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*Review*

# Structural path analysis and its applications: literature review

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**Abstract:** In the context of the global value chains and international trade rapid development, the links among different countries have become closer and more complex. The differences in the role of trade in economic, energy, and environmental formation in different countries, sectors, or different regions and sectors within the same country are becoming increasingly apparent. Structural path analysis (SPA) is an important method to study the transfer influence and path relationship between different factors in the production supply chain. This article mainly summarizes and analyzes the literature on the application of SPA in economy, environment and energy. First, introducing briefly the concept, model and application of SPA. Second, specifically analyze and summary the main application scope and field of SPA. Based on the summary of the literature, the following prospects are proposed for subsequent research: use SPA to explore the formation path of added value; Extend the single-region SPA model to a multi-region form to study the path of economic, environmental and energy formation and the impact of different factors on the global perspective; combine with a trade spillover model to analyze trade spillover effects of economic, environmental and energy.

**Keywords:** structural path analysis; economic development; environment; carbon emissions; energy

**JEL Codes:** Q56, P18, F64

## 1. Introduction

Structural path analysis (SPA) is a technology based on consumer accounts that breaks analysis indicators into the sum of an unlimited number of production chains (or paths), and can be used to analyze the contribution rate of different paths. In economics, it is mainly used to describe the complexity of the economy, and in the energy environment, it is mainly used to analyze the path of

different influencing factors. SPA was first proposed by Defouny, Thorbecke, and Crama in 1984. Wood & Lenzen (2003) described it as "using the series to extend Leontief's inverse". Sonis & Hewings (1998), Aroche-Reyes (2003) and Ferreira et al. (2007) considered that SPA extracts inter-industry relationships and sectors similarities to aggregate sectors to analyze the role of different industries and sectors on different paths. Muñiz (2013) believed that SPA can decompose the major upstream impacts of products or organizations hierarchically, and identify different production chains.

With the development of input-output technology, the combination of SPA and input-output technology has been widely promoted. First, SPA is applied to economic analysis and input-output databases comparison. Secondly, it is applied to the environment and energy fields, mainly used to explore the emission paths of carbon dioxide and other pollutants, the flow path of energy, and has gradually expanded from the national level to the provincial and departmental levels within the country, thereby making the results more detailed. At present, SPA has been extended to many fields. Many scholars use SPA or combine SPA with other methods (such as: SDA, input-output (IO), etc.) to study different problems.

The SPA method has the following advantages when analyzing economic and environmental issues: SPA analysis can consider the relationship between upstream and downstream in production activities, and then can clarify the impact path of different factors on the economy and the environment. It provides new ideas for exploring economic and environmental issues, and provides more specific inspiration for making policy measures.

This article mainly reviews the relevant literature on the application of SPA, and provides a systematic framework for researchers to understand the function, application conditions and application fields of SPA, and provides some useful inspiration for scholars using this method for subsequent research. According to the existing literature, it can be found that the SPA application mainly includes three aspects: economic, environmental and energy analysis. Therefore, this article will conduct a detailed review based on these three aspects.

## 2. Application of SPA in economic analysis

The development of global value chains has made the vertical specialization more sophisticated, and the links between different countries have become increasingly tighter and more complicated, which has led to the world's economic development becoming more complicated. In order to explore the relationships and influence paths between different economies and within the same economy, some scholars use SPA to analyze them. The model is as follows:

In the input-output analysis, Leontief inverse is $(I-A)^{-1}$, and its expansion can be obtained on Taylor formula:

$$(I-A)^{-1} = I + A + A^2 + A^3 + \ldots \tag{1}$$

where $I$ is the identity matrix; $A$ is the direct consumption coefficient matrix.

Therefore, the row-balance relationship of input-output can be transformed into the following form:

$$X = (I - A)^{-1} Y$$

$$= (I + A + A^2 + A^3 + ...) Y \quad (2)$$

where $IY$ represents the impact of self-demand on the total output ( $X$ ) at 0th layer (layer is the path in the SPA); $AY$ represents the demand at the 1st layer, that is, the impact of direct final demand on total output ( $X$ ); $A^2Y$ represents the impact of final demand through an intermediate country transmission on total output, for example, the demand of country C for country B comes from country B's imports from country A, that is, the impact of country C's demand on country A through Country B's transmission on country A's total output, namely A→B→C. With the increase of layer, it means that the influence on the total output of a country is transmitted through more intermediate countries.

Defourny & Thorbecke (1984), Sonis & Hewings (1998) applied SPA to the social accounting matrix to analyze the influence and transfer path of complex economic networks. They believed that the results of SPA analysis can help policy makers and analysts understand the channels of macroeconomic communication to improve the quality of policy decisions. Thorbecke (2017) used SPA to analyze social accounting accounts. Sonis et al. (1997) applied SPA to economic research in Indonesia, and found that information, technology, and culture played an important role in the spread of international economic networks. Ngandu et al. (2010) used SPA to analyze the impact path of South Africa's economic policies, and found that the construction industry has a greater impact on the economy, and affects other sectors' economic activities through direct and indirect links with the infrastructure sector. And in production activities, commercial services, non-metal products, mining and metal products are the main sectors where economic policy comes into play. Based on data from 2002 and 2009, Gunluk-Senesen et al. (2018) analyze the path of Turkish labor force and import intermediate input demand by using SPA. Castaño et al. (2019) explored the impact of Chilean mining supply chain links on other economic activities in Chile by SPA, they found that the path of mining activities affecting other economic sectors is limited. Itoh (2016) evaluated the impact of Japanese national and regional government actions on the economy by SPA. The results showed that there are differences in the impact paths of local government expenditure on regional income.

The above results show that SPA can be used to analyze economic complexity, explore the interaction paths between different sectors, and provide more information for making, managing, and effectiveness testing of economic policy.

## 3. Application of SPA in environment analysis

Due to the increasingly severe global environmental situation, environmental pressures faced by countries are increasing. In order to solve environmental problems, countries around the world are actively exploring the reasons behind environmental problems, the influence paths of various factors, and countermeasures. With the development of economy and science and technology, environmental issues have become more complicated. Exploring their causes and impact paths have become an important prerequisite for making relevant policies. Many literatures use SPA, or combine SPA with other methods, to analyze ecological footprints and the formation and impact paths of carbon emissions, PM2.5, and other emissions in the global, national, or industry-level.

When using SPA to analyze environmental problems, the formula (2) is transformed into the following form:

$$E = e\left(I - A\right)^{-1} Y$$

$$= e\left(I + A + A^2 + A^3 + ...\right)Y \quad (3)$$

where $E$ is the environmental variable (e.g., carbon or sulfur emissions); $e$ is an environmental coefficient (for example, the ratio of a country's or sector's carbon or sulfur emissions to total output). $eIY$ represents the impact of the 0th layer on environmental variables, that is, the impact of the country's own demands on the environment; $eAY$ represents the impact of the 1st layer on environmental variables, that is, the impact of direct final demand on a country's environment; $eA^2Y$ represents the impact of the 2nd layer on environmental variables, that is, the impact on the environment caused by transmission through an intermediate country. A higher layer indicates the impact on the environment through more countries' transmission. There are many aspects of environmental problems, such as the quality of the ecological environment, carbon dioxide, sulfur dioxide, and other pollutants, etc. Therefore, SPA has been applied in the analysis of the above content.

Ecological footprint is an important indicator for evaluating ecological environment governance. It can not only compare the environmental development quality of different countries, regions, or industries, but also reveal its sustainable development capabilities. Because economic development has a large impact on the environment, the internal and external trade relations of a country make a spatial impact on the ecological footprint. Therefore, analyzing the formation and change path of ecological footprint is a prerequisite for grasping its causes. Using SPA to analyze the ecological footprint, ecological network, and sustainable development, the results can explore the ecological development network and ecological economic relations from the impact path of the ecological footprint. Wood & Lenzen (2003) used SPA to analyze the ecological footprint and measure the ecological sustainability. The results show that the higher-order layer has a greater impact on the ecological footprint. Lenzen (2007) used SPA technology to measure the flow of ecological and eco-economic networks, and found that the total flow of the ecosystem network was mainly concentrated on a limited number of paths. Mattila (2012) used SPA to analyze the ecological footprint and economic structure of the Netherlands, and found that the overall economic and ecological efficiency of the Netherlands had improved from 2002 to 2005, especially in sawmill processing and electricity production. In addition, there are differences between the ecological footprint and the economic formation path. The biggest impact on the ecological footprint is the consumption of wood, food, electricity, and the demand for intermediate products in the construction industry. The economic formation path is short, and most of them are located before the final product is consumed. Wilting & van (2017) used SPA to analyze the biodiversity path in the Netherlands, and found that the impact of the food and chemical industries on biodiversity is mainly caused by upstream direct suppliers. The above research results show that the improvement of ecological efficiency should focus on the first several paths of ecological footprint formation and upstream sectors' role.

Carbon dioxide is the main source of greenhouse gases and the main product of production activities. Because carbon dioxide is mainly caused by product production, processing and demand, what's more, the links between different products are more complicated, many scholars use SPA to study the path of carbon emissions. Some scholars have shown that carbon emissions are high in sectors such as construction, power and chemical industries, metal minerals, and non-metallic minerals (Acquaye et al., 2011; Yang et al., 2015; Liang et al., 2016; Wang et al., 2017; Liang et al., 2017; Peng et al., 2018; Tian et al., 2018). Yang et al. (2015) used SPA to analyze the carbon emission paths of

different demand categories, such as household consumption, government consumption, investment, and exports. They found that urban carbon emissions are higher than that in rural areas. Therefore, the emission reduction policy should be based on cities. In addition, reducing unreasonable demand for electricity and chemical products will help reduce carbon emissions. Based on global multi-region input-output tables and related energy data, Peng et al. (2018) used SPA to determine the key supply chain paths that affect carbon emissions of the Chinese steel industry, and analyze the impact of different final demand categories and input-output relations between industries on industry carbon emissions. They found that construction industry, electrical appliances, and optical equipment caused a large amount of carbon emissions in the steel sector through consumer demand for the steel sector. Peters & Hertwich (2006) used SPA to determine the connection between consumption and production, and calculated the emission paths of sulfur dioxide, nitrides and other substances, and found that indirect economic demand is an important factor affecting the environment. Owen et al. (2016) used SPA to compare the differences in the embodied carbon emission paths of value chains in different databases, and founded that the differences in the paths between databases can be used to trace the information of carbon emission sources. Tian et al. (2018) used SPA to analyze carbon emission path of China's manufacturing industry, and found that at the high layer, the carbon emissions from the paths started by the metal smelting and rolling, power and steam production sectors are higher. In addition, carbon emissions from chemical and non-metallic mineral product manufacturing sectors are mainly caused by export demand increasing.

Lenzen & Murray (2010) used SPA to analyze carbon emissions paths in Australia and the United States, and found that the downstream carbon footprint is not as obvious as the upstream footprint; and there are significant differences in SPA thresholds in different industries. Therefore, when analyzing the carbon emission paths of different industries, we need to consider different numbers of paths. Based on Japan's 1990–2000 data, Oshita (2012) used SPA to explore the relationship between changes in aggregate demand and changes in key carbon emission paths, and found that changes in final demand can change carbon emissions, for example, Declining household demand for fish has contributed to reducing carbon emissions from marine fisheries. And believed that the increase in demand for the power service is an important reason for the increase in total carbon emissions. Wang et al. (2018) used input-output analysis and SPA to research the supply chain network of the Beijing-Tianjin-Hebei in 2010 and 2012 to identify the direction of emissions from the carbon-emission-driven sectors to the key economic sectors and the maximum carbon emissions flows in these key directions. They found that inter-regional linkages played an active role in the carbon emissions network, especially, Beijing has closer ties with other regions. Gui et al. (2014) used SPA to analyze the inter-departmental carbon emission path, and found that the supply paths with the highest carbon emissions are "chemical industry→export", "metal processing→export", "non-metal production→fixed capital", and "metal Processing→Fixed Capital". In addition, "metal processing→manufacturing→export" and "metal processing→ manufacturing→ fixed capital" are the paths with the highest carbon emissions in the three-sector supply chain. Based on global multi-region input-output tables, Kanemoto et al. (2014) used SPA to compare carbon emission paths between developed and developing countries, and found that carbon emissions in developed countries have increased, and the path of the fastest increase in embodied carbon emissions is mainly from countries outside the countries that have signed the Annex B to the Kyoto Protocol. Li et al. (2018) used SPA to analyze India's carbon emissions path. The results show that investment and household consumption are the main sources of carbon emissions in India's industries, so further reduction of

carbon emissions cannot be focused only on energy-intensive industries. Shao et al. (2018) used SPA to analyze the carbon emission path of different provinces in China, and found that imports and exports in most parts of China have a greater impact on carbon emissions, and they mainly function through the 1st layer. Huang et al. (2009) used SPA to analyze the 20 pathways with higher carbon emissions from crude oil and natural gas in Australia and the United States, and found that some sources with higher carbon emissions may exist in their upstream sectors.

The results of the carbon emission path research through SPA can be found that the sectors that affect carbon emissions are mainly industrial sectors. Embodied carbon emissions from import and export trade are an important reason for carbon emissions transfer. Among them, the embodied carbon emissions of developed countries are relatively high. Interregional links also plays an important role in carbon emissions networks. Therefore, reducing carbon emissions must not only focus on energy-intensive industries, but also on the impact of the linkages between upstream and downstream industries.

In addition to carbon dioxide, some other pollutants have a greater impact on the economy and the environment, such as sulfur dioxide and PM2.5. Sulfur dioxide is the main substance that causes acid rain and has a strong corrosive effect on crops and buildings. PM2.5 is the main cause of smog, which is more harmful to social and economic development and human health. Therefore, it is of great practical significance to analyze the discharge paths of these pollutants and make more efficient management measures. Yang et al. (2018) used SPA to study the sulfur dioxide emission path of 28 sectors in China, and found that the power and thermal production are the main sectors for sulfur dioxide emissions from production side, while the construction industry has the highest emissions from demand side. Due to demand increase for metal products in construction and manufacturing, sulfur dioxide emissions from the metal sector increased from 15% in 2002 to 22% in 2012. Meng et al. (2015) used SPA to analyze China's PM2.5 emission path, and found that the path of the power and transportation is mainly at the 0th layer, while the path of construction and service sector are mainly at higher layer. The above results are instructive for understanding the path of sulfur dioxide and PM2.5, and also provide some inspiration for the follow-up research.

The above literature uses SPA to study global, national or sector carbon emissions, PM2.5, sulfur dioxide, etc. The results show that the impact of different paths on the environment is quite different. Among them, the upstream and downstream industrial links have the most significant impact on environmental pollutant emissions, and their impact paths are mainly on the first few layers. Therefore, to improve the ecological environment, attention should be paid to the role of the upstream sector and the heavy industry sector on the low-level path.

## 4. Application of SPA in energy analysis

Energy plays an important role in social and economic development, but economic development has led to an increase in energy demand. The growth rate of world energy demand continues to increase. In 2018, world energy demand increased by 2.3%, the fastest growth in recent decades. Due to development models differences in different countries and industries, energy demand also varies widely. Therefore, many scholars use SPA to explore the energy demand path from the national and industry levels.

When SPA is applied to analyze energy problems, formula (2) can be transformed into the following form:

$$Ey = f\left(I - A\right)^{-1} Y$$

$$= f\left(I + A + A^2 + A^3 + ...\right)Y \quad (4)$$

where $Ey$ is the energy, that is, the energy consumption of a country; $f$ is the energy consumption coefficient, which is the ratio of a country's energy consumption to its total output. $fIY$ represents the impact of the 0th layer on energy, that is, the impact of the country's own demand on energy consumption; $fAY$ represents the impact of the 1st layer on energy, that is, the impact of direct final demand on a country's energy consumption; $fA^2Y$ represents the impact of the 2nd layer on energy, that is, the impact on energy consumption caused by transmission through an intermediate country. A higher layer indicates the impact on energy consumption through more countries' transmission.

Each sectors' development has different degrees of energy demand, especially the energy demand of the production and processing sector is high. However, there are differences in energy demand and consumption paths between different sectors. Some sectors are direct energy demand sectors; some sectors are indirect energy demand sectors, that is, their energy demand is mainly caused by upstream sectors. Embodied energy driven by import and export demand is also an important reason for affecting energy demand and flow. Therefore, some scholars use SPA to explore the energy path. Wang et al. (2019) investigated the flow of natural resources in China's economy from raw material mining to final production. They used SPA and intermediary methods to identify key departments in different locations in the supply chain, distinguish the importance of the same department at different locations, and find out the key supply chain paths for natural resource consumption. It was found that the most critical resource supply path came from the mining sector and the construction industry was the end sector; the dematerialized key supply path originated from the non-metallic mineral product sector and ended in the construction sector. Qu et al. (2017), Zhang et al. (2018) used SPA to analyze China's energy path and found that the embodied energy of manufacturing, construction, and service industries is high. Based on Australian input-output data from 1986 to 1987, Treloar (1997) combined SPA and process analysis to determine the most important embodied energy paths in the residential construction industry. The results show that the 1st and 2nd layers have higher embodied energy to the construction industry. Based on multi-regional input-output analysis, SPA, and LCA models, Hong et al. (2018) explained the embodied energy indicators at the level of computing technology differences and regional characteristics, and proposed a framework using computing modules and data sources. According to the analysis of the embodied energy path of Chinese construction industry, it is found that energy production and services of the upstream sector on the higher layer occupy a higher proportion of the construction industry total energy consumption. Zhang et al. (2017) used SPA to explore China's energy path and found that the embodied energy of China's exports accounted for about a quarter of the country's total supply; manufacturing, construction, service, power , and thermal sector have a greater impact on energy; and believed that analyzing downstream responsibilities will help improve energy conditions. Some scholars also analyze the impact of industry development status on related resources from the specific industries perspective. For example, Seung (2016) used the Interregional Structural Path Analysis (IRSPA) to study the impact paths of Alaska fishery transmission on the initial impact of seafood. It shows that the service industry and imported goods have a greater impact on fisheries. The above studies analyze the industries and key paths that affect energy demand and consumption, and has guiding significance for formulating future energy conservation measures.

Energy demand and consumption are closely related to economic development, and then analyzing the energy intensity, that is, the ratio of energy demand to value added, can help to understand the interaction between the economy and energy. Hong et al. (2016) used SPA to analyze the energy intensity path of the Chinese construction industry and found that direct energy input (the 1st layer) and on-site construction (the 0th layer) consumed about 50% energy supply; On the SPA path, the first two layers contain more than 50% information, which is the main path for analyzing the construction industry energy intensity. In addition, non-metallic minerals, metal smelting, and rolling processing sector have a greater impact on the construction industry energy intensity.

According to the above research, different sectors have different levels of demand for energy, and the production and processing sector has a higher demand for energy. But there are differences in energy demand and consumption paths in different sectors, and the level of the paths is also an important factor affecting energy consumption. Therefore, controlling energy demand needs to make corresponding policies based on the role of different departments on different paths and the contribution of different paths to energy needs, to improve the accuracy and efficiency of the policy.

## 5. Application of SPA in substance supply chain analysis

The material supply chain can not only describe the production demand connection between the upstream and downstream sectors, but also reflect the transmission paths of different substances in different industries or regions. Among them, energy, water, land, and pollutants are the main substances in the supply chain of production activities. Some scholars have used SPA to conduct related research on the conduction paths of the above substances. Oshita et al. (2014) used SPA to analyze the flow paths of agricultural, forestry, animal husbandry, and fishery products in Japan, and found that rice, potatoes, sweet potatoes, vegetables, and fruits were supplied to consumers directly or through one step processing, while sugar crops and logs passed through more processed to supply consumers. Owen et al. (2018) analyzed the key supply chains of energy, water and food in the UK according to SPA. The results show that the 0th layer has the most impact on energy and labor, and the 1st layer has the most impact on food and water. Lenzen (2003) used SPA to analyze the relationship between energy, land, water, greenhouse gas of Australian and industrial sectors. It found that the primary industries, such as grazing and mining, have strong forward links; the secondary industry, such as meat and dairy products, finance and textiles, have strong backward links. On different paths, the 0th layer has the largest impact, followed by the 1st and 2nd layers. In addition, much of the environmental and energy pressures come into play along the export path of final demand. Lenzen (2002) used SPA to analyze the input paths of energy, land, water, greenhouse gases and other substances in the Australian industrial sector, and found that the 2nd and 3rd layers are important paths for material conversion. The above results show that there are large differences in the production demand paths of different sectors for different substances. Among them, the industrial sector has the most obvious impact on environmental substances, while the agricultural sector influences material conversion mainly on the 0th layer.

The earth's water resources are relatively abundant, but the water resources available to humans are relatively small, and the global water shortage situation is becoming increasingly severe. Therefore, some scholars have applied SPA to explore water resources issues. Based on expanded standard input-output table of the water resources sector account, Wu et al. (2018) took Heihe River Basin of China's Zhangye city as an example, and used SPA to identify key water sectors. It found

that higher water consumption was the furniture, wood processing and handmade industries, followed by the food and tobacco industries. According to the input-output table of U.S in 2002, Mo et al. (2011) combined a mixed input-output analysis with SPA to analyze the impact path of the groundwater supply system in Michigan and the surface water supply system in Florida on water supply energy. Llop & Ponce-Alifonso (2015) used SPA to analyze water resource paths and consider the impact of different final demand categories. It found that the water responsibility of a sector is affected by different sectors in upstream and downstream. In addition, the final demand category of the sector is also affected the sector's water demand. The above studies show that industrial and agricultural water consumption is high, and the connection between upstream and downstream is an important reason affecting water demand and flow. The results have implications for the formulation of water conservation management measures.

## 6. Conclusions and prospects

As the SPA is proposed and developed, this method has been introduced and applied in more literatures. This paper systematically sorts and summarizes the related literatures. It can be found that the main application areas of SPA can be divided into three aspects. First, the economic field, including the analysis of economic networks and paths, and regional economic links. Second, the environmental field, including ecological footprint, carbon dioxide, PM2.5 and other pollutant emissions research. Third, the energy field, including the total resources, specific resources (such as: water) demand and flow path research. By using SPA model, it is possible to explore the flow paths of different factors, the paths of interaction between upstream and downstream departments, and find the path that plays a key role, and then provide more accurate information for the formulation of related policies.

According to the literature review in this article, the future research of SPA can be prospected in the following aspects. First, the single-country model can be extended to a multi-country model, which can be based on the perspective of the global value chain to analyze the impact of trade links between different countries on the economy, energy and environment, and explore the role of different countries in global economic, energy, environmental development and change paths. Second, under the global multi-region model, the role played by different sectors in different countries on different flow paths can be analyzed at the sector level. To provide more new information to identify the energy and environmental responsibilities of different countries and their contribution to global economic development. Third, the SPA model is applied to the analysis of value-added formation, exploring the formation and proportion of value-added on different paths to identify the impact of different paths on value-added formation. Fourth, the SPA method is used to analyze the impact of trade spillover effects on the economy, environment and energy.

## Conflict of interest

All authors declare no conflicts of interest in this paper.

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