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Average Propagation Length Analysis for the Construction Industry and Industrial Supply Chains

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Abstract: ***This study employs Average Propagation Length (APL) analysis to investigate the structural linkages within regional industrial supply chains in the United Kingdom and its devolved nations, Scotland and Northern Ireland, with a focus on the construction industry. APL analysis is a pivotal method in Industrial Engineering, offering quantitative insights into the strength, complexity, and extent of cross-industry interconnections. This approach provides a robust framework for understanding manufacturing systems and the intricate relationships that drive sectoral interactions in production chains. Findings reveal that in the UK, the construction industry maintains significant connections with electricity transmission and distribution, gas distribution, and steam and air conditioning distribution. These connections highlight the construction sector's role as a critical node in the broader industrial network. Geographical distinctions in supply chain dynamics were observed: while inter-industry linkages span two steps in the UK overall, they reduce to a single step in Northern Ireland and Scotland due to their simpler economic structures. The complexity of the UK's economy facilitates diverse pathways between sectors, resulting in the emergence of intermediate steps during inter-industry transitions. The study emphasizes that industrial linkages across the UK are robust and interconnected, with the service sector forming the core of the industrial supply chain. By driving outward expansion and providing key inputs to industries such as construction and utilities, the service sector underscores the critical role of cross-sectoral integration in enhancing supply chain efficiency and resilience. These findings contribute to the field of Industrial Engineering by providing a comprehensive understanding of regional supply chain dynamics, offering insights into optimizing industrial frameworks and fostering sustainable economic development.***

Keywords: Industrial Supply Chains, Industrial Engineering, Average Propagation Length, Algorithms and Complexity, Economic Structure Complexity, Construction Industry.

Abbreviations:
APL: Average Propagation Length (APL)
IO: Input-Output (IO)
A: Agriculture, hunting, and related services
MQ: Mining and quarrying
F: Manufacture of food products
E: Electricity transmission and distribution, gas distribution
C: Construction industry
TS: Wholesale trade services, except for motor vehicles and motorcycles
LT: Land transport services and transport services via pipelines, excluding rail transport
SS: Warehousing and support services for transportation
OS: Other services

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I. INTRODUCTION

The construction industry plays a crucial role in driving rapid economic development, yet it also contributes significantly to environmental issues. It accounts for 40% of global energy consumption and 25% of carbon dioxide emissions. Additionally, the construction sector is deeply interconnected with numerous other industries, providing critical infrastructure and material foundations for various sectors. At the same time, it creates opportunities for growth in different industries. Conversely, these industries supply essential products and services that support construction activities. Analyzing the relationship between the construction sector and other industries is crucial for understanding the interdependent linkages between them.

The linkage between industries is typically measured along two dimensions: strength and length. The strength of these connections is often assessed using the Leontief inverse matrix, derived from Input-Output Tables. The length, representing the economic distance between industries, is measured using the Average Propagation Length (APL), as introduced by [1]. This distance reflects the average number of steps it takes for an external change in one sector to impact production in another [2]. By analyzing both the strength and distance of these inter-industry connections, the production structure and relationships across sectors and regions within supply chains become clearer. APL analysis captures both direct and indirect linkages, providing insight into the overall strength of these connections. Industry linkages are categorised into two directions: forward linkages and backwards linkages. Understanding both the strength and length of these inter-industry linkages is crucial for intuitively visualizing the production structure and relationships between sectors within the supply chain.

In this paper, from an industry chain perspective, we define the construction industry chain at a macro level for the UK and its two devolved nations, Northern Ireland and Scotland, and analyse the linkage between the construction industry and other related economic industries at these three regional levels. It is crucial to investigate the responsibility, role, and position of each region along the whole production and consumption processes. To our knowledge, this is the first study to focus on the distance between the construction sector and other sectors, visualising the production structure and correlation between each industry and region along the production chains for the UK and its two devolved nations, Scotland and Northern Ireland.

The rest of the study is as follows. The next section presents a literature review of research on the construction industry, along with an analysis of the

average propagation length. The linkages between the construction industry and other industries vary in different regions. The third part provides a detailed explanation of the APL methodology. The fourth section is the analysis results for three regional cases. This section will examine the connections among various industries. Finally, the conclusions summarise the previous and current evolutions of the construction industry and other industries in the UK, Scotland, and Northern Ireland based on the APL model.

II. LITERATURE ON AVERAGE PROPAGATION LENGTH (APL)

Average propagation length is a powerful indicator to analyze the production chain [2]. It is crucial to identify the strength and length of cross-industry interconnections to establish the manufacturing framework and relationships across sectors in the production chain. Strength and length are the two main metrics used to assess these linkages. Strength indicates the resistance to external factors that may adversely affect the linkages. This is measured by the Leontief inverse matrix retrieved from the calculations in the input-output model [3]. Length, on the other hand, is the other significant element indicating how economically closely various sectors in the construction industry are connected, taking into account the direct and indirect consequences on different industries [4].

The construction industry of six European countries' APL from their input-output tables in 1985 has been studied in [5]. They figure out that, in the beginning phases, industries tend to have a one-way direction, whereas a large number of intra-industrial reciprocal linkages are present at a later stage of the industrial chain [5]. APL is a convenient indicator of an economy's complexity and integrity [6]. They prove that the strength of the macro multipliers in a supply chain is inversely correlated to the length of that chain between industries. A more detailed analysis of interdependent sectors is carried out by [7]. Based on the input-output table of the Chinese construction industry from 2007 to 2017, it was found that eight sectors, including the mining industry and the metal product manufacturing industry, are most closely linked to the growth of the construction industry. They demonstrate that a complex supply chain illustrates how the development of every sector is interconnected with several other businesses within the context of the modern, rapidly expanding economy.

III. METHODOLOGY

The input-output table provides information about inputs and outputs from different production sectors, as represented in Table 1 below. Each column represents an input factor for sector *j*, whereas each row shows the output value from sector *i*. In Table 1, X_{ij} depicts the value of the input in sector *j* that will be used as a demand for output sector *i* in the manufacturing activities. X_i represents the total output from sector *i*, and X_j shows the total input for sector *j*. In addition, Y_i shows the final demand for sector *i*, and V_j represents the total value added to sector *j*.

Table 1: A Typical Example of an Input-Output

Output Input		Production Sector - Intermediate Output			Final Demand	Total Output
		Sector -1	…	Sector n		
Production sector-intermediate input	Sector 1	X11				
	-		xij		Yi	Xi
	Sector n			xnn		
Total value added			Vj			
Total input			Xj			

Therefore, the aggregate input X_j for sector *j* is the sum of intermediate input from sector *1* to sector *n* plus the total value added, V_j, which is

$$X_j = \sum_{j=1}^{n} x_{ij} + V_j \quad \ldots \quad (1)$$

Similarly, the value of the total output X_i for sector *i* equals the sum of the intermediate output from sector *1* to sector *n* and the final demand, Y_i, as follows

$$X_i = \sum_{i=1}^{n} x_{ij} + Y_i \quad \ldots \quad (2)$$

Viewing from the backwards perspective, the input coefficient a_{ij}, or in matrix form, A, is calculated as the current flow x_{ij} from sector *i* to sector *j* divided by the aggregate input in industry *j*, X_j, By the formula:

$$a_{ij} = \frac{x_{ij}}{X_j} \quad \ldots \quad (3)$$

It refers to the number of resources and goods from different sectors used directly by another particular sector to generate one additional unit of aggregate output. In other words, it is the ratio of the quantity of an intermediate input, X_{ij}, to the total input of that product X_j.

Based on the formula (3), the overall input coefficient b_{ij} (or complete consumption coefficient [7]) is used to represent the aggregate number of diverse resources and goods that are used either directly or indirectly by a specific sector in that industry to create an additional unit of total output. It equals the sum of every individual input coefficient, and in the formula, it is as follows:

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$$b_{ij} = a_{ij} + \sum_{k=1}^{n} a_{ik}a_{kj} + \sum_{k=1}^{n}\sum_{s=1}^{n} a_{is}a_{sk}a_{kj} + \cdots \quad (i,j = 1,2,\ldots) \quad \ldots \quad (4)$$

When written in the matrix form, the overall input coefficient matrix is:

$$B = A + A^2 + A^3 + \cdots = (I - A)^{-1} - I \quad \ldots \quad (5)$$

Since the input coefficient calculates the backwards (demand-pull) linkages between industries, this linkage represents the extent to which an industry's production factors depend on supplies from other industries. Usually, the backwards linkage between industries is shown by the Leontief inverse [8], L, which is calculated in the matrix form as follows:

$$L \equiv (I - A)^{-1} \quad \ldots \quad (6)$$

This inverse is a measurement of linkages for the total input. For instance, if one sector of the output in industry *i*, the final demand Y_iIf it is going to increase by one unit, the change will lead to an increase in each part of the input sectors from all the other industries. This change is because of the overall input coefficient. b_{ij} Consists of all related input coefficients with *i* and *j*. An increase in the output of industry *i* will affect all the factors related to *i*, including a_{ij}, $\sum_{k=1}^{n} a_{ik}a_{kj}$, and each subsequent step. As a result, the change in the industry's output will influence every other sector.

In addition, from a forward-looking perspective, the output coefficient h_{ij} (or direct distribution coefficient [7]) equals the current flow x_{ij} from sector i to sector j divided by the aggregate output X_i. It is described as the number of resources and goods from different sectors that are acquired directly by another particular industry to use one additional unit of aggregate input. In other words, it is the ratio of the quantity of an intermediate output, X_{ij}, to the total production of that product X_i. The formula is as follows:

$$h_{ij} = \frac{x_{ij}}{X_i} \quad \ldots \quad (7)$$

Similarly, the overall output coefficient m_{ij} (or complete distribution coefficient [7]) is the sum of all the individual output coefficients h_{ij}. It represents the aggregate number of diverse resources and goods derived from a specific sector within an industry due to a unit change in total value added. It equals the sum of every individual input coefficient, whereas, in the matrix form, it is indicated by M as follows:

$$M = (I - H)^{-1} - I \quad \ldots \quad (8)$$

The output coefficient calculates the forward (cost-push) linkages between industries. Forward linkages illustrate the significant contribution of the input industry to the output of other industries. It shows the degree of change in all output sectors in industry *i* when there is a specific change in the input of industry *j*. The Ghost inverse usually represents this linkage:

$$G \equiv (I - H)^{-1} \quad \ldots \quad (9)$$

This calculates the total forward linkages between industries. Based on these formulas, the backwards and forward linkages are visually depicted, showing the extent to which various industries are linked with each other. Generally, a higher level of input coefficient indicates a more vital backwards linkage, suggesting that this industry is more dependent on the supply of different sectors. A higher level of output coefficient shows a tendency toward forward linkages within an industry, as other sectors demand inputs from this industry.

A. Average Propagation Length (APL)

The construction industry is characterised by numerous complex linkages that are influenced by diverse inputs and outputs. Numerous studies have utilized it as a potent indicator of the industrial chain to analyze [2].

The total propagation length is shown as l_{ij}, or Δx, as follows:

$$\Delta x = l_{ij} = a_{ij} + \sum_{k=1}^{n} a_{ik}a_{kj} + \sum_{k=1}^{n}\sum_{s=1}^{n} a_{is}a_{sk}a_{kj} + \quad \ldots \quad (10)$$

This formula indicates that each unit increase in final demand. Y_i For sector *j* will lead to $\Delta x = l_{ij}$ Increase in the output of sector *i*. The first term, a_{ij}, represents direct linkage, whereas the rest of the terms mean indirect linkages. Considering the case when $i = j$An initial effect exists, as the additional final demand must be generated independently [5]. The formula (10) can then be expressed as:

$$\Delta x = l_{jj} = 1 + a_{jj} + \sum_{k=1}^{n} a_{jk}a_{kj} + \sum_{k=1}^{n}\sum_{s=1}^{n} a_{js}a_{sk}a_{kj} + \cdots \quad (11)$$

This formula is also consistent with the Leontief inverse. When expressed in the matrix form, $L \equiv (I - A)^{-1} = I + A + A^2 + A^3 + \cdots$ For a Δf unit change for the j^{th} sector, $\Delta \boldsymbol{x} = (I + A + A^2 + A^3 + \cdots)(\Delta f) = L(\Delta f)$.

Hence, from equation (10), the APL between sectors *i* and *j* can be expressed as $\Delta x / l_{ij}$. This is the sum of the average length of each share. The first fraction is a one-step share. a_{ij}/l_{ij}, whereas the second fraction is a two-step share $\sum_{k=1}^{n} a_{ik}a_{kj}\,/l_{ij}$, similar to all subsequent fractions with three or more steps. As a result, the expression of APL becomes:

$$\frac{\Delta x}{l_{ij}} = \frac{1 \times a_{ij}}{l_{ij}} + \frac{2 \times \sum_{k=1}^{n} a_{is}a_{kj}}{l_{ij}} + \frac{3 \times \sum_{k=1}^{n}\sum_{s=1}^{n} a_{is}a_{sk}a_{kj}}{l_{ij}} + \cdots (i \neq j) \quad \ldots \quad (12)$$

When $i = j$, $\Delta x - 1 = l_{jj} - 1$The average propagation length (APL) is $\frac{\Delta x - 1}{l_{ij} - 1}$. It is clear from formulas (4) and (10) that $\Delta x = l_{ij} = b_{ij}$. Therefore, the APL formula for the input case (backwards linkages) can be expressed as:

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$$APL_b = \begin{cases} \frac{b_{ij}}{l_{ij}} \; for \; i \neq j \\ \frac{b_{ij}}{l_{ij} - 1} \; for \; i = j \end{cases} \quad \ldots \quad (13)$$

Similarly, based on the output coefficient (formulas (7) and (8)) and the Ghost inverse (formula (9)), the APL for the forward (output) case can be expressed as:

$$APL_f = \begin{cases} \frac{m_{ij}}{g_{ij}} \; for \; i \neq j \\ \frac{m_{ij}}{g_{ij} - 1} \; for \; i = j \end{cases} \quad \ldots \quad (14)$$

Where m_{ij} Is the overall output coefficient and g_{ij} Represents the change in the output in sector i for one additional unit of total value added in the input in sector j.

Therefore, the average can be used for both backwards and forward cases when considering the distances between any two sectors in the supply chain. For an industry with n sectors, the backwards average APL is as follows:

$$\overline{B_j} = \frac{1}{n}\sum_{i=1}^{n} APL_{b_{ij}} \quad \ldots \quad (15)$$

Similarly, the forward average APL is referred to as:

$$\overline{F_i} = \frac{1}{n}\sum_{j=1}^{n} APL_{f_{ij}} \quad \ldots \quad (16)$$

The backwards average APL $\overline{B_j}$ shows the average length between sector j and any sector in I the

Industry I, whereas the forward average APL $\overline{F_i}$ Indicates the mean length between sector i and the sectors in industry j.

Finally, it can be proved that backwards APL is the same as forward APL, which is $APL_b = APL_f$. Formulas (3) and (7) show that $a_{ij} = \frac{x_{ij}}{X_j}$ and $h_{ij} = \frac{x_{ij}}{X_i}$. Hence, for an equilibrium industrial sector, the total input for a specific industry j should equal the total output in a particular industry i. Therefore, $X_j = X_i$, such that $a_{ij} = h_{ij}$, as well as the sum of both coefficients b_{ij} and m_{ij}. In the matrix form, since $L \equiv (I - A)^{-1}$ and $G \equiv (I - H)^{-1}$, when $A = H$The Leontief inverse L is equal to the Ghost inverse G. $L = G$, such that $l_{ij} = g_{ij}$. Hence, the APL_i in the backwards calculation, $\frac{b_{ij}}{l_{ij}} = \frac{m_{ij}}{g_{ij}}$, is the APL_o calculated in the forward case.

Lastly, the analyses were carried out using the 2019 Input-Output (IO) Tables for the United Kingdom, Northern Ireland, and Scotland. The table below represents an aggregated list of sectors. Input-output tables can be found on official websites, such as those of the Office for National Statistics (ONS), the Northern Ireland Statistics and Research Agency (NISRA), and Scotland's Official Statistics (ScotOS).

Table 2: Aggregated Sectors of the Input-Output

No.	Sector
1	Agriculture, hunting, and related services
2	Mining and quarrying
3	Manufacture of food products
4	Electricity transmission and distribution, gas distribution, steam and air conditioning distribution and supply
5	Construction industry
6	Wholesale trade services, except for motor vehicles and motorcycles
7	Land transport services and transport services via pipelines, excluding rail transport
8	Warehousing and support services for transportation
9	Other services

IV. ANALYSIS RESULTS

This paper will discuss the results separately for the UK, Northern Ireland, and Scotland. Each section includes tables of the economic linkage coefficients derived from each region's IO table, APL values, and economic distances between the nine regional sectors. The industrial sectors are represented by numbers shown in Table 2. The numbers in the table of economic linkage coefficients that exceed the threshold will be bolded.

A. Results for the UK Case

APL values represent the trade distances between producers and consumers. Table 3 highlights the backwards industrial linkages, showing the average number of trade steps from producers to a specific consumer. Backwards linkages indicate a sector's position within demand-driven chains. A larger average backwards value suggests that the industry is further upstream in the production chain, while a smaller value indicates proximity to final consumers. A smaller backwards value for the sector implies that fulfilling its final demand requires fewer trade steps, resulting in a more straightforward production process. Conversely, sectors with larger backwards values have more complex production chains, involving more trading activities to meet their final consumption needs.

Tables 3, 4, and 5 present the economic linkages and APLs between UK industries, using data from 2019.

Table 3: Economic Linkage Indicators Between UK Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.19	0.00	0.19	0.00	0.00	0.00	0.01	0.00	0.00
2	0.00	0.11	0.00	0.04	0.01	0.00	0.00	0.00	0.00
3	0.08	0.01	0.24	0.00	0.00	0.01	0.03	0.03	0.01
4	0.04	0.03	0.06	1.06	0.03	0.03	0.02	0.03	0.02
5	0.03	3.00	0.02	0.10	0.49	0.03	0.01	0.02	0.03
6	0.11	5.00	0.14	0.03	0.07	0.03	0.03	0.03	0.02
7	0.03	0.02	0.05	0.01	0.02	0.06	0.13	0.03	0.01
8	0.01	0.01	0.01	0.00	0.01	0.05	0.02	0.16	0.01
9	0.24	0.20	0.26	0.23	0.22	0.25	0.26	0.28	0.32

Table 4: APL Between UK Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.20	3.45	1.44	3.16	3.38	2.40	2.46	2.85	2.68
2	3.02	0.11	3.68	2.24	1.90	2.59	1.73	3.51	2.96
3	1.55	2.49	0.26	3.64	3.27	1.93	1.62	1.65	1.74
4	3.03	2.68	2.77	1.07	3.20	2.68	2.87	2.68	2.67
5	2.43	2.11	3.32	2.69	0.51	2.02	3.02	2.40	1.97
6	1.56	1.65	1.60	2.89	1.88	0.05	1.90	2.12	1.80

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7	1.94	1.86	1.85	3.72	2.64	1.30	0.14	1.59	2.01
8	2.83	2.70	2.75	3.94	3.10	1.33	1.70	0.17	2.13
9	2.03	1.75	2.16	2.68	2.17	1.63	1.70	1.74	0.35

Table 5: Economic Distances Between UK Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0
5	0	0	0	2	0	0	0	0	0
6	1	0	1	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	0	0
9	2	1	2	2	2	1	1	1	0

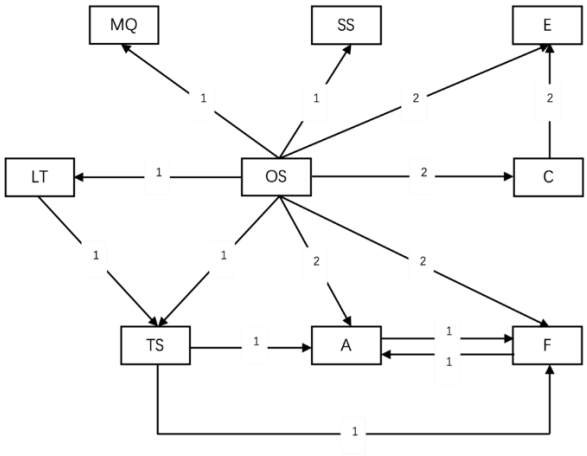
In the calculation for the UK,
the threshold α Takes a value of 0.06, and every number larger than 0.06 is bolded. Table 3 shows that the most significant economic linkage indicator ($f_{4.4} = 1.06$) exists on the diagonal within the Electricity transmission and distribution, gas distribution, steam, and air conditioning distribution and supply (No. 4). The closest relationship indicates a solid internal connection within the industry. This is because the process of electricity, gas, steam, and air distribution requires a large amount of electricity. The output of electricity and gas may be used to generate more electricity and gas. The self-sufficient industrial mode streamlines the production structure, leading to enhanced industrial efficiency. In addition, the construction industry (No.5) has the second strongest internal economic relationship ($f_{5.5} = 0.49$). The output of the construction industry has further fueled its development. For instance, the improvement of power systems and infrastructure assists in the construction of larger buildings. On the other hand, the construction industry has a significant impact on electricity transmission and distribution, as well as gas distribution, steam, and air conditioning distribution and supply (No. 4). This is because the construction industry provides essential equipment, such as cables and pipelines, for these purposes. The rapid development of the construction industry in the UK increases the supply to other sectors, promoting the growth of related industries.

Another apparent characteristic is that Other Services (No. 9) has a significant impact on every other sector in the table. As a developed country, the service sector has the largest share of the UK's economy, reaching nearly 79.6% of the total economic output in 2022. Therefore, the service industry inevitably provides a certain amount of production to other sectors. For example, the restaurant and hotel service may stimulate the growth of the manufacturing of food products (No.3). In contrast, the storage and communication service may lead to the development of Land transport services (No.7). The economic benefits from the service industry may be used as an investment to the construction industry (No.5). Therefore, the service industry has close connections with the rest of sectors in the UK.

The APL values in Table 4 show the distance between industries in the UK. Each number represents the steps an industry needs to reach another industry. APL simultaneously reflects both the forward cost-push effect of industry *i* on industry j and the backwards demand-pull effect of industry *j* on industry *i*. In Table 4, for instance, the value 3.38 in the first row and fifth column indicates that the cost-push effect of Agriculture (No. 1) requires 3.38 steps to reach the construction industry (No. 5). In comparison, the demand-pull impact of the construction industry on Agriculture also requires 3.38 steps. The smaller the number of APLs, the closer the relationship between the two industries, and vice versa. This suggests that industries with a greater economic distance may involve sequential economic activities during transformation, which can significantly impact the country's economic growth. On the contrary, their individual demand and supply changes may affect closely related industries with smaller steps. The APLs on the diagonal are relatively minor compared to the other APLs. This is because each industry has an immediate impact on itself, which accords with the solid economic linkage indicators on the diagonal.

Based on the data from Tables 3 and 4, Table 5 displays the integral economic distance between industries in the UK in 2019. The result demonstrates that the construction industry (No. 5) has a two-step pushing effect on electricity transmission and distribution, as well as gas distribution, steam, and air conditioning distribution and supply (No. 4). Conversely, the construction industry has a two-step pulling effect on Other Services (No. 9).

According to Table 5, this paper presents the supply chain of 9 industries in the UK, as illustrated in Figure 2. The arrows show the direction of the economic linkages, and the numbers on the arrows represent the economic distance in steps. The abbreviated names of these nine industrial sectors are shown in Table 6.



[Fig.2: UK Industrial Supply Chains (Compiled by Author)]

Figure 2 shows that the construction industry (C) is related to Other Services (OS) and Electricity transmission and distribution, as well as gas distribution, steam and air conditioning distribution, and supply (E). Other Services provide construction materials for the construction industry with an economic value that takes into account distance. This indicates that the construction industry has a significant pulling effect on Other Services. Furthermore, the construction industry has a 2-step economic impact on electricity and gas. This is because the construction industry provides basic infrastructure, such as the construction of turbines and generators, for the growth of the electricity industry. Moreover, current climate policy stimulates the

development of the electricity industry. Therefore, Other Services are connected to the electricity industry through the construction industry, with an economic distance of 4 in total. In addition, Other Services are directly linked to the electricity industry, taking a 2-value economic distance. Other Services demand electricity, directly promoting the development of the electricity industry. At the same time, Other Services provides economic support for the growth of that industry. On the other part of the figure, agriculture (A) and the Manufacture of food products (F) are closely connected, with an economic distance value of 1. Agriculture provides raw materials, such as crops and livestock, for the food industry, while the food industry in turn provides economic support to agriculture. Agriculture and the food industry also strongly depend on Wholesale trade services, except for motor vehicles and motorcycles (TS). Trade services directly provide materials for the food industry in one step, or they correlate with agriculture through one economic unit and further link to the food industry with an additional unit. Another interesting point is that Mining and quarrying (MQ) has no significant connection to the Construction Industry (C). In reality, the two industries are closely interrelated. However, since the value added, such as labour and capital, of primary products in developed countries is high along the supply chain, the dominant part of the product's price comes from the service sector rather than the construction industry.

Moreover, Other Services have significant connections with other industries, including Mining and Quarrying (MQ), Land Transport Services, and Transport Services via Pipelines, excluding Rail Transport (LT), Wholesale Trade Services (TS), and the agriculture and food industry. Due to the country's high economic development, the service sector is a dominant industry in the UK. For instance, the financial sector of the service industry provides substantial economic support and meets a wide range of consumer demands, thereby contributing to the country's economic growth. Therefore, the Other Services industry is an essential component of the UK's financial structure. It has diverse linkages and significant pushing effects on overall industrial, economic, and social growth. As a result, every other industry in the UK is closely correlated with the service industry.

B. Northern Ireland Case

In Northern Ireland, the threshold α Takes a value of 0.04. Similar to the situation in the UK, the most significant economic linkage indicator appears on the diagonal within the construction industry ($f_{5.5} = 0.41$) in Table 6. The construction process reflects the industry's progress, fostering robust internal linkages within the industry. In addition, from Table 3, the construction industry has a significant pushing effect on Agriculture (No.1), Electricity transmission and distribution, gas distribution, steam and air conditioning distribution and supply (No.4). Like the UK, the NI construction industry provides basic infrastructure for generating electricity and distributing gas across the region, thus having a significant economic linkage. Moreover, agriculture is promoted by the construction industry. Farming accounts for a substantial portion of Northern Ireland's financial structure. 75% of the agricultural area in NI is used for farming, whereas the meat, dairy, and egg industries constitute nearly 80% of the industrial output (FOE). Both concentrated animal feeding operations (CAFOs) and free-range grazing require advanced equipment to proceed. Therefore, the construction industry meets the basic equipment needs of agricultural production. On the other hand, Other Services still exist as a supporting industry for NI industries.

Tables 6, 7, and 8 illustrate the economic linkages and APLs between Northern Ireland's industries, using data from 2019.

Table 6: Economic Linkage Indicators Between NI Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.07	0.00	0.26	0.00	0.00	0.01	0.00	0.00	0.00
2	0.00	0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.00
3	0.26	0.01	0.20	0.00	0.00	0.02	0.01	0.01	0.01
4	0.02	0.02	0.02	0.10	0.01	0.01	0.02	0.03	0.01
5	0.04	0.01	0.02	0.17	0.41	0.01	0.01	0.02	0.02
6	0.09	0.04	0.11	0.02	0.06	0.05	0.01	0.01	0.02
7	0.02	0.07	0.03	0.01	0.02	0.02	0.13	0.02	0.01
8	0.01	0.00	0.01	0.00	0.00	0.03	0.01	0.17	0.00
9	0.14	0.10	0.10	0.24	0.10	0.06	0.13	0.17	0.19

Table 7: APL Between NI Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.14	1.95	1.28	1.95	2.18	2.35	2.06	2.26	2.19
2	2.76	0.04	214	2.08	1.49	2.36	2.63	2.98	2.36
3	1.29	2.12	0.26	2.68	2.99	1.49	1.66	1.78	1.63
4	1.72	1.45	1.83	0.11	2.27	1.72	1.49	1.44	1.46
5	1.84	2.64	2.74	1.56	0.41	1.86	2.31	2.09	1.78
6	1.56	1.33	1.57	2.08	1.78	0.06	1.7	2.03	1.62
7	1.81	1.28	1.8	2.45	2.36	1.35	0.13	1.44	1.68
8	2.64	2.2	2.39	2.16	2.77	1.3	1.54	0.17	1.79
9	1.71	1.55	2.04	1.41	1.98	1.68	1.44	1.49	0.2

Table 8: Economic Distances Between NI Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	1	0	0	1	0	0	0	0	0
6	1	1	1	0	1	0	0	0	0
7	0	1	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	1	1	2	1	1	1	1	1	0

Unlike the UK, Wholesale trade services (No. 6) and Land transport (No. 7) are closely connected to Mining and quarrying (No. 2). Wholesalers sell goods and services to the mining industry, including industrial equipment for mining and mineral extraction. Therefore, this industry also has a significant impact on the construction industry due to the substantial demand for equipment. Land transport and pipelines provide convenient ways for the mining industry to distribute its output to other parts of the world. The development of transportation ensures the timely use of materials and drives the economic growth of the surrounding areas.

Table 7 shows the APL values in Northern Ireland. The diagonal APLs, which indicate the internal linkages within every industry, are smaller than the rest of the table. A similar trend to the case in the UK suggests that industries in NI have a strong influence on themselves. Besides the data on the diagonal, most APLs take the value around 2. It can be concluded that most industries in NI have only two steps to transition from one

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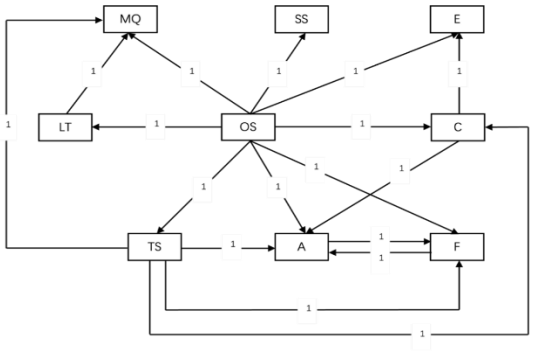
sector to another, which is a relatively short distance. The close connections among industries represent a developed supply chain, where goods and services can be easily transmitted, and cooperation often occurs during industrial development.



[Fig.3: NI Industrial Supply Chains]

Based on the economic linkage and APL in Tables 6 and 7, Figure 3 represents the supply chain in NI, with economic distance indicated on each line. Many parts of this supply chain are similar to those in the UK. The construction industry is closely tied to the electricity and service industries. Agriculture, the food industry, and wholesale trade services are closely related to exchangeable linkages. However, additional connections are also visible in this figure. First, the distance between Other Services (OS), the construction industry (C), and the electricity industry (E) is set to 1 rather than 2 in the UK. This indicates a closer connection among these industries, as each industry is directly linked to the other without intermediate steps. A change in the output of one of these industries may directly affect the other two industries. Therefore, when considering economic development, these three industries should be combined to achieve the maximum economic benefit. Second, the construction industry has several new connections in the figure. It exerts a pushing effect on agriculture at a distance of 1. Since farming plays a significant role in NI's economic sector, the construction industry provides basic agricultural equipment and facilities for harvesting and cultivating activities. Hence, Other Services can directly support agriculture with an economic linkage of 1, or it can first connect to the construction industry and then to agriculture, with a total distance of 2. Third, wholesale trade services (TS) also have an additional pushing effect on the construction industry and mining and quarrying (MQ). The construction and mining industries are heavily industrial-related sectors that require numerous facilities and components to install and construct large pieces of equipment. As a result, wholesale trade services provide these industries with fundamental equipment to promote the development of the construction and mining industries. In addition, Figure 3 indicates that these two new linkages in NI have a distance of 1, suggesting close economic connections between wholesale trade services and the construction and mining industries.

C. Scotland Case

In Scotland, the threshold of the economic indicator is 0.03. Table 10 shows the most significant economic linkages that appear inside the electricity industry ($f_{4.4} = 0.48$) and the construction industry ($f_{5.5} = 0.27$). Therefore, these two industries have the most significant impacts on themselves across the UK, including Northern Ireland and Scotland. In addition, linkages on the diagonal and related to Other Services are more important than the rest of the table, consistent with the situation in the UK and NI. However, unlike Northern Ireland, the construction industry (No. 5) in Scotland has a limited impact on agriculture (No. 1). This is because the majority of Scotland's land is classified as rural. The construction industry does not directly support the development of agriculture in Scotland. Moreover, unlike Northern Ireland, wholesale trade services (No. 6) and land transport (No. 7) have a minimal impact on mining and quarrying (No. 2) in Scotland. Although few coal and mineral mines exist in Scotland, they are not critical components of the Scottish economy. Without significant output from mining and quarrying, other industries have few demands for products related to that industry. Additionally, traditional open-pit coal mining poses substantial environmental hazards. Due to the prevalence of environmentally friendly and sustainable development, old mines are ceasing to operate. Hence, the economic linkage is weak between mining and quarrying and other sectors of the economy.

Tables 9, 10, and 11 illustrate the economic linkages and APLs between Scotland's industries, using data from 2019.

Table 9: Economic Linkage Indicators Between SCT Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.12	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.06	0.00	0.00	0.01	0.00	0.00	0.00	0.00
3	0.04	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
4	0.02	0.02	0.03	0.48	0.01	0.02	0.01	0.01	0.01
5	0.02	0.02	0.01	0.04	0.27	0.03	0.00	0.01	0.02
6	0.04	0.02	0.07	0.01	0.02	0.02	0.01	0.01	0.01
7	0.02	0.02	0.02	0.00	0.00	0.03	0.03	0.04	0.00
8	0.01	0.00	0.01	0.00	0.00	0.04	0.01	0.10	0.00
9	0.11	0.19	0.08	0.08	0.10	0.13	0.14	0.11	0.16

Table 10: APL Between SCT Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0.12	1.64	1.19	1.78	1.67	1.26	1.65	1.70	1.73
2	1.51	0.07	1.56	2.46	1.45	1.44	1.29	1.34	1.72
3	1.19	2.10	0.07	2.70	2.44	1.38	2.07	1.38	1.29
4	1.99	1.89	1.83	0.48	2.30	1.77	1.91	1.82	1.74
5	1.62	1.58	2.52	1.81	0.28	1.46	2.31	1.69	1.50
6	1.30	1.32	1.24	1.98	1.50	0.02	1.29	1.60	1.37
7	1.33	1.22	1.43	2.39	2.12	1.17	0.03	1.16	1.45
8	1.86	2.11	2.06	2.20	2.29	1.17	1.24	0.11	1.62
9	1.50	1.31	1.81	1.75	1.59	1.33	1.26	1.39	0.17

Table 11: Economic Distances Between SCT Industries (Compiled by Author)

No.	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	1	0	0	0	0	0
6	1	0	1	0	0	0	0	0	0
7	0	0	0	0	0	0	0	1	0
8	0	0	0	0	0	1	0	0	0
9	1	1	1	1	1	1	1	1	0

APLs of Scotland are shown in Table 10. Similarly, the values on the diagonal are below 1, indicating that the

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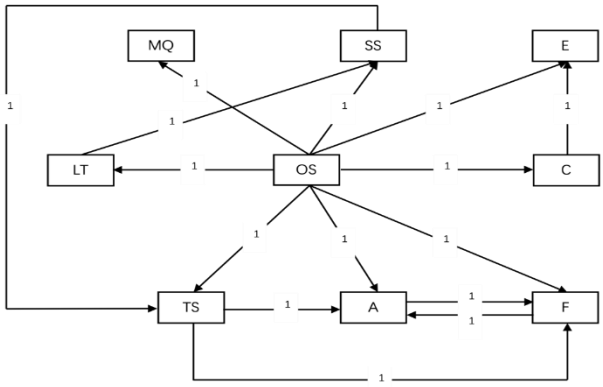
shortest economic distance is found within every industry. Other industries have pushing and pulling effects on each other, with most having an average of a 2-step economic linkage, similar to the situation in Northern Ireland. Additionally, as shown in Table 12, all significant economic distances in Scotland have a value of 1. This indicates that essential industries in Scotland are closely and directly connected. Every sector can cooperate directly without intermediaries. Therefore, the links between Scottish businesses are powerful. The economic development of one sector may result in joint development between closely linked industries.



[Fig.4: SCT Industrial Supply Chain (Compiled by Author)]

Figure 4 shows the supply chain in Scotland. Based on the calculation, the Scottish construction industry (C) is directly connected to the electricity and service sectors. However, unlike Northern Ireland, the construction industry is not closely linked to agriculture (A) due to the large area of rural land in Scotland, which decreases the demand for facilities for large-scale production. Additionally, the figure indicates that land transport (LT) is not directly linked to mining and quarrying (MQ), but rather connects to warehousing and support services for transportation (SS). This is because the service sector dominates the economy, while environmental concerns arise about traditional coal mining. On the other hand, more efficient transportation systems are in place to facilitate other industries. The advent of various modes of transport, including bridges, tunnels, airports, and harbours, has facilitated the integration of land transport with other forms of transportation, resulting in a strong connection between land transport and warehousing and support services for transportation. In this way, a smoother flow of goods and services appears in the Scottish economy, as well as a more convenient journey for everyday life. Therefore, support services for transportation have a 1-step significant pushing effect on wholesale trade services (TS). The reason is that commodities in industrial production require different types of transportation. Flights can carry light, valuable items, while cargo ships are more suited for transporting staple and bulk commodities. The development of transportation modes provides trade services with a variety of choices to decide how to transport different products. Moreover, this new connection provides Other Services (OS) with an additional means of accessing trade services. There are three routes between OS and TS:

1. They are directly connected by 1 step.
2. The OS connects to SS and then proceeds to TS, covering a total distance of 2.
3. The OS connects to LT, while LT connects to SS and TS in three steps.

The diverse range of choices here indicates the complexity of the economy. Promoting economic growth requires a careful consideration of the industrial structure and linkages.

D. Summary of the Empirical Results for the UK, NI, and SCT

Based on the tables and figures about economic linkages and distances in the UK, NI, and SCT, the construction industry has strong connections with each region's electricity and gas industry and service sector. The service sector provides labour and capital inputs to the construction and electricity and gas industries, while the construction industry also accelerates the development of the electricity and gas sector. The difference here is that the distance between these industries requires two steps in the UK, but decreases to one step in Northern Ireland and Scotland in terms of the production supply chain. This is because the UK has a more complex economic structure than Northern Ireland and Scotland. A complex economy provides a variety of pathways to connect different sectors. Therefore, intermediate steps appear during the transition from one industry to another in the UK.

Second, the agriculture and food industries are significantly interconnected, while wholesale trade services have a substantial impact on them in all regions. Agriculture is the primary source of food, and the development of the food industry increases demand for agricultural products. In a modern economy, food marketing plays a significant role in promoting joint development, thereby linking trade services to these two sectors. The primary difference lies in the connection between the construction industry and agriculture in Northern Ireland. Due to the concentration on farming, the construction industry produces agricultural equipment for large-scale farming activities. Therefore, the growth of the construction industry could lead to the development of agriculture in Northern Ireland.

Third, unlike the situation in Turkey and China, the APL analysis of the UK's economic linkage indicators and APLs reveals that the service sector, including transportation, wholesale trade services, and Other Services, is at the heart of economic growth, rather than the construction industry. The regional industrial supply chain figures show that Other Services (OS) has close connections to every other key sector in the UK, NI, and SCT, and most pathways have a distance of 1 step. On the contrary, the construction industry is merely connected to the electricity industry, as shown in the figures above. As a developed European country, the UK's economy has transitioned from an industrial to a tertiary sector, primarily the service sector. At the same time, as environmental concerns have become more significant, the pulling and pushing effects of the construction industry are being further weakened in favour of the tertiary sector. Therefore, a focus on the service sector has become the dominant trend for industrial success in the UK. However, this does not mean that the Construction Industry and industries other than the service sector are meaningless in the economy. Although the service sector dominates the

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economic structure, it cannot grow sustainably without the support of different sectors. Other sectors "feed" the service sector as they provide raw materials for the development of labour and capital.

V. CONCLUSION

This paper utilises input-output tables based on 2019 data for the UK, Northern Ireland, and Scotland to calculate economic linkages and APLs, and examines the industrial chains. Unlike developing countries, the construction industry in the UK acts as a “basic industry” rather than a “pillar industry”. This industry is closely connected to two primary industries in the industrial supply chain: electricity transmission and distribution, gas distribution, steam and air conditioning distribution and supply, and other related services. The primary reason for the differences in the construction industry across various locations is the distinct economic structures between developing and developed countries. The UK was one of the first countries to have an industrial revolution. The industrial focus has changed from the second to the tertiary sector, which is the service industry. Hence, the importance of the construction industry has declined. This input shift reflects economic development, consistent with previous US research [9].

Second, as the influence of the construction industry has declined, the service industry has taken the lead in the UK economy. Other Services, involving personal and organizational service activities, appear at the heart of the three supply chains in this paper. This sector has a significant impact on all the other primary industries, as per APL analysis. Moreover, other service industries, such as Land transport services and Wholesale trade services, also have strong connections in the supply chains. As economic growth continues in the UK, these industries will consistently drive industrial development.

Third, the economic distance between industries is relatively short, indicating strong inter-industrial connections within the supply chain. Most economic linkage indicators take the value of 1, suggesting they are directly interconnected. The close connection makes it easier to be affected by changes in one sector. Therefore, to achieve economic growth in the UK, promoting the service sector is significant. Since the service sector has the most significant impact on the economy, the development of the service industry will lead to the co-progression of other sectors.

Fourth, different regions have unique industrial structures. The linkages between the construction industry and other sectors decreased from 2 to 1 in Northern Ireland and Scotland compared to the rest of the UK. The construction industry in Northern Ireland, for instance, has a significant impact on agricultural production, given the region's importance in the farming sector. In Scotland, mining and quarrying have no significant connections with land transport due to environmental concerns arising from traditional coal mining. To a certain extent, the unique industrial chains in different regions reflect the distinct characteristics of the industrial structures in those regions.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

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- **Author's Contributions:** The authorship of this article is contributed solely.

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