Hierarchical Approach for Engineering Skills Acquisition

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Abstract. The article addresses the use of hierarchical morphological design framework for engineering skills acquisition. The hierarchical approach is the best way for structuring some complex design skills in the field of composite systems. Applications of the hierarchical morphological approach involve hierarchical description, design and analysis of composite systems, and an analysis of system evolution. Our material describes the following: (i) some hierarchical structures and combinatorial operations, (ii) hierarchical information, (iii) hierarchical processes (e.g., AHP, hierarchical decision making), (iv) our hierarchical morphological approach (HMA), (v) many applications of hierarchical morphological approach, (vi) some strategies for acquisition of engineering skills, and (vii) usefulness for engineering education and extension / structuring of engineering skills.

1 Introduction

In recent years, issues of skill / knowledge acquisition have been played a central role in many domains (e.g., cognitive modeling, information technology, problem solving, knowledge based systems, system design, engineering design, systems engineering, process systems engineering, team distributed design processes) ([2], [3], [10], [11], [16], [40], [46], [44], etc.). Let us point out some other important research directions closed to the above-mentioned domain: (a) cognitive modeling of design processes [1], [2], [3], etc.); (b) relation between cognitive processes and operations research [19]; (c) organization and management of engineering information on complex products / systems and their reengineering ([4], [24], [39], [48], etc.); (d) studying and developing the knowledge and skills of specialists ([10], [11], etc.); and (e) cognitive modeling for conceptual design ([24], [33], etc.).

This article focuses an experience in acquisition of systems engineering / system design skills. In our opinion, the significance of the direction is increasing because engineering of many complex systems is based on domain expert knowledge. The following human operations for information processing have been considered as basic ones [35], etc.): *1.* accumulation of knowledge; *2.* generalization of knowledge; *3.* revelation of problems; *4.* usage of judgment for problem solving; *5.* explanation of judgment; *6.* joint work with other specialists and, as a

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result; accumulation of new knowledge; *7.* restructuring of knowledge; *8.* usage of exceptions; and *9.* understanding a situation that a problem is connected with a certain expert domain.

In this paper, a hierarchical morphological framework is examined which is an useful organizational basis for a systems engineering process: to execute operations for the description, design, analysis and improvement of composite systems. Hierarchical approach allows to combine the above-mentioned operations at various hierarchical levels, and decompose a global problem into more simple problem domains. Note we consider, at the same time, declarative hierarchical information on a system and procedure hierarchical information (mainly, system description, selection and composing of alternatives, revelation of bottlenecks) on the analysis, design and transformation of the system. Usually the systems engineering process has to integrate cooperative works of many domain experts. As a result, the organizational workflow problem is the following: (a) to divide an initial system problem into subproblems, (b) to solve the subproblems, and (c) to integrate local decisions for subproblems above into a global decision of the initial system problem. This workflow is a *cascade-like* one.

Conclin has pointed out that a hierarchical representation of information is more natural for users with an engineering background [9]. Thus the hierarchical approach is the best way for structuring some complex design skills in the field of composite systems. In this paper, our way is the following:

(i) some hierarchical structures and combinatorial operations,

(ii) hierarchical information,

(iii) hierarchical processes (e.g., AHP, hierarchical decision making),

(iv) our hierarchical morphological approach (HMA),

(v) applications of hierarchical morphological approach,

(vi) some strategies for acquisition of engineering skills, and

(vii) usefulness for engineering education and extension / structuring of engineering skills.

Note construction of a generalization space some domain knowledge is a contemporary approach in the field of conceptual structuring ([6], [7], etc.). Minsky has pointed out the following architecture of representations ([37] and [38]): (1) stories written in natural language; (2) story-like scripts; (3) transframes; (4) frame-arrays and picture-frames; (5) semantic nets; (6) K-lines; (7) neural nets; and (8) micronemes.

HMA is a hierarchical combination of several types of the above-mentioned representations including the following:

(a) description of goals, system components, criteria, etc (stories and story-like scripts);

(b) frame arrays, picture-frames and their graph-like modeling (e.g., system structure, interconnection between system parts and components, alternatives and relations on them, criteria and preference relations on them);

(c) semantics nets (e.g., for system improvement process, modeling the system evolution as a network of system generations).

Our hierarchical system model is a special generalized space for modeling many composite systems and their generations ([24] and [29]).

2 Hierarchical Information Systems

2.1 Hierarchical Structures and Operations

Shenhar has described three kinds (levels) of complex systems (assembly, system, array) [45]. Thus it is necessary to apply various kinds of hierarchical structures for the description of systems ([5], [9], [24], [42], [48], etc.), for example: (a) tree; (b) forest; (c) hierarchy of various kinds, e.g., organic hierarchy [8]); and (d) pyramid. Here the following requirement have to be taken into account: (i) correspondence (adequacy) to the described system; (ii) correspondence to an experience / background of domain expert(s) (usefulness for human); and (iii) usefulness from viewpoint of data processing (simpleness for computer processing).

At the same time, it is reasonable to take into account main life cycle stages for a structure as design and support (search, coordination, improvement, merging / integration, transformation). Well-known operations are the following ([15], [17], [24], [42], [47], etc.):

I. Traditional operations: input of data, correction, search (retrieval).

II. Structural processing: (1) comparison; (2) revelation of substructure of a certain kind; (3) analysis of interconnection between some substructures; (4) analysis of some properties (e.g., balance) (4) integration of structures; (5) approximation of structures by some structures of a certain kind (e.g., by tree-like ones); and (6) transformation.

For each operation above, we can use well-known and some new kinds of mathematical models (e.g., various types of metrics or proximity; models of matching; models of integration; models of approximation or covering) ([5], [15], [21], [24], etc.).

2.2 Some Hierarchical Information Systems

Main functional operations for the design, utilization, and maintenance of design information systems are the following ([12], [22], and [41]): (1) acquisition of new data and knowledge; (2) structuring, modeling; (3) representation; (4) learning; (5) access, control; (6) analysis, evaluation, correction; and (7) maintenance. Support information systems may be oriented to various components of a systems engineering (system design) process. Also, it is reasonable to list reference examples of some information systems:

(1) Information Design Model (EDM) for engineering design [13];

(2) hierarchical hypertext system (HHS) involving components of different kinds and their criterial descriptions for various problem domains ([21] and [22];

(3) Designer's Electronic Guidebook for mechanical engineering in Cambridge Engineering Center [14]; and

(4) An Information Model for Cooperative Product Development SHARED [48].

3 Hierarchical Morphological Approach

Hierarchical processes and problem solving techniques on the basis of decomposition (problem partitioning) are well-known ones, for example: (a) dynamic programming ([15], etc.); (b) Analytic Hierarchy Process AHP [43]; and (c) Branch-And-Bound method in combinatorial optimization ([15], etc.).

In this section, we briefly describe our hierarchical morphological approach HMA which integrates the following methodologies:

1. design frameworks (generalized hierarchical design approach to the description, analysis and synthesis of the designed and / or redesigned composite system;

2. multicriteria decision making (e.g., for ranking some design alternatives, for analysis of composite decisions);

3. morphological analysis (for composition of composite alternatives);

4. combinatorial optimization (e.g., morphological clique model to combine local decision into a resultant composite one); and

5. knowledge based methodology and knowledge engineering (e.g., techniques for acquisition of ordinal expert knowledge on design alternatives and their compatibility).

Note an explanation of our approach and the above-mentioned components (methodologies) to an domain expert / specialist is an essential part of each application project.

3.1 Description

Our basic framework or hierarchical morphological multicriteria design HMMD [24] 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 (system parts, components) including ordinal scales for each criterion; and *1.3.* design of multi-factor description for compatibility between design alternatives of different system parts.

II. System Synthesis: *2.1.* generation of design alternatives (DA's) for the system parts / components; *2.2.* evaluation of DA's upon criteria; *2.3.* evaluation of compatibility between DA's; and *2.4.* step-by-step synthesis of DA's to obtain composite DA's for a higher level of the model hierarchy.

III. Analysis of composite DA's to reveal bottlenecks (by DA's, by Ins).

IV. Design of improvement actions for the system: *4.1.* generation / selection of a set of some possible improvement actions; *4.2.* selection / composition of the best subset of the improvement actions under taking into account certain design and technological situations; and *4.3.* scheduling of the improvement actions.

HMMD uses hierarchical tree-like structure (organic hierarchy) of a designed system as a basic hierarchy. The representation of this hierarchy is easy. Many of researches apply similar approach ([13], [18], [20], [34], etc.).

HMMD implements "cascade-like" strategy of organizational process:

1. Divergent stage: “Top-Down” Hierarchical description of the system.

2. Convergent stage: “Bottom-Up” system design (generation of alternatives, their selection and composition)

Basic information components are the following (information support is pointed out in brackets):

1. Hierarchical system model.

2. Design module:

2.1 Requirements: 2.1.1 criteria (standard criteria); 2.1.2 compatibility factors (standard factors); and 2.1.3 restrictions (standard restrictions).

2.2 Design alternatives DA's: 2.2.1 set of DA's (standard design alternatives); 2.2.2 estimates; and 2.2.3 priorities.

2.3 Interconnection Ins (standard interconnection): 2.3.1 estimates on factors; and 2.3.2 resultant estimates.

3. Composite solutions (standard constraints):

4. Improvement as a set of improvement actions and schedule (basic examples, strategies of improvement).

5. Systems versions (basic examples of systems versions, tendencies for various problem domains).

3.2 Examples of Hierarchical Morphological Approach

Realistic system design examples illustrate our framework (domain, domain expert, complexity of a problem by scale [1...5], existence of a basic example, level of structural thinking of expert by scale [1...5] and type of strategy, reference):

1. Information technology; M.Sh. Levin & L.S. Levinsky; 5; Yes; 5,d; [24].

2. Composite software system; M.Sh. Levin; 3; Yes; 5,p; [24].

3. User interface; M.Sh. Levin; 5; No; 5,d; [24].

4. Team design; M.Sh. Levin; 3; Yes; 5,d; [24].

5. Allocation of personnel; M.Sh. Levin; 4; Yes; 5,d; [24].

6. Design of curriculum; M.Sh. Levin; 4; Yes; 5,d; [24].

7. Design of problem solving strategy; M.Sh. Levin; 3; No; 5,p; [24].

8. Geological exploration; V.I. Poroskoon; 3; No; 5,d; [24].

9. Concrete technology; M.L. Nisnevich; 3; No; 3,d; [32].

10. Redesign of buildings; M.A. Danieli; 3; Yes; 2,d; [28].

11. Vibration conveyor; Yu.T. Kaganov; 5; No; 2,d; [24].

12. Product marketing trajectories; M.Sh. Levin et al.; 3; Yes; 4,p; [26].

13. Design of product life cycle; M.Sh. Levin et al.; 3; Yes; 4,p; [27].

14. Medical treatment; L. Sokolova; 4; No; 4,p; [31].

15. System evolution: example for software; M.Sh. Levin; 4; No; 5,d; [24].

16. System evolution: example for signal processing; B.J. Feldman & M.Sh. Levin; 5; [29].

17. Immunoassay technology; M. Firer; 5; No; 5,d; [30].

3.3 Strategies for Skill Acquisition

Now let us point out some basic strategies as follows:

1. Direct strategy (step-by-step execution of HMA) ("d" in section 3.2).

2. Prototype strategy ("p" in section 3.2): (a) preparation of a simple example (prototype); for the system description of an design; and (b) analysis of the example with the expert(s); (c) correction / improvement / extension of the example.

Evidently, the second strategy is more useful for experts who has no experience in problem structuring. In this case, we can often to organize our dialogue with expert on the level of a language (system description) of his / her problem domain. At the same time, it is impossible to use the prototype strategy for new domain. Thus it was very difficult to design a system description for vibration conveyor. An additional useful stage consists in a preliminary explanation of the HMA for the expert including an analysis of examples.

Note the most hard stages of HMA are the following: (a) start of the work with expert(s); (b) explanation for expert the main problems and work strategy (e.g., knowledge-based system methodology); (c) generation of design alternatives; (d) analysis and evaluation of compatibility between design alternatives, and (e) analysis of results.

It is necessary to point out that domain specialists often are not ready to understand HMA and its components. In this case, it is reasonable to conduct an application project and after that to explain HMA on the basis of the joint work.

4 Ethics Issues of Expert Procedure Support

A procedure of engineering skill acquisition involves two main sides (roles): (a) domain expert (E), (b) "knowledge engineer" who is an organizer of the procedure (O). It is reasonable to consider a set of principles (that are close to the Hippocratic oath) for the organizer, for example ([23], etc.):

1. Honesty.

2. Orientation to global goals.

3. To tell "No" , "It is impossible".

4. To take into account properties of the expert (background, experience, mentality, style of thinking).

5. To support the collaboration by special instrumental (tables, software, etc.) and organizational (useful time, style, etc.) efforts.

6. To apply various approaches.

7. To learn the expert (e.g., decision making technology, required models).

5 Structuring / Extension of Skills and Engineering Education

In fact, HMA combines all basic learning operations [36]: (i) direct indications; (ii) explanations; (iii) observation of examples; and (iv) discovery. Thus we can usually decompose faced engineering problems and decrease their intellectual levels. Note basic system analysis / design procedures are the same ones: (a) hierarchical design and description of system model; (b) selection of alternatives; and (c) synthesis of composite decisions. Expert experience in the above-mentioned basic procedures is a fundamental to increase a level of expert thinking and to extend expert skills. Thus HMA can be used as an organizational basis for structuring and extension of the engineering skills including team work modes. Note some issues of engineering education on the basis of HMA are considered in ([23] and [25]).

6 Conclusion

We have described our experience in the use of HMA for engineering skills acquisition. Our results are preliminary one, and it is reasonable to investigate the following:

1. examination of additional real engineering examples including systems engineering problems and strategic design problems;

2. analysis of negative results of the applications from various viewpoints (e.g., organizational, psychological, educational);

3. significance of expert classification (type of thinking, design styles, etc.);

4. usage of our approach for engineering skills acquisition in maintenance of complex industrial systems (e.g., diagnosis, planning, information allocation and personnel management);

5. realization of the hierarchical morphological approach in engineering education (e.g., course on systems engineering, course on design methods, continues education course); and

6. development of special support educational computer tools (computer environment).

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