Towards Systems Engineering Education

Mark Sh. Levin
The Research Inst., College of Judea & Samaria, Ariel 44837 Israel
Email: mslevin@research.yosh.ac.il

Abstract

The paper describes a glance (domain-independent engineering) to systems engineering including contemporary situation in design of large systems and some required educational efforts. Systems engineering, concurrent engineering, design of technical systems and their historical evolution, combinatorial hierarchical system design/synthesis, quality analysis, project management, discrete structures and algorithms are examined as basic educational disciplines. In general, domain-independent engineering is oriented to undegraduate, graduate, post-graduate studies and continuous education. An educational program is proposed.

1 Introduction

Many years systems engineering researches (SERs) (e.g., analysis, design and planning of large scale systems) were oriented to special applications (airspace industry, etc.). In recent years, there are needs to use SERs in many other application domains. For example, we can point out the following: (a) complex products; (b) product life cycle (R & D, manufacturing, marketing, utilization, etc.); (c) human-computer systems, including special computer environment (e.g., CAD/CAM systems); (d) distributed information systems; and (e) enterprise modeling, etc.

Note many contemporary scientific research technologies (e.g., mechanical manufacturing, biotechnology) are very complicated, multidisciplinary and require systems approach.

Often some important investigations of complex systems are really only domain-dependent (e.g., design of engines, software development). This situation depends on human factor because many excellent specialists in design of complex systems have obtained their experience in certain engineering domain (e.g., structural design, communication systems, computer architecture, chemical engineering, VLSI design). As a result, many attempts to organize systems engineering divisions really are based only on an integration of domain-dependent specialists without taking into account domain-independent (or multidisciplinary, general) issues of contemporary engineering. In addition, it is reasonable to take into account that design processes require several design roles (e.g., innovation, decision making, engineering analysis, management, etc.) [Dixon, 1966; Hales, 1985; Levin, 1998; etc.].

Now complex systems are multi-disciplinary including subsystems of various kinds: user teams, software, hardware/electronics, mechanical subsystems, distributed information subsystems and special needs of search technology, communication networks, mathematical models & algorithms, economical issues (marketing, etc.), and educational components, etc.

A new basic two dimensional typology of project management styles which is depended on *system scope* (array, system, assembly, component) and *technological uncertainty* (low-level, medium level, high level, and super high level) has been proposed and analyzed in [Shenhar, 1998]. Domain-independent modularity in design of products and systems has been described in [Huang and Kusiak, 1998].

Thus needs of domain-independent SERs are increasing. Here human resource has to be considered as a key factor. We can point out two possible ways as follows:

1. Searching for and selection of persons who has an inclination to complex multi-disciplinary system thinking, analysis, design, etc.

2. Organization of a special educational direction in the field of domain-independent SERs (undergraduate, graduate and post-graduate studies, continuous education).

This discussion paper describes some issues in teaching of domain-independent SERs and a preliminary educational program. The following directions are considered as basic ones: (a) basic systems engineering; (b) concurrent engineering; (c) hierarchical design of complex systems (including systems decomposition); (d) history of technical systems and their evolution; (e) quality analysis and management; (f) project management; and (g) discrete structures, algorithms, and optimization (including multi-criteria decision making).

2 Trends in Engineering

Let us consider some basic recent trends in engineering as follows:

Changes of engineering practice in all domains of engineering (civil engineering, electrical engineering, circuit design, VLSI design, software engineering, information engineering, etc.), i.e., moving:

FROM *"design of some basic elements"*

TO *"selection and integration of system components into whole system".*

In other words, the system part of engineering activity is increasing.

We can consider a systems consisting of the following main hierarchical levels [Shenhar, 1998; etc.]: (1) array, (2) system, (3) assembly, and (4) components.

Many years, majority of engineers were oriented to the design of system components. Recent trends have leaded to the following situation:

(i) there are accumulated many design results for the design of system components and these local design decisions are collected as databases, libraries, catalogues, repositories, etc.: local design decisions for VLSI design, software libraries / repositories, catalogues of construction elements in civil engineering, catalogues of elements, design blocks, and local design decisions in mechanical engineering, libraries of information blocks in information engineering, and catalogues of design decisions in chemical engineering, etc.);

(ii) complexity of system /subsystem design is increasing by the following reasons: (a) complexity of systems multidisciplinarity; (b) time requirements for new system design (decreasing of product life cycle from 12 years to 0.5 ... 2 years, for example, in car industry); (c) distributed engineering design processes when design groups are located in different places (different countries, different continents); (d) integration of design engineering issues and other problems for product life cycle design and maintenance (design & manufacturing & marketing & utilization); and (e) distributed computer-aided support environments (groupware, etc.).

As a resume, let us point out the following:

(1) new divisions (departments, groups) for systems design engineering are establishing; and

(2) new professional domains "systems design engineering" has been appeared (a need of several "systems" persons is changed to thousands of required system engineers in all basic engineering domains).

3 Basic Design Flow

Let us examine the following basic stages of design activity [Bahill and Gissing, 1998; Chen et al., 1996; Goel and Singh, 1998; Kuppuraju, et al., 1985; Levin, 1998; Prasad, 1996; Sage and Rouse, 1999; Sause and Powell, 1991; Van Gigch, 1978; etc.]:

Phase 1. Conceptual design of new systems and/or system architecture (i.e., system structure), design of system specifications, requirements engineering.

Phase 2. Requirements to searching for local design decisions for system components.

Phase 3. Selection of the best local design decisions.

Phase 4. Integration of the local design decisions into global system decisions (engineering systems, product life cycle).

Note a comparative analysis of main approaches to *system design process* is described in [Bahill and Gissing, 1998].

Generally, basic operations of traditional logic include the following [Wert, 1961]: **1.** *Definition.* **2.** *Comparison and discrimination.* **3.** *Analysis.* **4.** *Abstraction.* **5.** *Generalization.* **6.** *Forming close concepts.* **7.** *Subsumption.* **8.** *Forming proposition.* **9.** *Forming inference.* **10.** *Forming syllogisms.*

Here we consider basic functional systems engineering operations as follows [Levin, 1998; Prasad, 1996; Van Gigch, 1978, etc.]: *1.* description /presentation/modeling of complex systems; *2.* analysis and evaluation; *3.* design/synthesis; *4.* transformation (modification, improvement, adaptation); and *5.* analysis and planning of system life-cycle (including issues of reengineering, reuse, redesign, etc.).

Thus it is reasonable to point out some fundamentals for domain-independent engineering:

1. knowledge (information) based systems as conceptual engineering spaces (new information field for engineering):

FROM *professional handbooks*

TO *multidisciplinary engineering spaces*;

2. new information retrieval technology (associative thinking, multidisciplinary thinking, engineering concept spaces, etc.) (new information field for engineering:

FROM *traditional domain-oriented engineering education & practice*

TO *multidisciplinary associative thinking*;

3. multicriteria decision making technology;

4. combinatorial thinking for combinatorial design of new systems on the basis of the following:

(a) discrete system models (graphs & orders);

(b) combinatorial models (applied combinatorics, combinatorial optimization);

5. systems integration/synthesis technology (new engineering field);

6. systems dynamics including dynamics of discrete systems;

7. system's evolution (for example, as in biology: morphological genesis);

8. extended background in socio-economical issues (marketing, ecology, maintenance, human factors);

9. special approaches to evaluate system performance / excellence; and

10. system's simulation (to analyze system's features, etc.).

As a result, engineering community has faced new requirements in the field of human resources as follows [Levin, 1995]: (a) searching for persons with an inclination to domain-independent (general) engineering; (b) selection of the persons with multidisciplinary thinking; (c) special educational student courses; and (e) continuous education.

4 Educational Components

Basic examples of some domain-independent directions, that are oriented to SERs, are the following: (i) systems engineering; (ii) large scale systems; (iii) system analysis; (iv) multi- and inter-disciplinary studies; (v) integrated engineering; analysis and integration of large systems; (vi) concurrent engineering; and (vii) quality analysis and management.

Trends to SERs exist in many university departments, for example, systems engineering; mechanical engineering; electrical engineering; computer engineering; software engineering; information systems engineering; and management and business administration. Some organizational (scientific or / and educational) efforts can be pointed out, for example:

(a) Intl. Council on Systems Engineering (Seattle, *www.incose.org*);

(b) Intl. Society for Multidisciplinary Optimization (design of complex aerospace systems, *www.aero.ufl.edu/~issmo*);

(c) NSF Synthesis Coalition (research and education in the design of complex mechanotronic systems, *www.synthesis.org*);

(d) Institute for Complex Engineered Systems (Carnegie Mellon Univ., *www.edrc.cmu.edu*);

(e) Rochester Inst. of Technology (system architecture, systems engineering, and project management courses [Grant et al., 1999]);

(f) Program on System Science and Engineering (Dept. of EE & CS, Univ. of Michigan, *www.eecs.umich.edu/systems*);

(g) Program on Systems Engineering (Dept. of SIE, Univ. of Arizona, *www.sie.arizona.edu*); and

(h) System Science Educational Program (Univ. of Ottawa, *www.prism.admin.ottawa.ca*).

Basic research topics are the following: (1) systems decomposition; (2) hierarchical approaches to design and hierarchical decision making; (3) control theory; (4) modeling and simulation; (5) dynamical systems; (6) computer-aided systems (e.g., CAD/CAM); (7) information & knowledge engineering (including IS, MIS, DBMS, DSS, and AI) and software engineering; (8) engineering and technological management; (9) concurrent engineering; (10) design of large scale distributed systems; (11) integrated design, development, and evaluation methods for systems; and (12) quality analysis and management.

In our opinion, the number of educational institutions, that are oriented to SERs, will be increasing in near years. Here it is reasonable to point out some crucial person requirements which correspond to basic goals as educational components:

1. system domain-independent thinking [Bahill and Gissing, 1998; Dixon, 1966; Forrester, 1994; Hubka and Eder, 1988; Jones, 1981; Kron, 1963; Mecarovic et al., 1970; Nadler, 1985; Pahl and Beitz, 1988; Prasad, 1996; Sage and Rouse, 1999; Stub et al., 1994; Van Gigch, 1977; etc.];

2. associative multi-disciplinary thinking (not only in engineering/science disciplines but including economical, social and ecological issues) [Levin, 1998; Prasad, 1996; Simon et al., 1987; etc.];

3. combinatorial thinking, synthesis [Ayres, 1969; Jones; 1981; Levin, 1998; Wert, 1961; etc.];

4. creativity and usage of artificial intelligence [Ackoff and Vergara, 1981; Altshuller, 1984; Goel and Singh, 1998; Jones, 1981; Souder and Ziegler, 1977; etc.];

5. dynamical thinking (e.g., by systems evolution) [Forrester, 1994; Sahal, 1981; etc.];

6. experience in strategic systems design [Ayres, 1969; Levin, 1998, Stub et al., 1994; etc.];

7. applied domain-dependent experience in systems analysis, design and planning; [Brooks, 1995; Dixon, 1966; Hubka and Eder, 1988; Pahl and Beitz, 1988; Stub et al., 1994; etc.];

8. background in discrete mathematics and algorithms [Garey and Johnson, 1979; Roberts, 1976]; and

9. experience in application of operations research (including optimization, multicriteria decision making) for engineering (design, manufacturing, etc.) [Gero, 1985; Steuer, 1986; etc.].

5 Educational Program

We intend the following basic preliminary background (one or several): *1.* software engineering; *2.* mechanical engineering; *3.* civil engineering; *4.* computer engineering; *5.* communication engineering; *6.* chemical engineering; *7.* economics & management; *8.* computer science; and *9.* psychology.

The following educational directions can be considered as basic ones (*C* corresponds to a big course, *SC* corresponds to a small course / introduction, *IP* corresponds to an individual project, and *TP* corresponds to a big team project):

Part 1. Domain-Independent System Thinking: (a) Systems Engineering *C*; (b) Systems Architecture *SC*; (c) Combinatorial Engineering (course and individual project) *SC*, *IP*; (d) Quality Analysis & Management *SC*; (e) Innovations & Reengineering *SC*; (f) Concurrent Engineering *C*; (g) Team Design (several lectures and seminars) *SC*; (h) History of Art (painting, theatre) *SC*; (i) Multicriteria Decision Making *SC*; (j) Enterprise Modeling *SC*; and (k) Preparation of Business-Plans/Proposals *IP*.

Part 2. Associative Thinking including Engineering Concept Spaces: (a) Knowledge Engineering *SC*; (b) Financial Engineering (flows of "money") *SC*; (c) Distributed Information Systems *SC*; (d) Marketing *SC*; (e) Usability *Sc*; and (f) **5b**.

Part 3. Combinatorial Thinking: (a) Discrete Structures & Algorithms (graphs, networks, orders) *C*; (b) Chemical Synthesis, Chemical Engineering *SC*; (c) Material Engineering *SC*; (d) **1c**; and (e) **6b**.

Part 4. Systems Evolution (life cycle, generations of systems): (a) Evolution in Biology *SC*; (b) History of Technical Systems (including airspace systems, transportation systems, manufacturing systems, communication systems, computer systems, information systems, civil engineering, chemical engineering, mechatronics, opto-electronical systems, biotechnology) *C*; and (c) Information Project on Evolution of a System (Internet home-page) *IP*.

Part 5. Systems Design: (a) Creativity Techniques *SC*; (b) Design of an information home-page on a composite multi-disciplinary topic (methodology, models, algorithms, applications, bibliography, scientific centers, conferences, journals, connection with other scientific & engineering domains) *IP*; (c) multi-disciplinary composite projects (big team composite project, connection with previous background) *TP*; (d) Design of Applied Systems (e.g., air space systems, mechatronics, communications, networks, socio-economical systems) (one or more applied courses, connection with *TP*) *C*; (e) Project Management *C*; (f) **1c**; and (g) **3** (**a**, **b**, and **c**).

Part 6. Mathematics & Algorithms: (a) Systems Dynamics *SC*; (b) Applied Combinatorics *SC*; (c) Automata Theory *SC*; (d) Petri-Networks *SC*; (e) Dynamical Systems, Chaos, Self-organization *SC*; (f) Problem Solving, Algorithms, Complexity *C*; (g) Simulation *SC* and *IP*; (h) Optimization & Operations Research *C* and applied *IP*; and (j) Heuristics and Evolutionary Computing *SC* and *IP*.

6 Implementation of Program

It is reasonable to consider several series levels of the educational process in the field of domain-independent engineering as follows [Levin, 1998; etc.]:

Level 1. A basic professional engineering domain (courses, project), for example: (a) design/planning an information system; (b) design of human-computer interface; (c) design of hypertext; (d) design of team; and (e) design of composite packaged software.

Level 2. Analysis, design, and planning of individual educational system/program (*IP*). Examples of similar problems are the following: (a) planning of student career; (b) design of educational courses; and (c) analysis of an initial professional individual profile and planning an educational process.

Level 3. A project in a composite engineering domain, for example, as follows (*IP* of *TP*): (a) information project on a system evolution as a composite home-page for Internet (an engineering domain, information engineering, and software engineering including system architecture issues); (b) design/planning a composite engineering systems, for example, mechatronical system (e.g., vibration conveyor with control system in [Levin, 1998]).

Level 4. Multidisciplinary composite project (including engineering, economical, sociological, and ecological issues) (*IP* or *TP*). Some example are the following: (a) interdisciplinary project works in at De Monfort University [Ivins, 1997]; (b) design of a composite business plan; (c) planning of product life cycle including stages of design, manufacturing, marketing.

Level 3 is very important for associative & multidisciplinary thinking and communication skills. Here some unique advanced composite topics have to be examined, for example, (i) civil engineering & chemical engineering & discrete structures & issues of re-use, re-design; (ii) biotechnology & information systems & concurrent scheduling; (iii) computer architecture & biotechnology & knowledge based systems & enterprise modelling; (iv) taxonomy in structural engineering & material engineering & distributed information systems & quality management; (v) structural engineering & life cycle management & reengineering & coordination; and (vi) communication systems & multicriteria decision making & multi-agent systems & cooperative work-groups.

Generally, composite projects can be based on the selection and composition of the following:

Part 1. Engineering (mechanical engineering, civil engineering, etc.).

Part 2. Information technology (information systems based on Internet, software engineering, knowledge based systems, etc.).

Part 3. Economical, sociological, and ecological issues (e.g., human factors and usability, marketing).

Part 4. Mathematical fundamentals.

The proposed approach is mainly oriented to levels 2, 3, and 4. Note the analysis, design, and planning of the individual educational program is a fundamental for the educational process including the following:

Stage 1. Description and analysis of an initial individual professional profile.

Stage 2. Design of a target professional profile.

Stage 3. Design of structure of educational plan and selection of educational elements (courses, projects).

Stage 4. Design/planning of the resultant composite concurrent individual educational plan while taking into account the following: (a) properties of educational elements (correspondence to individual goals, complementation of educational elements, etc.); (b) resource constraints (time, auditorium, other students, professors, etc.); and (c) educational plans of other students.

Note stage 4 has to be considered as concurrent engineering approach in education.

Fig. 1 depicts a framework for systems engineering (*SysEng*) education where o corresponds to an educational *input*, * corresponds to an educational *output*, C_i corresponds to course/studies in *SysEng* at educational level i, C_i^- corresponds to another course/studies at educational level i. We have examined the following educational path: $C_1^- \rightarrow C_2 \rightarrow W_2$. Evidently, other educational paths are very important too, for example: (a) $C_1 \rightarrow C_2 \rightarrow C_3$, (b) $C_1^- \rightarrow C_2 \rightarrow W_2 \rightarrow C_3$, and (c) $C_1 \rightarrow W_1 \rightarrow C_2^- \rightarrow C_3$.

7 Conclusion

In this paper, we have described a situation in the field of domain-independent engineering and proposed a preliminary version for a composite educational program at the levels of graduate & postgraduate studies and continuous education. Domain-independent engineering is based on recent advances in information technology (networking, distributed information systems, knowledge based systems, engineering concept spaces, etc.). Evidently, considered educational programs have to be adapted to certain students or specialists while taking into account their inclination to engineering, multi-disciplinary issues, mathematical fundamentals, etc. Some problems of the analysis and planning of flexible educational processes (e.g., an analysis of specialist profiles, comparison of initial specialist profile and a target profile, design of an educational strategy) are examined in [Levin, 1998].

Note this paper is only the author opinion which involves an author multi-disciplinary experience. It is reasonable to organize a special research on the basis of expert judgment while taking into account of expert information from universities and from all professional industrial domains. Also, the future activity in this field can be oriented to an experimental realization of composite multi-disciplinary courses / studies, investigation of other educational paths (Fig. 1), and an analysis of obtained results.

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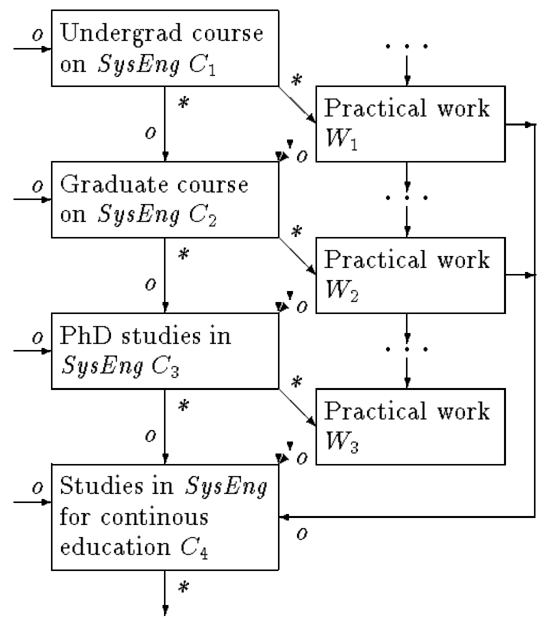

Fig. 1. Framework for systems engineering education

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