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Open multilevel hierarchic intelligent control system for eco-industrial system

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Abstract: In allusion to the characteristics of the open complex giant system, an open multilevel hierarchic intelligent control system is established for the eco-industrial system. With the idea of the open engineering system, using the hall for workshop of metasynthetic engineering (HWME), intelligent control techniques, the expert system and the design of experiments are integrated within the framework of the nonlinear multi-objective decision support system to develop a robust, top-level design specification so as to make the system have the quality of adaptive control, self-organizing, self-learning and robustness. Finally, an illustrative example is given to clarify the effectiveness of the method.

Key words: eco-industry; complex giant systems; hall for workshop of metasynthetic engineering; open engineering system; intelligent control; nonlinear multi-objective

The development of eco-industry is holding the balance to be good for the utilization of resources and the sustainable development of humans[1-2]. Quantitative eco-industrial system analysis has been a weakness all along[3]. There are methods mostly in the present: input-output analysis[4], system simulant analysis[5], limited network analysis[6], MINLP model[7], and so on. The eco-industrial system is argued to be an open complex giant system[8]. The characteristics of the system are openness, complexity, evolution, emergence, hierarchy and giant etc. At the same time, the disagreements between the system's whole aims and each enterprise's local aims result in the instable accrete relationships among enterprises. These questions are the study emphases for eco-industry from theory to practice, but they are very difficult to solve using existing decision-making analysis methods. An open multilevel hierarchic intelligent control system is established in this paper. With the idea of the open engineering system, using the hall for workshop of metasynthetic engineering (HWME), intelligent control techniques, the expert system and the design of experiments are integrated within the framework of the nonlinear multi-objective decision support system (DSS) to develop a robust, top-level design specification so as to make the system have the quality of adaptive control, self-organizing, self-learning and robustness.

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1 Design Ideology of Open Multilevel Hierarchic Intelligent Control System

1.1 Hall for workshop of metasynthetic engineering

By an ideology of "from qualitative to quantitative", the HWME was advanced by Prof. Qian Xuesen in 1992. The eco-industrial system was an open system, which keeps qualitative and quantitative exchanges (matter, energy and information) from the outside environment. There are a lot of human activities among each subsystem. Using the HWME to design the eco-industrial system is to integrate expert system, advanced management thinking, communication technology, computer, network technology, manufacture, all kinds of information, data, successful cases before and correlated knowledge to the hall for workshop, so as to enhance the best qualities of human beings and computers, respectively.

1.2 Open engineering systems

The idea of the open engineering system is strongly tied to the concept of accomplishing more with fewer resources in a globally competitive marketplace. The definition of an open engineering system is as follows[9].

Open engineering systems are systems of industrial products, services, and/or processes that are readily adaptable to changes in their environment and enable producers to remain competitive in a global marketplace. The key to this definition is the concept of a system being readily adaptable to changes in its environment. An adaptable eco-industrial system is able to compete for a longer period of time than a rigid one since adaptable systems can be changed to meet the needs of a changing market. Being readily adaptable can often lead to families of products. The concept behind a family of products is to have one base product from which many other versions of that product are made. In designing the families, many aspects of the design process can be eliminated since the base product already exists. Therefore, a family of products can accommodate the same customers as several closed systems while using fewer resources.

Benefits gained from designing systems to be open engineering systems can only be seen from a long-term perspective. Development of open engineering systems may seem costly in the initial stages of design, but being able to adapt to changes in a system's environment they will lead to greater success over a longer period of time. The long-term benefits of designing systems to be readily adaptable are decreased time-to-market, increased return on investment, and increased quality.

2 Structure of Open Multilevel Hierarchic Intelligent Control System

2.1 Constitution of eco-industrial system

From the angle of the system, and for the sake of briefness, well and true, an eco-industrial system in a local zone is taken into account. It is a multilevel complex system (see Fig. 1).

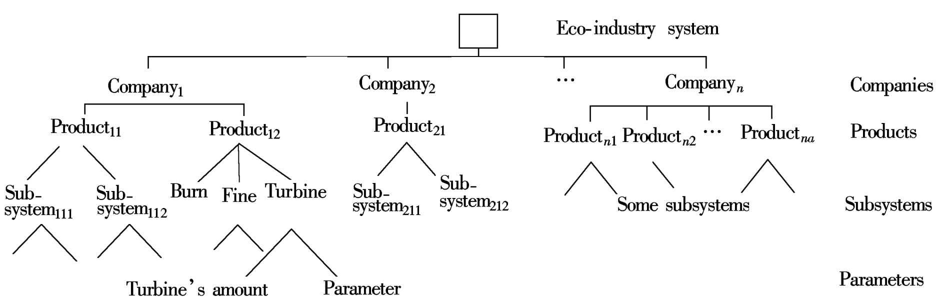

Fig. 1 A multilevel eco-industrial system

2.2 Steps of open multilevel hierarchic intelligent control system

In allusion to the structure of the eco-industrial system, an open multilevel hierarchic intelligent control system is devised. A graphical flow chart depiction is provided (see Fig. 2), with the relationship between steps and actions taken show that:

① Engineers and experts decide the collective requests and aims of the eco-industrial system.

② Classify factors (control factors, noise factors and output factors) and ranges. Additionally, the ranges of the control variables are defined with an initial concept exploration space. The identified design parameters are classified as either control or noise factors.

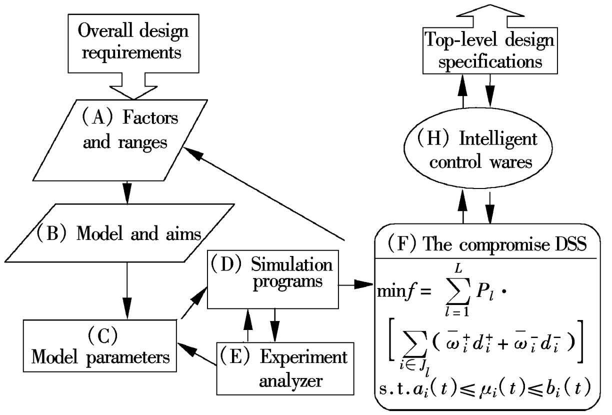

Fig. 2 Steps for complex eco-industrial system

③ Information engineers choose all kinds of modeling methods and the erect control system model by computers.

④ The corresponding aim functions are confirmed by expert systems based on collective requests and aims.

⑤ Intelligent accommodation wares establish expert systems and simulation programs based on environment. Significant design parameters are identified as the design drivers; insignificant parameters are fixed.

⑥ The screening experiments are used to eliminate control factors without significant effects on the responses. Higher order experiments are designed and conducted as necessary and the results analyzed (number and order of the experiments are increased while the size of the problem is reduced). The results ate cycled in steps C to E to develop exact model parameters.

⑦ The nonlinear multi-objective decision support system is established by experts based on environment[10] in intelligent harmonized wares, by which the values of control factors are identified to be the top level design specifications. Ranges of solutions are identified to increase the flexibility of the system.

⑧ The optimal control factors are chosen by expert systems from the satisfying sets of solutions and are passed to intelligent control wares to control the run of each subsystem.

⑨ Generate top-level design specifications.

Synthetically, an open multilevel hierarchic intelligent control system is established.

3 Strategies for Satisfying Sets of Solutions (SSS) Exploration

The reasons for pursuing a ranged set of solutions are tied to open engineering systems. One of the key tenets of open engineering systems that are applicable to the design of eco-industrial systems is the need for flexibility and adaptability in a design. Ranged sets of solutions are inherently more flexible and adaptable than point solutions. The ranged sets of solutions that result from the method used in this paper are satisfying solutions to the design problem. Since a model of the real system is used, an optimal point solution in a model has little chance of being an optimal solution in a real system. A satisfying solution from a model, defined by a plateau of "good enough" solutions, is more likely to result in the desired behavior in a real system. It is for these reasons that a ranged set of solutions is sought.

Definition 1 The control variable $\mu_i^*(t)$ $(i=1, 2, \ldots, n)$ of the optimal control factor $\boldsymbol{\mu}^* = \{\mu_1^*(t), \mu_2^*(t), \ldots, \mu_n^*(t)\}^{\mathrm{T}}$ is called the base point of each control variable $\mu_i(t)$ $(i=1,2,\ldots,n)$.

Definition 2 The set is called the satisfying set of a solution if the capability index values of any solution in this set are to be in a certainty scope of the capability index value f of the optimal control factors $\boldsymbol{\mu}^* = \{\mu_1^*(t), \mu_2^*(t), \ldots, \mu_n^*(t)\}^{\mathrm{T}}$.

Upon selection of a design scenario, regions of control variables for further exploration are determined. The determination of the ranges of each control variable for exploration is based on two simple principles (see Tabs. 1 to 4):

① If the base point of a control variable is not on a bound, that is $a_i(t) < \mu_i^*(t) < b_i(t)$ $(i=1, 2, \ldots, n)$, then some points which lie to either side of the base point, are heuristically selected for further exploration. These points do not have to be the same distance from the base point. On the other hand, if a base point of a control variable is on a bound, then some points with-

Tab. 1 Unitary exploration points

Points	μ_1	μ_2	μ_3	f
Base points	10	2	2	61. 20
2	10. 5	2	2	63. 25
3	10. 5	2	2. 2	63. 47
4	10. 5	2	2. 5	64. 30
5	10. 5	2. 5	2	64. 25
6	10. 5	2. 5	2. 2	64. 67
7	10. 5	2. 5	2. 5	65. 30
8	10. 5	2. 8	2	64. 85
9	10. 5	2. 8	2. 2	65. 27
10	10. 5	2. 8	2. 5	65. 90
11	11	2	2	65. 30
12	11	2	2. 2	65. 72
13	11	2	2. 5	66. 35
14	11	2. 5	2	66. 30
15	11	2. 5	2. 2	66. 72
16	11	2. 5	2. 5	67. 35
17	11	2. 8	2	66. 90
18	11	2. 8	2. 2	67. 32
19	11	2. 8	2. 5	67. 95
20	10	2. 5	2	62. 20
21	10	2. 5	2. 2	62. 62
22	10	2. 5	2. 5	63. 25
23	10	2. 8	2	62. 80
24	10	2. 8	2. 2	63. 22
25	10	2. 8	2. 5	63. 85
26	10	2	2. 2	61. 62
27	10	2	2. 5	62. 25

Tab. 2 Unitary exploration points in producer

Points	μ_1	μ_2	μ_3	D_1
Base point	10	[2, 4]	2	40. 00
2	10. 5		2	41. 50
3	10. 5		2. 2	41. 50
4	10. 5		2. 5	41. 50
5	10. 5		2	41. 50
6	10. 5		2. 2	41. 50
7	10. 5		2. 5	41. 50
8	10. 5		2	41. 50
9	10. 5		2. 2	41. 50
10	10. 5		2. 5	41. 50
11	11		2	43. 00
12	11		2. 2	43. 00
13	11		2. 5	43. 00
14	11		2	43. 00
15	11		2. 2	43. 00
16	11		2. 5	43. 00
17	11		2	43. 00
18	11		2. 2	43. 00
19	11		2. 5	43. 00
20	10		2	40. 00
21	10		2. 2	40. 00
22	10		2. 5	40. 00
23	10		2	40. 00
24	10		2. 2	40. 00
25	10		2. 5	40. 00
26	10		2. 2	40. 00
27	10		2. 2	40. 00

Tab. 3 Unitary exploration points in customer

Points	μ_1	μ_2	μ_3	D_2
Base point	14	2	3.5	13.00
2	13.5	2	3.5	13.00
3	13.5	2	3.2	13.00
4	13.5	2	3	13.00
5	13.5	2.5	3.5	14.00
6	13.5	2.5	3.2	14.00
7	13.5	2.5	3	14.00
8	13.5	2.8	3.5	14.60
9	13.5	2.8	3.2	14.60
10	13.5	2.8	3	14.60
11	13	2	3.5	13.00
12	13	2	3.2	13.00
13	13	2	3	13.00
14	13	2.5	3.5	14.00
15	13	2.5	3.2	14.00
16	13	2.5	3	14.00
17	13	2.8	3.5	14.60
18	13	2.8	3.2	14.60
19	13	2.8	3	14.60
20	14	2.5	3.5	14.00
21	14	2.5	3.2	14.00
22	14	2.5	3	14.00
23	14	2.8	3.5	14.60
24	14	2.8	3.2	14.60
25	14	2.8	3	14.60
26	14	2	3.2	13.00
27	14	2	3	13.00

Tab. 4 Unitary exploration points in recycler

Points	μ_1	μ_2	μ_3	D_3
Base point	10	[2,4]	2	10.00
2	10.5		2	10.00
3	10.5		2.2	10.30
4	10.5		2.5	10.75
5	10.5		2	10.00
6	10.5		2.2	10.30
7	10.5		2.5	10.75
8	10.5		2	10.00
9	10.5		2.2	10.30
10	10.5		2.5	10.75
11	11		2	10.00
12	11		2.2	10.30
13	11		2.5	10.75
14	11		2	10.00
15	11		2.2	10.30
16	11		2.5	10.75
17	11		2	10.00
18	11		2.2	10.30
19	11		2.5	10.75
20	10		2	10.00
21	10		2.2	10.30
22	10		2.5	10.75
23	10		2	10.00
24	10		2.2	10.30
25	10		2.5	10.75
26	10		2.2	10.30
27	10		2.2	10.75

in the bound are explored. The points used for further analysis, called exploration points, are determined heuristically.

② The decision-maker sets up a definite scope for the capability index value f of the optimal control factor $\boldsymbol{\mu}^* = \{\mu_1^*(t)^*\ \mu_2^*(t), \ldots, \mu_n^*(t))^{\mathrm{T}}$ (such as 5%). A certain exploration point is chosen in the nonlinear multi-objective decision-making support system. If the capability index value of the exploration point is within the scope, the exploration point belongs to the satisfying sets of solutions, whereas it is not the satisfying solution.

4 Constitution of Nonlinear Multi-Objective Intelligent Harmonized Subsystem

It is at the core of the control system that a multilevel intelligent harmonized subsystem is needed for the open multilevel hierarchic intelligent control system so as to harmonize the aims between the whole system and each process (see Fig. 3). Through the nonlinear multi-objective decision-making support system established among the harmonized ware and each decision-making cell, the decision-making final product is or approximate to the whole optimization.

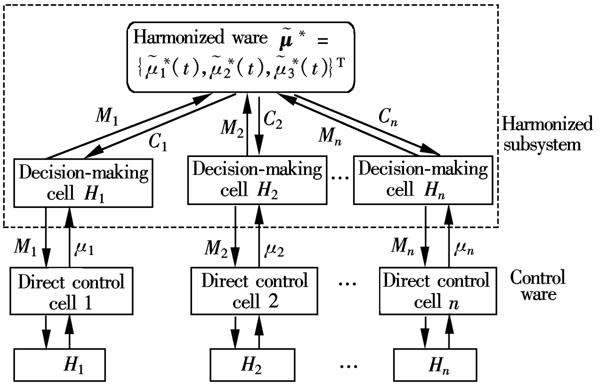

Fig. 3 Running steps of the intelligent harmonized ware

Running steps of the intelligent harmonized ware are as follows (see Fig. 3):

1) The respective optimal control factor $\boldsymbol{\mu}^* = \{\mu_1^*(t), \mu_2^*(t), \ldots, \mu_n^*(t)\}^{\mathrm{T}}$ and the capability index values f of the harmonized ware and each decision-making cell are found by the nonlinear multi-objective decision-making support system.

2) The respective satisfying sets of solution of the harmonized ware and each decision-making cell are found, which are based on the base points and a certainty scope of the capability index values f.

3) The satisfying sets of solution M_i of each decision-making cell are passed to the harmonized ware. If there are intersections between M_i and the satisfying

sets of solution M of the harmonized ware, the intersections are regarded as the final satisfying set of solutions. The decision maker in the intersections chooses a synthetically optimal control factor $\tilde{\boldsymbol{\mu}}^* = \{\tilde{\mu}_1^*(t), \tilde{\mu}_2^*(t), \ldots, \tilde{\mu}_n^*(t)\}^{\mathrm{T}}$. If there are not intersections, the harmonized ware ① utters interferential signal C, and readjusts base point or enlarges the scope of the capability index value f so as to find a new satisfying set of solutions; ② pays benefits on taxes or policies to the process who sacrifice their local capability index values according to the fact.

5 Applications

The structure of the industrial system is divided into three parts by eco-industry: producer, customer and recycler. An eco-industrial system is established with a master production—resorcin in the new developed industrial area of Wuxi (see Fig. 4). The dynamic input-output feedback control model and the corresponding nonlinear multi-objective decision-making support system are established. The satisfying set of solution M_i of each decision-making cell and the satisfying sets of solution M of the harmonized ware are found by using the Hooke-Jeeves' method[11] (see Tabs. 1 to 4). A synthetically optimal satisfying set of solutions is chosen by the decision maker (see Tab. 5).

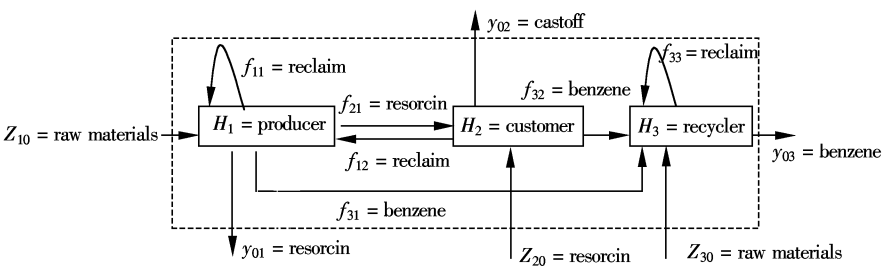

Fig. 4 One simple eco-industrial system

Tab. 5 Satisfying sets of solution M_i and M

SSS	Control variable		
	μ_1	μ_2	μ_3
M	[10, 10.5]	2	[2, 2.2]
M_1	[10, 10.5]	[2, 4]	[2, 2.5]
M_2	[13, 14]	3	[3, 3.5]
M_3	[10, 11]	[2, 4]	[2, 2.2]
M_4	[10, 10.5]	2	[2, 2.2]

6 Conclusion

Ecological industry is a kind of new and developing mode of industrial sustainable development. In this paper, the foundational principles behind industrial ecology and its design are presented. Motivation for a shift industry's perspective is given along with general, background information such as HWME, open engineering systems. Meanwhile a broad framework of design is introduced and a layout for answering the research questions is outlined. Additionally a graphical representation of this paper is used to guide readers to fluidly understand the method presented in this paper.

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生态工业系统开放的多级递阶智能控制系统

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摘要:针对生态工业系统开放的复杂巨系统特点,提出了开放的多级递阶智能控制系统的设计方法.该方法利用综合集成研讨厅体系,提出满意解集概念,把控制模型、专家系统、智能控制技术、仿真程序和实验分析综合在非线性多目标智能协调系统的框架中,探索设计空间,形成一个开放的稳定的设计,充分体现了把生态工业系统设计成一个开放的工程系统的指导思想,并使这个设计系统具有自适应、自组织、自学习和鲁棒性的特点.最后通过案例分析,表明该方法具有实际应用价值.

关键词:生态工业;复杂巨系统;综合集成研讨厅;开放的工程系统;智能控制;非线性多目标
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