ELSEVIER

Artificial Intelligence in Engineering 15 (2001) 321–327

ARTIFICIAL INTELLIGENCE in ENGINEERING

www.elsevier.com/locate/aieng

Synthesis and emergence — research overview

Kanji Ueda*

Department of Mechanical Engineering, Faculty of Engineering, Kobe University, Rokkodai, Nada-ku, Kobe 657-8501, Japan

Received 7 May 2001; accepted 7 August 2001

Abstract

The paper gives a concise overview of the present state of work in the project 'Methodology of Emergent Synthesis'. Starting with the conceptual questions concerning analysis, synthesis and emergence in the realm of artifacts, a critical overview is given of reductionism and of the problems with self-referential character of the artifactual environment. The concepts of syntax and semantics are used to distinguish between different kinds of emergence. The pieces of ongoing research work in the project are exposed using a three-fold classification with respect to the completeness of our knowledge of the environment and the specification of the purpose of the artifact. The capabilities of the related techniques are also discussed. © 2001 Published by Elsevier Science Ltd.

Keywords: Synthesis; Emergence; Complexity; Self-reference; Artifactual environment

1. Introduction

In the new era ahead of us we are facing increased complexity and uncertainty arising from factors like diversification of culture, individualization of lifestyle, globalization of industrial activities and growing consideration towards the natural environment. The increasing complexity and uncertainty bring about practical and theoretical difficulties [1,2] in all the domains of artifactual activities, from the planning phase up to post sales: nonlinear phenomena, incomplete data and knowledge, the combinatorial explosion of possible states, the dynamic changes in environment, the frame problem, etc are some notable examples of the difficulties. The most essential point is how to realize an artifactual system that achieves its purpose in unpredictable conditions. It is not easy to approach to solving such problems only by existing principles such as analysis and determinism.

In this introductory article, a new approach based on emergent synthesis is described. Synthesis is a necessary component of problem solving processes in almost all phases of artifact lifecycle, starting from design, planning, production and consumption until the disposal of the product. Emergence plays a key role in solving difficult problems arising in synthesis. This article first defines the problem of synthesis and classifies the difficulties with synthesis problems. Then, it attempts to clarify the concept of emergence and its relation to solving the difficulties. It also refers to the system-theoretical discussion. Finally, it shows emergent synthetic approaches in ongoing project 'Methodology of Emergent Synthesis' in the Research for the Future Program supported by JSPS (the Japan Society for the Promotion of Science).

2. Synthesis

2.1. Analysis and synthesis

In Webster Dictionary, *analysis* is described as a separation or breaking up of any whole into its parts, especially with an examination of these parts to find out their nature, proportion, function, interrelationship, etc., and a statement of the results of this process. From a logical viewpoint, it is tracing things to their source, and resolving knowledge into its original principles. On the other hand, *synthesis* is described as putting together of parts or elements so as to form a whole, or the combination of separate elements of thought into a whole, as of simple into complex conceptions, species into genera, individual propositions into systems. It is also argued that, analysis and synthesis, though commonly treated as two different methods, are, if properly understood, only the two necessary parts of the same method. Each is the relative and correlative of the other.

The usage of the term 'synthesis' here is somewhat different from the above description, although it is not contradictory to it. The synthesis is more clearly related to

* Tel.: +81-78-803-6139.
E-mail address: ueda@mech.kobe-u.ac.jp (K. Ueda).

0954-1810/01/$ - see front matter © 2001 Published by Elsevier Science Ltd.
PII: S0954-1810(01)00022-X

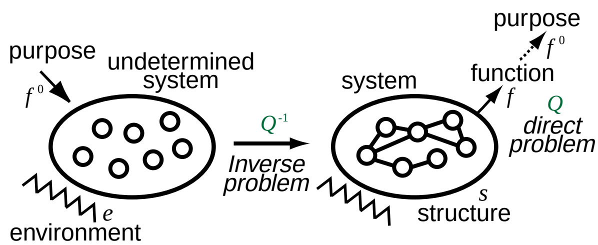

Fig. 1. Problem of synthesis.

human activities for creation of artificial things, while analysis is related to understanding natural things. Analysis is an effective method to clarify the causality of existing natural systems in such fields like physics. Methods of analysis enable one to unfold the structure that realizes the functions of the systems, no matter whether they are natural or artificial. On the other hand, synthesis is indispensable for creating novel artifacts that satisfy required functions as given by human. The latter type of problem, i.e. from function to structure, can be called inverse problem, while the former, from structure to function, called direct problem.

2.2. Problem of synthesis

Usually, an artifactual system is made with some purpose in mind; in other words, with the intention of human beings — unlike natural systems, e.g. the solar system — and it is related to a certain environment in which it should work. Now, the central question is how one can solve the problem of synthesis: how to determine the system's structure in order to realize its function to achieve a purpose under the constraints of a certain environment [3], as shown in Fig. 1. However, it is to be noticed that any framework for solving the synthesis problem has to include analysis as its part [4], as indicated in Fig. 2. It is unlikely that one finds the solution of a synthesis problem by either induction or deduction alone. It is more likely that abduction is needed, too. In abduction, one first makes a proposition of a candidate structure, then analyzes the structure in order to find the function within the environment; and once the function satisfies the specified purpose, adopts the structure to arrive at a solution.

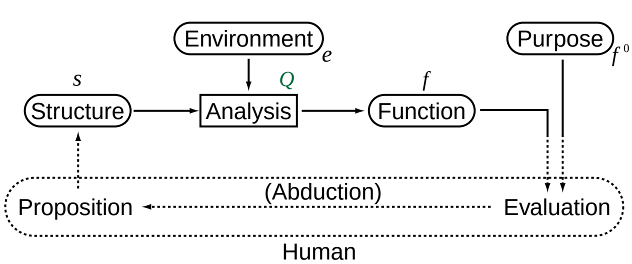

Fig. 2. Framework of synthesis.

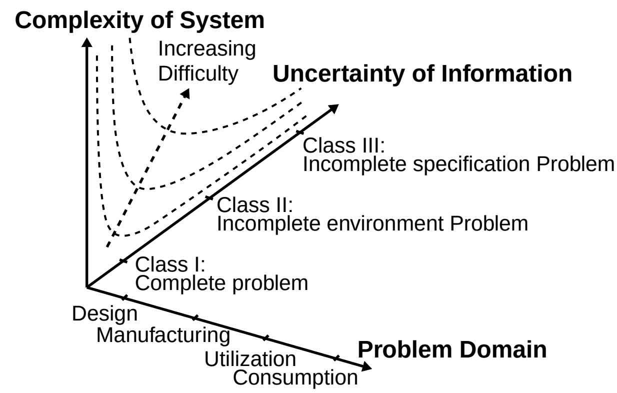

Fig. 3. Classification of synthesis problem and problem domains.

2.3. Problem difficulties in synthesis

The main concern here is when and whether completeness of the information could be achieved in the description of the environment and in the specification of the purpose of the artifactual system. With respect to incompleteness of information of the environment and/or the specification, the difficulties in synthesis can be categorized into three classes [3].

- *Class I: Problem with complete description*. If the information concerned with the environment and specification are given wholly, then the problem is completely described. However, it is often difficult to find an optimal solution.
- *Class II: Problem with incomplete environment description*. The specification is complete, but the information on the environment is incomplete. Since the problem is not wholly described now, it is difficult to cope with the dynamic properties of the unknown environment.
- *Class III: Problem with incomplete specification*. Not only the environment description but also the specification is incomplete. Therefore, the problem solving has to start with an ambiguous purpose and the human interaction becomes significant.

As shown in Fig. 3, the problem becomes more difficult as the system complexity and/or informational uncertainty increases [5]. The figure also indicates the problem domains, since synthesis is indispensable not only in design of artifacts but in almost all the other domains of artifactual activities as well.

3. Emergence

The traditional, analytic, deterministic approaches based on top–down decomposition principles are unsuitable for solving the above-mentioned problems. Instead, emergent approaches would be more feasible. The Oxford Dictionary provides that *emerge* is to become apparent, come to light; (of something unexpected) to turn up, present itself, to

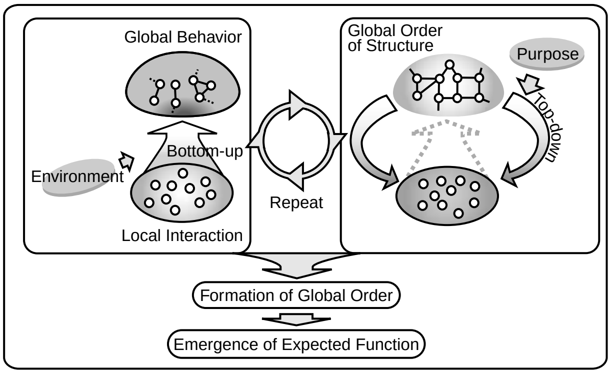

Fig. 4. Concept of emergence.

appear as a result, to emanate. In a historical perspective, the discussion of emergence addressed the origin of qualitative new structures and functions, which are not reducible to those already in existence. The problem of emergence is strongly related to hierarchical complexity, to the ancient Greek maxim 'the whole is more than the sum of the parts'. Thus, emergence has been mainly identified with two meanings, that is, novelty [6] and the generation of stable order of wholes. Emergence is also discussed in relation to consciousness or mind, for instance, as in the tacit dimension [7].

According to Cariani [8], "the pragmatic relevance of emergence is intimately related to Descartes Dictum: how can a designer build a device which outperforms the designer's specifications? Thus, the problem of emergence is the problem of specification vs. creativity, of closure and replicability vs. open-endless and surprise". Emergent device might be useful in amplifying our own creativity.

Various concepts of emergence have been discussed for a long time. Recently, Cariani presented the following three concepts:

- Computational emergence, in which global orders arise from local deterministic computational interactions: e.g. evolutionary computer simulation and self-reproduction behavior through the cellular automata, called Adam Loop, by Langton [9].
- Thermodynamic emergence, in which stable global structures arise thorough continuous, self-organization processes in physico-chemical systems far from equilibrium: e.g. the formation of a dissipative structure by Prigogine [10].
- Emergence relative-to-a model, which considers emergence as the deviation of the behavior of a physical system from an observer's model of it. In this way, emergence involves a change in the relationship between the observer and the physical system under observation: e.g. definition of emergence from ambiguity, realization of emergent function through the construction of semantically adaptive devices [11].

While the computational emergence is primarily a formal, mathematically based conception, and the thermodynamic emergence is a physically based materialism, the emergence relative to a model can be seen as a functionally based hylomorphism. Langton [12] defines emergence in terms of a feedback relation between the levels in a dynamical system: local microdynamics cause global macrodynamics while global macrodynamics constrains local microdynamics. This definition implies that implicit global complexity emerges from explicit local simplicity. With this computational concept of emergence — far both from mechanism and vitalism — Langton initiated a new direction in life science, known as Artificial Life.

As Fig. 4 indicates, the term 'emergence' is being used here in the following sense: 'a global order of structure expressing new function is formed through bi-directional dynamic processes; where local interactions between elements reveal global behavior, and the global behavior results in new constraints in the behavior of the elements' [3]. The importance here is the formation of stable global order, which is not fixed, periodical, nor chaotic, but complex structure. A stable global order gives a new function, and if the function meets the specified purpose, one can adopt it as a solution. The definition above is basically compatible with that used in Artificial Life and Complex Adaptive System studies.

However, concepts of purpose and environment are defined more definitely in our study, where emergence is investigated in association with the synthesis of artifactual systems — which has to be distinguished from the understanding of emergent phenomena as related to existing natural things as in the case of physics and biology. This artifactual context is concerned with the syntax and semantics of the problems under consideration.

4. Emergent synthetic approaches

Instead of the traditional, analytic, deterministic approaches based on the top–down problem decomposition, like operational research, symbolic artificial intelligence, knowledge-based engineering, etc., the emergence related approaches are being developed with both the bottom–up and the top–down features, which include evolutionary computation, self-organization, behavior-based methods, reinforcement learning, multi-agent systems etc. and they seem to be feasible for offering efficient, robust and adaptive solutions to the problem of synthesis.

Fig. 5 shows a schematic view of the emergent synthetic approaches to problems assigned into three classes as discussed above. For class I, since the specification of purpose and the constraints due to environment are fixed, the problem is completely known from the very beginning. However, in most cases, there are too many candidates of feasible solutions, and this leads to combinatorial explosion, typically to so-called NP hard problems. Therefore, it is essential to develop efficient, robust search methods to

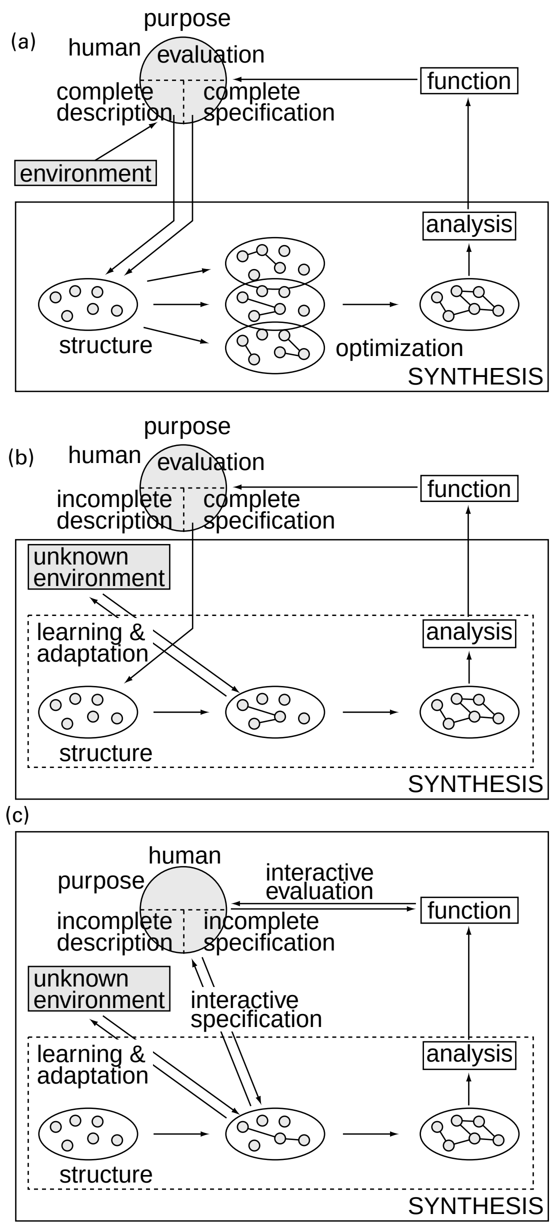

Fig. 5. Framework for synthesis problem classes and emergent approaches to them: (a) class I problem: complete description, (b) class II problem: incomplete environment description, (c) class III problem: incomplete specification.

find optimal solutions. For this type of problems, evolutionary computational methods such as Genetic Algorithms, Genetic Programming, Evolutionary Strategies and Evolutionary Programming have been successfully applied. One can use such emergence-related algorithms as problem solvers. Hence, this class of models can be characterized by fixed in both the syntax and the semantics.

In class II, in spite of the fixed specification, the lack of information about the environment causes unpredictable constraints in solving the problem. To deal with this problem, it is required to be capable to determine the constraint information through interaction with the environment during the system runs. Learning and adaptation based approaches such as Reinforcement Learning, Adaptive Behavior and Behavior-based are feasible to this class of problems. Fixed semantics and adaptive syntax characterize the model in this class.

Class III problems encounter, in addition to the lack of the environmental information, the difficulty caused by the ambiguity of human intention. This class has to cope with the iterative determination of the structure of the system, and the human as a designer should be included through the interactive specification. Therefore, in order to realize human participation in the design of the target system (object) including the designer itself (subject), further emergent properties such as interactivity, self-coordination, co-evolution and self-reference are essential. Here, multi-agent based approaches would also be effective once the system includes the observer as well as the observed. Adaptive syntax and interactive semantics can characterize the model in this class.

5. System-theoretical discussion

It is worthwhile to discuss the emergent synthesis from the aspects of artifactual environment and general systems theory. The artifactual environment includes three layers: the first one where the artifact is made, the second one where the artifact behaves, and the third one is the macro-environment, which surrounds these two [13]. The first one is the environment where the target of optimization is to realize the global goal of the whole through the mobilization of the elements when they receive their goals. The key word is ‘the part for the whole’. The second is related to the environmental problems of human society. At this layer, artifacts and humans becomes the environment of each other. The third environment is a super system, which includes nature with both the humans and their artifacts. The problem here is related to the excess of the myth, where additional raw materials and fuel are extracted from infinity and waste can be returned to infinity. The key word is ‘inside and outside’.

Now, let us consider the problems of artifactual environment from the point of view of systems theory (Table 1). The critique of element-reductionism says that it is not the linear sum of the simplified behavior of the elements, which determines the structure of the whole: the whole is much more complex. This critique can interpret the complexity of the whole, and the complexity is brought forth-by-self, in other words, self-organized.

However, there is an even harder problem here: the problem of self-reference. The introduction of feedback cannot solve this problem, because self-reference is the problem of an observer as related to the system. This is the same as the problem of inside/outside, seen in the context of the artifactual environment. Only when the observer stays outside of the environment, the environmental

Table 1
Classification of artifactual system and characteristics

	System type	Environment	Purpose	Syntax	Semantics	Parts and whole	Inside and outside	Subject and object	Model/theory
System class I	Closed (equilibrium)	Fixed	Fixed	Fixed	Fixed	From whole to parts	From outside to inside	Separable	General system theory (Bertalanffy)
System class II	Open (complexity)	Adaptive	Fixed	Adaptive	Fixed	From parts to whole	From outside to inside	Separable	Self-organization [14], Dissipative structure [10]
System class III	Boundary-less (self-reference)	Adaptive	Interactive	Adaptive	Interactive	From parts to whole	From inside to outside	Inseparable	Autpoiesis [15], Interactive engineering [16]

problem becomes an internal problem of this new system and the optimization of inside becomes possible. However, as the realm of the artifact expands, the system crosses this new boundary and the observer is forced to appear in the inside again. The essential point of self-reference is that, as discussed above, the artifactual systems become the ones without boundaries. Furthermore, the input and output cannot be defined to such a boundary-less system. Actually, self-reference is related to the first class as well. It becomes a self-reference problem concerning the purpose of engineering synthesis. Unlike for systems like those of heavenly bodies and living systems, it is usually assumed that an artifactual system first must be bound to a purpose. However, in reality, this assumption of infallibility would break down, and the loss of purposiveness in engineering could become an essentially harder problem than those of element-reductionism and self-organization. The difficulties we face today in solving artifactual problems are closely related to the difficulty in handling self-reference in the environment of the artifacts. Differentiation in the realm of information is essential in the history of Earth. Humanity has introduced information as a new entity into the systems of the Earth that are structured by cycles of materials and energy. The separation of the realms of information and artifacts have a negative side as well: the evolution of a closed artifact realm and a closed information realm has resulted in the reckless increase in artifacts on one side and the overflow of useless information on the other.

However, living organisms through their metabolism are able to adapt to changes in the environment and achieve homeostasis in order to maintain life activities. The transformation processes of materials and energy take place within the living organisms autonomously, without external control but through the expression of their own, inherent information. Originally, in the realm of living things, material and information are inseparable. This inseparability itself has made emergence possible. This also makes possible the coexistence of contradicting features such as flexibility and preservation of traits when living organisms realize themselves while adapting to the environment. If this holds, then with the re-unification of the realms of information and artifacts, metabolism and homeostasis in the artifact realm may become possible by a process of relational emergence of the autonomy of the individuals and the diversity of the whole [13].

Emergent synthesis based on the biological paradigm is an approach to dealing with the self-reference problem in the artifactual environment. The author proposes "Interactive Engineering" as the generalized concept of problems belonging to system class III. Interactive Engineering deals with the self-referential activities of the dynamic interactions among artifacts, producers and consumers [16].

6. Project 'methodology of emergent'

In the project 'Methodology of Emergent Synthesis', the difficulties of synthesis problem solving are classified and the role of the emergent processes is clarified in each stage of the design, manufacturing, utilization and interaction with users. By systematically composing an emergent methodology and verifying its effectiveness in solving the problem of synthesis, the project aims to contribute to establishment of the science of synthesis and towards the applicability to practical engineering phases. The research members participated from multiple disciplines is about twenty, such as mechanical engineering, information science, mathematics, biology, economics and philosophy. The period of the project is 5 years from 1996 to 2000.

The project includes the following five sub-themes (the details are available in http://www.mi-2.mech.kobe-u.ac.jp/~mirai/index-e.html):

(a) emergent synthesis of design systems,
(b) emergent synthesis of manufacturing systems,
(c) emergent computation for utilizing artifactual systems,
(d) synthesis of relational emergence in artifactual environment,
(e) fundamental theory of emergent synthesis.

6.1. Emergent synthesis of design systems

In this sub-theme, the characteristics of engineering systems and products are considered with respect to their structure as hierarchic systems. In synthesizing artifactual systems and/or products, such structures and their attributes should be fixed according to implicit structures. Since design aims at the construction of the whole structure of a system, so that to realize the required function, the design process as a whole — from concept design to detail design — is top–down at first glance. However, in order to describe this process of design, one has to compose the whole system with accumulating a number of subsystems. Thus, emergent methodologies could play an important role in discovering novel patterns of structures in an efficient way. Typical titles of researches here are such as Agent-based architecture of distributed design system, Large scale multi-objective optimization using Genetic Algorithms (GA), Designing of a multi-link moving robot using Evolutionary Strategy and Situation-directed design synthesis of mechanism systems.

6.2. Emergent synthesis of manufacturing systems

This sub-theme is carried out by the concept of biological manufacturing system (BMS) [1]. That conveys the adaptability of organisms. The BMS aims to deal with non-foreseen changes in manufacturing environment. It is based on the ideas inspired by biology, like self-organization, evolution, learning and adaptation. Earlier works of the author have shown the effectiveness of the BMS framework in solving manufacturing problems. For class I problem, a new GA with neutral mutation has been developed to solve Job-Shop Scheduling Problem with high performance [17]. For class II problem, learning and adaptation principles are effective. We have realized BMS models empowered with the idea of the unification of biological information with the system elements such as products and manufacturing cells, and with self-organization of the whole system. These BMS models have effectively solved the dynamic reconfiguration problem of a floor level system: the system has adapted itself both to changes in product demands and to failures of cells [18]. In addition, path-finding tasks of autonomous mobile robots in dynamic environment have been solved by developing a new Reinforcement Learning method called Instance-Based Classifier Generator. For class III, an approach of Interactive Manufacturing has been proposed [16]. In the approach, human beings — designers, manufacturers and customers — and artifacts interact with each other in a virtual space with the aid of self-organization, so that performance of each participant is improved in an interactive manner.

6.3. Emergent computation for utilizing artifactual systems

In order to construct an emergent approach for the optimization, the following research works are carried out: a multi-agent support system for manufacturing scheduling, multi-objective optimization with evolutionary computation, optimization in uncertain environments with evolutionary computation, scheduling by genetics based machine learning methods, optimization of the utilization of artifactual systems by reinforcement learning, and age models of GA for uncertain optimization problems. Here we give details of only one example, i.e. function optimization in an uncertain environment. In order to solve an optimization problem with an uncertain objective function, an extended GA has been proposed. In this method, optimization process is conducted not according to the objective function itself but according to the expected evaluation. The reliability of the expected value is eventually improved. The extended GA takes advantage, that individuals with higher fitness values are kept alive for longer generations. The evaluation for a solution is not executed by the currently observed fitness value, but by accumulating values having been observed through preceding generations. As a result, reliability for the expected value is improved from generation to generation. It is confirmed that this method is effective for finding robust solutions.

6.4. Synthesis of relational emergence in artifactual environment

Emergence in the relationships between manufacturers, consumers and artifacts has been considered, with nodes consisting of autonomous agents. These agents interact with each other via products. The interaction results in the product's evolution driven by consumers' tastes, manufacturers' productivity and their feedback. In order to make the consumers' behavior realistic, the model includes advertisement, trends, history and technical evaluation of the products. Individual differences between the consumers, such as tastes for novelty and majority, also make the model more realistic. The manufacturers' behavior has been described from two aspects, design and marketing. Computer simulation succeeded to exemplify the emergence of successful product lines and successful manufacturers. Interactive manufacturing with demand forecast has been investigated, and the emergence of products and supply networks by the customers' preference were observed as a global behavior resulting from the local interactions between the agents [19]. Cellular Automata were also successfully applied to examine consumer's theory.

6.5. Fundamental theory of emergent synthesis

To give theoretical basis for emergent synthesis from the viewpoint of mathematics, theoretical biology and philosophy, this sub-theme is started with a mathematical extension of Yoshikawa's General Design Theory (GDT) [20]. The focus is on mathematical logic formation of emergence and self-reference, modeling of self-referential behavior by theoretical biology and philosophical reflection on emergence of knowledge.

7. Concluding remarks

In this introductory article, a new approach based on emergent synthesis is described. Starting with the conceptual questions concerning analysis, synthesis and emergence, this article has classified the difficulties with synthesis problems with respect to the completeness of our knowledge of the environment and the specification of purpose of the artifact. Then, it has clarified the importance of emergence and self-reference and their relations to solving synthesis problems. This article has also reflected the system-theoretical problems, i.e. the parts and whole, and the inside and outside in artifactual environment. Finally, it has presented some contents of ongoing researches in the project 'Methodology of Emergent Synthesis'.

For the future research directions, the most important point no doubt, is, how to find proper means to solve the problem of self-reference in the artifactual environment of humanity: the realm of artifacts has expanded so drastically that this does not allow human beings to stay outside any more. A feasible solution to this problem could be found only by ceaseless design of systems including designers themselves. In this sense, the author has emphasized the new concept of interactive engineering. Interactive engineering will release designers from their present role, restricted by the myth of the complete design, and beside this, it will give birth to the richness of developing of artifacts.

Acknowledgements

This study has been conducted in 'Methodology of Emergent Synthesis' Project (JSPS-RFTF96P00702) supported by the Japan Society for the Promotion of Science. The author also acknowledges Dr A. Markus, Hungarian Academy of Science for his useful comments.

References

[1] Ueda K, Vaario J. The biological manufacturing system: adaptation to growing complexity and dynamics in manufacturing environment. CIRP-J Manufact Syst 1998;27(1):41–6.
[2] Peklenik J. Structural and operational complexity of future manufacturing systems. CIRP-J Manufact Syst 1998;27(1):5–11.
[3] Ueda K. Introduction of the project methodology of emergent synthesis. In: Ueda K, editor. Proceedings of Workshop on the methodology of emergent synthesis, Kobe, 1998. p. 1–4.
[4] Kitamura S, Kakuda Y, Tamaki H. An approach to the emergent design theory and applications. Artif Life Robot 1999;3(2):86–9.
[5] Ueda K, Vaario J, Takeshita T, Hatono I. An emergent synthetic approach to supply network. Ann CIRP 1999;48(1):377–80.
[6] Morgan CL. Emergent evolution. London: Northgate and Williams, 1927.
[7] Polanyi M. The tacit dimension. London: Routledge & Kegan Paul, 1967.
[8] Cariani P. Emergence and artificial life. In: Langton CG, editor. Artificial life II. Reading, MA: Addison-Wesley, 1991. p. 775–97.
[9] Langton CG. Self-reproduction in cellular automata. Physica D 1984;10:135–44.
[10] Prigogine I. From being to becoming. San Francisco, CA: Freeman, 1980.
[11] Pattee HH. Simulation, realization, and theories of life. In: Langton CG, editor. Artificial life. Reading, MA: Addison-Wesley, 1989. p. 63–77.
[12] Langton CG. Artificial life. In: Langton CG, editor. Artificial life. Reading, MA: Addison-Wesley, 1989. p. 1–47.
[13] Ueda K. Differentiation of the realms of artifacts and information: how does it relate to parts/whole and inside/outside? In: Langton CG, editor. Artificial life V. Cambridge, MA: MIT Press, 1996. p. 272–7.
[14] Kaufman S. At home in the universe: the search for laws of self-organization and complexity. New York: Oxford University Press, 1995.
[15] Varela F, Maturana H. Autopoiesis: the organization of living systems, its characteristics and a model. Biosystems 1974;5:187–95.
[16] Ueda K, Vaario J, Fujii N. Interactive manufacturing: human aspect for biological manufacturing systems. Ann CIRP 1998;47(1):389–92.
[17] Gohtoh T, Ohkura K, Ueda K. An application of genetic algorithm with neutral mutations to job shop scheduling problems, Advances in production management systems, IFIP. London: Chapman & Hall, 1996. p. 563–8.
[18] Ueda K, Vaario V, Ohkura K. Modelling of biological manufacturing systems for dynamic reconfiguration. Ann CIRP 1997;46(1):343–6.
[19] Ueda K, Vaario J, Takeshita T, Hatono I. An emergent synthetic approach to supply network. Ann CIRP 1999;48(1):377–80.
[20] Yoshikawa H. Design philosophy: the state of the art. Ann CIRP 1989;38(2):579–86.