

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

Metin Piskin



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, focusing 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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*Correspondence Author(s)

Metin Piskin*, Department of Institute for Sustainable Resources, University College London, Central house, London, United Kingdom. Email ID: m.piskin@ucl.ac.uk, ORCID ID: [0000-0002-1170-2273](https://orcid.org/0000-0002-1170-2273)

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I. INTRODUCTION

The construction industry is key in driving rapid economic development and 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 categorized in two directions: forward linkages and backward linkage. 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 the perspective of the industry chain, we define the construction industry chain at a macro level for the UK and two devolved nations Northern Ireland and Scotland, and analyse the linkage between the construction industry and other related economic industries in 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 that focuses on the distance between the construction sector and other sectors to visualize the production structure and correlation between each sector and region along the production chains for the UK and two devolved nations Scotland and Northern Ireland.

The rest of the study is as follows. The next part is the literature review of the research of the construction industry and average propagation length analysis. The linkages between the construction

industry and other industries vary in different regions. The third part is a detailed explanation of the methodology of APL. The fourth section is the analysis results for three regional cases. The paper will examine the connections among various industries in this section. 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 critical to identify the strength and length of the cross-industry interconnections to realize 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 shows the resistance to outside factors which 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 industries is carried out by [7]. Based on the input-output table of the Chinese construction industry from the year 2007 to 2017, they figured out that eight industries, such as the mining industry and metal product manufacturing industry, are most intimately linked to the growth of the construction industry. They prove that a complicated supply chain demonstrates how every industry's growth is interconnected with several other businesses in the context of the modern, rapidly expansive economy.

III. METHODOLOGY

Input-Output Table which provides information about inputs and outputs from different production sectors 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 *l* to sector *n* plus the total value added, V_j , which is

$$X_j = \sum_{l=1}^n x_{lj} + V_j \dots (1)$$

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

$$X_i = \sum_{l=1}^n x_{il} + Y_i \dots (2)$$

Viewing from the backward 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:

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

It is referred to as 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:

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

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



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

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

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

This inverse is a measurement of linkages for the total input. For instance, if one sector of the output in the industry i , final demand Y_i , 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 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 i 's output will influence every other industry.

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 sector 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 output of that product X_i . The formula is as follows:

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

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 that are derived from a specific sector in that industry due to a unit change in the total value added. It equals the sum of every individual input coefficient, whereas, in the matrix form, it is indicated by M as follows:

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

The output coefficient calculates the forward (cost-push) linkages between industries. Forward linkages demonstrate how much the input industry contributes 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:

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

which calculates the total forward linkages between industries. Based on these formulas, the backward and forward linkages are visually depicted and show to what extent various industries are linked with each other. Generally, a higher level of input coefficient means a more vital backward linkage, indicating that this industry is more dependent on the supply of other industries. A higher level of

output coefficient shows a tendency toward forward linkages within an industry, as other industries demand inputs from this industry.

A. Average Propagation Length (APL)

There are various complex linkages in the construction industry, which are affected 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:

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

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 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:

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

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

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:

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

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

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

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

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

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 backward and forward cases when taking into account the distances between any two sectors in the supply chain. For an industry with n sectors, the backward average APL is as follows:

$$\bar{B}_j = \frac{1}{n} \sum_{i=1}^n APL_{bij} \dots (15)$$

Similarly, the forward average APL is referred to as:

$$\bar{F}_i = \frac{1}{n} \sum_{j=1}^n APL_{fij} \dots (16)$$

The backward average APL \bar{B}_j shows the average length between sector j and any sector in I the

industry i , whereas the forward average APL \bar{F}_i indicates the mean length between sector i and sectors in industry j .

Finally, it can be proved that backward APL is the same as the 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 certain industry j should be equal to the total output for a certain 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 backward 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 by using 2019 Input-Output (IO) Tables for the United Kingdom, Northern Ireland, and Scotland and the Table below represents an aggregated sector list. Input-output tables can be found on official websites, such as the Office for National Statistics (ONS), 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 regional 9 sectors. The industrial sectors are represented by numbers shown in Table 2. The numbers in the table of the economic linkage coefficients that are greater than 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 backward industrial linkages, showing the average number of trade steps from producers to a specific consumer. Backward linkages indicate a sector's position within demand-driven chains. A larger average backward value suggests that the sector is further upstream in the production chain, while a smaller value indicates proximity to final consumers. A smaller backward value for the sector i means that fulfilling its final demand requires fewer trade steps, implying a simpler production process. Conversely, sectors with larger backward values have more complex production chains, involving more trading activities to meet their final consumption needs.

Table 3, Table 4, and Table 5 show the economic linkages and APLs between UK industries using data in 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
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 inside 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 regenerate more electricity and gas. The self-sufficient industrial mode simplifies 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 promoted the development of this industry. For instance, the improvement of power systems and infrastructure assists larger construction of buildings. On the other hand, the construction industry has a pushing effect on electricity transmission and distribution, 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 electricity transmission. The rapid development of the construction industry in the UK increases the supply to other industries, promoting the growth of related industries.

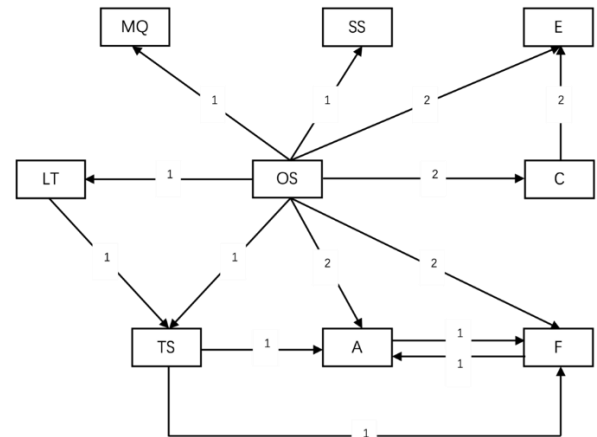
Another apparent characteristic is that Other Services (No.9) has a pushing effect on every other sector in the table. As a developed country, the service sector has the largest share of the UK's economy, reaching nearly 79.6% of the total economic output in 2022. Therefore, the service industry inevitably provides a certain amount of output to other industries. For example, the restaurant and hotel service may stimulate the growth of the manufacturing of food products (No.3), whereas 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 industries 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 to industry j and the backward demand-pull effect of industry j on industry i . In Table 4, for instance, 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 effect of the construction industry on Agriculture also needs 3.38 steps. The smaller the number of APLs, the closer the relationship between the two industries, and vice versa. This indicates that industries with a more considerable economic distance may involve consecutive economic activities during transformation, which may significantly influence the country's economic growth. On the contrary, their individual demand and supply changes may affect closer related industries with smaller steps. The APLs on the diagonal are relatively smaller than the rest 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 Table 3 and Table 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, gas distribution, steam, and air conditioning distribution and supply (No.4), while the construction industry has a two-step pulling effect on Other Services (No.9).

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



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

Figure 2 shows that the construction industry (C) relates to Other Services (OS) and Electricity transmission and distribution, gas distribution, steam and air conditioning distribution and supply (E). Other Services provide construction materials for the construction industry with an economic distance-taking value 2. This indicates that the construction industry has a significant pulling effect on Other Services. Furthermore, the construction industry has a 2-step economic pushing effect 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 connect 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 Manufacture of food products (F) are closely connected with an economic distance value 1. Agriculture provides raw materials, such as crops and meat, for the food industry, whereas the food industry gives back economic support to agriculture. Agriculture and 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 with 1 step, or it

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correlates with agriculture with one economic unit and further links 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 addition, such as labor and capital, of primary products in developed countries is high along the supply chain, the dominant part of the product's price is from the service sector instead of 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), agriculture, and food industry. Due to the high development of the economy, service is a dominant industry in the UK. For instance, the financial sector of the service industry provides sufficient economic support and a large number of consumers' demands for the country's economic growth. Therefore, Other Services is an important industry in the UK's economic 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 more or less correlates to 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 largest economic linkage indicator appears on the diagonal within the construction industry ($f_{5,5} = 0.41$) in Table 6. The construction process indicates the construction industry's progress, leading to a robust internal linkage inside this 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 significant portion of Northern Ireland's economic 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 provides basic equipment needs for agricultural production. On the other hand, Other Services still exist as a supporting industry for NI industries.

Table 6, Table 7, and Table 8 show the economic linkages and APLs between Northern Ireland's industries using data in 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)

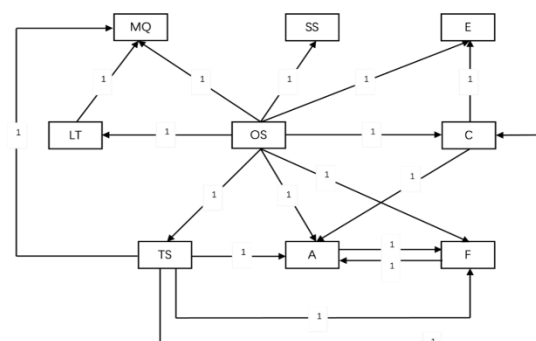
No.	1	2	3	4	5	6	7	8	9
1	0.14	1.95	1.28	1.95	2.18	2.35	2.06	2.26	2.19
2	2.76	0.04	2.14	2.08	1.49	2.36	2.63	2.98	2.36
3	1.29	2.12	0.26	2.68	2.99	1.49	1.66	1.78	1.63
4	1.72	1.45	1.83	0.11	2.27	1.72	1.49	1.44	1.46
5	1.84	2.64	2.74	1.56	0.41	1.86	2.31	2.09	1.78
6	1.56	1.33	1.57	2.08	1.78	0.06	1.7	2.03	1.62
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

Different from the UK, the Wholesale trade services (No.6) and Land transport (No.7) are closely connected to Mining and quarrying (No.2). Wholesalers sold goods and services to the mining industry, including the industrial equipment for mining and mineral extraction. Therefore, this industry also has a pushing effect on the construction industry due to the large 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 timely material usage 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 indicates 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 2 steps to go from one sector to the other, 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 Table 6 and Table 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 connected with the electricity industry and service industry. Agriculture, the food industry, and wholesale trade services are closely related to exchangeable linkages. However, additional connections appear in this figure. First, the distance between Other Services (OS), the construction industry (C), and the electricity industry (E) takes the value of 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, while considering the economic development, these three industries should be placed together to reach the maximum economic benefit. Second, the construction industry has several new connections in the figure. It exerts a pushing effect on agriculture with 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 further to agriculture with a distance of 2 in total. 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 demand many facilities and components to install and construct large 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, showing the close economic connections between wholesale trade service and the construction and mining industries.

C. Scotland Case

In Scotland, the threshold of economic indicator takes the value of 0.03. Table 10 shows the largest economic linkages that appear inside the electricity industry ($f_{4.4} = 0.48$) and 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, different from Northern Ireland, the construction industry (No.5) in Scotland does not have a significant impact on agriculture (No.1). This is because the majority of Scotland's land is defined as a rural area. 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 little 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. In addition, traditional open-pit coal mining is hazardous to the environment. Due to the prevalence of environmentally friendly sustainable development, old mines cease to operate. Hence, the economic linkage is weak between mining and quarrying and other sectors of the economy.

Table 9, Table 10, and Table 11 show the economic linkages and APLs between Scotland's industries using data in 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

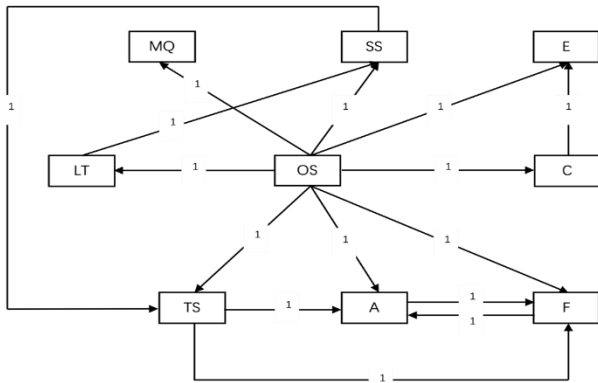
Table 11: Economic Distances Between SCT Industries (Compiled by Author)

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 the shortest economic distance appears inside every industry. Other industries more or less have pushing and pulling effects on other industries, most of which have an average of 2-step economic linkage, similar to the situation in Northern Ireland. Besides, as shown in Table 12, all significant economic distances in Scotland take the value of 1. This indicates that important industries in Scotland are closely and directly connected. Every industry can directly cooperate without intermediate steps. Therefore, the links between Scottish businesses are very strong. The economic development of one sector may result in joint development between closely linked industries.



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



[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) directly connects to the electricity industry and service sector. However, different from Northern Ireland, the construction industry is not linked to agriculture (A) due to the large area of rural lands in Scotland, decreasing the demand for facilities for large-scale production. Also, the figure shows that land transport (LT) does not link to mining and quarrying (MQ), but it connects to warehousing and support services for transportation (SS). This is because the service sector dominates the economy, while environmental concerns arise considering traditional coal mining. On the other hand, more efficient transport systems take place to facilitate other industries. The advent of different modes of transport, such as bridges, tunnels, airports, and harbors, has made it possible to connect land transport more easily with other transports, leading to a strong linkage 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 jewelry, while cargo ships are prone to transport 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 gives Other Services (OS) another way to connect to trade services. There are three routes between OS and TS:

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

The diverse choice 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 labor and capital inputs for the construction and

electricity and gas industries, while the construction industry also accelerates the development of the electricity and gas industry. The difference here is that the distance between these industries takes 2 steps in the UK but decreases to 1 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 strong pushing effects on them in all regions. Agriculture is the primary food source, and the development of the food industry increases agricultural demand. In a modern economy, food marketing becomes a meaningful way to enhance joint development, thus linking trade services to these two sectors. The only difference is 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, different from 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 the heart of economic growth instead of the construction industry. The regional industrial supply chain figures show that Other Services (OS) has close connections to every other key industry in the UK, NI, and SCT, and most pathways have a distance of 1 step. On the contrary, the construction industry merely connects to the electricity industry as shown in the figures above. As a developed European country, the UK's economy has transformed from industrialized to the tertiary sector, mainly the service sector. At the same time, since environmental concerns have become more significant, the pulling and pushing effects of the construction industry are further weakened in favor 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 economic structure, it cannot grow sustainably without other sectors. Other sectors "feed" the service sector as they provide raw materials for the development of labor and capital.

V. CONCLUSION

This paper uses input-output tables based on the 2019 data for the UK, Northern Ireland, and Scotland to calculate the economic linkages and APLs and study the industrial chains. Different from developing countries, the construction industry acts as a "basic industry" rather than a "pillar industry" in the UK. This industry is only 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 services. The main reason for different places of the construction industry is the different 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, since the influence of the construction industry declined, the service industry has taken the lead in the economy in the UK [10]. Other Services, involving personal and organizational service activities, appear at the heart of the three supply chains in this paper [11]. This sector has a significant pushing effect on all the rest primary industries based on APL analysis [12]. Moreover, other service industries, such as Land transport services and Wholesale trade services, have strong connections in the supply chains as well. Since the economic growth continues in the UK, these industries will constantly provide the impetus for industrial development.

Third, the economic distance between industries is very short, showing strong inter-industrial connections in the supply chain. Most economic linkage indicators take the value of 1, indicating 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, the promotion of the service sector is significant. Since the service sector has the most considerable pushing effect on the economy, the growth of the service industry will lead to the co-progress of other industries.

Fourth, different regions have unique industrial structures. Linkages between the construction industry and other sectors decrease from 2 to 1 in Northern Ireland and Scotland compared to the UK. The construction industry in Northern Ireland, for instance, has a strong pushing effect on agricultural production due to the significance of farming there. In Scotland, mining and quarrying have no significant connections with land transport as a result of the environmental concerns arising from traditional coal mining. To a certain extent, unique industrial chains in different regions express the characteristics of the industrial structures in different regions.

DECLARATION STATEMENT

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

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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

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AUTHOR PROFILE



Metin Piskin, received his Ph.D. from the Department of Economics at Istanbul Technical University in 2018. During his thesis, he has been as a visiting researcher at the Regional Economics Applications Laboratory at the University of Illinois at Urbana-Champaign (USA), focusing on sub-national General Equilibrium Modeling. Subsequently, between 2018 and 2022, he worked as a faculty member in the Department of Economics at Sabahattin Zaim University. From 2022 to 2024, he pursued postdoctoral research at the University College London (UCL) Institute for Sustainable Resources. At UCL, he focused on macroeconomic modeling of the circular economy in the construction sector, particularly the cement industry in the United Kingdom. He continues to work on Regional General Equilibrium models for Turkey and

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the United Kingdom, addressing various dimensions, including transportation investments, climate change, and circular economy.

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