Decision Engineering

Series editor

Rajkumar Roy, Cranfield, Bedfordshire, UK

More information about this series at http://www.springer.com/series/5112

Mark Sh. Levin

Modular System Design and Evaluation

Springer

Mark Sh. Levin
Institute for Information Transmission
Problems (Kharkevich Institute)
Russian Academy of Sciences
Moscow
Russia

ISSN 1619-5736 ISSN 2197-6589 (electronic)
ISBN 978-3-319-09875-3 ISBN 978-3-319-09876-0 (eBook)
DOI 10.1007/978-3-319-09876-0

Library of Congress Control Number: 2014947140

Springer Cham Heidelberg New York Dordrecht London

© Springer International Publishing Switzerland 2015
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

The book is dedicated to my lecturers and advisors:

(a) Moscow Technical University of Communications and Informatics (BS and MS program, 1965–1970, Radio Engineering);

(b) Lomonosov Moscow State University (MS program, 1971–1975, Mathematics);

(c) Lomonosov Moscow State University (Ph.D. program, 1977–1981, Mathematics and Computers in Management)

Preface

The frame approach for representing knowledge (i.e., collection of frames are linked together into frame-system) has been suggested by Marvin Minsky. In this approach, the frame corresponds to a data structure. In general, it is possible to consider the following three-component system: initial data/information, problem (s) (and corresponding models), and algorithm (or interactive procedure). For many complex applied problems, it is reasonable to examine special composite frameworks (i.e., composite solving schemes) consisting of problems (and corresponding models), which are interconnected/linked (e.g., by preference relation). For example, a basic simplified framework for data processing can be described as follows:

(a) analysis of input data/information and preliminary processing;
(b) processing; and
(c) analysis of results.

Another example of a framework is well-known in decision-making. Herbert A. Simon has suggested his framework for rational decision-making (choice problem): (i) the identification and listing of all the alternatives, (ii) determination of all the consequences resulting from each of the alternatives, and (iii) the comparison of the accuracy and efficiency of each of theses sets of consequences. A modified version of this decision-making framework is the following:

Stage 1. Analysis of the examined system/process, extraction of the problem.
Stage 2. Structuring of the decision-making problem:

- 2.1 generation of an alternatives set,
- 2.2 generation of criteria for evaluation of the alternatives and generation of a scale for each criterion.

Stage 3. Obtaining the initial information (estimates of the alternatives, preferences over the alternatives).
Stage 4. Solving process to obtain the decision(s).
Stage 5. Analysis of the obtained decision(s).

Now there exists a trend to design, to describe, and to use a set of basic typical engineering (technological) frameworks (i.e., typical composite combinatorial solving schemes), which can be considered as basic standard blocks in systems research/design and in systems education (engineering, computer science, applied mathematics).

In recent decades, modular approaches have been used in all engineering domains. Thus, many systems can be designed (composed) from basic modules (e.g., software engineering, computer engineering, information engineering, method engineering, protocol engineering, industrial engineering). Evidently, special combinatorial methods have to be studied and applied for system analysis/design at all stages of the system life cycles. The methods can have the following structure types: series, parallel, series-parallel, cascade-like. Here, the following basic problems are very important: (1) partitioning the initial problem (or partitioning the examined system), (2) solving the local problems, and (3) aggregation of solutions for the local problems above into the global system solution.

The material of this book enhances the materials of the previous author's books: "Composite Systems Decisions", Springer, 2006; "Combinatorial Engineering of Decomposable Systems", Springer, 1998. The book contains an author's attempt to examine a new

"Decision Support Technology Platform for Modular Systems"

as a set of typical combinatorial engineering frameworks for hierarchical modular systems (with hierarchical structures). This approach is based on the following five-layer architecture:

Layer 1. Basic combinatorial optimization problems (e.g., knapsack problem, multiple choice problem, multicriteria ranking/selection, clustering, minimum spanning tree problem, minimum Steiner tree problem, clique problem).

Layer 2. Complex (e.g., multicriteria) combinatorial optimization problems (e.g., multicriteria knapsack-like problems, multicriteria multiple choice problem, multicriteria Steiner tree, morphological clique problem, design of multilayer network topology).

Layer 3. Basic support frameworks (e.g., hierarchical design, aggregation of structures, restructuring of knapsack problem, restructuring of multiple choice problem).

Layer 4. Combinatorial engineering frameworks (consisting of a set of linked combinatorial problems) (e.g., hierarchical system modeling, design, evaluation, detection of bottlenecks, improvement, design of trajectory, combinatorial evolution, and forecasting).

Layer 5. Applied combinatorial engineering frameworks (e.g., modeling, design and improvement of system components for information-communication systems).

Note, engineering system design/synthesis can be considered/implemented on the basis of various methods, for example: design principles and systematic invention, general design theory as theory of knowledge, theory of technical systems, knowledge operations (reasoning, etc.), prototype-based design, morphological analysis, design catalogues based methods, system configuration design

based on AI methods, TRIZ (the Altshullerian approach to solving innovation problems), synthesis based on function-means trees, and synthesis of system topology using genetic programming. In this book, basic standard combinatorial engineering (technological) frameworks for modular systems are systematically described while taking into account the system life cycles (i.e., layer 4 above):

Framework 1. Design of system hierarchical model.
Framework 2. Combinatorial synthesis ("bottom-up" process for system design).
Framework 3. System evaluation (for system parts/components, for whole system).
Framework 4. Detection of system bottlenecks (e.g., by system elements, by compatibility of system elements, by system structure).
Framework 5. System improvement (redesign, upgrade, extension).
Framework 6. Multistage design (design of system trajectory).
Framework 7. Combinatorial modeling of system evolution/development and system forecasting.

The material extends previous author's publications by the following ways:

(a) description of hierarchical structures and their design,
(b) description of system bottlenecks and approaches to their detection,
(c) description and usage of new interval multiset estimates,
(d) special description of system configuration based on combinatorial optimization,
(e) description of combinatorial synthesis based on interval multiset estimates for system components,
(f) description of special procedures for aggregation of modular solutions,
(g) brief description of a new restructuring approach in combinatorial optimization, and
(h) a set of various new applied examples for some parts of information technology (e.g., electronic shopping, Web-based system, integrated security system, telemetry system, wireless sensor, communication protocol, and standard for multimedia information).

The applied examples are based on the usage of the suggested combinatorial engineering frameworks including new methods above (e.g., interval multiset estimates, aggregation of structured solutions, system design, and system improvement). Generally, the suggested material corresponds to modular systems engineering in the field of information technology, but suggested approaches (frameworks) can be successfully applied in many domains (engineering, computer science, applied mathematics, management, social engineering).

The book consists of two parts:

The first part of the book (*Basic Combinatorial Engineering Frameworks*) involves the following: description of basic hierarchical system structures and basic standard combinatorial engineering frameworks (i.e., hierarchical system modeling, combinatorial synthesis, system evaluation, detection of system bottlenecks, system improvement, design of system trajectory, combinatorial system evolution, and

forecasting). Here, our version of morphological design approach plays a central role. In addition, a special attention is targeted to system configuration problems.

The second part of the book (*Applications in Information-Communication Systems*) contains the following real-world applied examples: description of applications (composite solving strategy for multicriteria ranking, electronic shopping of composite product, Web-based system, integrated security system, connection of end-users and access points in communication network, telemetry system, MPEG-like standard for multimedia information processing, wireless sensor, ZigBee communication protocol, management system for smart homes). In each applied example above, several combinatorial engineering frameworks are used, for example: (a) hierarchical system modeling, system design, system improvement, (b) hierarchical system modeling, system design, combinatorial system evolution and forecasting. The applications described can be used as a set of basic analogues (prototypes) for various applied domains.

In general, the book can be considered as an information and operation environment for hierarchical modular systems: combinatorial modeling, processing (design, evaluation, improvement, forecasting, etc.). In fact, this material corresponds to a "combinatorial ABC-book" for modular systems and/or for decision-making based on composite decisions (composite alternatives).

A preliminary version of this book was published as an electronic book in Russian:

Mark Sh. Levin, Decision Support Technology for Modular Systems. Electronic book, 2013 (in Russian); http://www.mslevin.iitp.ru/Levin-bk-Nov2013-071.pdf

This may be of interest to Russian-language readers.

The suggested book is oriented to applied researchers, students, and practitioners in many domains. Concurrently, the material will be of interest to various scientists (e.g., computer scientists, mathematicians, economists, social engineers). In addition, the book can be used as a useful text for some educational courses (e.g., systems engineering, system design, life cycle engineering, engineering design, combinatorial synthesis) at various levels: senior undergraduate level (a compressed version), graduate/Ph.D. levels, and for continuing education. The material of the book will be useful for modular curriculum design including the design of individual student educational programs.

Moscow, June 2014 Mark Sh. Levin

Acknowledgments

First, I am grateful IEEE for the permission to use some materials from my published conference papers:

Levin MS (2009) Towards morphological system design. In: Proc. of 7th IEEE Int. Conf. on Industrial Informatics INDIN-2009, Cardiff, UK, pp. 95–100

Levin MS (2010) Towards communication network development. In: Proc. of IEEE Region 8 Int. Conf. SIBIRCON-2010, Irkutsk, Russia, vol. 1, pp. 204–208

Levin MS, Andrushevich A, Kistler R, Klapproth A (2010) Combinatorial evolution of ZigBee protocol. In: Proc. of IEEE Region 8 Int. Conf. SIBIRCON-2010, Irkutsk, Russia, vol. 1, pp. 314–319

Second, I thank my students in Moscow Institute of Physics and Technology (State University) for our successful joint research projects (2004–2012): Alexander V. Safonov (improvement of communication networks), Rustem I. Nuriakhmetov (multicriteria Steiner problem), Maxim V. Petukhov (connection of end-users and access points), Andrey V. Leus (integrated security system), Alexander V. Fimin (wireless sensor), Igor A. Khodakovsky (telemetry system), Roman O. Vishnitsky (GSM network), Alexey O. Merzlyakov (testing of microprocessor systems), and Anton A. Zamkovoy (multicriteria Steiner problem with cost of Steiner nodes).

Third, I thank colleagues from Lucerne University of Applied Science (Switzerland, CEESAR-iHomeLab) for our successful research collaboration in the fields of management systems for smart homes and ZigBee communication protocol for sensor networks (2009–2011): Aliaksei Andruchevich, Alexander Klapproth, Rolf Kistler.

Four, I would like to acknowledge the Institute for Information Transmission Problems (Kharkevich Institute) of Russian Academy of Sciences where I am working (recent 10 years).

Contents

1 Modular Systems, Combinatorial Engineering Frameworks 1
1.1 Preliminaries 1
1.2 Basic Types of Hierarchies. 4
1.3 Combinatorial Engineering Frameworks. 7
1.4 Summary 9

2 Methods of Morphological Design (Synthesis). 11
2.1 Introduction 11
2.2 Morphological Design Approaches 14
2.2.1 Morphological Analysis. 14
2.2.2 Method of Closeness to Ideal Point. 15
2.2.3 Pareto-Based Morphological Approach 16
2.2.4 Linear Programming 16
2.2.5 Multiple Choice Problem. 17
2.2.6 Assignment/Allocation Problems. 18
2.2.7 Hierarchical Morphological Multicriteria Design (HMMD) 19
2.3 Design Examples for GSM Network 21
2.3.1 Initial Example. 22
2.3.2 Morphological Analysis. 23
2.3.3 Method of Closeness to Ideal Point. 25
2.3.4 Pareto-Based Morphological Analysis 28
2.3.5 Multiple Choice Problem. 29
2.3.6 Hierarchical Morphological Design 30
2.3.7 Comparison of Methods and Discussion 32
2.4 Towards Other Approaches 34
2.5 Summary 36

3 Multiset Estimates and Combinatorial Synthesis 37
3.1 Introduction 37
3.2 Basic Assessment Problems 39

3.3 Operations Over Multiset Estimates . . . 40
3.3.1 Integrated Estimates . . . 41
3.3.2 Vector-Like Proximity . . . 43
3.3.3 Comparison of Estimates . . . 45
3.3.4 Aggregation of Estimates . . . 46
3.3.5 Alignment of Estimates . . . 47
3.4 Combinatorial Synthesis (Morphological Approach) . . . 48
3.4.1 Example: Basic HMMD, Three-Component System . . . 49
3.4.2 Example: Basic HMMD, Four-Component System . . . 49
3.4.3 Modified Version of HMMD Method . . . 50
3.4.4 Example: Three-Component System, Three-Element Assessment . . . 53
3.4.5 Example: Four-Component System, Four Elements Assessment . . . 54
3.4.6 Example: Three-Layer Hierarchical System . . . 57
3.5 Multiset Estimates in Knapsack-Like Problems . . . 60
3.6 Multiset Estimates and Multi-attribute Alternatives . . . 64
3.7 Summary . . . 66

4 Design of Hierarchical Structure . . . 67
4.1 Introduction . . . 67
4.2 Expert Based 'Top-Down' Procedure . . . 68
4.3 Hierarchical Clustering . . . 69
4.4 Towards Ontology . . . 71
4.5 Spanning Trees . . . 72
4.6 Towards Optimal Organizational Hierarchies . . . 76
4.7 Multi-layer Structures . . . 77
4.7.1 Multi-layer Approach . . . 77
4.7.2 Typical Hierarchical Layers in Communication Network . . . 78
4.7.3 Layered K-Connected Network . . . 79
4.7.4 Towards Hierarchical Network Design Problems . . . 82
4.7.5 Connection in Two-Layer Network (Access Points—Users) . . . 83
4.8 Morphological Hierarchy . . . 85
4.9 General Design Framework for Multi-layer Structure . . . 86
4.10 Summary . . . 87

5 System Configuration and Combinatorial Optimization . . . 89
5.1 Introduction . . . 89
5.2 Underlaying Combinatorial Problems and Schemes . . . 92
5.2.1 Problem of Representatives . . . 92
5.2.2 Shortest Path Problem . . . 93

5.2.3 Multipartite Graph Clustering and Weighted Clique in Multipartite Graph 94
5.2.4 Extended Assignment/Allocation Problem 95
5.2.5 Graph Coloring Problems 100
5.2.6 Some Related Problems 103
5.3 Applied Versions of System Configuration Problem 105
5.4 Towards Dynamic System Reconfiguration 108
5.5 Summary 108

6 System Evaluation 111
6.1 Introduction 111
6.2 Considered Types of Assessment Scales 114
6.3 Transformation of Scales 119
6.4 Integration of Scales and System Quality 122
6.5 Numerical Examples 126
6.6 Summary 129

7 Detection of System Bottlenecks 131
7.1 Introduction 131
7.2 Traditional Quality Management Methods 132
7.3 Detection of Bottlenecks in Morphological Design 137
7.4 Critical Elements in Multi-layer Structures/Networks 140
7.5 Predictive Detection of System Bottlenecks 142
7.5.1 Predictive Detection of System Components 143
7.5.2 Predictive Detection of Interconnected System Components 143
7.6 Clique-Based Fusion on Graph Streams 145
7.6.1 Preliminaries 145
7.6.2 Notations 147
7.6.3 Basic Problem 148
7.6.4 Problems over Graph Streams 150
7.6.5 Example 151
7.6.6 Discussion 153
7.7 Summary 154

8 System Improvement/Extension 155
8.1 Introduction 155
8.2 Four System Improvement Situations 157
8.2.1 Basic System Improvement Situation 157
8.2.2 Basic Improvement Situation, Combinatorial Problems 159
8.2.3 Additional System Improvement Situations 159

8.3 Approaches to System Evaluation and Improvement 160
8.3.1 System Quality and Improvement 160
8.3.2 Towards Reoptimization 164
8.4 Improvement by System Components 166
8.4.1 Basic Framework 166
8.4.2 Graph Vertex Recoloring Problem 168
8.5 Modification of System Structure 170
8.5.1 Modification of Tree via Condensing of Weighted Edges 170
8.5.2 Hotlink Assignment Problems 176
8.5.3 Transformation of Tree into Steiner Tree 178
8.5.4 Augmentation Problem 181
8.5.5 Transformation of Morphological Structure 181
8.5.6 Transformation of Layered Structure 182
8.6 Examples for Network Improvement/Extension 182
8.6.1 Network Hierarchy 182
8.6.2 Requirements/Criteria 183
8.6.3 Network Design/Development: Basic Problems 183
8.6.4 Network Improvement 184
8.6.5 Network Extension 186
8.7 Summary 190

9 Aggregation of Structured Solutions 191
9.1 Introduction 191
9.2 Auxiliary Problems and Aggregation Strategies 194
9.2.1 Basic Auxiliary Problems 194
9.2.2 Building of "System Kernel" 196
9.2.3 Aggregation Strategies 196
9.3 Examined Structures, Substructure, Superstructure 199
9.3.1 Sets 199
9.3.2 Rankings (Layered Sets) 199
9.3.3 Morphological Sets 200
9.3.4 Trees and Morphological Structures 201
9.4 Preliminary Illustrative Example for Notebook 203
9.5 Metrics and Proximities 207
9.5.1 Metric/Proximity for Sets 207
9.5.2 Proximity for Strings/Sequences 208
9.5.3 Proximity for Rankings 209
9.5.4 Proximity for Trees 212
9.5.5 Proximity for Morphological Structures 215
9.6 Median/Consensus Problems, Aggregation Problems 217
9.6.1 Sets 217
9.6.2 Rankings 218

9.6.3 Trees . . . 221
9.6.4 Morphological Structures . . . 221
9.7 Illustrative Applied Numerical Examples . . . 222
9.7.1 Continuation of Example for Notebook . . . 222
9.7.2 Common Educational Course . . . 225
9.7.3 Plan of Students Art Activity . . . 229
9.7.4 Combinatorial Investment . . . 230
9.7.5 Modular Educational Course on Design . . . 231
9.8 Summary . . . 245

10 Multistage Design . . . 247
10.1 Introduction . . . 247
10.2 General Schemes . . . 249
10.3 Applied Illustrative Examples . . . 252
10.3.1 Four-Stage Trajectory for Start-Up Team . . . 252
10.3.2 Tree-Like Trajectory for Medical Treatment . . . 256
10.3.3 Simplified Example Over Directed Graph . . . 260
10.3.4 On Multiple Domain Problems . . . 262
10.4 Summary . . . 263

11 Combinatorial Evolution and Forecasting . . . 265
11.1 Introduction . . . 265
11.2 General Scheme . . . 267
11.3 Typical Change Items . . . 269
11.4 Example for Modular Educational Course . . . 269
11.4.1 Hierarchical Morphological Model . . . 269
11.4.2 Problem Formulation, Design . . . 271
11.4.3 Aggregation of Solutions . . . 275
11.5 Summary . . . 276

12 Composite Strategy for Multicriteria Ranking . . . 279
12.1 Introduction . . . 279
12.2 Methodological Issues . . . 281
12.2.1 Decision Making Framework, Solving Scheme, Problems . . . 281
12.2.2 Multicriteria Ranking (Sorting) . . . 281
12.2.3 Towards Reconfigurable Problem Solving Framework . . . 286
12.3 DSS COMBI for Multicriteria Ranking . . . 290
12.3.1 History of DSS COMBI . . . 290
12.3.2 Main Components of DSS . . . 292
12.3.3 Example of Composite Strategy . . . 296
12.4 Summary . . . 298

13 Electronic Shopping of Composite Product 299
13.1 Introduction 299
13.2 Structured Model of Product 301
13.3 Basic Frameworks. 303
13.4 Examples. 304
13.4.1 Multicriteria Ranking/Selection. 304
13.4.2 Synthesis of Composite Product 305
13.4.3 Synthesis of Extended Composite Product 305
13.4.4 Synthesis of Product Repair Plan 306
13.4.5 Synthesis of Product Trajectory 309
13.4.6 Aggregation of Modular Products 311
13.5 Summary. 314

14 Web-based Applied System 315
14.1 Introduction 315
14.2 General Hierarchical Model and Components 317
14.3 Communication Service Provider 319
14.4 Corporate Application 321
14.5 Academic Application 322
14.6 Towards Analysis of Solutions 323
14.7 Usage of Multiple Choice Problem 323
14.8 Design of System Trajectory 324
14.9 Aggregation of Configurations 326
14.10 Summary. 329

15 Integrated Security System 331
15.1 Introduction 331
15.2 Example 332
15.2.1 System Hierarchical Model and Components 332
15.2.2 Composite Decisions. 334
15.2.3 Improvement of Solutions 336
15.2.4 Illustration of Multistage Design. 336
15.3 Aggregation of Solutions 337
15.4 Summary. 338

16 Connection of Users and Access Points 339
16.1 Introduction 339
16.2 Problem Statement 340
16.3 Solving Scheme 343
16.4 Numerical Example. 344
16.5 Summary. 349

17 Telemetry System 351
17.1 Introduction 351
17.2 Example for On-Board Telemetry Subsystem 352
17.2.1 Composite Solutions 355
17.2.2 Analysis and Improvement of Solutions 356
17.2.3 Aggregation of Solutions 357
17.3 Summary 359

18 Standard for Multimedia Information Processing 361
18.1 Introduction 361
18.2 Changes in Standard 364
18.3 Illustrative Numerical Examples 372
18.4 Generalized Example of Combinatorial Synthesis 377
18.5 Summary 379

19 Wireless Sensor 381
19.1 Introduction 381
19.2 Structure of Sensor and Estimates 381
19.3 Combinatorial Synthesis 384
19.4 Aggregation of Solutions 385
19.5 Summary 387

20 Management System for Smart Home 389
20.1 Introduction 389
20.2 Management System for Smart Home 391
20.2.1 Hierarchical Model and Components 391
20.2.2 Composite Decisions 394
20.2.3 Improvement of Solutions 395
20.3 Building Automation System 396
20.3.1 System Morphology and Design 396
20.3.2 System Extension by Additional Part 396
20.3.3 System Improvement by Systems Parts 398
20.4 Summary 399

21 ZigBee Communication Protocol 401
21.1 Introduction 401
21.2 Description of Protocol Generations 402
21.3 Change Operations 406
21.4 Computation of Preliminary Forecasts 408
21.5 Aggregation of Preliminary Forecasts 411
21.6 Summary 413

Conclusion 415

References 417

Index 461

About the Author

Dr. Mark Sh. Levin received the M.S. degree in Radio Engineering from Moscow Technical University of Communications and Informatics (1970), the M.S. degree in Mathematics from Lomonosov Moscow State University (1975), the Ph.D. degree in Systems Analysis from Russian Academy of Sciences (1982).

From 1970 to 1983, he was with Moscow R&D organizations as an Engineer, a Senior Engineer, and a Head of Laboratory (algorithms for air-traffic control, software, and information engineering for government and industry, management information systems, and decision support systems). From 1983, he conducted his research projects in Russia, Japan, Canada, and Israel (research institutes, universities). Now, Dr. Levin is with Institute for Information Transmission Problems of Russian Academy of Sciences (Moscow) as a Leading Research Scientist.

Application domains of Levin's methodological approaches involved information technology, control engineering, management, geology, civil engineering, machine building, standardization, marketing, biomedicine. Dr. Levin has multiyear experience in the following: (i) advanced development and leadership roles for advanced multidisciplinary systems development projects, (ii) multidisciplinary education in systems engineering, applied mathematics, and information technology. In recent decade, Levin's researches are targeted to combinatorial systems approaches in systems engineering and system design for information-communication systems.

Dr. Levin authored many research articles and several books. He is a member of IEEE, ACM (SM'2006), SIAM, INCOSE, Int. Society on MCDM, and ORSIS.