A study on China's "silver economy" based on SHAP interpretability modeling

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Abstract. This paper aims to explore the development models of China's provincial silver economy, identify their core influencing factors and interaction effects, so as to provide a basis for formulating targeted policies. To achieve this goal, it selects the panel data related to the silver economy from 2014 to 2023 in 31 provinces, municipalities and autonomous regions across the country, constructs a measurement index system including population structure, uses the EWM-CRITIC coupled weight system to measure the development level of the provincial silver economy, divides three types of models through spectral clustering and analyzes their characteristics and causes, and then uses random forests and SHAP method in explainable machine learning to identify the influencing factors and interaction effects. The results show that the provincial silver economy can be summarized into three types of models: high population structure-high consumption capacity type, low consumption capacity-medium pension security type, and low population structure-low elderly service resources type. Pension security and elderly service resources are the core influencing factors of the silver economic development model, and the population structure and consumption capacity constitute the demand base, and policy subsidies play a regulating role. The research innovation combines EWM and CRITIC methods to determine weights, and uses SHAP algorithm to analyze nonlinear effects and interaction effects, which can provide a basis for local governments to formulate policies, enterprises to tap potential, and the elderly to enhance consumer confidence.

Keywords: Silver Economics, EWM-CRITIC coupled weight system, Spectral Clustering, SHAP.

1. Introduction

The silver economy, as an important practical area in addressing population aging, has garnered significant academic attention. Wang Yongmei et al.(2024)[1] verified through a double difference model that China's pilot reforms of home and community-based elderly care services exhibit a high level of family spillover effects. Liu Huijun et al. (2025)[2], after constructing indicators for healthy aging services, pointed out notable inter-provincial differences in the effectiveness of these services, revealing a spatial distribution pattern where the eastern region is high, the western region is low, and the central region is collapsed. Zeng Xiaoqi et al.(2024)[3] utilized PIO data and a series of machine learning algorithms for comparison and employed the SHAP algorithm to predict the spatial layout of silver elderly care enterprise service facilities in Hangzhou. Fan Yun et al.(2024)[4] employed the KANO model to explore the service quality of the chain-based elderly care service model in Nantong City within the context of the silver economy, identifying key points for service improvement. Qiu Wenwen et al.(2024)[5] verified through a moderating effect model that the development of the silver economy has a significant positive moderating effect on the consumption of the elderly population promoted by the digital economy.

This study constructs an EWM-CRITIC (Entropy Weight Method-Criteria Importance Through Intercriteria Correlation, abbreviated as EWM-CRITIC, the same below) coupled weight system. Through the organic combination of EWM and CRITIC methods, it preliminarily measures indicators for multi-dimensional quantitative evaluation of the development level of the silver economy, providing a supplementary approach for academic research on measuring the development level of the silver economy. By utilizing spectral clustering technology to depict different provincial and municipal profiles, and adopting the SHAP (Shapley Additive Explanations, abbreviated as SHAP, the same below) algorithm in random forest and interpretable machine learning to identify silver economy models, this study preliminarily reveals the differences in the development of the silver economy across provinces in China from a comparative static perspective. It provides an exploratory reference framework for formulating policies tailored to local conditions for the national silver economy.(Data source: official website of the National Bureau of Statistics, www.stats.gov.cn)

2. Measurement of silver economy indicators

2.1. Construction of indicator system

The measurement scope and indicator selection for the silver economy are flexible and diverse, and different understandings of its connotation give rise to various research methods. Population structure serves as an important foundation for the scale of demand in the silver economy; consumption capacity reflects the spending power and propensity of the silver population; pension security is a crucial issue in ensuring a happy old age for the people and constitutes the backbone for the stable operation of the silver economy; the allocation of elderly service resources determines the service supply capacity of the silver economy; and policy subsidies for the elderly population, such as senior citizen subsidies and nursing care subsidies, are an important component of the social pension service system, directly affecting the accessibility of silver economy-related services. Based on this, this paper divides the target layer of the silver economy indicator system into five dimensions: population structure, consumption capacity, pension security, elderly service resources, and policy subsidies. It constructs a silver economy measurement indicator system that includes primary and secondary indicators, comprehensively covering key factors of the silver economy. Specific indicators are shown in Table 1.

Table 1: Silver Economy Indicator System

Target layer	Primary indicator	Secondary indicator	Code	Attribute
Silver Economics	Population Structure A	The number of people aged 65 and above	A1	+
		Dependency ratio of elderly population	A2	-
		The average number of years of education for the elderly	A3	+
	Consumption Capacity B	Per capita GDP	B1	+
		Per capita disposable income	B2	+
		Engel's coefficient	B3	-
		Per capita consumption expenditure	B4	+
	Pension Security C	Number of retired personnel participating in pension insurance	C1	+
		Number of in-service employees participating in pension insurance	C2	+
		Number of urban employees participating in pension insurance	C3	+
		Number of insured individuals in the social endowment insurance program for urban and rural resident	C4	+
		Expenditure/income of basic endowment insurance fund	C5	-
	Elderly Service Resources D	Number of medical and health institutions	D1	+
		Number of medical and health institutions	D2	+
		Number of medical and health institutions	D3	+
		Number of elderly care beds in the community	D4	+

Policy Subsidy E	Number of elderly people receiving old-age subsidies	E1	+
	Number of elderly people receiving nursing subsidies	E2	+
	Number of elderly people receiving subsidies for elderly care services	E3	+

EWM is an objective evaluation method based on information entropy. The CRITIC method, when calculating weights, comprehensively considers the comparative strength and conflictiveness of evaluation indicators, and can better measure the distribution of criterion weights. This paper combines these two methods to take into account the variability, dispersion, and correlation of indicator data[6], resulting in a combined weight:

$$Wj = \frac{W1j \cdot W2j}{\sum_{j=1}^{m} W1j \cdot W2j} \tag{1}$$

Where $W1_j$ and $W2_j$ represent the weights of the j-th indicator obtained based on the EWM method and the CRITIC method, respectively.

The results of the combined weights show that E (policy subsidies) has a total weight of 0.358, which is the highest weight among the first-level indicators, reflecting the key driving role and core position of policy subsidies in the silver economy. B (consumption capacity) has a total weight of 0.262, which is second only to policy subsidies in importance. The combined weights of C (pension security) and D (elderly service resources) follow closely behind, while A (population structure) has the smallest combined weight.

3. Economic development model of silver industry in each province

3.1. Spectral clustering modeling

Spectral clustering is a clustering method based on graph theory. It transforms data points into nodes of a graph, with edge weights representing similarity, and utilizes the eigenvectors of the Laplacian matrix for dimensionality reduction or direct clustering[7]. Spectral clustering excels at handling nonlinear data structures and performs well on clusters with complex shapes, making it suitable for high-dimensional and non-convex data.

Based on the EWM-CRITIC coupled weight model, the weights of various indicators are determined to measure the annual development level of silver economy in Chinese provinces. As shown in Table 2, the spectral clustering results obtained from 310 samples are presented.

Table 2 Spectral clustering results

Category	Spectral clustering result
Category 1	Shanxi Province, Liaoning Province, Jilin Province, Heilongjiang Province, Fujian Province, Jiangxi Province, Guangxi Zhuang Autonomous Region, Chongqing, Guizhou Province, Yunnan Province, Shaanxi Province, Gansu Province
Category 2	Beijing, Tianjin, Shanghai, Inner Mongolia Autonomous Region, Hainan Province, Tibet Autonomous Region, Qinghai Province ,Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region
Category 3	Hebei Province, Jiangsu Province, Zhejiang Province, Anhui Province, Shandong Province, Henan Province, Hubei Province, Hunan Province, Guangdong Province, Sichuan Province

3.2. Silver economy model

Table 3 presents three types of silver economy development models along with the average values of each indicator. For ease of explanation of the silver economy models, high development level is defined as "H" , medium development level as "M", and low development level as "L"[8]. Population structure is defined as "P" , consumption capacity as "C", pension security as "S", and elderly service resources as "R".

Table 3 Mean values of indicators for three types of silver economy

Type	Population Structure	Consumption Capacity	Pension Security	Elderly Service Resources	Policy Subsidy
LC-MS	0.277	-0.448	-0.172	-0.255	-0.391
LP-LR	-1.035	0.473	-1.071	-1.019	-0.473
HP-HC	1.263	0.112	1.170	1.223	0.896

(1) Low consumption capacity-medium-level pension security (LC-MS) silver economy.

Represented by 12 provinces like Shanxi and Liaoning, it features below-average consumption capacity and weak market vitality. For instance, Shanxi's 2023 per capita GDP was 74,000 yuan, lower than the national 89,400 yuan. Local governments invest moderately in basic pension insurance, with security levels ranking mid-national.

(2) Low population structure-low elderly service resource (LP-LR) silver economy.

Divided into two categories by economic development:Super cities (Beijing, Shanghai, Tianjin) with strong economies attract young migrants, leading to low aging, small elderly populations, weak demand for elderly care, and slow market expansion.Underdeveloped border provinces (Tibet, Qinghai, etc.) lag in aging due to small total population and harsh geography, with scarce elderly care resources. Tibet, for example, had 3.66 million permanent residents in 2022, and its vast, sparsely populated land hinders centralized resource allocation.

Both share low elderly care resource allocation: the former due to "inbound rejuvenation" and low demand; the latter due to "endogenous rejuvenation" and insufficient supply.

(3) High population structure-high consumption capability (HP-HC) silver economy

Typified by 10 provinces including Shandong and Jiangsu, showing "double high" traits. It has large populations with aging degrees above the national average, and strong consumption capacity. Zhejiang's 2023 per capita disposable income (68,308 yuan) and consumption expenditure (42,163 yuan) far exceeded the national averages (39,218 yuan; 26,796 yuan), boosting elderly spending on health and entertainment.

4. Recognition of development patterns based on SHAP

4.1. Random forest and feature importance

Let the original dataset be denoted as $D=\{(x_i, y_i)\}_{i=1}^{N}$, where $x_i \in R^5$ is a vector consisting of 5 primary indicators, and $y_i \in \{C_0, C_1, C_2\}$ is the discrete category label generated by spectral clustering, where cluster 0 represents LC-MS type silver economy, cluster 1 represents LP-LR type silver economy, and cluster 2 represents HP-HC type silver economy. The dataset is divided into a training set and a test set in a ratio of 7:3. The random forest classification model exhibits excellent classification performance in this experiment: as shown in Figure 1, the model can completely distinguish between category 1 and category 2 in the spectral clustering results, with only very slight misclassification of category 0.

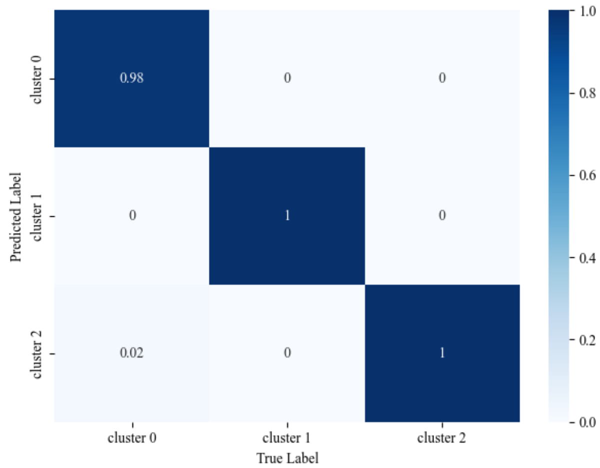

Figure 1 Normalized confusion matrix

Feature1 importance analysis reveals the extent to which each variable influences the classification results. In this study, we utilize the random forest model to assess the five primary indicators that affect the spectral clustering results. The feature importance results are as follows: pension security is the most crucial feature, playing a dominant role in the classification results; elderly service resources come next, followed by population structure, and consumption ability,policy subsidies, with their importance decreasing in that order.

4.2. Interpretability results based on SHAP

(1) SHAP modeling

However, the feature importance obtained from random forests cannot precisely indicate whether a larger or smaller value of a feature has a positive or negative impact on model predictions. Therefore, to further reveal the complex nonlinear relationships between feature variables, we introduce the SHAP algorithm to analyze the direction of influence of feature variables and the interpretability of samples[9].

The core idea of the SHAP algorithm originates from the Shapley value in cooperative game theory, cleverly integrating the classic Shapley value theory in game theory with the optimal credit allocation principle in local interpretation. In this scenario, each primary indicator is equivalent to a feature value, and the SHAP value measures the contribution of the feature to the spectral clustering result. The contribution degree is calculated by the following formula[10]:

$$\phi_f^{(k)}(x) = \sum_{S \subseteq F \setminus \{f\}} \frac{|S|!(|F|-|S|-1)!}{|F|!}\left[E(pk \mid S \cup f) - E(pk \mid S)\right] \tag{2}$$

Where F is the full set of features, S is a subset of features, and $E(p_k \mid S)$ represents the conditional expectation prediction probability based on S.

(2) Distribution of SHAP values

Using the SHAP algorithm, we analyzed the impact of various features in the random forest algorithm on the results of three types of spectral clustering. Due to the similar distribution of SHAP values across the three types of results, and due to space limitations, we only present the distribution of SHAP values for category 2 as shown in Figure 2.

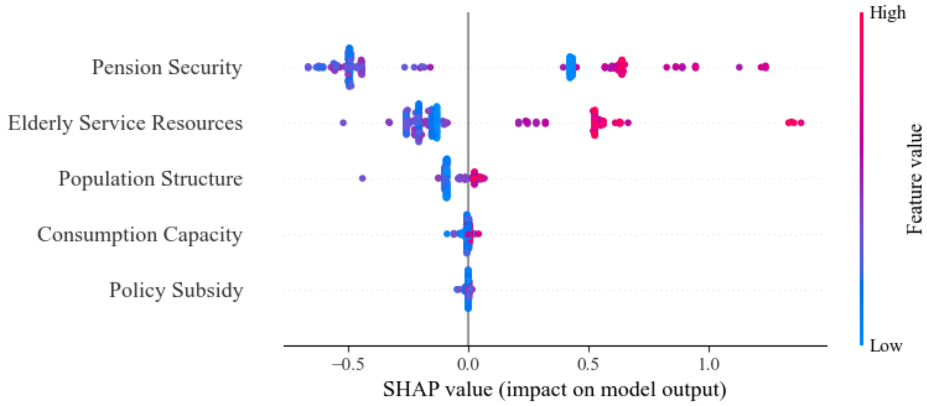

Figure 2 Distribution of SHAP values

Among the three characteristics of pension security, elderly service resources, and population structure, there is a significant correlation between their levels and the resulting output effects: higher levels of these characteristics usually have a positive effect, while lower levels tend to trigger a negative effect. For example, a high level of pension security significantly promotes the formation of the HP-HC type, while a low level tends to lead to the LC-MS or LP-LR type Although there are a few special cases where the level of a characteristic is contrary to the direction of the effect, the overall mechanism of action follows the following pattern: the positive effect increases with the increase in the level of the characteristic, while the negative effect decreases with the increase in the level of the characteristic, and the intensity of the negative effect in the low-level state is significantly higher than the intensity of the positive effect in the high-level state.

The logic of the effects of policy subsidies and consumption capacity follows the same pattern: they exhibit a positive effect at high levels and a negative effect at low levels, with occasional instances of reverse effects. However, they differ significantly from the first three characteristics: their overall impact is significantly less pronounced than the former three, and the intensity of positive and negative effects tends to be more balanced.

(3) Interactive effects of various features

As shown in Figure 3, the interaction strengths of the five features exhibit significant differences: the self-interaction strengths of pension security (self-interaction 0.23) and elderly service resources (self-interaction 0.17) are significantly higher than those of other features.

Figure 3 Heatmap of SHAP interaction strength among features

Based on the differences in the interaction intensity of the aforementioned characteristics, the following analysis focuses on the interaction effects between pension security and elderly service resources, aiming to clarify the potential correlation mechanism between the two in the process of interaction.

As shown in Figure 4, when the level of pension security is low, it has a strong negative impact on elderly service resources. As the level of pension security increases, its negative impact on elderly service resources weakens, and its positive impact strengthens. This is consistent with the situation in real life where insufficient pension security can limit investment in elderly care services, leading to prominent issues such as a shortage of beds in elderly care institutions and a lack of professional nursing staff, making it difficult to meet the needs of the elderly.

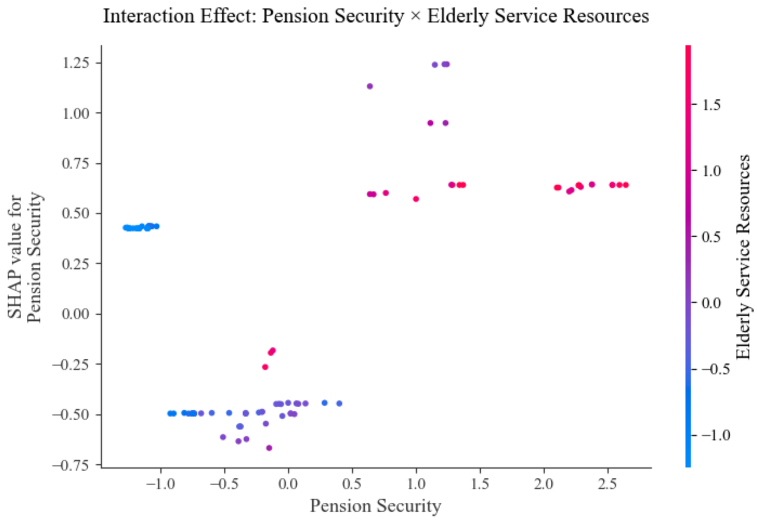

Figure 4 Interaction effect diagram

5. Conclusions

This study has constructed an evaluation index system for the silver economy, encompassing five dimensions.Through the EWM-CRITIC coupled weight method, it was quantitatively found that policy subsidies (0.358), consumption capacity (0.262), and elderly service resources (0.192) ranked the top three in terms of weight.

Based on spectral clustering technology, the study divides China's provincial silver economy into three differentiated models: HP-HC (High Population Structure-High Consumption Ability) type, represented by Shandong, Jiangsu, etc., with a large elderly population and high consumption ability; LC-MS (Low Consumption Ability-Medium Pension Security) type, typified by Shanxi, Liaoning, etc., facing the contradiction of "getting old before becoming rich" and with medium-level pension security; LP-LR (Low Population Structure-Low Elderly Service Resources) type, covering two types of regions: one is super-large cities such as Beijing and Shanghai and border provinces such as Tibet and Qinghai.

Based on the interpretable analysis of impact mechanisms using SHAP, pension security and elderly service resources are the core influencing factors, which positively interact with each other. Population structure and consumption capacity constitute the demand foundation, while policy subsidies play a moderating role. This study provides quantitative support and a model analysis framework for the formulation of differentiated policies for the silver economy at the provincial level, facilitating the transformation of aging pressure into development momentum.

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