods: (a) HMMD for design, evaluation, and redesign of composite systems (Levin, 1998; Levin, 2001) and (b) simple hierarchical integration of ordinal information on the basis of tables (Glotov and Paveljev, 1984).

2.1. *Morphological Design and Redesign (Partitioning/Synthesis Macroheuristic)*

In this paper, we examine composite (modular, decomposable) systems, consisting of components and their interconnection (Is) or compatibility. We use Hierarchical Morphological Multicriteria Design (HMMD) (Levin, 1998; Levin, 2001) that implements a *partitioning/synthesis* search strategy. HMMD extends well-known morphological analysis (Jones, 1981; Zwicky, 1969) by the use of ordinal quality estimates for design alternatives and their compatibility.

There exist two main problems: 1) design of combinatorial search space and 2) design of a search strategy at the space. Fig. 1 illustrates the *partitioning/synthesis* strategy on the basis of the following stages: (a) partitioning the initial search space into subspaces; (b) search for the best local decision for each subspace; and (c) combination (composition, synthesis) of the local decisions into the global resultant decision.

Basic assumptions of HMMD are the following: (a) a considered system has a tree-like structure; (b) a system excellence is a composite estimate which integrates components (subsystems, parts) qualities and qualities of Is (compatibility) among subsystems; (c) monotone criteria for the system and its components are used; (d) quality of system components and Is are evaluated on the basis of coordinated ordinal scales. The following designations are used: (1) design alternatives (DA's) for leaf nodes of the model; (2) priorities of DA's ($r = 1, \dots, k$; 1 corresponds to the best one); (3) ordinal compatibility (Is) for each pair of DA's ($w = 0, \dots, l$, l corresponds to the best one).

A basic version of HMMD involves the following phases:

1) design of the tree-like system model;
2) generation of DA's for leaf nodes of the model;
3) hierarchical selection and composing of DA's into composite DA's for the corresponding higher level of the system hierarchy;
4) analysis and improvement of composite DA's (decisions).

The synthesis problem for composite DA's is the following. Let S be a composite system consisting of m parts (components): $P(1), \dots, P(i), \dots, P(m)$. A set of design alternatives exists for each system part above. The problem is:

Find a composite design alternative $S = S(1) \star \dots \star S(i) \star \dots \star S(m)$ of DA's (one representative design alternative $S(i)$ for each system component/part $P(i)$, $i = 1, \dots, m$) with non-zero Is between design alternatives.

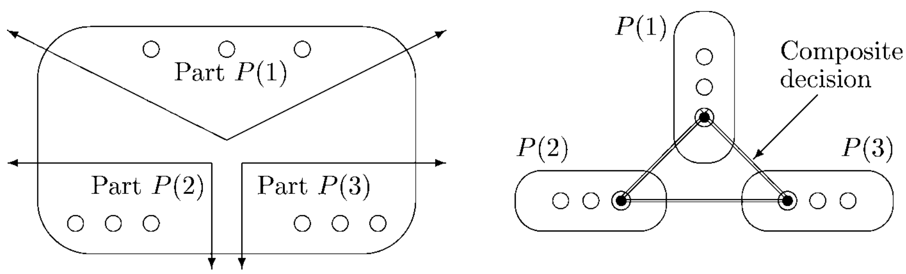

Fig. 1. Partitioning/synthesis strategy.

A discrete space of the system excellence on the basis of the following vector is used: $N(S) = (w(S); n(S))$, where $w(S)$ is the minimum of pairwise compatibility between DA's which correspond to different system components (i.e., $\forall\ P_{j_1}$ and P_{j_2}, $1 \leqslant j_1 \neq j_2 \leqslant m$) in S, $n(S) = (n_1, \dots, n_r, \dots n_k)$, where n_r is the number of DA's of the rth quality in S. As a result, we search for composite decisions which are nondominated by $N(S)$. Thus, the following layers of system excellence can be considered: (i) ideal point; (ii) Pareto-effective points; (iii) a neighborhood of Pareto-effective DA's (e.g., a composite decision of this set can be transformed into a Pareto-effective point on the basis of an improvement action(s)).

Fig. 2 illustrates decomposable system $S = X{\star}Y{\star}Z$. Here examples of the composite decisions are: $S_1 = X_1{\star}Y_4{\star}Z_3$; $S_2 = X_1{\star}Y_1{\star}Z_2$; and $S_3 = X_2{\star}Y_5{\star}Z_2$. For composite decision in Fig. 2, we get $N(S_1) = (1; 0, 2, 1)$, $N(S_2) = (3; 1, 1, 1)$, and $N(S_3) = (2; 2, 0, 1)$. Thus $N(S_2)$ and $N(S_3)$ are Pareto-effective points and $N(S_2) \succ N(S_1)$, $N(S_3) \succ N(S_1)$. Fig. 3 depicts an example of the discrete space of system quality for a fixed level of compatibility (for $n(S)$). Fig. 4 illustrates the integrated discrete space of system quality (for $N(S)$) and examples of decisions. This space consists of three ordered lattices each of them corresponds to the lattice from Fig. 3. In general case, a lattice that represents $n(S) = (n_1, \dots, n_r, \dots, n_k)$ has a "triangle" form.

Fig. 5 illustrates decomposable system $S = A \star B \star C$ and its redesign (up-grade) into $S = A \star B \star D$: change of system components (deletion is denoted by X^- and addition is denoted by X^+) and change of system model ($C \to D$), for example: $S' = A_2 \star B_1 \star C_1 \Rightarrow S'' = A_3 \star B_3 \star D_2$.

The following kinds of elements (DA's, Is) with respect to solution S can be examined: S-*improving*, S-*neutral*, and S-*aggravating* ones by vector N; where S-*aggravating* elements are examined as bottlenecks.

Fig. 6 illustrates an improvement process for a composite system. Here we examine the following layers of decisions: (1) an initial point; (2) points that are close to the Pareto-effective layer; (3) the Pareto-effective decisions; (4) points that are a little better than the Pareto-effective decisions; (5) points that are close to the ideal decision; and (6) the ideal decision. Thus it is reasonable to improve step-by-step an initial decision.

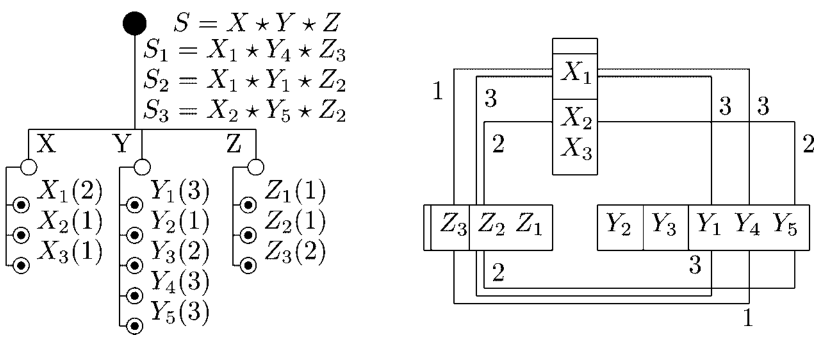

Fig. 2. Example of composition problem (priorities of DA's are shown in brackets).

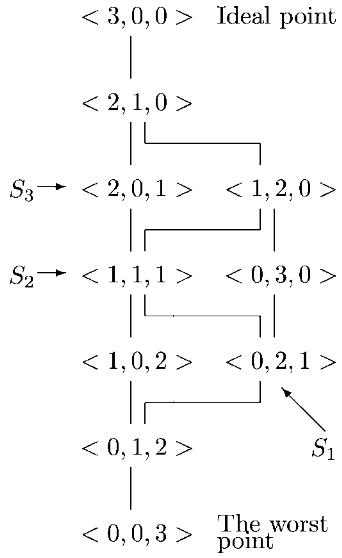

Fig. 3. Position (histogram) presentation of the lattice of system quality for $N = (w; n_1, n_2, n_3)$, $w = \text{const}$, $m = 3$, $l = 3$.

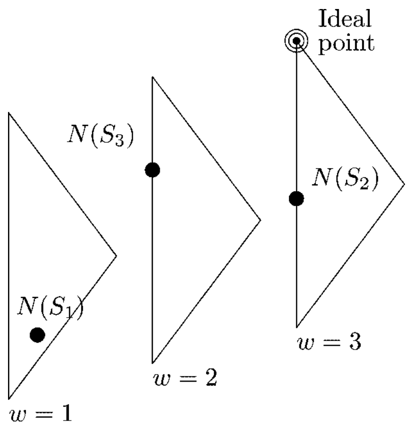

Fig. 4. Discrete space of system excellence for $N(S)$.

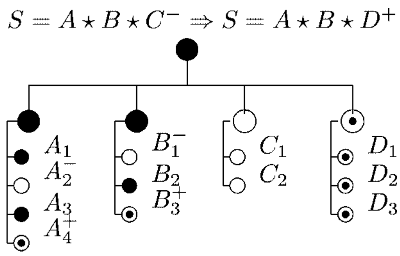

Fig. 5. Example of redesigned system.

In Fig. 6, the following points and trajectories are depicted: (a) *points*: (i) initial point S_o; (ii) intermediate points of improvements S_{o1} and S_{o2}; (iii) four Pareto-effective points; (iv) additional intermediate points S_1^i and S_2^i; (v) resultant points S_1^* and S_2^*; and (vi) the ideal point I; (b) series *trajectories* of improvements: $\alpha =< S_o, S_{o1}, S_1^i, S_1^* >$ and $\beta =< S_o, S_{o2}, S_2^i, S_2^* >$.

Note extended versions of discrete spaces for system excellence are proposed in (Levin, 2001). Now let us list some support procedures as follows:

1) mulricriteria ranking to get the above-mentioned ordinal priorities of DA's or ordinal estimates of Is (Buede, 1992);
2) morphological clique problem to find composite DA's (Levin, 1998);
3) multicriteria analysis (ranking) of composite DA's (Levin, 1998);
4) generation of improvement actions, for example, on the basis of domain expert judgment;

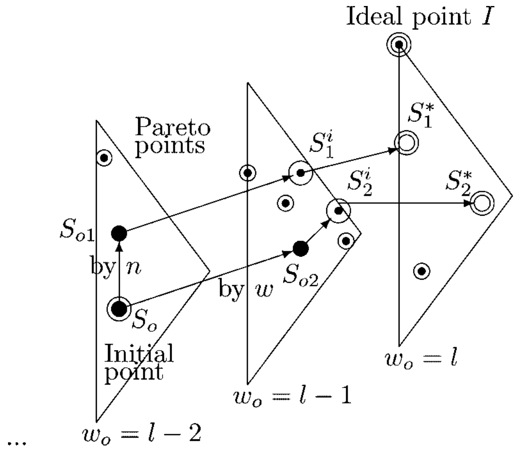

Fig. 6. Excellence lattice, improvements (→).

5) design of series-parallel schedule for improvement actions (Blazewicz *et al.*, 1994);
6) searching for the best trajectory in an operational network on the basis of the following: (i) operations management (Singhal and Katz, 1990), (ii) network methods and techniques, e.g., dynamic programming (Garey and Johnson, 1979), hierarchical task-network planning (Erol *et al.*, 1996), scheduling (Blazewicz *et al.*, 1994; Garey and Johnson, 1979).

2.2. *Hierarchical Integration of Ordinal Information*

Here we briefly describe a hierarchical procedure for integration of ordinal estimates that was proposed in (Glotov and Paveljev, 1984). In this case, parts/components of a system are evaluated upon ordinal scales and integration of the scales for composite system parts/components is based on integration tables that are obtained from expert judgment. The integration tables correspond to monotone functions of algebraic logic (or multiple-valued logic) which have been studied in mathematical logic (Serzantov, 1984) and in decision making procedures, e.g., in DSS COMBI (Levin, 1998). Note close techniques are applied in technical diagnosis for electronic systems. A numerical example is presented in Fig. 7 (system structure and ordinal scales of quality for the system and each its component) and in Fig. 8 (a process of information integration on the basis of integration tables). For example, let us consider some estimates for the system components B, C, and D as follows: $3,\ 2,\ 1$ accordantly. On the basis of integration table for $B\&C$ we get an estimate for A: 3; and on the basis of integration table for $A\&D$ we get an estimate for S: 2.

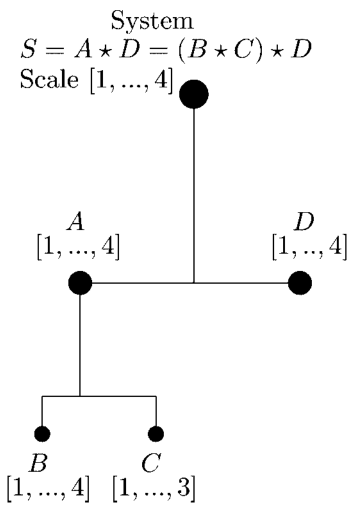

Fig. 7. System structure.

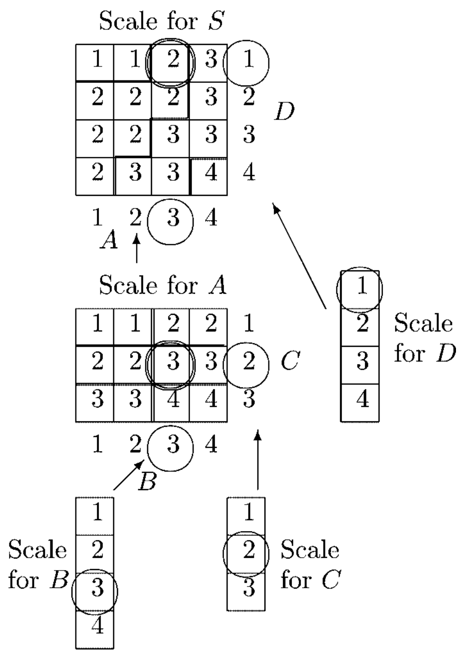

Fig. 8. Integration of ordinal scales.

3. Scheme of Improvement/Redesign

3.1. *Framework*

Our framework for a system (building) is based on hierarchical morphological multicriteria design HMMD from (Levin, 1998) and consists of the following:

I. Design of hierarchical model and description for a system.

1.1. Design of hierarchical model for a system.

1.2. Design of multicriteria (multifactor) hierarchical description of the model nodes (building parts, components) including ordinal scales for each criterion.

II. Evaluation.

2.1. Assessment of the system parts/components upon criteria.

2.2. Step-by-step aggregation of information to get an estimate for a higher level of the model hierarchy (on the basis of multicriteria decision making techniques from (Glotov and Paveljev, 1984; Levin, 1998).

III. Analysis of the building and revelation of bottlenecks (Levin, 1998).

3.1. Analysis of the resultant integrated estimate for the system, analysis of system parts/components and their interconnection.

3.2. Revelation of the bottlenecks as some weak building parts/components or their interconnection (if it is necessary).

IV. Design of improvement process for the system (Levin, 1998):

4.1. Generation/selection of a set of some possible improvement actions.

4.2. Selection/composition of the best subset of the improvement actions while taking into account certain design and technological requirements (situations).

4.3. Scheduling of the improvement actions above.

The above-mentioned framework is described and realized for building in next sections from the generalized viewpoint and as a numerical example:

(a) hierarchical system model for building, criteria, and the ordinal scales for evaluation of the building parts in Section 3.2;

(b) evaluation examples: (i) on the basis of integration tables (Section 4.1), (ii) on the basis of hierarchical morphological approach (Section 4.2);

(c) analysis of the system and redesign: (i) generalized basic set of improvement actions for building (Section 3.4), (ii) a certain set of the redesign operations with binary relations, criteria, estimates, and ranking (Section 4.3); (iii) models for the selection and scheduling of the redesign operations (models in Section 3.2 and an improvement process on the basis of these models in Section 4.4).

3.2. *Structure of Building, Criteria, and Scales*

In this section, the following is examined: (i) tree-like model for a building; (ii) criteria for the improvement/redesign of building; and (iii) weights and scales for the criteria. Note a basic overview of critical problems and issues associated with hierarchical modeling of large scale systems is contained in (Haimes, 1982). The algorithms for the design of hierarchical models for engineering systems are described in (Papalambros and Michelena, 1997).

In our paper, the weights of the criteria are oriented to a certain redesign problem. Here, the problem of project redesigning from the viewpoint of earthquake engineering is considered. In the example, it is assumed a certain earthquake situation (8-mark estimate, scale of seismic intensivity MSK-64). Other redesign problems can be studied on the basis of other improvement (redesign) actions and a weight system for the criteria. Note classification of building types and main classes of structural failures and damages are considered in (Kanda and Shah, 1997).

Our basic hierarchical structure of a building is the following:

1. Building S.

1.1. Foundation A.

1.2. Basic structure B.

1.2.1. Bearing structures D:

1.2.1.1. Frame E,

1.2.1.2. Rigidity core G,

1.2.1.3. Staircase H.

1.2.2. Nonbearing structures F:
1.2.2.1. Filler walls I,
1.2.2.2. Partitioning walls J.

1.3. Floors C.

Note that **configuration** of buildings (e.g., symmetry) plays a crucial role (Arnold and Reitherman, 1982; Baglivo and Graver, 1983; Park, 2000; Shubnikov and Koptsik, 1974). The following scale can be used for **configuration**: 1 corresponds to *bad*, 2 corresponds to *good*, and 3 corresponds to *excellent* (symmetrical, etc.). In our opinion, the *good* **configuration** deals to decreasing of building damage (i.e., decreasing an damage estimate by one level).

Our hierarchical criteria set is based on the following two parts:

1. Characteristics of the building including the following main parameters: (a) volume-plan design decisions (regularity of a building system, symmetry, location of rigidity building mass or mass of rigidity core for building, dimensions); (b) engineering-geological situation, etc.

2. A hierarchical criteria set for the evaluation of a certain building at a certain situation (on the basis of extremal influence): (a) volume; (b) type (vertical, horizontal); (c) correspondence between direction of influence and plan of building; and (d) dynamical character of oscillations.

The following basic coordinated ordinal scales for the building parts/components is proposed ($[1,\dots,5]$): global destruction (1); local destruction (2); chinks (3); small chinks (hair-like) (4); and without damage (5). For each building part/components we use a special ordinal scale that is a subscale of the scale above (Table 2). Note ordinal multi-level/multi-state classification decisions are used in many engineering domains, e.g., a small survey is contained in (Levin, 1998). An example of the ordinal four-state

Table 2

Ordinal scale for evaluation of building components

Parts of building	Scales				
	destruction (global) (1)	destruction (local) (2)	chinks (3)	small chinks (4)	without damage (5)
1		*	*	*	*
1.1			*	*	*
1.2		*	*	*	*
1.2.1			*	*	*
1.2.1.1			*	*	*
1.2.1.2				*	*
1.2.1.3			*	*	*
1.2.2		*	*	*	*
1.2.2.1		*	*	*	*
1.2.2.2		*	*	*	*
1.3		*	*	*	*

classification to classify firms is the following: *healthy*, *divided reduction*, *debt default*, and *bankrupt* (Agarwal *et al.*, 2001).

Thus in our case of building, we use, for example, the following ordinal scales (Table 2): scale $[3, 4, 5]$ for foundation A (**1.1**); scale $[4, 5]$ for rigidity core G (*1.2.1.2*); scale $[2, 3, 4, 5]$ for floors C (**1.3**);

3.3. *Models and Procedures*

In this paper, two described hierarchical approaches, i.e., hierarchical morphological design (and corresponding morphological clique problem) and hierarchical integration of ordinal information by tables, are oriented to the system evaluation. At the same time, hierarchical morphological design is useful for revelation of a set of system bottlenecks which are a basis for the improvement stage (e.g., a set of possible improvement actions). On the other hand, this generation of possible improvement actions (operations) can be based on expert judgment. Further, it is necessary to select the more important improvement operations and to design a plan (a schedule) for the selected operations. At this stage, the list of basic support procedures is the following:

1. Selection of items (e.g., design/redesign alternative operations).
2. Selection of items while taking into account some resource constraints.
3. Definition of parameter values for items.
4. Integration/synthesis of items into a composite system (subsystem).
5. Ranking of items while taking into account their attributes.
6. Ordering/scheduling the items.

Let us briefly point out some support models for the above-mentioned procedures as follows:

1. Knapsack problem for selection of improvement actions while taking into account their "utility" and some resource constraints. The basic problem is (Garey and Johnson, 1979; Martello and Toth, 1990):

$$\max \sum_{i=1}^{m} c_i x_i, \quad \text{s.t.} \quad \sum_{i=1}^{m} a_i x_i \leqslant b \quad x_i = 0 \cup 1, \quad i = 1, \ldots, m,$$

and additional resource constraints $\sum_{i=1}^{m} a_{i,k} x_i \leqslant b_k$; $k = 1, \ldots, l$; where $x_i = 1$ if item i is selected, for ith item c_i is a value ("utility"), and a_i is a weight. Often nonnegative coefficients are assumed.

2. Multiple-choice problem for selection of improvement actions while taking into account their "utility" and some resource constraints. In this case, the actions are divided into groups and we select actions from each group. The problem is (Martello and Toth, 1990):

$$\max \sum_{j=1}^{m} \sum_{i=1}^{q_j} c_{i,j} x_{i,j} \quad \text{s.t.} \quad \sum_{j=1}^{m} \sum_{i=1}^{q_j} a_{i,j} x_{i,j} \leqslant b$$

$$\sum_{i=1}^{q_j} x_{i,j} \leqslant 1; \quad j = 1, \ldots, m, \quad x_{i,j} = 0 \cup 1; \;\; i = 1, \ldots, q_j; \;\; j = 1, \ldots, m.$$

3. Multiple criteria ranking for ordering the actions while taking into account their estimates upon criteria. The problem is the following. Let $V = \{1, \dots, i, \dots, p\}$ be a set of items which are evaluated upon criteria $K = 1, \dots, j, \dots, d$ and $z_{i,j}$ is an estimate (quantitative, ordinal) of item i on criterion j. The matrix $\{z_{i,j}\}$ can be mapped into a partial order on V. The following partition as linear ordered subsets of V is searching for:

$$V = \cup_{k=1}^{m} V(k), \quad \left|V(k_1) \& V(k_2)\right| = 0 \ \text{ if } \ k_1 \neq k_2,$$
$$i_2 \preceq i_1 \ \ \forall i_1 \in V(k_1), \ \ \forall i_2 \in V(k_2), \ \ k_1 \leqslant k_2.$$

Set $V(k)$ is called layer k, and each item $i \in V$ get priority r_i that equals the number of the corresponding layer.

4. The morphological clique problem was briefly described in Section 2.1 (Levin, 1998).

5. Scheduling the redesign actions can be based on well-known scheduling problems. Formulations of scheduling problems are described in (Blazewiz *et al.*, 1994).

6. For some complicated situations, it may be reasonable to examine mixed integer non-linear programming models (Floudas, 1995; Grossmann, 1990). Here our efforts are oriented not only to select the best operations while taking into account their "utilities" and resource constraints but to define some continuous parameter values for the operations too.

The usage of the first four pointed out support models will be illustrated in Subsection 4.4.

3.4. *Basic Set of Improvement Actions*

Upgrading issues for structures/buildings including strengthening of an existing building have been considered by many authors (Bertero, 1992; Cheng and Wang, 1996; Davidovici, 1993; Marino, 1997; Tudor and Ciuhandu, 1992). Here the following basic set of improvement actions (redesign operations) for buildings from the viewpoint of earthquake engineering is considered:

A. Internal actions

1. Decreasing the weight: *1.1.* insulating materials (e.g., thermal, acoustic, etc.); *1.2.* bearing walls (a frame); *1.3.* non-bearing walls; and *1.4.* floors.

2. Modification of static scheme: *2.1.* design of rigidity core and *2.2.* increasing a static indetermination of structure (*2.2.1* redesign of hinge joints into rigid ones; *2.2.2.* design of additional supporters; *2.2.3.* design of additional joints; and *2.2.4.* design of additional connectors).

3. Strengthening some structural elements and connectors (design of additional elements): *3.1.* beams; *3.2.* columns; *3.3.* walls; *3.4.* floor slabs; *3.5.* partition walls; *3.6.* connectors; *3.7.* floors (dome, vanet, etc.); and *3.8.* foundation.

4. Additional structural systems and elements: *4.1.* flexible antiseismic girt; *4.2.* rigid antiseismic girt (metal, concrete); *4.3.* metal rigidity frame; *4.4.* concrete rigidity frame; and *4.5.* shear wall.

B. External decisions

In addition, it is reasonable to define the following three kinds of binary relations on the improvement actions set: (1) equivalence of actions R^e; (2) complementarity R^c; and (3) precedence R^p. Further, the above-mentioned generalized improvement actions are transformed into certain 11 redesign operations in Section 4.3.

4. Numerical Examples

In this section an illustrative example for the improvement (redesign) of a building is described. We examine (from the viewpoint of earthquake engineering) a simple two-floor building (Fig. 9) that is widely used in many countries (Greece, Turkey, Israel, etc.). The evaluation examples are contained in Sections 4.1 (integration tables) and 4.2 (morphological hierarchical approach). Further, Section 4.3 contains 11 redesign operations and their description, Section 4.4 depicts an improvement process with a comparison of four support models. Evidently, our example is based on our expert judgment (e.g., integration tables, estimates in hierarchical morphological approach, redesign operations and their description). Thus the example and its parts can be used as an illustration and as a basis of other applications.

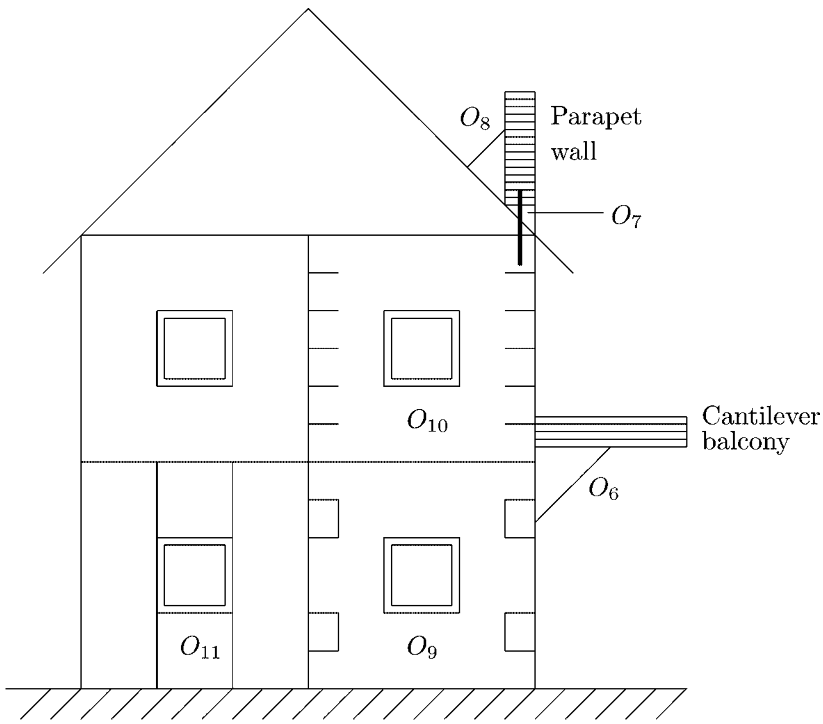

Fig. 9. Draft of a building example and redesign operations.

4.1. *Evaluation Example: Integration Tables*

Here an evaluation example for a building after earthquake is examined. Integration tables are presented in Figs. 10, 11, and 12 ("−" corresponds to impossible situations). As a

Nonbearing structure **1.2.2**
[2, ..., 5]

Filler walls *1.2.2.1* \ Partitioning walls *1.2.2.2*	2	3	4	5
2	2	2	−	−
3	3	3	−	−
4	3	3	4	−
5	−	4	4	5

Basic structure **1.2**
[2, ..., 5]

Bearing structures **1.2.1** \ Nonbearing structures **1.2.2**	2	3	4	5
3	2	3	−	−
4	3	4	4	−
5	−	4	5	5

Fig. 10. Integration tables for system and parts **1.2** and **1.2.2**.

1.1[3...5]	*1.2*[4...5]	*1.3*[3...5]	**1**
3	2	2	2
3	2	3	–
3	2	4	–
3	2	5	–
3	3	2	2
3	3	3	3
3	3	4	3
3	3	5	–
3	4	2	–
3	4	3	–
3	4	4	–
3	4	5	–
3	5	2	–
3	5	3	–
3	5	4	–
3	5	5	–
5	2	2	2
5	2	3	–
5	2	4	–
5	2	5	–
5	3	2	–
5	3	3	–
5	3	4	3
5	3	5	3
5	4	2	–
5	4	3	–
5	4	4	4
5	4	5	4
5	5	2	–
5	5	3	–
5	5	4	–
5	5	5	5

1.1[3...5]	*1.2*[4...5]	*1.3*[3...5]	**1**
4	2	2	2
4	2	3	–
4	2	4	–
4	2	5	–
4	3	2	–
4	3	3	3
4	3	4	3
4	3	5	–
4	4	2	–
4	4	3	–
4	4	4	4
4	4	5	4
4	5	2	–
4	5	3	–
4	5	4	–
4	5	5	–

Fig. 11. Integration tables for building **1** ([2, ..., 5]).

1.2.1.1 [3...5]	*1.2.1.2* [4...5]	*1.2.1.3* [3...5]	**1.2.1**
3	4	3	3
3	4	4	3
3	4	5	–
3	5	3	3
3	5	4	3
3	5	5	–
5	4	3	3
5	4	4	4
5	4	5	4
5	5	3	4
5	5	4	4
5	5	5	5

1.2.1.1 [3...5]	*1.2.1.2* [4...5]	*1.2.1.3* [3...5]	**1.2.1**
4	4	3	3
4	4	4	4
4	4	5	–
4	5	3	3
4	5	4	4
4	5	5	4

Fig. 12. Integration tables for bearing structures **1.2.1** ($[3, \ldots, 5]$).

result, now it is possible to evaluate a building after earthquake:

Example 1. Local expert evaluation of a building: **1.1**: 4, *1.2.1.1*: 3, *1.2.1.2*: 4, *1.2.1.3*: 3, *1.2.2.1*: 2, *1.2.2.2*: 2, and **1.3**: 2; resultant estimate for building **1** equals 2.

Example 2. Local expert evaluation of a building: **1.1**: 5, *1.2.1.1*: 4, *1.2.1.2*: 5, *1.2.1.3*: 4, *1.2.2.1*: 4, *1.2.2.2*: 3, and **1.3**: 4; resultant estimate for building **1** equals 4.

Example 3. Local expert evaluation of a building: **1.1**: 5, *1.2.1.1*: 3, *1.2.1.2*: 5, *1.2.1.3*: 4, *1.2.2.1*: 3, *1.2.2.2*: 3, and **1.3**: 4; resultant estimate for building **1** equals 3.

Example 4. Local expert evaluation of a building: **1.1**: 5, *1.2.1.1*: 5, *1.2.1.2*: 5, *1.2.1.3*: 5, *1.2.2.1*: 4, *1.2.2.2*: 4, and **1.3**: 5; resultant estimate for building **1** equals 5.

4.2. *Evaluation Example: Morphological Design*

In this section, an evaluation example for a building project is described. First, let us generate design alternatives (DA's) for building components as follows (priorities from the viewpoint of earthquake engineering are shown in brackets):

Foundation: A_1, strip foundation (2), A_2, bedplate foundation (1), A_3, foundation consisting of isolated parts (2).

Frame: E_1, monolith frame (1), E_2, precast frame (2).

Rigidity core: G_1, monolith rigid core (1), G_2, precast rigid core (2).

Staircase: H_1, monolith staircase (1), H_2, precast staircase (2), H_3, composite staircase consisting of precast and monolith elements (3).

Filler walls: I_1, small elements (2), I_2, curtain panel walls (2), I_3, precast enclosure panel walls (1), I_4, frame walls (1).

Partitioning walls: J_1, precast panel walls (1), J_2, small elements (3), J_3, frame walls (2).

Floors: C_1, monolith slabs (1), C_2, composite slabs (3), C_3, precast slabs (3).

Note the example is compressed one. It is reasonable to use many criteria to evaluate the above-mentioned DA's (see Section 4.3).

Here the following composite DA's are considered:

$D_1 = E_1 \star G_1 \star H_1$, $N(D_1) = (3; 3, 0, 0)$; $D_2 = E_1 \star G_1 \star H_2$, $N(D_2) = (1; 2, 1, 0)$;

$D_3 = E_1 \star G_1 \star H_3$, $N(D_3) = (1; 2, 0, 1)$; $D_4 = E_1 \star G_2 \star H_1$, $N(D_4) = (2; 2, 1, 0)$; $D_5 = E_1 \star G_2 \star H_2$, $N(D_5) = (1; 1, 2, 0)$; $D_6 = E_1 \star G_2 \star H_3$, $N(D_6) = (1; 1, 1, 1)$; $D_7 = E_2 \star G_1 \star H_1$, $N(D_7) = (2; 2, 1, 0)$; $D_8 = E_2 \star G_1 \star H_2$, $N(D_8) = (1; 1, 2, 0)$; $D_9 = E_2 \star G_1 \star H_3$, $N(D_9) = (1; 1, 1, 1)$; $D_{10} = E_2 \star G_2 \star H_1$, $N(D_{10}) = (1; 1, 2, 0)$; $D_{11} = E_2 \star G_2 \star H_2$, $N(D_{11}) = (1; 3, 0, 0)$; $D_{12} = E_2 \star G_2 \star H_3$, $N(D_{12}) = (1; 2, 0, 1)$;

$F_1 = I_1 \star J_1$, $N(F_1) = (1; 1, 1, 0)$; $F_2 = I_1 \star J_2$, $N(F_2) = (1; 0, 1, 1)$; $F_3 = I_1 \star J_3$, $N(F_3) = (1; 0, 2, 0)$; $F_4 = I_2 \star J_1$, $N(F_4) = (2; 1, 1, 0)$; $F_5 = I_2 \star J_2$, $N(F_5) = (1; 0, 1, 1)$; $F_6 = I_2 \star J_3$, $N(F_6) = (2; 0, 2, 1)$; $F_7 = I_3 \star J_1$, $N(F_7) = (3; 2, 0, 0)$; $F_8 = I_3 \star J_2$, $N(F_8) = (1; 1, 0, 1)$; $F_9 = I_3 \star J_3$, $N(F_9) = (3; 1, 1, 0)$; $F_{10} = I_4 \star J_1$, $N(F_{10}) = (3; 2, 0, 0)$; $F_{11} = I_4 \star J_2$, $N(F_{11}) = (1; 1, 0, 1)$; $F_{12} = I_4 \star J_3$, $N(F_{12}) = (3; 1, 1, 0)$.

Compatibility of DA's is shown in Tables 3, 4, 5, and 6.

Thus, we can select for our next examination the following four best and good DA's for D (Fig. 13): (a) D_1 (ideal solutions, priority equals 1); (b) D_4, D_7, and D_{11} (some Pareto-effective solutions without taking into account D_1, priority equals 2).

Analogically, we can select for our next examination the following four best and good DA's for F (Fig. 14): (a) F_7, F_{10} (ideal solutions, priority equals 1); (b) F_9, F_{12} (good solutions, priority equals 2).

Generally, we can assume that the priority of other DA's for D and F will equal 3.

Now let us consider 12 composite DA's for B on the basis of the above-mentioned selected four DA's for D and for F (accordingly):

$B_1 = D_1 \star F_7$,	$N(B_1) = (2; 2, 0, 0)$;	$B_2 = D_1 \star F_9$,	$N(B_2) = (2; 1, 1, 0)$;
$B_3 = D_1 \star F_{10}$,	$N(B_3) = (2; 2, 0, 0)$;	$B_4 = D_1 \star F_{12}$,	$N(B_4) = (3; 1, 1, 0)$;
$B_5 = D_4 \star F_7$,	$N(B_5) = (2; 0, 1, 1)$;	$B_6 = D_4 \star F_9$,	$N(B_6) = (2; 0, 2, 0)$;
$B_7 = D_4 \star F_{10}$,	$N(B_7) = (2; 1, 1, 0)$;	$B_8 = D_4 \star F_{12}$,	$N(B_8) = (2; 0, 2, 0)$;
$B_9 = D_7 \star F_7$,	$N(B_9) = (2; 0, 1, 1)$;	$B_{10} = D_7 \star F_9$,	$N(B_{10}) = (2; 0, 2, 0)$;
$B_{11} = D_7 \star F_{10}$,	$N(B_{11}) = (2; 1, 1, 0)$;	$B_{12} = D_7 \star F_{12}$,	$N(B_{12}) = (2; 0, 2, 0)$;
$B_{13} = D_{11} \star F_7$,	$N(B_{13}) = (3; 1, 1, 0)$;	$B_{14} = D_{11} \star F_9$,	$N(B_{14}) = (2; 0, 2, 0)$;
$B_{15} = D_{11} \star F_{10}$,	$N(B_{15}) = (2; 1, 1, 0)$;	$B_{16} = D_{11} \star F_{12}$,	$N(B_{16}) = (2; 0, 2, 0)$.

As a result, we have to select the following DA's for B (Fig. 15):

(a) $N = (3; 1, 1, 0)$: $B_4 = D_1 \star F_{12}$, $B_{13} = D_{11} \star F_7$;

(b) $N = (2; 2, 1, 0)$: $B_1 = D_1 \star F_7$, $B_3 = D_1 \star F_{10}$.

Evidently, these DA's have a priority that equals 2 (priority for all others equals 3).

Finally, we get the following composite DA's for our system (building, Fig. 16):

(a) $N = (3; 2, 1, 0)$: $S_1 = A_2 \star B_1 \star C_1$, $S_2 = A_2 \star B_3 \star C_1$, $S_3 = A_2 \star B_4 \star C_1$ (*resultant quality level* equals 2);

(b) $N = (2; 2, 1, 0)$: $S_4 = A_2 \star B_{13} \star C_1$ (*resultant quality level* equals 3).

For other combinations of DA's for considered here A, B and C priority will equal 4 and for all others *resultant quality level* will equal 5. Here *resultant quality level* 1 is impossible, e.g., the ideal decision from the viewpoint of earthquake engineering is absent. A reason of this situation consists in the following: filler walls and partitioning walls are not ideal ones. We can obtain an ideal decision if the above-mentioned walls will

Table 3

Compatibility for D

	G_1	G_2	H_1	H_2	H_3
E_1	3	2	3	1	2
E_2	2	1	2	1	2
G_1			3	2	1
G_2			2	1	1

Table 4

Compatibility for F

	I_1	I_2	I_3	I_4
J_1	1	2	3	3
J_2	1	1	1	1
J_3	1	2	3	3

Table 5

Compatibility for B

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}
D_1	3	3	3	2	2	2	2	2	2	2	2	3
D_2	2	2	2	2	2	2	2	2	2	2	2	2
D_3	2	2	2	2	2	2	2	2	2	2	2	2
D_4	2	2	2	2	2	2	2	2	2	2	2	2
D_5	2	2	2	2	2	2	2	2	2	2	2	2
D_6	2	2	2	2	2	2	2	2	2	2	2	2
D_7	2	2	2	2	2	2	2	2	2	2	2	2
D_8	2	2	2	2	2	2	2	2	2	2	2	2
D_9	2	2	2	2	2	2	2	2	2	2	2	2
D_{10}	2	2	2	2	2	2	2	2	2	2	2	2
D_{11}	1	1	1	3	2	2	3	2	2	2	2	2
D_{12}	2	2	2	2	2	2	2	2	2	2	2	2

Table 6

Compatibility for S

	C_1	C_2	C_3	B_1	B_3	B_4	B_{13}
A_1	2	2	2	2	2	2	1
A_2	3	2	2	3	3	3	2
A_3	2	2	2	2	2	2	1
C_1				3	3	3	2
C_2				3	3	3	2
C_3				2	2	2	3

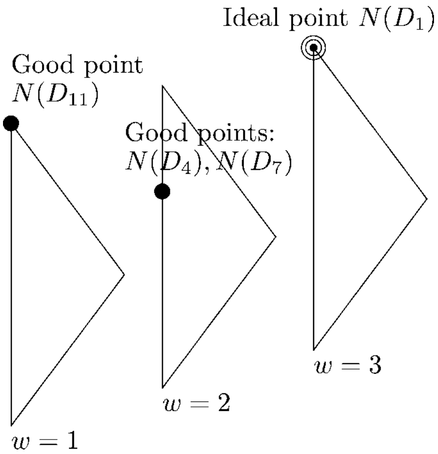

Fig. 13. System excellence for D.

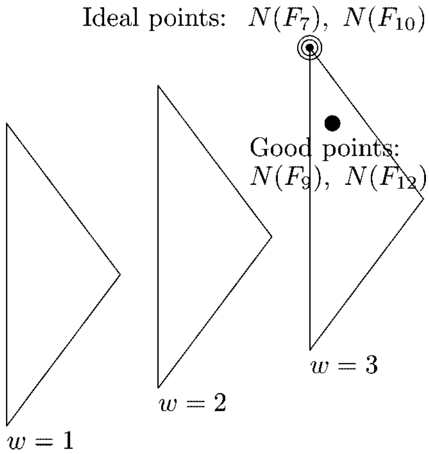

Fig. 14. System excellence for F.

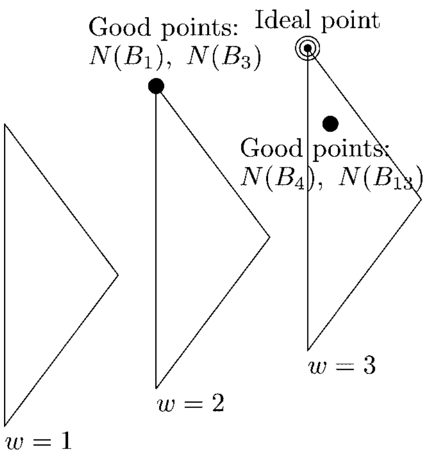

Fig. 15. System excellence for B.

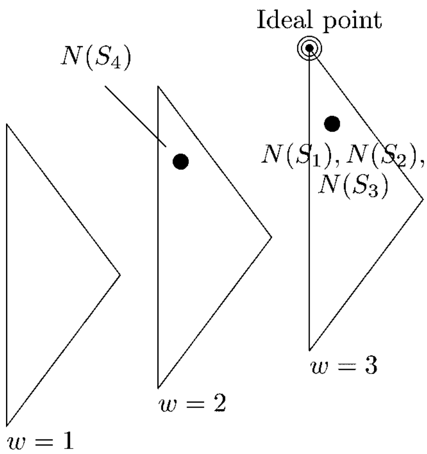

Fig. 16. System excellence for S.

be designed as monolith concrete. But in this case, we will get another kind of building structure: building with monolith concrete walls which are strengthening by frames. Note the obtained building will have an increased weight and a decreased level of thermotechnic and acoustic properties. A way to an ideal decision is based on the usage of monolith light concrete or light composite non-structural elements.

Thus we get an ordinal scale for composite DA's $[1, \dots, 5]$, (1 corresponds to the best level). Let us consider the following examples:

(i) $S^i = A_2 \star (E_1 \star G_1 \star H_1) \star (I_3 \star J_1) \star C_1$, *resultant quality level* equals 2;
(ii) $S^{ii} = A_2 \star (E_2 \star G_2 \star H_2) \star (I_3 \star J_1) \star C_1$, *resultant quality level* equals 2;
(iii) $S^{iii} = A_1 \star (E_2 \star G_2 \star H_2) \star (I_3 \star J_1) \star C_3$, *resultant quality level* equals 3;
(iv) $S^{iv} = A_2 \star (E_2 \star G_2 \star H_2) \star (I_3 \star J_1) \star C_3$, *resultant quality level* equals 3;
(v) $S^v = A_1 \star (E_2 \star G_1 \star H_1) \star (I_3 \star J_3) \star C_3$, *resultant quality level* equals 4.

4.3. *Improvement Actions and Criteria*

Our list of the basic improvement actions (operations) for the example is the following:

Operation group I (frames):
1. Increasing a geometrical dimension and active reinforcement O_1.
2. Increasing of active reinforcement O_2.

Operation group II (joints):
3. Increasing a level for fixing a longitudinal active reinforcement in zone of joints O_3.
4. Decreasing the step of reinforced cross rods in zone of joint O_4.

Operation group III (cantilever and cantilever balcony):
5. Decreasing the projection cantilever O_5.
6. Supplementary supporting the cantilever O_6.

Operation group IV (fronton and parapet wall):
7. Fixing a bottom part O_7.
8. Designing a 3D structure (special) O_8.

Operation group V (connection between frame and filler walls):
9. Design of shear keys O_9.
10. Design of mesh reinforcement O_{10}.
11. Partition of filler walls by auxiliary frame O_{11}.

Application of several redesign operations is depicted in Fig. 9.

Binary relations on the above-mentioned operations are the following:

(1) equivalence $R^e = \{(1,2),(1,3),(1,4),(2,3),(2,4),(5,6),(7,8),(9,10),$ $(9,11),(10,11)\}$, nonequivalence $\widetilde{R}^e = \{(3,4)\}$;

(2) complementarity $R^c = \{(1,2),(1,3),(1,4),(1,5),(1,6),(1,7),(1,8),$ $(1,9),(1,10),(1,11),(2,3),(1,4),(1,5),(1,6),(1,7),(1,8),$ $(3,4),(3,5),(3,6),(3,7),(3,8)(3,9),(3,10),(3,11),(4,5),(4,6),(4,7),(4,8),$ $(4,9),(4,10),(4,11),(5,7),(5,8),(5,9),(5,10),(5,11),$ $(6,7),(6,8),(6,9),(6,10),(6,11),(7,9),(7,10),(7,11),$ $(8,9),(8,10),(8,11)\}$,
noncomplementarity $\widetilde{R}^c = \{(5,6),(7,8),(9,10),(9,11),(10,11)\}$; and

(3) precedence $R^p = \{(1,2)(1,3)(1,4)(1,5),(1,6),(1,7),(1,8),(1,9),$ $(1,10),(1,11),(2,3)(2,4)(2,5),(2,6),(2,7),(2,8),(2,9),(2,10),(2,11),$ $(3,5),(3,6),(3,7),(3,8),(3,9),(3,10),(3,11),(4,5),(4,6),(4,7),$ $(4,8),(4,9),(4,10),(4,11),(5,9),(5,10),(5,11),(6,9),(6,10),$ $(6,11),(7,9),(7,10),(7,11),(8,9),(8,10),(8,11)\}$.

The following criteria are considered (corresponded ordinal scales and criterion weights are pointed out in brackets):

Improvement of earthquake resistance:
1. Decreasing a dead weight (or loading) ($[-2,\dots,2],3$): K_1.
2. Increasing a load capacity ($[1,\dots,5],5$): K_2.
3. Increasing a reliability ($[1,\dots,5],5$): K_3.

Quality of architecture and plan decisions:

4. Facade ($[0, ..5,], -3$): K_4.
5. Plan ($[0, \dots, 4], -3$): K_5.
6. Free space ($[0, .., 2], -3$): K_6.

Utilization properties:

7. Thermotechnics ($[0, .., 2], -1$): K_7.
8. Acoustics ($[0, 1], -1$): K_8.
9. Fire-risk ($[0, 1, 2], -4$): K_9.

Expenditure:

10. Materials ($[0, .., 10], -3$): K_{10}.
11. Cost ($[0, \dots, 10], -4$): K_{11}.
12. Time expenditure ($[0, \dots, 10], -3$): K_{12}.

Table 7 contains expert estimates for the above-mentioned building improvement actions upon criteria and a resultant priority (rank).

4.4. *Improvement Process*

The structure (model) of the process is based on binary relation R^c as follows: (a) operations for frame (e.g., O_1, O_2); (b) operations for joints (e.g., O_3, O_4); (c) operations for parapet wall (e.g., O_5, O_6); (d) operations for cantilever balcony (e.g., O_7, O_8); and (e) operations for connection between frame and filler wall (e.g., O_9, O_{10}, O_{11}).

Note precedence of the above-mentioned operation groups is the following: (a); (b); (c) and (d) concurrently; (e). Binary relation R^c is a basis to generate the following aggregated operations: $O_1 \& O_2$ and $O_3 \& O_4$. Binary relation $\widetilde{R}^c$ is a reason to delete the

Table 7

Estimates of improvement actions

Improvement actions	Criteria												Rank
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}	
O_1	−2	5	5	1	3	2	0	0	0	5	5	5	3
O_2	0	4	4	0	0	0	0	0	0	3	3	3	1
O_3	0	2	3	0	0	0	0	0	0	1	1	1	2
O_4	0	3	4	0	0	0	0	0	0	2	3	3	1
O_5	2	2	4	3	4	1	1	1	1	0	0	0	3
O_6	−1	3	5	5	1	1	0	0	2	5	4	5	4
O_7	2	3	4	0	0	0	0	0	1	1	2	2	1
O_8	1	4	5	2	1	1	0	0	1	2	3	4	2
O_9	0	2	3	0	0	0	0	0	1	1	1	1	3
O_{10}	0	3	4	0	0	0	0	0	1	4	3	4	2
O_{11}	0	2	4	0	0	0	2	1	0	5	5	5	3
$O_1 \& O_2$	−2	5	5	1	3	2	0	0	0	8	8	8	4
$O_3 \& O_4$	0	3	4	0	0	0	0	0	0	3	4	4	2

following aggregated operations $O_5\&O_6$, $O_7\&O_8$, $O_9\&O_{10}$, $O_9\&O_{11}$, $O_{10}\&O_{11}$, and $O_9\&O_{10}\&O_{11}$. The structure of the multi-stage improvement/redesign process and generated operations are shown in Fig. 17. All pointed out operations are compatible (by relation R_c).

Now let us consider the usage of models for the design of the improvement strategy:

Knapsack problem: The usage of knapsack problem is based on independence of the items/operations ($\{O_1, \ldots, O_{11}\}$), the only one objective function (mainly), and quantitative nature of the required resources. In our case, we can examine the following problem formulation:

(i) *objective function:* improvement of earthquake resistance, i.e., criterion K_1 or K_2 or K_3;

(ii) *restrictions for resources:* (a) quality of architecture and plan decisions: K_4, K_5, and K_6; (b) utilization properties: K_7, (K_8), and K_9; and (c) expenditure: materials (K_{10}), cost (K_{11}), time (K_{12});

Unfortunately, our redesign operations are interconnected (i.e., binary relations of *equivalence*, *complementarity*, and *precedence*) and it is reasonable to use more complicated model.

Multiple choice problem: In this case, we can consider the approach to problem formulation from the previous section while taking into account operation grouping (Fig. 17), i.e., the structure of the redesign process. In addition, here it is necessary to define resource restrictions for each operation group. Note quantitative scales are basic ones for this model.

Multiple criteria ranking: Table 7 contains the results of multicriteria selection (ranks of operations). This model is the basic one in multicriteria decision making and can be recommended and a significant part of more general solving schemes.

Morphological clique problem: This approach is based on multicriteria ranking and taking into account operation dependence or the structure of the redesign process (Fig. 17). Evidently, here the best redesign strategy is the following: $O_2 \Rightarrow O_4 \Rightarrow O_5\&O_7 \Rightarrow O_{10}$.

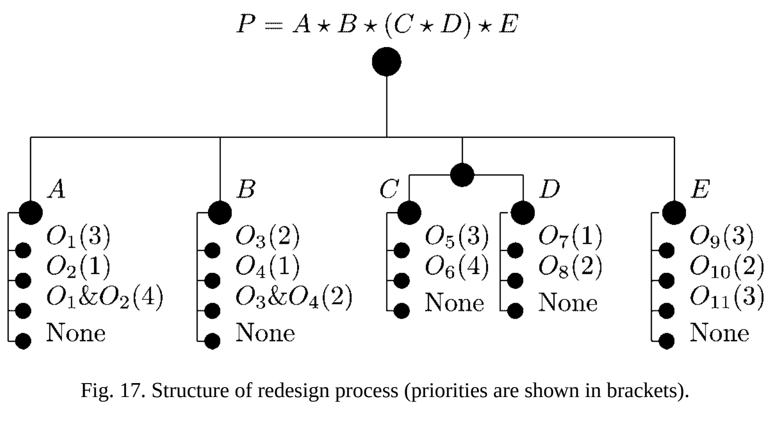

Fig. 17. Structure of redesign process (priorities are shown in brackets).

5. Conclusion

Recently, issues of evaluation and improvement of complex systems play often a central role in many engineering domains (e.g., software engineering, electrical engineering, structural engineering). This process (i.e., evaluation and improvement/redesign or adaptation) can be considered and used in two modes: off-line mode and on-line mode. In this article, we have suggested the general hierarchical decision making framework for the evaluation and improvement/redesign of composite systems. The material consists of the following main parts:

Part 1. Description of Hierarchical Morphological Multicriteria Design which realizes "partitioning/synthesis macroheuristic" and applications for three design problems: (i) hierarchical modular design, (ii) hierarchical assessment of composite systems; and (iii) improvement/redesign of composite systems.

Part 2. Brief description of the integration tables method for hierarchical system assessment.

Part 3. Framework for system improvement/redesign. The third part involves the following:

1. Design of hierarchical system model.
2. Hierarchical evaluation of the system.
3. Revelation of bottlenecks.
4. Design of improvement processes including the following: *4.1.* generation of improvement action set and its description via special binary relations and multicriteria estimates; *4.2.* selection/composition of the best subset of the improvement actions while taking into account certain design and technological requirements; and *4.3.* scheduling of the selected improvement actions. Several combinatorial optimization models (knapsack problem, multiple choice problem, multiple criteria ranking, and morphological clique problem) are used for the design of improvement processes.

The above-mentioned general hierarchical framework is illustrated by the numerical example of a two-floor building. Future investigations include the following:

I. Examination and enhancement of the hierarchical framework, Hierarchical Morphological Multicriteria Design and "partitioning/synthesis macroheuristic" including the following issues: (i) complexity of the combinatorial problems and computing procedures, (ii) participation of domain experts in all stages of the solving process, (iii) development of a special interactive environment.

II. Investigation of off-line and on-line improvement processes for applied composite systems in various engineering domains.

III. Educational efforts (i.e., special courses and projects as the evaluation and improvement/redesign of applied composite systems).

6. Acknowledgments

Early versions of the material were prepared in 1999–2003. At this stage, Mark Sh. Levin was with The College of Judea & Samaria and The Ben-Gurion University of the Negev (Israel).

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Hierarchinė sprendimų priėmimo struktūra kompozicinėms sistemoms vertinti ir tobulinti (statinių pavyzdžiu)

Mark Sh. LEVIN, Moshe A. DANIELI

Straipsnyje aprašoma sprendimų priėmimo hierarchinė struktūra, skirta vertinti sudėtingas sistemas jų tobulinimo/perprojektavimo metu. Struktūra apjungia hierarchinį, morfologinį ir daugiakriterinį projektavimą (HMDP), morfologinę grupinę problemą ir atlieka dalinimo arba sintezės makroeuristiką.

Sistemos vertinimo procesas apjungia hierarchinį ekspertinių metodų integravimą: integruojamų lentelių metodą arba morfologinį projektavimą. Taip atliekama daugiapakopė sutvarkomoji klasifikacija. Sistemos tobulinimo procesas nagrinėjamas kaip perprojektavimo operacijų parinkimas ir planavimas įvertinant operacijų (procesų) charakteristikas ir binarinius ryšius operacijų aibėms. Sistemos tobulinimo proceso modeliavimui naudojamas keletas kombinatorinės optimizacijos modelių, įskaitant HMDP.

Siūlomas metodas pritaikytas sprendžiant realų dviaukščio pastato perprojektavimo uždavinį, įvertinant, kad statyba numatoma padidinto seismingumo teritorijoje.