A Multi-Agent Model for Urban Water-Energy-Food Sustainable Development Simulation

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ABSTRACT[1]

Water, energy and food are basic resource for sustainable urban development. It has been acknowledged that there are numerous complex non-linear interconnections among them, or called WEF-Nexus, meaning that any strategies that focus on single resource would lead to unexpected results. As one of the most effective tools for simulating the complex system, Agent-Based Modeling has a unique advantage in optimizing WEF allocation and promoting its use efficiency at the city level. Basing on characters of various agents in a complex urban system, this paper first divides various agents into three types: household, firm and government, which are all living in the same urban space and sharing independent but competitive demand for WEF resources respectively. And then under the guidance of behavior rules for household, firm and government agents, Netlogo programmable modeling environment are proposing to explore the complex interaction between those three agents in the process of WEF production and consumption. On the basis of WEF-Nexus with different agents, we finally build a new Multi-Agent Model, and conclude that by setting some sustainable development goals, this model can effectively simulate the urban WEF consumption pattern and its dynamic changes with the evolution of time.

CCS CONCEPTS

•Human-centered computing→ Computer supported cooperative work •Human-centered computing→ Social engineering (social sciences)

KEYWORDS

Urban sustainable development, WEF(water, energy and food), Multi-Agent Model, Simulation

1 INTRODUCTION

The rapid development of urbanization in China characterized by large-scale population transfer puts great pressure on the cities' resources and environment. Meanwhile, climate change and globalization also profoundly affect the development model of the city in the future. To cope with the internal and external constraints in urban development and to build a sustainable green city, international organizations attach greater importance to Water-Energy-Food Nexus (WEF-Nexus) [1]. As the fundamental elements for urban development, The WEF systems are highly interconnected: food production requires both water and energy; treating and transporting water requires energy; energy production requires water [2]. These three resources are in a complex non-linear relationship, whether in the process of production, consumption, or management, which means that any strategy that only take into account a single resource will bring about unexpected consequences [3].

The Agent-Based Modeling (ABM), which integrates complex adaptive system theory, artificial life and distributed artificial intelligence, serves as an important tool for simulating and analyzing complicated systems [4,5]. Its principle is to divide the complex system into corresponding agents (each agent has its own data, knowledge, model and interface etc. [6]) by simulating the real world and to adopt a bottom-up approach to study individual's behavior at the micro level, from which the researcher draw an conclusion about the system behavior at the macro level [7]. Urban space can be regarded as an intricate environmental system in which WEF production and consumption activities keep going and different types of agents independently make behavior decisions by receiving and screening the information from external resources and in turn generate demand for WEF at different levels. Additionally, there will be interactions between various agents and environmental systems,

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from which they can accumulate learning experience, and change their structures and behaviors for survival and development [8].

The previous studies concerning the relationship between different agents in the city mainly concentrated on the migration of population and households, the transformation of land utilization patterns, and the changes and adjustments to space like ecological protection zones; few touches upon the flow of resources that do not have significant spatial distribution characteristics, which is also of great importance to achieve urban sustainable development. In the long run, the sustainability of WEF is the prerequisite for the sustainable development of the city. All the agents within the city should not only coordinate with each other in terms of land space, but also need to make joint decisions to effectively allocate and dispose the limited fundamental resources.

2 AGENTS AND ITS FRAMEWORK

The urban sustainable development model constructed in this paper mainly takes into account three agents and their decision-making behaviors, namely, household agent, firm agent and government agent, which constitute an environmental system. In the n × n-dimensional network, agents are connected by the relation between WEF production and consumption. Government decision-making, which comprises public's participation and enterprises' behavior, reflects the impact and contributions of different parties to the sustainable development of the city, and is conducive to alleviating the conflicts between the increasing consumption of resources and the promotion of low-carbon society.

2.1 Household Agent

As a key terminal for WEF consumption, household agent refers to the individuals who can think and act independently in the pursuit of a better life. The differences within households account for their differentiated consumption patterns. On the one hand, objective factors like family income, size and living space determine how much resources the family needs to obtain from outside. On the other hand, their behaviors and attitudes in the utilization of resources are influenced by subjective factors like consumption habits, the awareness of saving and the inclination to follow neighbors' suits [9]. According to the factors that influence household consumption, household agents can be classified into four subtypes [10], as shown in the Fig.1: ① represents the household agent that has a large size, population and living space. Although they need more resources for survival and development, their family members have awareness of saving and keep a low-carbon energy-saving consumption habit, thereby increasing the utilization efficiency of the resources. Likewise, the cases of ②, ③, ④ can be inferred in a similar way.

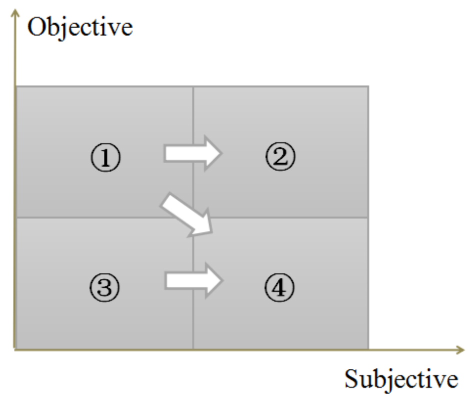

Figure 1: Sub-types of Household Agents and Their Conversion Mechanism

These four types of family consumption patterns are not immutable. Rather, they can be converted from and to each other. Assuming that the objective factors that affect the family consumption of WEF is fixed, the only way to maintain the sustainability of household consumption is from ① to ②, and from ③ to ④, that is, arousing energy-saving awareness and promoting low-carbon behavior in all households. The reality is that the income of residents in the long term has an upward trend: the increase in income will lead to the expansion of living area, which in turn expands the demand for resources consumption. Therefore, sustainable development requires the forming of good consumption habits among residents.

2.2 Firm Agent

Firms shoulder multiple functions: they are responsible for the production and supply of WEF while at the same time they consume part of WEF. Firm Agent can be further categorized into the agent accountable for the production of WEF and the one that consumes WEF. With regard to the former, the supply of WEF depends on the demand of individuals, the cost of WEF production and market prices. For the latter, the amount of consuming resources is not only related to the price of products, but also has close connections to the city's industrial structure and resource utilization efficiency. Moreover, the firm agent also needs to recycle the remaining waste produced in the consumption process, including waste water, waste gas, and solid waste etc. (see Fig.2).

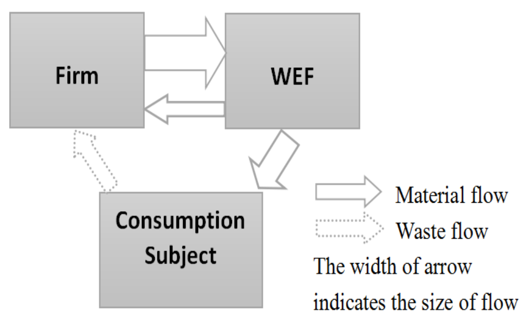

Figure 2: Firm Agents' Supply and Recycle of WEF

2.3 Government Agent

Government Agent is special because it does not have evident spatial attributes and cannot live without a certain amount of WEF. The function of government agent is to coordinate the allocation and mobilization of WEF in the entire urban system by formulating economic policies and take administrative intervention. For example, it curbs residents' excessive consumption by increasing the price of WEF, and arouses their environmental protection awareness by raising the garbage recycling prices. At the same time, residents and other consumers give feedback about the consumption information to governments, such as exorbitant water and electricity prices that may affect their quality of life.

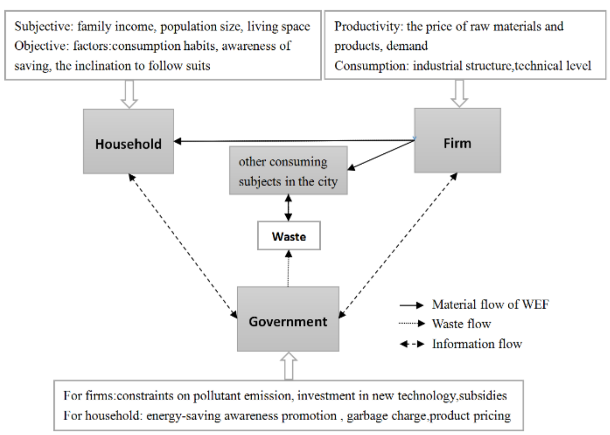

Figure 3: The Relationship of WEF Between Various Agents in Urban Space

Therefore, we formed a model in which different agents within the urban space are connected by WEF (see Fig.3). The production firms are the source of WEF supply. All agents will have the demand for resources consumption and the waste produced in the consumption process will eventually be recycled by the firms. The flow of material and waste forms a consumption cycle. Households are at the terminal of consumption, which includes the demand for water, energy and food. Apart from consuming WEF, the governments also guide and restrain the production of firms and the consumption of households through information flow.

To achieve the goal of sustainable development, various agents that have the ability to act independently in the urban environment must coordinate the limited supply of resources and rationally allocate the resources like water, energy and food to avoid conflicts and vicious competition. An agent may achieve optimum by adjusting the consumption of resources in accordance to the WEF price set by the government. It may also interact with other agents to adjust its own consumption behavior.

3 WEF CONSUMPTION RULES

The following part mainly discusses the WEF consumption rules of different agents and the allocation and mobility of WEF in the entire urban space.

3.1 Households' WEF consumption

W: According to the function and quality of domestic water, households' WEF consumption can be divided into three layers: water consumption for outdoor activities as the first layer, domestic water as the second layer and drinking water as the third layer. To improve water utilization efficiency, you can take water-saving measures like putting a brick in the toilet tank to reduce the flush volume, or promote the multiple use of water like watering the flowers with recycled water.

E: The major types of energy that urban residents consume are electricity, gas, liquefied petroleum gas and natural gas. The consumption terminal can be divided into outdoor and indoor parts: the former mainly refers to the energy consumed in transportation while the latter includes the energy utilized in lighting, heating, cooking and household appliances. To improve the efficiency of energy utilization, we can encourage the development of energy-saving technology and the exploration to new energy, and give subsidies to low-emission cars.

F: Households' food consumption is composed of indoor food consumption and outdoor food consumption. The expansion of urban area and traffic congestion contribute to the trend that more and more people tend to eat in the restaurants, considering the fact the distance between workplace and home is long and the trip is time-consuming. Although it can on the one hand reduce household consumption of food and the production of kitchen waste, it will on the other hand increase the demand for consumption in catering industries like the restaurants, canteens and other places: the city's total amount of consumption and emissions have not changed.

There is certain correlation between household agent and WEF. For example, cooking in the kitchen needs food (as raw materials), water and energy. Arranging the meals based on family members' actual needs can avoid unnecessary food waste and save water and electricity.

The expression of households' WEF consumption:

$$H_i^{WEF}{=}\alpha\mathrm{W}{+}\beta\mathrm{E}{+}\gamma\mathrm{F}{+}\varepsilon_i \tag{1}$$

(α、β、γ are preferences and weight and α+β+γ=1, ε_i is a random perturbation variable)

Different households have different preference for WEF and they will choose their own consumption patterns according to subjective and objective conditions. The probability that each consumption pattern is selected is:

$$\mathrm{P(x|i)} = \frac{\exp\left(WEF_{x,i}\right)}{\sum_x \exp\left(WEF_{x,i}\right)} \tag{2}$$

To make the random utility decision-making more realistic, the author employed the Monto Carlo simulation, and chose the most appropriate model from the alternative consumption patterns.

The searching rules for household consumption patterns are presented as follows:

(1) So long as the conditions of the family permit, we randomly seek practical consumption patterns until we arrive at the limits of constraint conditions.

(2) Select the alternative that is better than the family's current consumption model. If there is no proper alternative, we will stop the effort.

(3) Calculate the total utility of these alternatives.

(4) Figure out the conditional probability of the consumption pattern in the formula, employ Monte Carlo simulation to produce the optimal consumption choice, and finally adopt it.

(5) Update relevant data in both old and new consumption patterns.

3.2 Firms' WEF Consumption

First of all, set a total amount for the firms' WEF supply (T_{WEF}) and analyze their needs for WEF. Firms not only supply water but also have a demand for it. The water consumption by firms can be divided into the water used for production and processing and that used for service industry. All firms need to consume certain amount of energy to carry out its production and business activities. As for food consumption, we assume that employees either consume food in the households or in catering service industry in the cities.

The firm's resources consumption in the model constitutes at least three parts: WEF production, waste disposal, and the provision of necessities and services for society. The first two parts aim to maintain the WEF cycle while the last one is not only the basis for economic and social operation of the whole city but also the source of family income for residents.

The expression of firms' WEF consumption：

$$E_{WEF} = C_{Production\,WEF} + C_{waste\ disposal} + C_{providing\ goods\ and\ services} \quad (3)$$

This is the sum of WEF consumption by all the enterprises in the city and a single firm's resource consumption is only a part of it. Water plants, power stations and garbage disposal plants are responsible for water supply, power generation, and waste disposal respectively. Other production and processing enterprises, commercial corporations and service firms take on the responsibilities to provide a wide range of products and services.

$$E_{WEF} + H_{WEF} < T_{WEF} \quad (4)$$

（T_{WEF} is relatively fixed）

Since the total supply of WEF is fixed, the WEF consumption of firms and households are in a competitive relationship, that is, an increase in household consumption will cause a decrease in that of firms. Therefore, the household agent and the firm agent should interact with each other before they make behavioral decisions.

To figure out the optimal WEF consumption of firms, it is necessary to set certain environmental parameters for them that influenced by the government policies and constrained by their industrial structure and available capital [11]. The government's investment in the development of energy-saving and new energy technologies and price setting in WEF and its waste will influence the WEF consumption of enterprises. Besides, the upgrading from secondary industry to the third industry means that the enterprises gradually get rid of the production mode marked by high energy consumption and pollution and that the resource consumption of unit output will decline. Firm agents can feel the changes and adapt their own behaviors to the environment, and even predict the future.

3.3 Governments' WEF consumption

The water consumption of governments is part of public services water consumption, and the energy they consume is provided by energy production enterprises. We assume that civil servants rely on families to consume food as the employees in the companies do.

The government agent in the model should behave in consistent with other agents. If the government changes the system environment by implementing a subsidy policy for low-emission or new energy vehicles, then the household agent's purchasing behavior will be influenced by the policy. Meanwhile, government's procurement behavior should take into account current environmental conditions.

4 MODEL DESIGN

Having establishing the consumption rules of different agents within the urban area, we need to explore how these agents carry out consumption activities within the supply constraints of WEF and how does their interaction cause the dynamic change to WEF consumption pattern in whole city. To simulate the complex agent system, we can simulate WEF consumption in Netlogo's programmable modeling environment, in which Netlogo modelers can issue commands to hundreds of independent agents, making it possible to explore the relationship between individual behavior at the micro level and the macro-model derived from the interaction between individuals [12, 13].

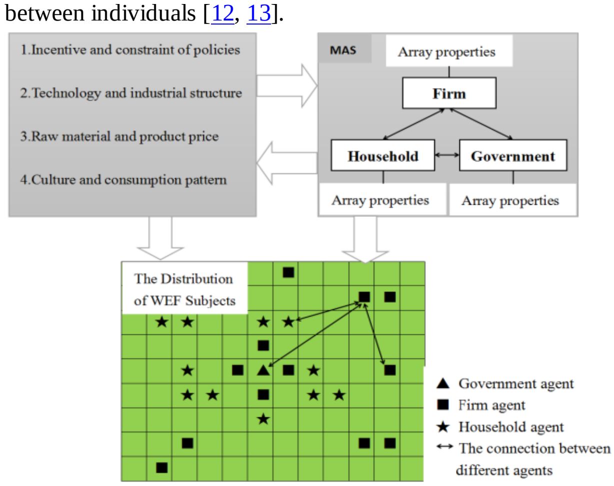

Figure 4: Netlogo Simulation Model for Urban WEF Sustainability

Netlogo Simulation Model is built on the basis of WEF-Nexus with different agents in the urban space. The model shown in Fig.4 consists of three parts: social environment, multi-intelligent system, simulation of WEF consumption distribution .The first two parts have been elaborated in the previous section: the social environment constitutes factors like policy objectives, market mechanisms and consumption concept; multi-intelligent system reflects the relationship between different agents, with each agent array storing attributes like its consumption behavior and background. The distribution model of WEF consumption mainly includes urban electronic map, residential area, industrial area, the distribution of government agencies and their consumption density. The consumption model is determined by the current situation of various agents in the city and affected by and reacted to social environment.

As for the dynamic simulation of WEF consumption model, there is a large number of movable agents like households, firms and governments etc. in a two-dimensional virtual world, who can take the initiative to follow directions and participate in activities. They interact with each other and change the characteristics of the urban consumption system at macro level. The Netlogo simulation model contains three categories: turtles, patches, and observers [14]. Small turtles in this model refer to the agents like household, firm, and government, who move in the two-dimensional world and consume WEF; The patch is the networks in the two-dimensional world, with each one occupying a small rectangular pieces. The patch in this model is marked in light green, and the darker the color is, the greater amount of WEF stock there is. We assume that WEF can flow rapidly within the urban area and that the distribution density in each part is even, so the color of WEF in each patch is the same. If the government set the energy-saving emission reduction targets, it means that the resources in each patch will decrease and their color will correspondently become lighter. The observer represents the one who is observing the world and who is capable of executing instructions, acquiring information about all or part of the world's states, or controlling the world. The observer in this model can be understood as the government, because governments not only play a vital role in formulating the long-term development plan for the city and helping it maintain sustainable development, but also is the main force to regulate and guide consumer behaviors.

5 DISCUSSION

The rapid development of urbanization in China has caused a string of problems such as population congestion, resource shortages and environmental degradation. Therefore, the city needs to seek a sustainable development pattern to save resources for its future development. As the basic elements for human survival and urban development, the supply and consumption of water, energy and food become the top priority, and they also have numerous interconnections in the process of production, consumption and management which could be called WEF-Nexus [15].

This paper introduces the Multi-Agent Modeling (ABM), simulates and analyzes the complex systems of WEF's allocation and flow in the city. By subdividing the urban system into different types of agents, household, firm and government, we discuss the relationship pattern and micro rules of various kinds of agents in WEF production and consumption, and then establish the Netlogo simulation model of urban consumption. Based on the interaction between social environment and multi-intelligent system, this model forms the simulation of WEF consumption distribution in the city, and simulates the interaction of various agents with the evolution of time, which facilitates research on the relationship between individual behavior at the micro level and macro model. However, we have just proposed a framework for agent analysis in urban WEF consumption in this paper, while further discussions on this agent model using empirical data are of great important, especially on supply and demand of WEF in a specific city, the distribution of agents and their resource consumption patterns.

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