Journal of Universal Computer Science, vol. 12, no. 9 (2006), 1393-1404
submitted: 31/12/05, accepted: 12/5/06, appeared: 28/9/06 © J.UCS

Systems Engineering: A New Approach to Complex IT-based Technological Systems in Engineering Education

Tibor Tóth
Production Information Engineering Research Team (PIERT)
of the Hungarian Academy of Sciences,
Department of Information Engineering
University of Miskolc, Hungary
toth@ait.iit.uni-miskolc.hu)

Ferenc Erdélyi
Production Information Engineering Research Team (PIERT)
of the Hungarian Academy of Sciences
University of Miskolc, Hungary
erdelyi@ait.iit.uni-miskolc.hu)

Abstract: Introduction of the multi-degree linear education system consisting of BSc, MSc and PhD programs in the Hungarian higher education, according to the goals and requirements of the Bologna Process, necessitates reviewing, enhancing and changing the three-level subject-structures consisting of fundamental, foundation enlarging and special subjects. In the course of the last 50 years the quantity of the number of subject areas and the number of engineering branches have been increasing in technological faculties around the world and they have already reached the limits of rationality. Recently there is an increasing demand for integrated and interdisciplinary special branches such as Systems Engineering. After having surveyed the paradigm changes in the progress of engineering sciences, the paper gives a brief summary on the concept, formation and significance of Systems Engineering. The paper also deals with Production Information Engineering as a characteristic field of Systems Engineering, which offers important application possibilities for IT-based system integration.

Keywords: systems engineering, higher education, production information engineering, system integration
Categories: H.4.2, J.0, J.6

1 Increasing number of tasks in engineering education

The tasks to be solved in engineering education have recently increased. The new tasks have derived mainly from the changing demands of curricula. For more than a hundred years the progress of engineering education has been characterized by increasing the quantity and specialization of subjects.

The growth of the number of engineering faculties, branches and special courses has achieved the limits of rationality. Introduction of the multi-degree linear education system (BSc, MSc, PhD) in Hungarian higher education can be considered as a reform to European measure (which means taking a chance to a great extent), which is also a good possibility for reassessing subject structures at the same time. It seems to be inevitable, for example, to meet the requirements of industrial and institutional employers that practical skills, which are very important and immediately useful in engineering practice, should get a place in BSc courses, in addition to the emphasis on theoretical fundamentals of natural sciences. The practical (or special) knowledge means technological, management and information technology-based learning and skills in general. Furthermore it is very difficult task to decide how fundamental knowledge in Mathematics and Physics can be divided into two levels (BSc and MSc). Without this change, those higher level requirements which are expected for a deeper theoretical knowledge, as well as for greater readiness and capability in design, planning, research and development, cannot be performed.

In the education of special knowledge, the number of special branches can be increased no longer. At the same time, there is an increasing need for new integrated and interdisciplinary branches in science and technology, such as seen in Industrial Engineering, Mechatronics and Energetics in the recent past. The block of expert knowledge summarized by the name “Systems Engineering” in Anglo-American specialist literature is similar to the above-mentioned branches. Systems Engineering deals with the design, control and operation of complex technical systems.

2 Paradigm changes in the progress of engineering sciences

The history of the progress of engineering sciences is a history of great paradigm changes [*Prohászka* (ed.) 2001]. Of course, such paradigm changes have taken place in Mathematics, Physics and social sciences too. It is enough to refer to the influence of the new theoretical approach in Physics which is connected with *Einstein’s* name (The Relativity Theory and the Theory of Quantum Mechanics as new paradigms). Engineering sciences, in comparison with the pure empiric (inductive) and pure theoretical (deductive) sciences, can be named *reductive* sciences [see *Tóth*, 2004]. This means that engineering sciences concentrate on selecting the best solutions from those potential solutions, which meet all the constraints under the effects of the known laws of nature. In general, the best solutions meet the market (social) requirements to the greatest extent.

During the last 150 years in the history of engineering sciences the following great paradigm changes can be identified:

- 1850 Energy transformation, raw materials and the properties of materials are in the focus.
- 1920 Product properties, processing industries and mass production are in the centre.
- 1980 Control, computer and communication (3C) are in the front line.
- 2000 Information technology (IT), management methods, large-scale systems and networks in the centre of interest.

The steam machine, induction motor and then the internal combustion engine made it possible to transform different energy types in an effective way. Knowing the properties of materials and producing the raw materials (Materials Science) were the next indispensable link in the chain.

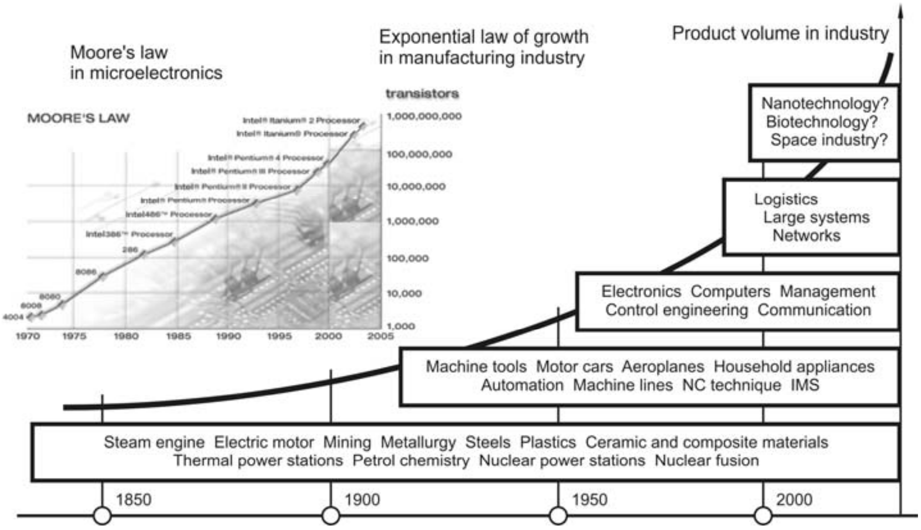

Figure 1: Paradigms in the progress of engineering sciences and technology

With this knowledge of the material and energy laws, the science of machine design created complex yet reliable machines, among other things the automobile, the machine that changes the world [see *Womack* et al. 1991]. Mass production called into being the science of manufacturing engineering that has led to the extremely high productivity of the present days, including the automated manufacturing lines and assembly lines, numerical control and intelligent manufacturing systems. It is insufficiently known by the general public that the present social, economic and political role of “industrially developed countries”, their outstanding GDP and the “welfare state” are largely due to the high-level productivity of industrial and agricultural technology.

The invention of the transistor started the spread of electronics, which caused the third great change of the engineering paradigm. Nowadays microelectronics has become the basis of control, computer and communication technology. *Gordon Moore* drew up the famous empiric law according to which the performance of electronic tools (processors and memory elements) doubles every 14-18 months on the average. The law is also valid at present.

While utilizing the knowledge gained so far, engineering sciences have to face up to new challenges. One of these challenges is the complex problem of design and reliable operation of the ever more complicated systems produced for production, distribution, control and communication. Another increasingly urgent problem is the protection of the natural environment, or substitutes for non-renewable resources.

In spite of the fact that we are in possession of many tools suitable for design and control of large-scale systems through the integrating role of Computer Science and Information Technology, nevertheless the task is enormous. The science of system modelling has recently revealed such fields of nonlinear properties (e.g. chaos theory and network theory), the conscious engineering application of which is a task for the future.

3 The traditional structure and branches of engineering education

The traditional structure of engineering education is based upon a well-proved solution of three-stepped pyramid form. The knowledge of engineering foundations must be built on the reliable fundamentals of natural sciences. The expert knowledge of an engineer in some kind of special field should be made utilizable by means of the principles, tools and methods of design, planning and control in practice.

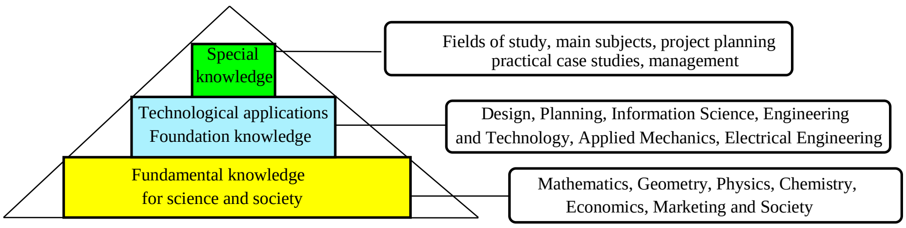

Figure 2: The traditional structure of engineering knowledge

Within the framework of this traditional structure large-scale engineering faculties came into being such as Mechanical Engineering, Electrical and Electronic Engineering, Chemical Engineering, Civil Engineering, Architectural Engineering, Materials Science, Computer Science, Information Science and Technology, Industrial Engineering, etc. – faculties that can be found at the overwhelming majority of universities of technology all over the world. Because of the considerable extension of fundamentals for natural and engineering sciences, engineering planning and design methods or applications could be placed in the framework of branches only because of the limited academic time available. For instance, at many engineering faculties the branch for machine design and the branch for manufacturing engineering have been separated from each other. The cases of practical applications (case studies), the methods and tools of design, planning and application could be arranged in the curriculum within the framework of branches only. Universities have protected against exaggerated specialization by means of comprehensive subject-blocks, optionally selectable subjects, as well as so-called *major* and *minor* blocks of subjects.

In higher education there has been no such system of programs and courses that would be better than the previously outlined one to a significant extent, despite the fact that the following problems return from time to time in a persistent way:

- Fast change of the internal proportions in the current knowledge;
- Dissection of the structure, series and parallel subjects in the curriculum;
- The internal proportions of theory and practice;
- The number of the branches and other specialties (subject areas).

Standpoints sharply differing from each other have appeared over and over again, especially regarding the required number of branches and specialties. Debate on these questions is reasonable, because the progress of science and the demands of industry require up-to-date expert knowledge; however these can be inserted into the curricula only through the reduction of the outdated knowledge.

If we examine minutely what influences the special courses in engineering education, we come at numerous influencing factors, such as (without the demand of completeness or insistence on priority):

- the internal progress or development of sciences,
- the changing demand of economy and industry,
- interests of the administrations of universities (faculties, departments, sections),
- important local traditions,
- the national or governmental policy of education and,
- priority or capability of the society for education, including state and private economy.

The structures of curricula and the content of the prevailing courses have been formed under the effect of these factors. The traditionally high-level performance of the Hungarian universities of technology came into being within the framework of a five-year (German type) education program structure oriented for engineering design/planning and developing activities. Because of increasing demands from industry, the three-year college (polytechnic) program with a practical orientation has developed independently in several respects. Therefore there have been only a few and occasional integration points from the polytechnic to the university courses.

Introduction of the linear multilevel education programs established in the Anglo-American countries has also raised serious problems. Because of this, reassessment of the structures of curricula must be carried out. In the university-level mechanical engineering program, for instance, the machine design branch was its historical basis. Technology-oriented branches came into being after 1950, i.e. as a consequence of the great technological paradigm change. The branch of “production management” only joined the traditional designer and “production engineer” branch-pair after the next paradigm change. The appearance of this branch was motivated by three new demands: (1) the ever increasing significance of economic, financial, organizational and marketing processes in engineering practice; (2) the quickly increasing role of information technology based systems; (3) growth of demand for engineers skilled in organizational, management and decision processes.

Similar processes have led to the establishment of “Mechatronics and Energetics” branches. In both cases there was a social requirement for interdisciplinary unification of the expert knowledge of electrical and traditional mechanical engineering. At the branch of Mechatronics the integration of the knowledge from the field of Information Sciences has a crucial role (as is encoded in the definition of Mechatronics).

Faculties and branches of Information Sciences, Engineering and Technology have special stories in the life of universities. After a long development process Information Science became an independent branch of science in the early seventies. It originated from two main sources: Electrical and Electronic Engineering and Computational Science as a branch of Mathematics. Nowadays these two sources can be considered as the main theoretical basis of the special knowledge involved in hardware and software. Systems Theory and an early variant of Systems Engineering also played an important role in the process of Information Science becoming independent. The third aspect of the development in Information Science is related to application systems where the specifications of the fields of application come to the front-line. The fields of Engineering (for example Mechanical Engineering), Economics, Communication and Multimedia could only be developed within the framework of different branches.

4 Concept of Systems Engineering

It can be seen from the previous chapters that in engineering education there is an increasing demand for new, integrated and interdisciplinary branches. This is a direct consequence of the development of sciences and the changes in social requirements. It is worth while mentioning here the famous saying of *de Gaulle*: "Fatal events must be governed to survive."

There is currently a new field of great significance to the whole of engineering education. This field is referred to by the name Systems Engineering (SE) in Anglo-American special literature. ***Systems Engineering*** **contains all the special knowledge aimed at the design, realisation and operation of complex engineering systems.** At present experts in "Systems Engineering" are not necessarily identical with the expert characterised by the term "Systems Engineer". The latter is mainly related to the introduction and maintenance of application systems (Internet, MS Office, Oracle, SAP, AutoCAD, etc.). The special knowledge of a systems engineer can be considered as a product of the appearance of sophisticated and large scale engineering systems, especially in the last 25 years. In this process Information Technology (IT) which makes it possible to control the modern large systems, has a key role. In industrial practice System Controlling is supported by a new, special expert service called IT Service Management (ITSM). SE has two basic sources (pillars):

- Structure and dynamics of engineering systems,
- Structure and operation of information systems.

The first deals with the theory of generic, particular and individual engineering systems, studying their structure, processes, behaviour in time and sources of energy. "Enterprise modelling and integration" is the common term when it concerns industrial production systems. The other source discusses the theory, tools and practice of system integration and studies problems related to information infrastructure.

5 How these fields came to be

Recently in the USA and Japan numerous technical universities have reformed and strengthened the framework and the contents of their Systems Engineering curriculum. The traditional Industrial Engineering branches also are gradually approaching the new educational form. Linking of the two special fields is also frequently used.

This process can be characterized with the conceptions of two famous and authoritative universities. One of them is the conception of Massachusetts Institute of Technology [MIT 2006]:

> "*MIT is tackling the large-scale engineering challenges of the 21st century through a new organization.* ***The Engineering Systems Division*** *(ESD) creates and shares interdisciplinary knowledge about complex engineering systems through initiatives in education, research, and industry partnerships. ESD broadens engineering practice to include the context of each challenge as well as the consequences of technological advancement*."

The other citation is the philosophy of Cornell University [Cornell 2006]:

> "*There is an increasing need from industry for engineers who not only have expertise in a particular engineering discipline, but who also possess interdisciplinary skills, can integrate system components, can ensure total system operability, and can understand the various economic forces in the marketplace*."

It is clear from these conceptions that this is not about a variant of the branch of production engineer. In this case we do not focus on the knowledge related to industrial and economic management, the controlling and decision mechanisms but the centre is the engineering system itself, with its internal complexity and typical characteristics.

There is no tradition of this educational trend in Hungary, but in its initial stage the form exists in each of the three highly-regarded universities of technology of Hungary (Budapest University of Technology and Economics, University of Miskolc, University of Veszprém). In Electrical and Information Engineering education several system-based disciplines have been introduced. One of the main groups of knowledge contains the following subjects: theory and functional modelling of systems, dynamics and mathematical modelling of systems, operation research, project-based planning and control, design principles and methods of systems and processes, systems organization, and discrete event-based simulation (DES). The other group is the IT infrastructure containing computer systems, networks, Internet and Intranet, distributed application systems, data bases and data mining, artificial intelligence methods, and optimization of systems.

There is an increasing need for engineers possessing systems engineering knowledge, especially in the lead of departments and divisions of numerous large enterprises.

6 Production Information Engineering as a case of Systems Engineering

Manufacturing Technology based on discrete parts and assembly is one of the leading technologies in industrial practice and its position seems to be immutable. In mechanical engineering practice production systems, logistic systems, energetic systems, transport systems are good examples of systems approach for engineering applications. At the University of Miskolc the Information Engineering program was formed from a Mechanical Engineering background in the 1990's. It was clear from the beginning that the students of Information Engineering program should attain the special IT knowledge such a way that particular application fields suitable for testing their current expertise would be available already in the course of their undergraduate period.

At the Faculty of Mechanical Engineering there were many departments that used and taught applications connected with Information Sciences. This was the basis of the complex planning work of Information Engineering students. Joining to this process, at the Department of Information Engineering of the University of Miskolc, we have taught and studied Production Information Engineering for several years, a field that fits to a great extent to the line of Systems Engineering [*Jedrzejewski* 1999], [*Rao* et al. 1993], [*Tóth* 2004], [*Tóth* 2001]. Figure 3 represents the bounds of the interdisciplinary expert knowledge.

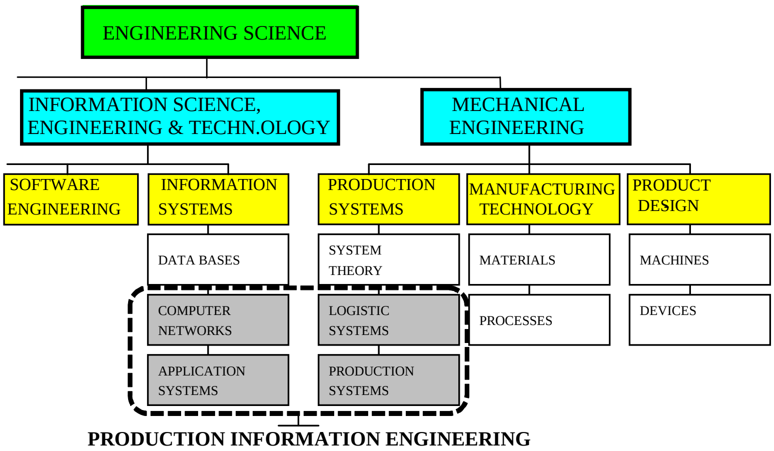

Figure 3: The bounds of Production Information Engineering

Previously this expert knowledge was based in the branch of Information Sciences of Mechanical Engineering studies, where the knowledge of technological processes was naturally strong. Later the students of Information Engineering could choose the branch of Production Information Engineering, where the knowledge of Systems Engineering was supported by a thorough grounding in Information Sciences.

What kind of subjects has been developed? The most important ones are as follows:

- Production Systems and Processes [*Buzacott* and *Shanthikumar* 1993], [*Dorf* and *Kusiak* 1994], [*Tóth* 2004],
- Operation Research and Mathematical Programming [*Nagy* 1998], [*Galántai* and *Hujter* 1997], [*Varga* 1977], [*Rao* 1979], [*Foulds* 1981], [*Nagy* 1985],
- Modelling of Production Processes [*Tóth* 2004], [*Vernadat* 1996], [*Waldner* 1992],
- Data Bases I and II. [*Kovács* 2004],
- Elements of Artificial Intelligence [*Charniak* and *McDermott* 1985], [*Dagli* 1994], [*Dudás* 2006],
- Logistic Systems and Supply Chain Management [*Christopher* 1998], [*Bányai* and *Cselényi* 2004],
- Production Planning and Control [*Buzacott* and *Shanthikumar* 1993], [*Dorf* and *Kusiak* 1994], [*Tóth* 1998], [*Tóth* 2004],
- Computer Aided Manufacturing I. (PLC, NC, Robotics) [*Askin* and *Standridge* 1993], [*Buzacott* and *Shanthikumar* 1993], [*Tóth* 1998], [*Tóth* 2004],
- Computer Aided Manufacturing II. (Manufacturing Systems, Scheduling, Manufacturing Execution System (MES)) [*Askin* and *Standridge* 1993], [*Buzacott* and *Shanthikumar* 1993], [*Tóth* 1998], [*Tóth* 2004],
- Computer Aided Quality Assurance [*Horváth* and *Juhász* 1996], [*Köppe* 1992], [*Tóth* (ed) 1999],
- Computer Integrated Manufacturing (CIM-OSA, Industrial Networks, Data Bases) [*Kovács* 2004], [*Tóth* 1998], [*Waldner* 1992],
- Virtual Enterprise [*Mahoney* 1998], [*Erdélyi* and *Tóth* 2000].

In a ten-year period more than 50 students have prepared their graduation projects using the methods of this field. In the beginning in the Doctoral Program of the Faculty of Mechanical Engineering (1994-2002) and then, within the framework of the Hatvany József Doctoral School for Information Science, Engineering and Technology established and accredited in 2002, more than 20 PhD students have got the Absolutory (completed the first stage of their doctoral studies) and 12 have successfully defended their doctoral theses.

7 The Systems Engineering specialisation in MSc program

In the academic year 2006-2007 the accredited BSc education starts in most of the engineering faculties of the institutes of Hungarian higher education. The tasks related to MSc courses are also have to be prepared because they will start in three years. The branch of Systems Engineering could meet important industrial and social requirements, and it is worth joining the international development getting quicker in this field. This kind of branch can be offered both by the faculties of Information Sciences and Mechanical Engineering or could be chosen in any other engineering faculty. The conception of the structure of the curriculum is represented in Figure 4.

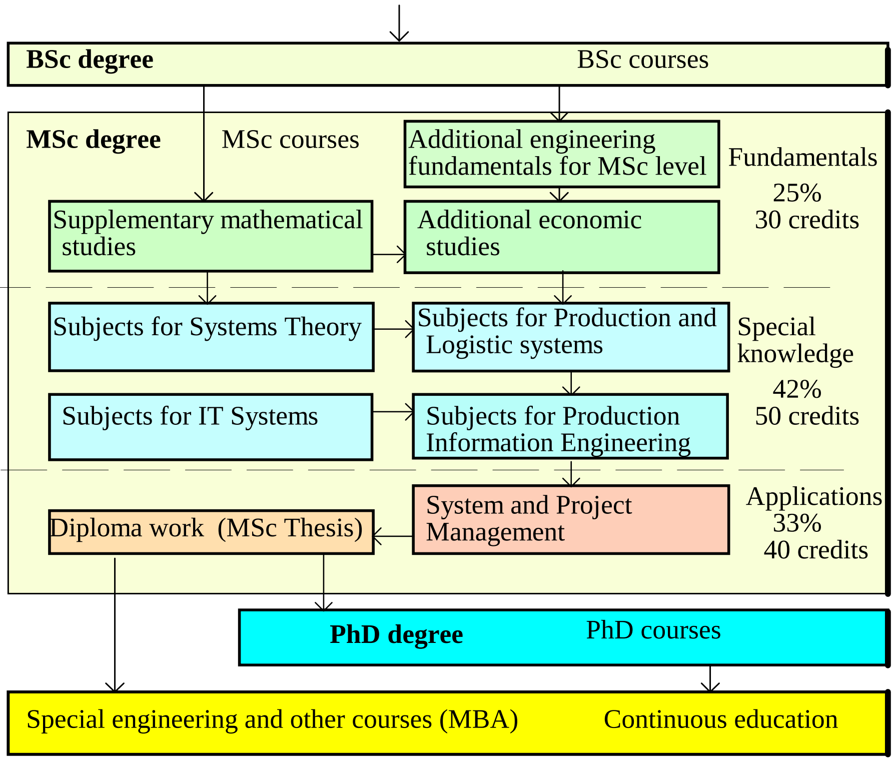

Figure 4: The structure of special knowledge block for Systems Engineering in a roughly outlined form

What are the reasons for introduction of a special knowledge block for Systems Engineering? We list some of them:

1. The growing number of large systems in the economy.
2. The tools developed by information and communication technology enable (and necessite) the innovation of system design and planning the activities to be carried out within the system, as well as innovation of system control.
3. The sustainable and global environment of competition forces the development of systems controlling [*Vernadat* 1996].
4. By building on the basic education of engineering and reducing the descriptive knowledge related to the technological processes, we can form and the students can learn the special knowledge of Systems Engineering.
5. There is a significant demand in industry for experts possessing Systems Engineering knowledge.
6. Modern mathematical and computer modelling methods provide a theoretical and practical background for the analysis and synthesis of systems dynamics.
7. All over the world more than 60 prestigious universities of technology have declared in its educational program the development of Systems Engineering [Cornell 2006], [MIT 2006], [UMICH 2006], [USC 2006].

References

[Askin and Standridge 1993] Askin, G.R. and Standridge, R.C.: "Modelling and Analysis of Manufacturing Systems."; John Wiley & Sons., New York (1993)

[Bányai and Cselényi 2004] Bányai, T. and Cselényi, J. (eds): "Logistics Networks: Models, Methods and Applications"; University of Miskolc, Miskolc-Egyetemváros (2004) (In Hungarian)

[Betounes and Redfern 2002] Betounes, D. and Redfern, M.: "Mathematical Computing"; Springer-Verlag, New York (2002)

[Brucke 1998] Brucke, P.: "Scheduling Algorithms"; Springer Verlag, Berlin (1998)

[Buzacott and Shanthikumar 1993] Buzacott, J.A. and Shanthikumar, J.G.: "Stochastic Models of Manufacturing Systems"; Prentice Hall, Englewood Cliffs, New Jersey (1993)

[Charniak and McDermott 1985] Charniak, E. and McDermott, D.: "Introduction to Artificial Intelligence"; Addison-Wesley Publishing Company, Inc. (1985)

[Christopher 1998] Christopher, M.: "Logistics and Supply Chain Management: Strategies for Reducing Cost and Improving Service"; 2nd edition, Prentice Hall; Englewood Cliffs, New Jersey (1998)

[Cornell 2006] "Cornell University (2006)"; http://www.engineering.cornell.edu/

[Dagli 1994] Dagli, C.H.: "Artificial Neural Networks for Intelligent Manufacturing"; Chapman & Hall, London (1994)

[Dorf and Kusiak 1994] Dorf, C.R., and Kusiak, A.: "Handbook of Design, Manufacturing and Automation"; John Wiley & Sons, New York (1994)

[Dudás 2006] Dudás, L.: "Artificial Intelligence"; Study-aid of education, University of Miskolc (2006) (In Hungarian), http://ait.iit.uni-miskolc.hu/

[Elsayed 1994] Elsayed, A.E.: "Analysis and Control of Production Systems"; Prentice-Hall, Englewood Cliffs, New Jersey (1994)

[Erdélyi and Tóth 2000] Erdélyi, F. and Tóth, T.: "Virtual Enterprise – Vogue Word or a New Integration Paradigm?"; GÉP, LI, 3-4 (2000), 3-8.

[Foulds 1981] Foulds, L.R.: "Optimization Techniques"; Springer Verlag (1981)

[Galántai and Hujter 1997] Galántai, A. and Hujter, M.: "Optimisation Methods"; Publisher of the University of Miskolc, Miskolc-Egyetemváros (1997) (In Hungarian)

[Horváth and Juhász 1996] Horváth, I. and Juhász, I.: "Computer Aided Design"; Technical Publisher, Budapest (1996) (In Hungarian)

[Jedrzejewski 1999] Jedrzejewski, I.: "Innovative and Integrated Manufacturing"; Politechniki Wroclawskiej (1999)

[Kovács 2004] Kovács, L.: "The Methodology of Design and Management of Data Bases"; ComputerBooks, Budapest (2004) (In Hungarian)

[Köppe 1992] Köppe, D.: “CAQ-Datenmodell. Anwendungen in der rechnerintegrierten Produktion”; VDI Verlag GmbH, Düsseldorf (1992)

[Mahoney 1998] Mahoney, D.: “The Virtual Enterprise”; (1998) http://137.99.64.20/courses/coms239/spring98/

[MIT 2006] “MIT (Massachusetts Institute of Technology) Engineering Systems Division (2006)”; http://esd.mit.edu/

[Nagy 1985] Nagy, T.: “Mathematical Programming”; Textbook Publisher, Budapest (1985) (In Hungarian)

[Nagy 1998] Nagy, T.: “Operations Research”; Publisher of the University of Miskolc, Miskolc-Egyetemváros (1998) (In Hungarian)

[Prohászka (ed.) 2001] Prohászka, J. (editor): “The Present and the Future of Technology”; Hungarian Academy of Sciences, Budapest (2001) (In Hungarian)

[Rao 1979] Rao, S.S.: “Optimization. Theory and Applications”; Wiley Eastern Limited (1979)

[Rao et al. 1993] Rao, M., Wang, Q. and Cha, J.: “Intelligent Systems in Manufacturing”; Chapman & Hall, London (1993)

[Tóth 1998] Tóth, T.: “Design and Planning Principles, Models and Methods in Computer Integrated Manufacturing”; Publisher of the University of Miskolc, Miskolc-Egyetemváros (1998) (In Hungarian)

[Tóth 2004] Tóth, T.: “Production Systems and Processes”; Publisher of the University of Miskolc, Miskolc-Egyetemváros (2004) (In Hungarian)

[Tóth (ed.) 1999] Tóth, T. (editor): “Quality Management and Information Technology”; Technical Publisher and Hungarian Society of Quality Management, Budapest (1999) (In Hungarian)

[Tóth 2001] Tóth, T.: “Production Information Engineering”; GÉPGYÁRTÁS, XLI, 9-10 (2001), 49-57.

[UMICH 2006] “University of Michigan (2006)” http://www.engin.umd.umich.edu/IMSE/

[USC 2006] “University of Southern California”; (2006) http://www.usc.edu

[Varga 1977] Varga, J.: “Mathematical Programming”; Textbook Publisher, Budapest (1977) (In Hungarian)

[Vernadat 1996] Vernadat, F.B.: “Enterprise Modelling and Integration”; Chapman & Hall, London (1996)

[Waldner 1992] Waldner, J.-B.: “CIM: Principles of Computer-integrated Manufacturing”; John Wiley & Sons, Chicester (1992)

[Womack et al. 1991] Womack, J.P., Jones, D.T. and Ross, D.: “The Machine That Changed the World”; Perennial Publisher, New York (1991).