A New Design and Optimization Method for Complex Products and System

Chaoan Lai
School of Business Administration
South China University of Technology, Guangzhou, China
EMAIL: chalai@scut.edu.cn

Abstract: The technology composition and system architecture of complex products and system (CoPS) is very sophisticated so that the success rate of CoPS development is low. A system-based simulation tool for optimal design of CoPS was presented with causality graph of system dynamics (SD) as the study framework, and Rough Set (RS) was used to analysis the multi-level structure of feedback loops graph of CoPS, so as to find non-linear dynamics correcting rules of CoPS, which can assist inexperienced users to perform simulation analysis for quality and reliability improvement, alternative design evaluation and forecasting and controlling the performance of CoPS, thus helping to enhance robustness of CoPS at the design stage and increase the success rate. This paper showed the practical application with a simulation case at last.

Keywords: complex products and systems; product development; Optimization; simulation

I. The Complexity of CoPS Development

With the development of the science and technology, Complex Products and System (CoPS) play a more important role in the modem economy and society. CoPS can be defined as high cost, technology and software intensive products, systems and networks, which, often customized parts, designed in a hierarchical manner and tailor-made for specific customers. A high degree of customer involvement in the innovation process can also be noted. Based on the survey of 700 industry enterprises in the abroad, the integrated success rate of CoPS development was only 35%. The low success rate has roots in the complexity of CoPS development and the difficulty of forecasting and controlling originated from complexity.

It takes into account that an optimal CoPS design requires concurrent, integrated, and system-based thinking with regard to all design parameters and criteria involved in the CoPS. The motivations for system-based and integrated CoPS design include the following: Increased efficiency; Cost effectiveness; Ease of system integration; Ease of cooperation with other systems; Better component matching; Increasing reliability. Primarily the following two main research aspects have to be investigated: Analysis and evaluation of CoPS; Design and simulation methodologies.

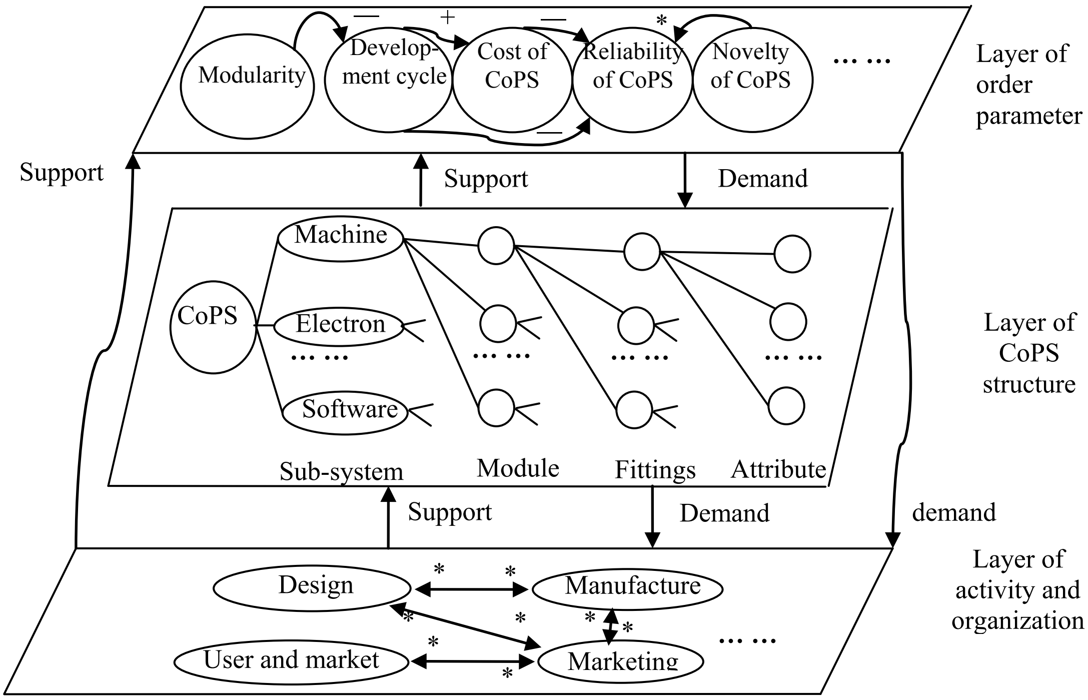

Fig. 1 Layers of CoPS development

There are complex non-linear reciprocal actions among the units in several layers of CoPS shown in Fig 1. One tiny change can influence many decisions in many layers by feedback loops. For example, a tiny change of design scheme such as the modification of novelty of CoPS can have a great impact on the units of development cycle and market share in the layer of order parameter and the unit of design team in the layer of activity and organization, so as to provide outstanding account for the enterprise or lead to the death of the enterprise, or make no change, which was hard to forecasted. The reason is that the micro-disturb of variables lead to the self-organization revolution of system by complex feedback systems.
System Dynamics (SD) is a methodology that can be used for analyzing and understanding complex feedback systems. The essence of revolution process of CoPS development can be illuminated with the frame of SD studying on the complexity and feedback systems of CoPS, so that we can forecast the influence of change of some parameters on the process and result of product development, and resolve the problems of low success rate of CoPS development.

II. Study on Methods for CoPS Design

CoPS is a natural stage in the evolution of modern products, many containing components from different engineering domains, such as mechanical, electrical, and control systems. As part of concurrent engineering practice, CoPS is a synergistic system design philosophy to optimize the system as a whole simultaneously.
The methods commonly used for simulation of development process include: GERT, Integrated Computer Aided Manufacturing Definition (IDEF3), Design Structure Matrix (DSM), Design Activity Networks, model based on Multi-Agent [1], and so on.
Fault tree analysis (FTA) methods have been classified as static analysis; hence, is not sufficient to deal with complex and hybrid systems, such as CoPS. Interaction between subsystems and the reconfiguration of a complex system cannot be properly considered by these conventional approaches. The main strength modes and effect analysis (FMEA) are of these methods lies in that been commonly used by system engineers and have been standardized to some extent. Nevertheless, it is only suitable if the system architecture in unchanged [2].
In dealing with the dynamic characteristics of a complex system, two methods have been addressed in literature: the Markov approach and Petri nets (PN). In the Markov approach, the probabilities of different events are considered time-variant and then differential equations governing these reliability functions are derived. The main drawback of this method is that the number of differential equations increases exponentially with the number of the states in the system.
Jochen Stier (2006) developed a method to derive critical scenarios from the Petri net model of complex products [3]. This technique contributes to the safety evaluation and selection of system architecture in the design stage.
Guerin et al. (2002) have proposed that beyond ten components, only the Petri nets associated with a Monte Carlo simulation is usable [4]. Petri nets allow modeling the functional behavior of the parts and also modeling the interactions between them and describe the complete behavior of a product development system. Unexpected behavior can arise due to interaction between parts. They have used Petri nets analysis for reliability analysis of an antilock braking system (ABS).
Bond graphs (BG) are proved to be an effective modeling method for mixed systems [5]. Bond graph draws on the similarities among different domain physical systems by means of a unified treatment of energy and power. It uses a small set of components to capture the complex behavior of dynamic systems and provides a seamless interfacing with mixed-domain engineering systems.
Those modeling methods emphasize different aspects, and their applications are different. They have played an important role in manufacture, plan, and management in enterprise, but they are not good at modeling CoPS in two main headings:

1) The product development process has to be simplified when the common used mathematical tools, algorithms and information tools are used to establish operational model because the CoPS is a kind of complex system. The mapping from factual product development process to process model is incomplete, local, similar, and conditional at the same time, because only in this way can the model be settled.

2) The quantized measure is lacked in the study of non-linear mapping relationship among units in system. The traditional methods of modeling product development process is hard to represent this kind of non-linear relationship [6], and the former study lacks operational quantized measure method, so that this kind of methods can only provide some qualitative directions.

Yet there is still lack of support of multi-domain design principle in practice. To date, conventional design tools have been limited to single domain problems and require a trial-and-error synthesis process. Therefore theoretical modeling of multi-domain engineering systems, with a formal unified representation and a well-defined algorithmic and flexible synthesis procedure, is needed.
Modeling of CoPS is a challenging task due to the presence of complex subsystems in different domains and the need to integrate different engineering fields, in representing the overall mixed system. A system-based simulation system tool was developed to model and identify CoPS in a rather optimal manner. Integration of SD and RS modeling provided a domain-independent simulation environment suitable for CoPS.

III. Integrate CoPS design environment

Figure 2 provides a graphical overview of the integrated CoPS design environment developed. The Graphical User Interface (GUI) is designed to understand customer needs. Engineering design is guided by physical principles, considering flows and functions in different engineering domains. We use unified design representation to model CoPS at different hierarchical levels. The multi-level feedback loop graphs are used to represent CoPS in a unified way. Evolutionary computation is applied to support the computational synthesis process at the conceptual design stage, to generate alternative design options. Dynamics performance of the designed CoPS is verified through frequency domain analysis and time domain simulation. Synthesis and analysis are iterative until design process converges to satisfying solutions.

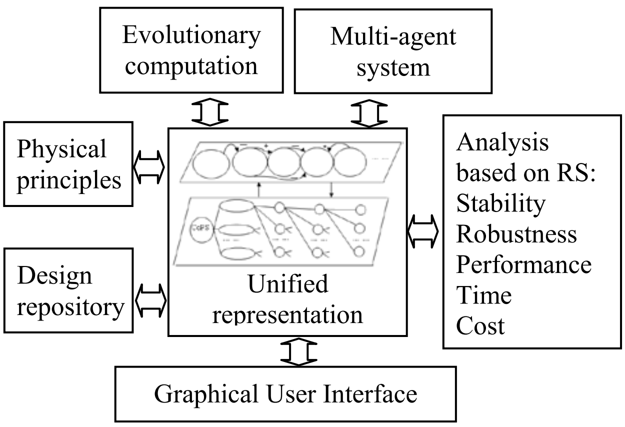

Fig. 2 Integrate CoPS design environment

IV. Unified Representation of CoPS

Table I. Multi-domain System Units of CoPS

Dimension	Gene	Data
Innovation Performance	Innovation Performances	1 development speed 2 market share of new product (NP) 3 rate of NP to all products 4 outsource of development 5 profit margin of NP
organization	Specialty of project group	6 Complementarities between subjects 7 stability of item group 8 suitable partner 9 veteran customer
	Specialty of project member	10 veteran project manager 11 support of senior 12 responsibility 13 veteran project member 14 contribute degree of cutting-edge technicians 15 existing key personal
	Communication factor	16 effective inner communication 17 effective communication with outer organization
	Process factor	18 feasible project plan 19 inspect and feedback of process 20 flexibility of process 21 emergency mechanism 22 ability of document 23 interface management
technology	Complexity of technology	24 variability of technology 25 difficulty of technology 26 product novelty
	Complexity of system	27 number of modules 28 ratio of software 29 product modularity 30 product solidity
	Technology ability of system integrator	30 ability of layout and design 32 ability of integration 33 ability of persisting product upgrade 34 maturation of leading technology
Resource and soft ability	Supporting resource	35 capital and material 36 manpower 37 knowledge and intelligence shared
	soft ability	38 ability of negotiation 39 ability of inner coordination 40 ability of obtaining information and technology 41 controlling of subcontractor 42 marketing ability
Circum-stance	Industry circum-stance	43 force of policy 44 Competitiveness index 45 Degree of industry cluster
	Marketing circum-stance	45 growth rate of former marketing 46 growth rate of new marketing 47 latent profit 48 growth rate of patent 49 growth rate of translation of technical achievements

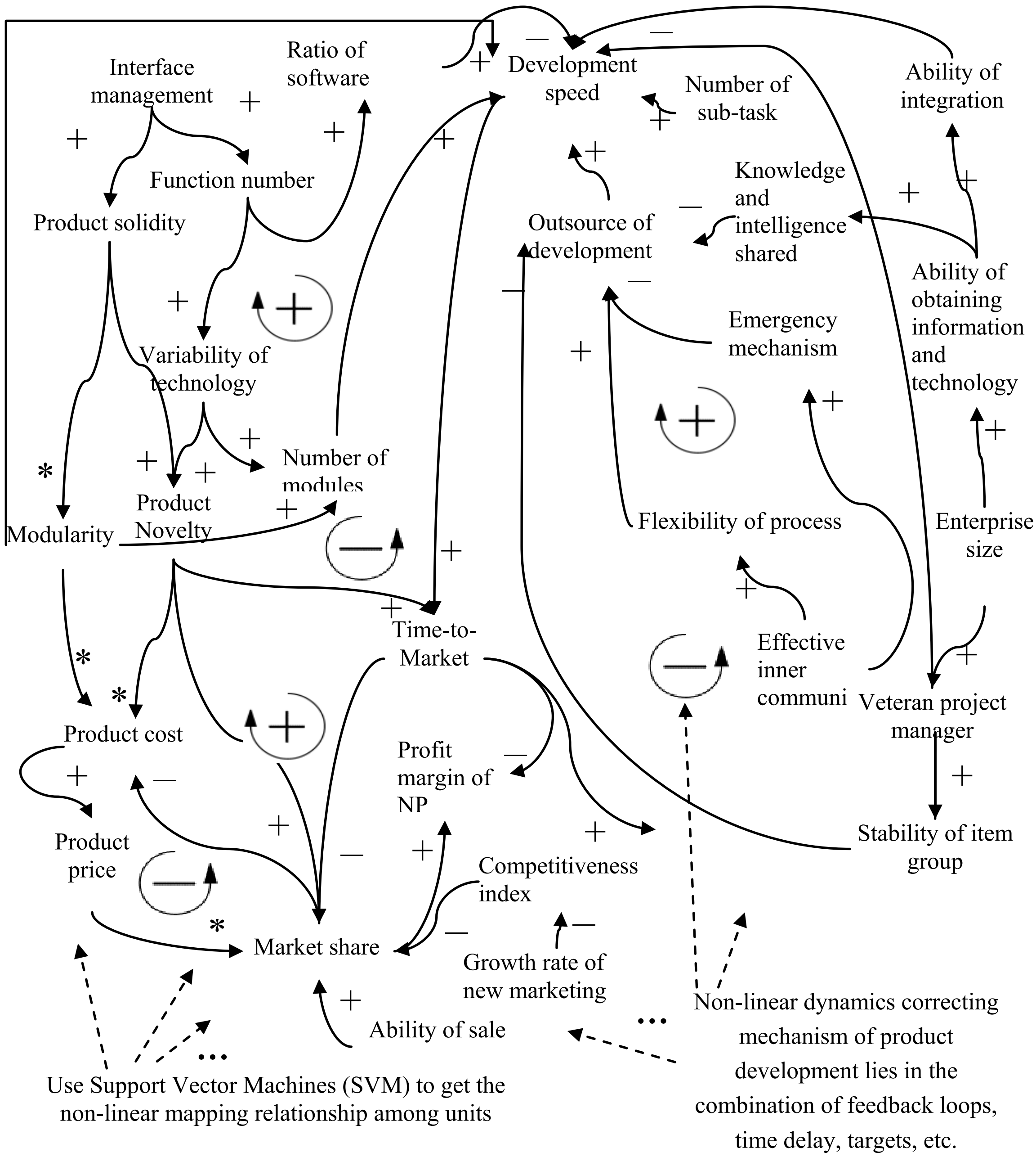

Fig. 3 system units and their non-linear mapping relationship in CoPS

1) The definition of units and choice of methods

This paper is to use the ability of nonlinear modeling and generalization of SVM to obtain the relationship among units, and then construct the SD equations. The units selected are shown in table I and Fig. 3.

Take the relationship among product novelty, product modularity and market success rate as examples to show the definition process.

Define: product novelty of CoPS (N) is presented with the multiplication of the percentage of new patent (P_T) and the percentage of new function (P_F):

$$N=P_T*P_F. \quad (1)$$

Define: product modularity (M) is presented with the ratio of the number of modules with standard interface (M') to the number of functions (F):

$$M=M'/F. \quad (2)$$

2) Acquisition and Processing of data

Acquisition of data: A qualitative pre-study involving twenty-four expert interviews was followed by a broad empirical assessment in quantitative terms. After gathering

295 data sets derived from five international CoPS development projects.

Processing of data: Use SVM to establish the model of CoPS based on above data. Take Gaussian RBF as the kernel function, $K(x_i,x_j)=\exp(-||x_i-x_j||^2/\sigma^2)$, set $\sigma^2 = 0.18$, $\varepsilon=0.1$, $C=\infty$.

V. Analysis of Non-Linear Dynamics Correcting Mechanism based on RS

Non-linear dynamics correcting mechanism of product development lies in the combination of feedback loops, time delay, and targets, etc. The combinations contain some kinds of structures which can correct harmful tiny change in system.

On the other hand, if there are too many units in systems, the rules set produced will be huge, so that it is hard to distinguish the key factors which influence the performance of system and succeed rate of CoPS development. Therefore, one method was necessary for system simplification and elimination of redundant units.

Rough Set (RS) was used to put forward the non-linear dynamics correcting mechanism of CoPS development as bellows:

Input: system dynamics flowchart G;

Output: reduced system dynamics flowchart G';

1) Produce flowchart G in terms of causal relationship chart of system dynamics;

2) Choose one unit as output unit, and others as input units. One information table was produced according to the simulation of flowchart G and the interaction among the output unit and input units

3) Output decision table according to the information table.

4) Simplification of decision table;

A. consistency inspection of decision table;

B. Attribute simplification of decision table based on RS. It means that the input units corresponding to reduced attributes are redundant so far as the output unit is concerned.

C. Attribute value simplification of decision table based on RS. It means that the input units will not make the current output unit change violently in the space of reduced attributes value.

5) Choose another unit as output unit, and the others as input units. Repeat step 2 to 5 until all units have been taken as output unit once.

6) Delete those units in flowchart G in terms of the times of corresponding attribute reduced, because those units reduced many times are not necessary. And then the flowchart G'.

In addition, the rules of stable space of system units were obtained on basis of reduce table of attribute value.

VI. Experiment

Use MATLAB and simulation software VENSIM, carry out reduce of SD flowchart with RS method shown as above, and found the factors which were largely responsible for the steady of CoPS. Those key factors divided into four kinds: technology factor, industrial factor, user demand factor, and competition factor.

A. Technology factor: factor reflecting the technology level and inner character of product development process and product itself. It includes Product Modularity, Product Novelty, Ability of obtaining information and technology;

B. User demand factor: factor reflecting the market demand and those elements which were responsible for market demand. It includes Product price, Product cost, Time-to-market;

C. Industrial factor: factor reflecting industry colony and corresponding supplementary industry. It includes growth rate of new marketing, Degree of industry cluster;

D. Competition factor: the COPS tragedy of enterprise and structure of industry competitive. . It includes Market share, Competitiveness index, Ability of sale;

In the system of essential factors found with above four kinds of factors, the relationship among essential factors is dynamic. One factor can be the motive forces of product development at one time and the disorders of product development at other time.

Simulate those essential factors and regulate the product novelty and product Modularity, and observe the interaction among essential factors. The market success rate is the multipurpose determine of time-to-market, profit, and quantity of sale. The result is shown below:

1) Degree of product novelty must be suitable. Degree of product novelty was defined by the percentage of new technology count and new function count of product. So far as lamp product was concerned, the percentage of new technology count should not exceed 10%, and the percentage of new function count should be between 30% and 60%.

Too high degree of product novelty increases the time-to-market and product cost; and too low degree of product novelty decreases market share. Suitable degree of product novelty will be responsible for the steady of CoPS;

2) Degree of product modularization must be suitable. Degree of product modularization was defined by the ratio of the count of modules with standard interface to the count of functions. So far as lamp product was concerned, the degree of product modularization should be between 0.4 and 0.7.

Too high degree of product modularization increases the manufacture cost of product; too low degree of product modularization make the development cycle hard to forecast and control. Two aspects above will cut down the product development success rate. Suitable degree of product modularization will be responsible for the steady of CoPS;

3) Many units such as the count of product functions, the competitiveness index of industry lie in many kinds of feedback loops, so as to influence the success rate of product development in different feedback loops, which waits for further study.

VII. Conclusions

1) The non-linear interaction mechanism of product novelty and product modularization to product success rate can be obtained with system dynamics, SVM and the CoPS simulation model found with these above methods.

This paper provides a unified CoPS design representation using multi-level feedback loop graphs that integrates active systems with passive physical systems formally and quantitatively. CoPS design in the physical domain and management domain preserves insight and provides guidance at the high-level design stage in selecting the proper overall system architecture and in the determination of necessary control schemes for a given design task. It gives insight into the physical causes of undesirable system phenomena and ways to improve its performance either passively or actively.

2) The essential factors which play an important role in the steady of CoPS can be found through reduce of system dynamics flowchart with RS theory.

Engineering design has been approached either from top-down decomposition approach or from bottom-up synthesis approach. This paper provided a qualitative framework to blend these two approaches and stated that this approach is beneficial to engineering design practices for having both "big picture" and "technical details". Our current work quantifies and automates this approach using cooperative coevolution by first breaking down the whole system needing to be designed into coadapted subsystems, and then automatically evolving subsystems from low-level building blocks to high-level functionality.

Acknowledgement

Supported by GuangDong province Natural Science Foundation (8151064101000004) and GuangDong Soft Science (2009B070300019) and the Fundamental Research Funds for the Central Universities, SCUT (2009ZM0074)

References

[1] Olaf A.M. Fisscher and Petra C. de Weerd-Nederhof. Social-dynamical aspects of quality management in NPD [J]. The TQM Magazine, Volume 12 . Number 6 . 2000 . 408-421

[2] Kurihara K, Nishiuchi N. Efficient Monte Carlo Simulation Method of GERT-Type Network for Project Management [J]. Computers and Industrial Engineering, 2002, 42(4): 521-531

[3] GUO Jian-fei, QIAO Li-hon. Modeling of product development process with graphical evaluation and review techniqu [J]. Computer Integrated Manufacturing System, 2004, 10(7): 758-763

[4] Yan H S, Wang Z, Jiao X C. Modeling, Scheduling and Simulation of Product Development Process by Extended Stochastic High-Level Evaluation Petri Nets [J]. Robotics and Computer Integrated Manufacturing, 2003, 19(4): 329-342

[5] Li Xiu, Jiang Chengyu, Wang Ningshen. Product Developing Process Modeling Based on Concurrent Engineerin [J]. Machine Design and Manufacturing Engineering, 2000, 29(1): 34-37

[6] Chen S J, Lin L. Decomposition of interdependent task group for concurrent engineering [J]. Computers and Industrial Engineering, 2003, 44(3): 435-459

[7] SHI Guo-qiang, LI Bo-hu, CHAI Xu-don. DSM-based modeling of project scheduling for complex product developmen. Computer Integrated Manufacturing System, 2007, 13(11): 2105-2110

[8] Wang zheng. Project Planning and Team Forming System in Concurrent Engineering [D]: [doctoral dissertation].NanJing: East-South University, 2001.

[9] Ryoke M，Nakamori Y. Agent-based approach to complex systems modeling [J]. European Journal of Operational Research，2005，166: 717-725.

[10] Lai Chaoan, Cao Jianxin. Connection theory and application of new product design in network organization. [M] .BeiJing: economy science press, 2007 (in Chinese)

[11] Bao zheJing. Applying SVM in intelligent modeling and its forecasting and controlling [D]: [doctoral dissertation]. HangZhou: ZheJing university, 2007.

[12] Dong Yilin. An MPEC Method for Optimal Parameter Selection in support erector Machines [D]: [doctoral dissertation]. Dalian: Dalian University of Technology, 2007.

[13] Wang Chifang. System dynamics[M], BeiJing: TsingHua university press, 1998

[14] XU Guang-qing. The Method of System Dynamics: Principle,Characteristics and New Development [J]，Social Sciences Journal of Harbin Institute of Technology(Social Science Edition)，2006，8（4）：72-77

[15] Sun Dongchun, Lin Fuyong. Introduction to System engineering [M], BeiJing: TsingHua university press, 2004.

[16] Qian xuesen. A New Discipline of Science: The Study of Open Complex Giant System and its Methodology [J]. Nature，1990，13(1):3-10.

[17] Wang Anlin. Analysis and modeling of complex system[M]. ShangHai: Shanghai Jiaotong University press, 2005.

[18] Gu Jifa, Tang Xijin. Meta-synthesis approach to complex system modeling [J]. European Journal of Operational Research, 2005, 166: 597-614.

[19] Nishiuchi N. Practical and Analytical Studies on the Development of Formal Evaluation and Design Methodologies for Mechatronic Systems [D]: [doctoral dissertation].London: The University of British Columbia. February 2007

Background of Authors

Chaoan Lai received the PH.D. degree from South China University of technology. He majors in product design and development, complex products and system (CoPS), and knowledge management.