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A Framework for Artificial Transportation Systems: From Computer Simulations to Computational Experiments

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Abstract—**This paper outlines the basic concepts, major methods, and key issues for the development of artificial transportation systems, which is a natural extension of computer simulations for systems analysis and decision support of transportation systems. The main idea is to integrate various transportation models into "artificial" transportation systems and convert computers into experimental "fields" for transportation analysis and decision making and evaluations. The keys to successful applications of such artificial transportations are the availability of agent-based programming and modeling, large scale distributed computing techniques, and new concepts and methods developed in complex systems, such as, artificial societies, computational experiments, and parallel systems.**

I. Introduction

Over the past 15 years, the urbanization process in China has been in a rapid development stage and the level of urbanization has almost doubled now with about 31% of the population living in more than 660 cities and 19000 towns across the country.

The rapid increase in metropolitan population and other urbanization activities have imposed a huge demand to Chinese metropolitan transportation systems, which in most cases are not prepared and do not have the capacity for such development. For example, in 2003, the number of passenger vehicles is increased by 85%, compared to the average rate of 1.5% in the rest of the world; 667,507 traffic accidents have been reported, caused 104,372 deaths and 494,174 injuries, and the traffic accident has now become the No.2 reason for accidental deaths in children in China. Pollution is another huge problem for transportation in China, contributing to over 90% of the total noise intensity, and 60% carbon monoxide (CO), 50% nitrogen oxides (NO), 30% hydrocarbon (HC) emission in the metropolitan areas. According to the Report on Human Development in China issued by the United Nations, China has 16 of the world's top 20 most air polluted cities in 2001. In addition, the land resource has been reducing at a rate of 2% to 3% due to the transportation infrastructure construction, which further intensifies the pollution problem. Finally, the weak and unreliable urban transportation systems have significantly increased the cost of logistic activities in China, currently at a level of 20% GDP, much higher than the average level of 10% in developed countries [1].

Although significant effort has been made over the past two decades in solving transportation problems in China, traffic congestion, pollution, accidents and other related problems are getting worse. It is our belief that the transportation problem cannot be solved by focused only on transportation systems alone, one must consider combined effects with other metropolitan systems, and concepts and methods developed in complex systems provide effective tools for studying integrated, coordinated and sustainable development of those systems. Specifically,

1) Since the transportation problem is only part of the overall urbanization problem, one must consider at least combined effects and interactions among transportation, logistics, and ecosystems, for building effective transportation systems to support integrated, coordinated and sustainable metropolitan development. Artificial systems, based on artificial societies and agent modeling technology, are effective tools for this purpose [2].
2) There are no once-for-all solutions for integrated, coordinated and sustainable development of metropolitan transportation, logistics, and ecosystems. Those systems involve human and society and are intrinsically open, dynamic, unpredictable, and complex in their behaviors and effects. One must adapt a management and control strategy for those systems based on the principle of continuously investigation and improvement (CII), and the method of computational experiments using artificial systems can be used to overcome the difficulty of experimenting with real systems [3].
3) There are no optimal solutions for integrated, coordinated and sustainable development for metropolitan transportation, logistics, and ecosystems, lest the unique optimal solution. One must consider the sensitivity of so-called optimal solutions to their assumed ideal conditions and the unavoidable disparity between ideal and actual conditions. We should adapt our thinking to the existence of multiple effective

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solutions in dealing with urban development problems. In such cases, the concept of parallel systems that utilize computational experiments and adaptive control methods can be applied in seeking adaptive dynamic and effective solutions [4].

Based on above considerations, our goal is to develop a framework of platforms based on concepts and methods in artificial societies and complex systems for studying integrated and sustainable development of metropolitan transportation, logistics, and ecosystems (see Figure 1). This effort can be considered as an important application of artificial societies [5, 6] and a further development of activity-based TRANSIMS project [7] and artificial transportation systems [8, 9].

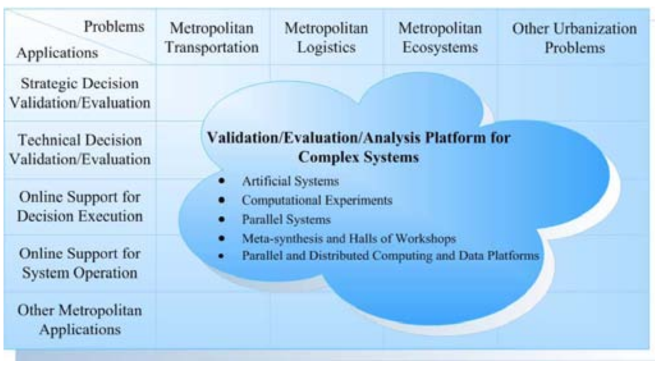

Fig. 1. Complex systems platform for integrated and sustainable development of metropolitan transportation, logistics, and ecosystems

II. Research Issues and Tasks

The key issues to be addressed in the development of artificial transportation systems are followings:

1) Modeling Problem: There are no effective methods available to model and analyze complex systems at this point, but since one is inclined to be agreeable with simple objects or relationships, thus it is useful to build agent models based on agreeable simple objects or relationships, then develop a bottom-up approach to "grow" complex systems and "observe" their behaviors through interaction of simple but autonomous agents according to specified rules in given environments. This approach will be used to develop agent-based models from the aspect of behavior generation for integrated artificial systems for transportation, logistics, and ecosystems.
2) Experimenting Problem: It is very difficult, many times even infeasible to experiment with complex systems, especially when human or societal subjects are involved. It is very helpful when artificial systems can be used for experimental purposes, that is, experiments through computers or computational experiments, which are natural extension of computer simulations. Artificial systems and computational experiments are ideal tools to validate goals and objectives or evaluate strategies and decisions for coordinated and sustainable development of metropolitan transportation, logistics, and ecosystems.
3) Decision-Making Problem: Through the interaction between real and artificial systems, one can construct "parallel systems" to use computational experiments, test different strategies and decisions and evaluate their effects for solving complex problems. Ideas and methods developed in adaptive control systems can be utilized effectively in the framework of parallel systems for decision-making in complex systems. Furthermore, artificial systems, computational experiments, and parallel systems provide both data sources and proving grounds for meta-synthesis and halls of workshops developed for decision support and analysis of complex systems [10]. The fusion of those methods offers a possible direction for establishing a computational framework for facilitating integrated, coordinated, and sustainable development of metropolitan transportation, logistics, and ecosystems under the principle of continuously investigation and improvement.
4) Computing Problem: How to use the new and advanced computing architectures and environments especially networked computing, such as grid computing and peer-to-peer computing to implement solutions for modeling, experimenting, and decision-making problems of complex systems.

To address those problems, seven major tasks in four areas have been specified in Figure 2. The roadmap of integrating those tasks into an effective and coherent framework for modeling, analysis, and management of complex systems is given in Figure 3.

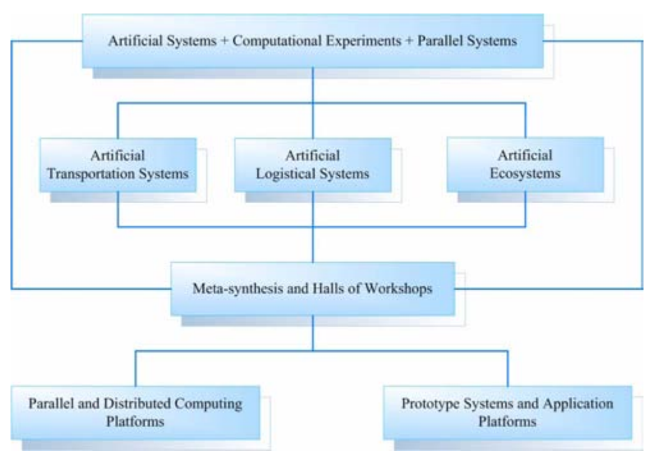

Fig. 2. Key Issues and tasks for integrated and sustainable development of metropolitan transportation, logistics, and ecosystems using artificial systems

Fig. 3. Roadmap for integrated and sustainable development of metropolitan transportation, logistics, and ecosystems using artificial systems

III. Modeling, Analysis, Synthesis and Management of Complex Systems Based on Artificial Systems

The goal of research in this area is to establish a computational theory that uses artificial systems as alternatives to real complex systems for the purposes of validation or evaluation with computational experiments (see Figure 4) and management or control with parallel systems (see Figure 5). Major tasks include:

1) Agent-based Modeling, Design, Analysis and Synthesis of Artificial Systems

1) Cellular automata and their generalization for modeling agents.
2) Linguistic dynamic systems for describing agent behaviors.
3) Multi-resolution observation and analysis of agent behaviors.
4) Petri nets for specifying networking and cooperation among agents.
5) Computational intelligence methods and game theoretic strategies for decision-making by agents.

2) Methods and Procedures of Computational Experiments

1) Transition of computer simulations to computational experiments.
2) Accelerated tests for pressure, limit, failures, or disasters
3) Emergence-based observation/explanation for computational experiments.
4) Multi-scale behavior analysis based on computational experiments.
5) Petri nets for specifying networking and cooperation among agents.
6) Design, calibration, and verification of computational experiments.

3) Theory and Methods of Parallel Systems

1) Framework of parallel systems and protocols and processes of interaction between real and artificial systems.
2) Validation/evaluation of strategies and decisions using parallel systems.
3) Internal feedback mechanisms for control and adaptation.
4) Perturbation analysis and ordinal optimization for effective operation based on parallel systems.
5) Active and online identification of behavior patterns using computational experiments and parallel systems.

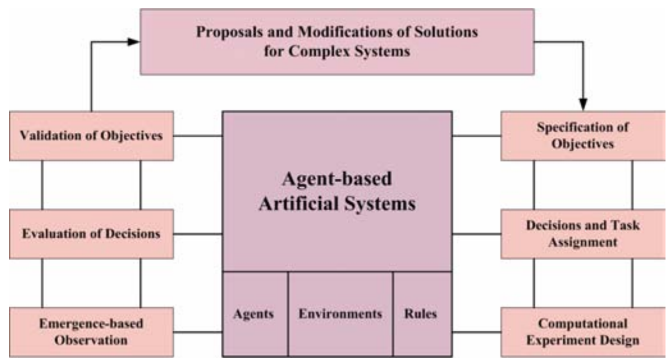

Fig. 4. Computational experiments for behavior analysis and decision evaluation of complex systems

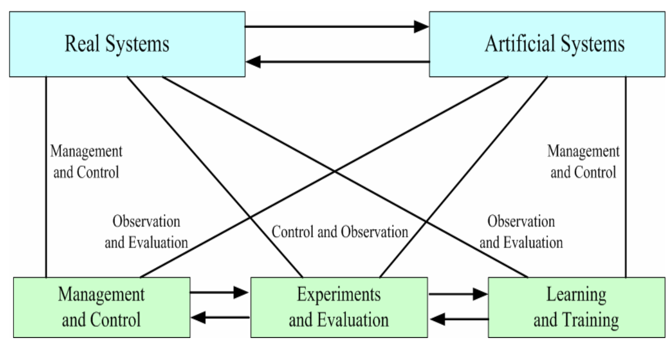

Fig. 5. Parallel systems for management and control of complex systems

IV. Design, Construction, and Analysis of Artificial Systems for Metropolitan Transportation, Logistics, and Ecosystems

The use of artificial systems for studying complex systems is a natural extension of computer simulations as the computational power grows. To maintain the coherence and achieve the integration of different artificial systems for transportation, logistics, and ecosystems, common agent models are used and shared across all artificial systems. Figure 6 presents major components for artificial systems and related tasks include:

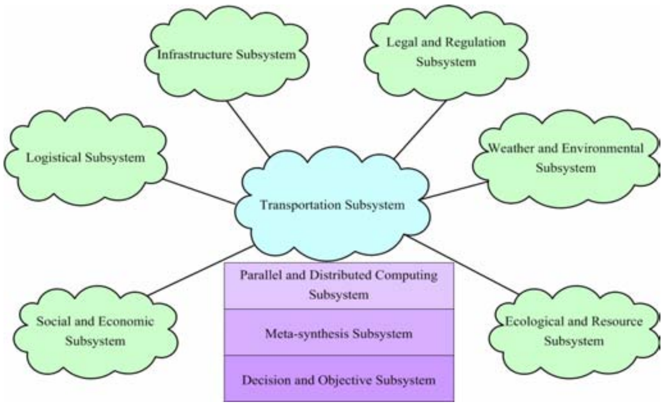

Fig. 6. Integrated artificial systems for transportation, logistics, and ecosystems

1) Design, Construction, and Analysis of Artificial Transportation Systems

1) Agent models for traffic behaviors in terms of selection of travels, destinations, times, means, and routes;
2) Interaction between transportation and social systems, economic systems, population, resources, environments, and information;
3) Estimation and analysis of transportation capacities in different situations;
4) Validation and evaluation of transportation strategies and decisions using computational experiments and parallel systems;
5) Standardized performance evaluation procedure of traffic management and control systems using artificial transportation systems.

2) Design, Construction, and Analysis of Artificial Logistical Systems

1) Agent models and their calibration for logistical activities.
2) Self-organizing and learning of artificial systems based on supply chains and service chains for logistical operations.
3) Emergence-based observation of logistical behaviors and their interaction with transportation systems.
4) Validation and evaluation of logistical strategies and decisions using computational experiments and parallel systems.
5) Standardized performance evaluation procedure for logistical management and control systems using artificial logistical systems.

3) Design, Construction, and Analysis of Artificial Ecosystems

1) Agent models for plant growths and plant-environment interaction;
2) Interaction and regulation between ecosystems and transportation systems;
3) Estimation and analysis of carrying capacities of ecosystems in terms of population, transportation and logistical development;
4) Sampling and generation of synthetic human and plant population;
5) Validation and evaluation of ecological strategies and decisions using computational experiments and parallel systems.

V. Meta-Synthesis and Halls of Workshops for Decision Support and Analysis for Metropolitan Transportation, Logistics, and Ecosystems

Meta-synthesis and halls of workshops are methods and tools proposed and developed by a research group led by H.S. Tisen, the founder of Engineering Cybernetics [11] and Chinese Space Program, and R.W. Dai in later 1980s for dealing with open complex and giant systems (OCGS) [10, 12]. Artificial systems, computational experiments, and parallel systems offer data source, methods, and techniques to develop application-specific meta-synthesis and halls of workshops for decision support and analysis with metropolitan transportation, logistics, and ecosystems (see Figure 7). The following tasks are scheduled in this team project:

1) Human-machine interaction based meta-synthesis for decision support and analysis for metropolitan transportation, logistics, and ecosystems.
2) Architectures and strategies of halls of workshops for decision support and analysis for metropolitan transportation, logistics, and ecosystems.
3) Workflows of halls of workshops for decision-making for metropolitan transportation, logistics, and ecosystems.
4) Software support and network environment for halls of workshops.
5) Integrated validation/evaluation environment based on meta-synthesis, computational experiments and parallel systems.

Fig. 7. Integrated artificial systems for transportation, logistics, and ecosystems

VI. PLATFORMS FOR PARALLEL AND DISTRIBUTED COMPUTING, PROTOTYPE DEVELOPMENT, AND FIELD APPLICATIONS

Powerful and effective computing and data processing platforms are essential to the success of this team endeavor. We will develop two types of parallel and distributed computing platforms, one is grid-computing based for management and control, and another is peer-to-peer based for research and development. Prototype systems and field applications in three major cities (Shanghai, Shenzhen, and Jinan) will be conducted to validate and evaluate the theory and framework developed in this project. Specifically,

1) Platforms of Parallel and Distributed Computing for Complex Systems

1) Open computing architectures and processes for artificial systems and their parallel and distributed models.
2) Petri nets for specifying and modeling parallel and distributed computing processes of artificial systems.
3) Data management, mining, fusion and reduction for artificial systems.
4) Effective parallel and distributed algorithms and synchronization methods for computational experiments, parallel systems, and halls of workshops.
5) Computing environments, tools, and intelligent user interfaces for computational experiments, parallel systems, and halls of workshops.

2) Platforms for Prototype Development and Field Applications

1) Prototype systems for field applications in Shanghai, Shenzhen, and Jinan.
2) Integrated control and management platform for traffic systems.
3) Integrated scheduling and management platform for logistical systems.
4) Integrated analysis and management platform for ecosystems.
5) Validation and evaluation of field testing and applications.

VII. CONCLUDING REMARK

Development of artificial transportation systems require knowledge and experiences from systems engineering, computer science, transportation, logistics, operations research, plant science, economics, population studies, management science, and social studies. Through the fusion of field-specific knowledge from diversified disciplines, our aim is to use a multidisciplinary approach to re-evaluate research and development strategies in transportation, logistics, and ecosystems and to establish a computational theory and framework with artificial systems, computational experiments, parallel systems, and meta-synthesis for decision support and analysis of complex systems in general, and for integrated, coordinated, and sustainable development of metropolitan transportation, logistics, and ecosystems in specific. Eventually, our goal is to develop a computational framework that enables us to model, analyze, and synthesize complex urban and metropolitan social systems from qualitative validation to quantitative evaluation.

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