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PRODUCTION CHAINS IN AN INTERREGIONAL FRAMEWORK: IDENTIFICATION BY MEANS OF AVERAGE PROPAGATION LENGTHS

ERIK DIETZENBACHER
Faculty of Economics, University of Groningen, Netherlands, and Regional Economics Applications Laboratory (REAL), University of Illinois at Urbana-Champaign, h.w.a.dietzenbacher@rug.nl

ISIDORO ROMERO
Faculty of Economics and Business Sciences, University of Seville, Seville, Spain, isidoro@us.es

When linkages between industries are studied from the perspective of production chains, sequencing is important. In this respect, both the strength of the linkages and the distance between industries are relevant. Distance is measured by the average propagation length, defined as the average number of steps it takes a stimulus in one industry to propagate and affect another industry. Using the 1985 intercountry input–output table for six European countries, we present three applications—visualizing the production structure by graphing its production chains, analyzing intercountry linkages between industries, and determining the role that each country plays within the system.

Keywords: *input–output analysis; production chains; linkages*

1. INTRODUCTION

Product or supply chains give a detailed description of all the steps taken in the production process of a good or service. This runs from the initial phase to the final product. Typically, supply chains are studied for a single good. Recently enterprise input–output models have been suggested for their analysis (see Albino et al. 2002, 2003).[1] In life-cycle assessments, the scope is further extended by considering products from the cradle to the grave, focusing on

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material and energy requirements and environmental issues, such as emissions and disposals of solid waste (see e.g., Joshi 2000).

This paper aims to describe or visualize the production processes in a group of national economies using an interregional (or intercountry) framework.[2] Interdependencies in the production structure of different countries are relevant in a globalized economy where perturbations quickly propagate from one country to another through industries and markets. We adopt the underlying concept of sequencing in supply chains by viewing production as a stepwise procedure. Consistent with the ideas of the Austrian school in economics, some industries should be placed in an early stage and other industries in a later stage when analyzing the production processes.[3] A detailed overview of the production processes would require an in-depth study of all product chains. However, many different goods and services are produced, and each industry is involved in a large set of product chains. An adequate description of the supply chains of all goods and services in an economy is therefore impossible. Even if input–output tables at their most detailed level (which comprise some 500 industries/commodities) were used, this would be a formidable task. Also, it should be noted that the classification in such tables still represents aggregates of groups of commodities, implying that the data cannot reflect "true" product chains. At the same time, the question arises whether this level of detail is desirable to visualize the production processes.

In this paper we will not study separate product chains. Instead, we aim at finding chains in the national and intercountry production structures. These chains are termed production chains, in contrast to product chains that focus on a single product. To sketch the methodology that we have used, consider the following simple example. The agricultural industry supplies a large part of its production to food processing, a major supplier for hotels and restaurants. There are direct links between agriculture and food processing and between food processing and hotels and restaurants. The link between agriculture and hotels and restaurants is indirect (via food processing). In determining this production chain, two aspects are important—the strength of the various links and the number of steps.

Measuring the strength of the links between industries has led to a substantial body of literature.[4] Various alternative measures have been proposed for such interindustry linkages. One of the ways to distinguish between linkage measures is by asking whether the measures go through the production chain in a backward or a forward fashion. If, for example, consumers make more use of hotels and restaurants, this industry requires more products from the food processing industry, which in turn needs more inputs from agriculture. In analyzing the linkages, note that hotels and restaurants depend on their purchases from food processing, which depends on inputs from agriculture. The dependencies in this backward approach are clearly buyers' dependencies. In the same way, we may trace a cost-push in agriculture in a forward fashion through the production chain to affect the total output value of hotels and restaurants. In this case, agriculture depends on its sales to food processing, which depends on its sales to hotels and restaurants. The dependencies in this forward approach are sellers' dependencies.

It should be stressed that these two approaches generally yield very different outcomes. As an example, suppose that hotels and restaurants (with an output value of $1,000) buy for $300 from food processing (with an output value of $3,000). Hence, inputs that are worth 30 percent of the output value of hotels and restaurants are bought from food processing, while food processing sells only 10 percent of its outputs to hotels and restaurants. The (direct) backward dependence of hotels and restaurants on food processing is thus much larger than the (direct) forward dependence of food processing on hotels and restaurants. For the determination of production chains, however, both elements need to be taken into account.

The second aspect is the number of steps or distance between the industries. In the example above, the case is simple because there are only three industries and no direct link between agriculture and hotels and restaurants. In general, however, input–output tables show that each industry sells something to every other industry and to itself. Therefore, each industry has a direct link with every other industry (although many of these links may be small in size). To measure the distance between industries, we will use the so-called average propagation length (APL). Taking the backward-looking approach as an example, the APL measures the average number of steps it takes a final demand increase in hotels and restaurants to propagate throughout the production process and affect the output value in agriculture (see also Sonis et al. 1996). In the forward-looking approach, it measures the average number of steps it takes a cost-push in agriculture to affect the output value of hotels and restaurants. The advantage of APLs is that both approaches yield exactly the same answer. So the distance between agriculture and hotels and restaurants does not depend on whether the forward or backward perspective is adopted.

In the next section, we will present our methodology and introduce the details of the APLs. Our empirical applications employ the intercountry input–output table of 1985 for six European countries and are discussed in section 3. First, we analyze the average APLs for the six countries and their aggregate, and present a graphical representation of the production chains in the aggregate production structure. Second, we use APLs to study the intercountry linkages between industries. Third, we apply the hypothetical extraction method in connection with APLs to determine the role that each country plays within the group of six. Section 4 summarizes and discusses further extensions of the methodology and further applications.

2. Methodology

For the ease of exposition, we will describe our methodology for the case of a national input–output table with n industries. Specific details for interregional tables will be examined when we discuss the empirical application. Let z_{ij} (the typical element of the matrix $\mathbf{Z}$) denote the domestic intermediate deliveries (in money terms) from industry i to industry j. The typical element f_i of column vector $\mathbf{f}$ denotes the final demand for the goods and services produced by industry i. Final demands include domestic consumption, domestic investments, government expenditures, and gross exports. The typical element w_j of the row vector $\mathbf{w}'$, gives the primary inputs of industry j, which include labor costs, capital depreciation, the operating surplus, and imports. The two accounting equations then yield

$$\mathbf{x} = \mathbf{Ze} + \mathbf{f} \tag{1}$$

$$\mathbf{x}' = \mathbf{e}'\mathbf{Z} + \mathbf{w}' \tag{2}$$

where $\mathbf{x}$ denotes the vector of gross domestic output values in each industry and $\mathbf{e}$ is the column summation vector consisting of ones.

From the backward-looking perspective, define input coefficients as $a_{ij} = z_{ij}/x_j$, or in matrix notation as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, where $\hat{\mathbf{x}}$ denotes the diagonal matrix with the elements of the vector $\mathbf{x}$ on its main diagonal. The coefficient a_{ij} gives the input from industry i that is necessary per dollar of output in industry j. It also reflects the direct backward linkage or dependence of industry j on inputs from industry i. Using the input coefficients, accounting equation 1 can be rewritten as

$$\mathbf{x} = \mathbf{Ax} + \mathbf{f} \tag{3}$$

The solution of this equation yields

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{Lf} \tag{4}$$

where $\mathbf{L} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ denotes the Leontief inverse. If the input coefficients remain the same, an increase $\Delta\mathbf{f}$ in final demands would require that production is increased by $\Delta\mathbf{x} = \mathbf{L}(\Delta\mathbf{f})$. Hence, the typical element l_{ij} gives the (extra) output in industry i, that is necessary to satisfy one (extra) dollar of final demand in industry j. The power series expansion of the Leontief inverse, i.e., $\mathbf{L} \equiv (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots$, yields $\Delta\mathbf{x} = \mathbf{L}(\Delta\mathbf{f}) = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots)(\Delta\mathbf{f})$. The total increase in the output of industry i, due to a final demand increase in industry j $(\neq i)$ by one dollar yields

$$\Delta x_i = l_{ij} = a_{ij} + \Sigma_k a_{ik}a_{kj} + \Sigma_k\Sigma_m a_{ik}a_{km}a_{mj} + \ldots \tag{5}$$

The first term on the right-hand side expresses the direct effect which requires one step. The other terms are the indirect effects. For example, $a_{ik}a_{kj}$ reflects the two-step indirect effect that runs via industry k. That is, the final demand increase in industry j will increase the output of industry k by a_{kj}, which requires extra inputs from (and thus extra output in) industry i. This holds for each industry k so that $\Sigma_k a_{ik} a_{kj}$ gives all two-step indirect effects between industries i and j. In the case $i = j$, also the so-called initial effect must be included because the extra final demand must first be produced. In that case, expression 5 changes into

$$\Delta x_j = l_{jj} = 1 + a_{jj} + \Sigma_k a_{jk} a_{kj} + \Sigma_k \Sigma_m a_{jk} a_{km} a_{mj} + \ldots \quad (6)$$

Next we derive the average propagation length (APL) between industries i and j, extending the technique proposed in Harthoorn (1988). If the final demand in industry j increases by 1, the output in industry i is affected by $\Delta x_i = l_{ij}$. From 5 it follows that the share a_{ij}/l_{ij} requires one step, the share $\Sigma_k a_{ik} a_{kj}/l_{ij}$ two steps, the share $\Sigma_k \Sigma_m a_{ik} a_{km} a_{mj}/l_{ij}$ three steps, etcetera. The average number of steps it takes the final demand increase in industry j to affect the output in industry i, thus becomes

$$(1 \times a_{ij} + 2 \times \Sigma_k a_{ik} a_{kj} + 3 \times \Sigma_k \Sigma_m a_{ik} a_{km} a_{mj} + \ldots)/l_{ij} \quad (7)$$

In the case where $i = j$, a similar reasoning applies. Because the initial effect occurs irrespective of the production structure, it does not provide any information on the dependencies and will be neglected (see, for example, Beyers 1983).[5] So a final demand increase by one in industry j yields (next to the initial effect) an increase in this industry's output of $\Delta x_j - 1 = l_{jj} - 1$. Using expression 6 gives for the APL

$$(1 \times a_{jj} + 2 \times \Sigma_k a_{jk} a_{kj} + 3 \times \Sigma_k \Sigma_m a_{jk} a_{km} a_{mj} + \ldots)/(l_{jj} - 1) \quad (8)$$

Note that the numerator in expressions 7 and 8 is given by the elements (i,j) and (j,j) of the matrix $\mathbf{H} = 1 \times \mathbf{A} + 2 \times \mathbf{A}^2 + 3 \times \mathbf{A}^3 + \ldots = \Sigma_{t=1}^{\infty} t\mathbf{A}^t$. Premultiplying $\mathbf{H}$ by $(\mathbf{I} - \mathbf{A})$ gives $(\mathbf{I} - \mathbf{A})\mathbf{H} = \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots = \mathbf{L} - \mathbf{I}$. Hence $\mathbf{H} = \mathbf{L}(\mathbf{L} - \mathbf{I})$.[6] The APLs are thus obtained as h_{ij}/l_{ij} for $i \neq j$ and as $h_{jj}/(l_{jj} - 1)$.

Next we consider the forward-looking approach. Using the sellers' perspective, output coefficients are defined as $b_{ij} = z_{ij}/x_i$ (or $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z}$), which gives the share of the output of industry i that is sold to industry j. It reflects the direct forward dependence of industry i on sales to industry j. Accounting equation 2 can now be rewritten as $\mathbf{x}' = \mathbf{x}'\mathbf{B} + \mathbf{w}'$, and its solution yields $\mathbf{x}' = \mathbf{w}'(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{w}'\mathbf{G}$. This model is well known as the supply-driven input–output model proposed by Ghosh (1958).[7]

The element g_{ij} of the Ghosh inverse $\mathbf{G} \equiv (\mathbf{I} - \mathbf{B})^{-1}$ reflects the total (or direct plus indirect) dependence of industry i on industry j.[8] In deriving the APL between industries i and j ($\neq i$), consider an increase in the primary costs of industry i by one dollar. The output value in industry j increases by $\Delta x_j = g_{ij} = b_{ij} + \Sigma_k b_{ik} b_{kj} + \Sigma_k \Sigma_m b_{ik} b_{km} b_{mj} + \ldots$. The first term gives the (one-step) direct effect, the second term the two-step indirect effect, the third term the three-step indirect effect, and so forth. The average number of steps it takes a cost-push in industry i to affect the output value in industry j is thus given by

$$(1 \times b_{ij} + 2 \times \Sigma_k b_{ik} b_{kj} + 3 \times \Sigma_k \Sigma_m b_{ik} b_{km} b_{mj} + \ldots)/g_{ij}$$

The numerator can be written as $\tilde{h}_{ij}$, with $\tilde{\mathbf{H}} = \mathbf{G}(\mathbf{G} - \mathbf{I})$, and the APLs are given by $\tilde{h}_{ij}/g_{ij}$. When $i = j$, the APLs are (similar to backward-looking case) given by $\tilde{h}_{jj}/(g_{jj} - 1)$ due to neglecting the initial effect.

Finally, we show that the APLs are the same for the forward and the backward case. From the definition of the input and the output coefficients it follows that $b_{ij} = a_{ij}x_j/x_i$, or $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}}$. As a consequence we have $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1} = \hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{x}} = \hat{\mathbf{x}}^{-1}\mathbf{L}\hat{\mathbf{x}}$ and also $\mathbf{G} - \mathbf{I} = \hat{\mathbf{x}}^{-1}(\mathbf{L} - \mathbf{I})\hat{\mathbf{x}}$. Therefore $\tilde{\mathbf{H}} = \mathbf{G}(\mathbf{G} - \mathbf{I}) = \hat{\mathbf{x}}^{-1}\mathbf{L}(\mathbf{L} - \mathbf{I})\hat{\mathbf{x}} = \hat{\mathbf{x}}^{-1}\mathbf{H}\hat{\mathbf{x}}$. That is, $\tilde{h}_{ij} = h_{ij}x_j/x_i$ and $g_{ij} = l_{ij}x_j/x_i$. For the APL in the forward case we thus find $\tilde{h}_{ij}/g_{ij} = h_{ij}/l_{ij}$, which is the APL in the backward case.

3. Application to the 1985 Intercountry Input–Output Table for Six European Countries

For our empirical analysis, we have used the intercountry input–output table for six European countries in 1985—Germany (G), France (F), Italy (I), Netherlands (N), Belgium (B), and Denmark (D). The table is constructed by combining the harmonized national input–output tables (see Eurostat 1979) of the six countries. In these tables the domestic transactions are valued in producers' prices, and the imports in ex-customs prices. Furthermore, the imports are described as being from within and outside the European Union (EU). To obtain the intercountry tables, the imports from within the EU have been disaggregated into country of origin using international trade data. Then to the thus obtained table of bilateral transactions, the RAS method has been applied to reassess the ex-customs valuation of intra-EU imports approximately into producers' prices. The full details of the construction method are given in van der Linden (1999); a summary is given by van der Linden and Oosterhaven (1995).[9]

The resulting table covers twenty-five industries and is a full interregional type of table. That is, all deliveries z_{ij}^{rs} from industry i in country r to industry j in country s are available. For our purpose of sketching the chains in the production structure, the original twenty-five-industry level provides too many details that blur the picture. Therefore, we have further aggregated the table to eight industries—Agriculture (AG), Energy (EN), Metal-related manufacturing (ME), Agro-related manufacturing (AM), Building and construction (BU), Other manufacturing (OM), Market services (MS), and Public services (PS). This implies that the starting-point for our calculations is a 48×48 matrix $\mathbf{Z}$ of intermediate deliveries. This matrix can be partitioned as follows:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{GG} & \mathbf{Z}^{GF} & \mathbf{Z}^{GI} & \mathbf{Z}^{GN} & \mathbf{Z}^{GB} & \mathbf{Z}^{GD} \\ \mathbf{Z}^{FG} & \mathbf{Z}^{FF} & \mathbf{Z}^{FI} & \mathbf{Z}^{FN} & \mathbf{Z}^{FB} & \mathbf{Z}^{FD} \\ \mathbf{Z}^{IG} & \mathbf{Z}^{IF} & \mathbf{Z}^{II} & \mathbf{Z}^{IN} & \mathbf{Z}^{IB} & \mathbf{Z}^{ID} \\ \mathbf{Z}^{NG} & \mathbf{Z}^{NF} & \mathbf{Z}^{NI} & \mathbf{Z}^{NN} & \mathbf{Z}^{NB} & \mathbf{Z}^{ND} \\ \mathbf{Z}^{BG} & \mathbf{Z}^{BF} & \mathbf{Z}^{BI} & \mathbf{Z}^{BN} & \mathbf{Z}^{BB} & \mathbf{Z}^{BD} \\ \mathbf{Z}^{DG} & \mathbf{Z}^{DF} & \mathbf{Z}^{DI} & \mathbf{Z}^{DN} & \mathbf{Z}^{DB} & \mathbf{Z}^{DD} \end{bmatrix}$$

The 8×8 submatrices $\mathbf{Z}^{rr}$ give the domestic deliveries within country $r = G, F, I, N, B, D$. The 8×8 submatrices $\mathbf{Z}^{rs}$ give the deliveries from country r that are used as inputs in country s (with $r, s = G, F, I, N, B, D$). Note that the imports from the rest of the world are included in the primary inputs. The exports of country r to private consumers or investors in one of the other five countries, as well as all exports to the rest of the world, are included in the final demand vector of country r.

3.1. *National and Aggregate Results*

As a first exercise, we consider the national results and the results for the aggregate of the entire region. That is, we have calculated the APLs on the basis of the domestic deliveries $\mathbf{Z}^{rr}$ for each country r separately. Also, we have aggregated the six countries as if they were a single region or country, using $\mathbf{Z}^{AGGR} = \Sigma_r \Sigma_s \mathbf{Z}^{rs}$. Table 1 lists the APLs as calculated from the aggregate input–output table for the six countries. Note that it follows from the definition that the APL between two different industries cannot be smaller than one (and typically is larger than one). The same holds for the APL between an industry and itself. An APL close to one reflects that the dependence is primarily direct, and indirect linkages play a minor role. Although we will focus primarily on the APLs between two different industries when determining the production chains, it is interesting to observe that the lowest APL values are found principally on the diagonal, i.e., from an industry to itself. This indicates that the self-dependence of the industries is very direct. Due to the substantial aggregation, each industry consists of many subindustries. It turns out that subindustries within any industry i exhibit a strong direct dependence on other subindustries in the same industry. The dependence is thus not brought about via one (or more) other industries, implying that the interindustry feedbacks (see Dietzenbacher and van der Linden 1997) are very small. To some extent, this also reflects the effects of outsourcing.

In interpreting the results in table 1, recall that each figure has a double interpretation. For example, the APL of 3.49 in row AG and column EN indicates the average propagation length of a cost-push in agriculture to affect the output value in energy. It deals with the dependence (which is directed forward) of agriculture on energy. At the same time, however, it gives the average propagation length of a demand-pull (which is directed backward) from energy to agriculture. So each figure may be interpreted in two directions. To avoid any confusion, we will use the terminology forward APL or backward APL,

TABLE 1. Average Propagation Lengths for the Aggregate Case

	AG	*EN*	*ME*	*AM*	*OM*	*BU*	*MS*	*PS*	*UA*	*WA*
AG	1.48	3.49	3.57	1.60	2.58	3.45	2.54	2.61	2.67	1.66
EN	2.01	1.31	2.15	2.34	1.84	2.39	1.88	1.93	1.98	1.79
ME	2.39	1.94	1.53	2.62	2.14	1.74	2.12	1.91	2.05	1.68
AM	1.70	2.80	2.57	1.56	2.11	2.71	1.84	1.79	2.13	1.73
OM	1.92	2.20	2.01	2.17	1.46	1.54	2.41	1.95	1.96	1.72
BU	2.16	1.47	2.45	2.68	2.42	1.40	1.51	1.38	1.93	1.55
MS	2.15	1.88	1.99	2.08	1.95	1.85	1.51	1.82	1.91	1.73
PS	2.03	1.76	2.06	2.29	1.98	2.21	1.60	1.18	1.89	1.44
UA	1.98	2.11	2.29	2.17	2.06	2.16	1.93	1.82	2.06	
WA	1.78	1.50	1.76	1.79	1.74	1.73	1.64	1.65		1.70

Note: AG = Agriculture; EN = Energy; ME = Metal-related manufacturing; AM = Agro-related manufacturing; OM = Other manufacturing; BU = Building and construction; MS = Market services; PS = Public services; UA = Unweighted average; WA = Weighted average.

depending on the type of interpretation. For example, the value 3.49 above gives the forward APL from AG to EN or, similarly, the backward APL from EN to AG. The smallest forward APLs (< 1.60)—neglecting the self-dependencies—are found from other manufacturing to building; from building to energy; from building to market services; and from building to public services. The largest forward APL values (> 3.00) are those from agriculture to energy; from agriculture to metal-related manufacturing; and from agriculture to building.

Next to a column with unweighted averages, table 1 includes a column with weighted averages. The weighted average forward APL for industry i is obtained as $\Sigma_j APL_{ij}(z_{ij}/\Sigma_j z_{ij})$, where z_{ij} are the intermediate deliveries which are used to reflect the size. In the same way, the weighted average backward APL for industry j is obtained from $\Sigma_i APL_{ij}(z_{ij}/\Sigma_i z_{ij})$ and the weighted overall average APL as $\Sigma_i \Sigma_j APL_{ij}(z_{ij}/\Sigma_i \Sigma_j z_{ij})$. It is interesting to note that all weighted averages are substantially smaller than the unweighted averages. This is caused by the fact that the linkages with a small APL (where direct linkages play a major role) are the ones with the largest weights. Note that the direct linkages are implicitly employed when using the intermediate deliveries as weights.

The most extreme example is the drop in the average forward APL for agriculture, from 2.67 in the unweighted case to 1.66 when using weights. It turns out that 70 percent of the intermediate deliveries go to agro-related manufacturing and 22 percent to agriculture itself. All the other linkages have a large APL, but appear to be almost irrelevant in terms of size. The agricultural industry thus has a strong and "short" connection to agro-related manufacturing and weak and "distant" connections to any other industry. Only the strong linkages will be taken into account when the production structure is visualized (in section 3.2). Because large direct linkages (i.e., large weights) typically induce strong linkages, the substantial decrease from unweighted to weighted averages

TABLE 2. Averages of the Average Propagation Lengths (APLs)

	Countries					
	Germany	*France*	*Italy*	*Netherlands*	*Belgium*	*Denmark*
Industries	Unweighted Average Forward APLs					
AG	2.48	2.55	2.57	2.43	2.16	2.32
EN	1.94	1.72	1.77	1.78	1.44	1.65
ME	2.01	1.79	1.90	1.65	1.44	1.67
AM	2.11	1.88	2.01	1.98	1.57	1.77
OM	1.93	1.66	1.83	1.66	1.41	1.73
BU	1.95	1.93	1.85	1.88	1.64	1.87
MS	1.89	1.75	1.77	1.66	1.40	1.62
PS	1.95	1.72	1.82	1.63	2.12	1.72
Average	2.03	1.87	1.94	1.83	1.65	1.79
Industries	Unweighted Average Backward APLs					
AG	1.81	1.85	2.00	1.85	1.57	1.57
EN	2.16	1.84	1.93	1.82	1.55	1.93
ME	2.27	2.01	2.08	1.83	1.82	1.86
AM	2.06	2.04	1.96	1.97	1.69	1.95
OM	2.04	1.75	1.93	1.74	1.58	1.69
BU	2.11	2.08	2.15	2.04	1.97	1.90
MS	1.90	1.81	1.77	1.75	1.60	1.79
PS	1.90	1.62	1.68	1.66	1.40	1.65
Average	2.03	1.87	1.94	1.83	1.65	1.79

Note: Industries: AG = Agriculture; EN = Energy; ME = Metal-related manufacturing; AM = Agro-related manufacturing; OM = Other manufacturing; BU = Building and construction; MS = Market services; PS = Public services.

indicates that the production structure will be characterized by connections that are direct, or require only one intermediate step.

A summary of the national domestic results is given by table 2 with unweighted average forward and backward APLs. Note that the two rows with overall averages are identical. Comparing the results, observe that the average APLs (forward or backward) for the aggregate case in table 1 are—almost without exception—larger than those in table 2 for any country. This is intuitive because at a national level there will be fewer and smaller domestic linkages than at the aggregate level. At a national scale of analysis, the identified production chains may therefore be expected to be shorter than in the case where international linkages are included.

A second observation arises when we compare the separate country results. A clear distinction can be made between the three large countries (Germany, France, and Italy) and the three small countries (Netherlands, Belgium, and Denmark). Small countries rely less on their own production structures than larger countries. The small countries depend much more on inputs from other countries (including the three large partners), so that their domestic linkages will be smaller and fewer. This is reflected by shorter domestic production chains. In this respect, it is interesting to note that Denmark's average APL is fairly large given its size. A similar observation was made by Dietzenbacher and van der Linden (1997), i.e., Denmark being surprisingly self-supporting for such a small economy and therefore behaving as if it were much larger than its actual size. The relationship of scale and the degree of self-support on the one hand, and the average size of the APLs on the other hand, is also confirmed by Dietzenbacher et al. (2005). In a preliminary analysis to test the methodology, they found that for Andalusia (a region in the south of Spain) the average APL was 1.56, and the maximum was 2.64. The calculations were based on the intraregional deliveries in the 1995 Andalusian input–output table, distinguishing six industries.

Third, observe that the domestic production structures show clear similarities. For example, the largest average forward APLs for a country are—almost invariably—found for agriculture and agro-related manufacturing, while market services and other manufacturing have the smallest. For the average backward APLs, large values occur for building and construction, metal-related manufacturing, and agro-related manufacturing, while the smallest values occur in public services. Occasionally, however, "outliers" occur, such as the average backward APL for energy, which is the second smallest in Belgium and the second largest in Germany. To a large extent this is caused by the fact that the Belgian energy industry depends largely on imports; the German energy industry depends on domestic industries. The domestic linkages are thus fewer and smaller in Belgium than in Germany, and the APLs are therefore smaller. A comparison between countries on the basis of the weighted average APLs (not shown in table 2) sketches a picture that is somewhat more diversified. This implies that these larger differences are caused by the differences in the national weighting schemes (i.e., the mix of intermediate deliveries), not by the APLs.

3.2. Visualizing the Structure of Production

For the visualization of the production structure, we will focus on the aggregate case, and we will single out the important linkages. Taking the size (or strength) of the linkages into account can be done in various ways, because many measures for linkages have been proposed. Consistent with the development of the APL, our choice is based on the total size of the effect of a cost-push and the effect of a demand-pull. Neglecting the initial effects (as we have done in section 2), these effects are obtained from the matrices $\mathbf{G} - \mathbf{I}$ and $\mathbf{L} - \mathbf{I}$, respectively. Recall that one of the attractive features of APLs was that it did not matter whether the forward approach of a cost-push or the backward approach of a demand-pull was considered. We would also like to retain this property when measuring the size of the linkages. So instead of using the Leontief inverse for the backward linkages and the Ghosh inverse for the forward effects, we have used the average to take both directions into account. The linkages are given by the elements of the matrix $\mathbf{F}$, which is defined as follows.

TABLE 3. Linkages between the Industries

	AG	*EN*	*ME*	*AM*	*OM*	*BU*	*MS*	*PS*
AG	***0.133***	0.004	0.034	***0.477***	0.040	0.011	0.117	0.054
EN	0.080	***0.265***	***0.161***	0.098	***0.161***	0.059	***0.156***	0.086
ME	0.033	0.044	***0.445***	0.033	0.049	0.084	0.052	0.065
AM	0.100	0.007	0.049	***0.302***	0.047	0.020	0.118	0.080
OM	0.061	0.016	***0.145***	0.082	***0.328***	***0.194***	0.061	0.083
BU	0.011	0.023	0.024	0.015	0.015	0.023	0.083	0.038
MS	0.111	0.070	***0.221***	***0.173***	***0.182***	***0.157***	***0.359***	***0.136***
PS	0.020	0.009	0.027	0.022	0.022	0.018	0.052	***0.216***

Note: AG = Agriculture; EN = Energy; ME = Metal-related manufacturing; AM = Agro-related manufacturing; OM = Other manufacturing; BU = Building and construction; MS = Market services; PS = Public services.

$$\mathbf{F} = \frac{1}{2}[(\mathbf{G} - \mathbf{I}) + (\mathbf{L} - \mathbf{I})] \tag{9}$$

The element f_{ij} gives the size of the linkage and equals the average of the forward effect of a cost-push in industry i on the output value in industry j and the backward effect of a demand-pull in industry j on the output in industry i.[10] The matrix **F**, as calculated on the basis of the aggregate input–output table for the six countries, is shown in table 3.

The limitation of focusing entirely on the matrix **F** is that it does not distinguish whether some linkage is mainly direct or indirect. In the latter case, the transmission from one industry to another takes at least two steps. APLs indicate the "distance" between two industries by expressing the average number of steps it takes to transmit a cost-push (or demand-pull) from one industry to the other. The limitation of focusing entirely on APLs is that the size (and thus the relevance) of the transmission itself may be negligible. To visualize the production structure in terms of production chains, both aspects (i.e., relevance of the linkages and distance between industries) are important.

The obvious solution is to combine the two types of indicators. That is, we take APLs into account only if the linkage is sufficiently large, using a threshold value a. In our study, we have taken a threshold value $a = 0.130$. All relevant linkages (i.e., with $f_{ij} \geq a$) are printed in table 3 in bold italics, and the corresponding APLs are given in table 1. For the irrelevant linkages (with $f_{ij} < a$), the APLs are neglected in the graphical representation in figure 1. Each arrow represents a relevant linkage and gives the (truncated or rounded-down) APL. Solid arrows reflect linkages with $1.00 \leq APL_{ij} < 2.00$; dotted arrows are $2.00 \leq APL_{ij} < 3.00$. They are termed APL-1 and APL-2 linkages, respectively. Note that the industry's self-dependence—which is larger than the threshold value in all industries except building and construction—has been omitted. Further, it should be emphasized that the arrows indicate the APLs from a forward perspective. For example, the arrow from agriculture to agro-related

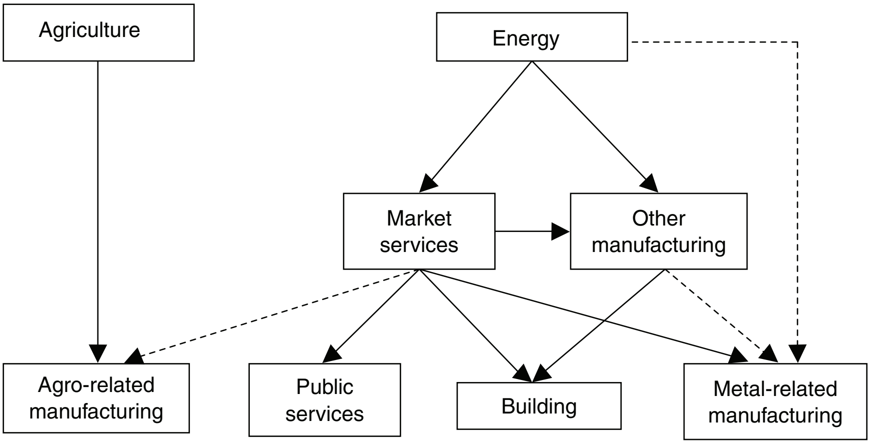


FIGURE 1. Production Chains in the Six-country European Economy

manufacturing indicates the forward dependence of agriculture (in transmitting its cost-push) on agro-related manufacturing. This is consistent with the usual graphs for product chains.

Figure 1 shows a clear distinction between the industries. Agriculture and energy (only outgoing arrows) are located in the beginning of the production chains. Agro-related manufacturing, public services, building and construction, and metal-related manufacturing have only incoming arrows, and are thus situated at the end of the production chains. Market services and other manufacturing take an intermediate position, having both incoming and outgoing arrows. Note that no relevant linkage has an APL that is larger than 3.00. It indicates that "all good things come fast," i.e., all relevant linkages essentially are direct or require only one intermediate step. This is consistent with the findings in table 1. That is, the difference between the unweighted and the weighted averages indicate that the connections with the stronger direct linkages have the smaller APLs. The direct linkages are also an important determinant of the (total) linkages f_{ij}.

Disregarding the APL-2 linkages for the moment, figure 1 shows that there are several production chains leading from energy to building, from energy to public services, and from energy to metal-related manufacturing. In all three cases, other manufacturing and/or market services serve as intermediate steps. Also there is a chain from agriculture to agro-related manufacturing, which is connected to the other chains in the sense that agro-related manufacturing shows an APL-2 backward dependence on market services.

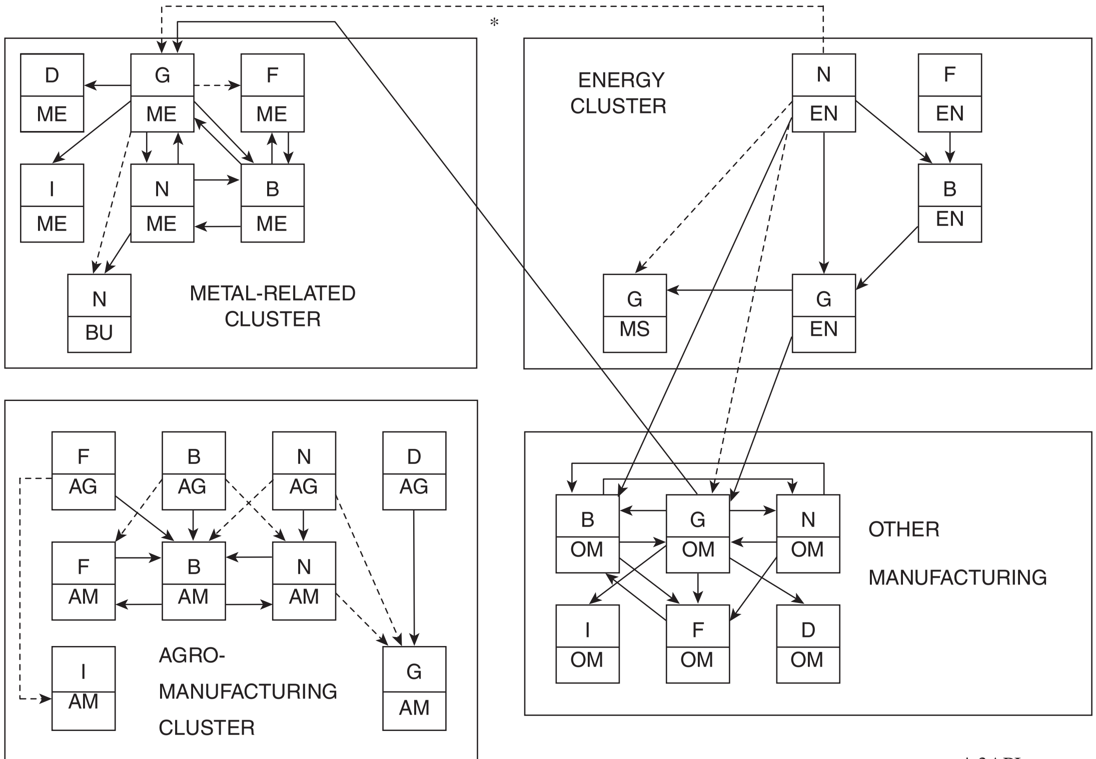
Figure 1 also shows that APL-2 linkages may be consistent with a sequence of APL-1 linkages, but there is no reason why this should always be the case. For example, metal-related manufacturing has a strong direct (i.e., APL-1) backward dependence on market services, which has a strong direct backward dependence on energy. Combining these two APL-1 linkages is consistent with the reported APL-2 arrow from energy to metal-related manufacturing. In contrast to this, the APL-2 linkage between market services and agro-related manufacturing cannot be "explained" from a simple combination of two APL-1 linkages. This case points to an accumulation of connections or routes. Each of them runs via one other industry, and none of these routes is sufficiently important on its own, although they are important as a group (given the fact that this linkage passed the threshold and is reported as APL-2). A similar reasoning holds for the APL-2 linkage between other manufacturing and metal-related manufacturing. The opposite need not be the case. For example, figure 1 shows that the connection between energy and building can be established by two routes based on APL-1 linkages. The first is through market services and the second via other manufacturing. Yet it turns out that even together they are not strong enough to warrant an APL-2 linkage from energy to building.

3.3. Intercountry Linkages

To study the interdependencies between industries in different countries, we have used the full intercountry input–output table. We calculated the 48×48 matrices with APLs and linkages using six countries and eight industries. As expected, it appeared that the intercountry linkages are generally fairly weak when compared to the domestic (or intra-country) linkages. Hence, setting a high threshold will essentially yield domestic linkages. Adopting a sufficiently low threshold will provide the most relevant intercountry linkages, but the picture will be blurred by a very large set of domestic linkages. We have chosen a relatively low threshold value (0.030) and focus only on the intercountry linkages. That is, in our graphical representation and discussion any domestic linkage will be neglected, unless it provides relevant information for intercountry issues.

In figure 2, we have re-grouped the linkages into four clusters to show the intercountry linkages. These are: a metal-related cluster (consisting of metal-related manufacturing and building and construction); an energy cluster (including also market services); an agro-related cluster (with agriculture and agro-related manufacturing); and other manufacturing. Note that no important linkages are found that involve public services. It is also interesting to observe that the central role played by market services in figure 1 has almost completely vanished in figure 2. The APL-2 connection between the German market services and Dutch energy is the only reported intercountry linkage (the APL-1 connection with German energy is domestic). The limited role of market services for intercountry linkages and the absence of public services clearly points to the domestic focus of these industries.

The results exhibit several interesting characteristics. First, almost all intercountry linkages are within a cluster. The only intercountry linkages between clusters are from energy in Netherlands to German metal-related manufacturing,



* 3APL

FIGURE 2. Main Intercountry Linkages Using Average Propagation Lengths

to German other manufacturing, and to Belgian other manufacturing. These strong backward dependencies on the Dutch energy industry clearly reflect the huge amounts of gas exports from Netherlands. Second, within the clusters the intercountry linkages seem to be of an intra-industry nature, except for those within the agro-related cluster. The only two interindusty linkages between two countries within the same cluster are from German metal-related manufacturing to Dutch building and construction, and from Dutch energy to German market services. The agro-related manufacturing cluster reports that the typical, strong forward dependence of agriculture on agro-related manufacturing is also found between countries.

A third finding is that several intra-industry linkages between two countries are mutual. This is the case for metal-related manufacturing, other manufacturing, and agro-related manufacturing. Also, observe that no mutual linkages are found for agriculture and energy, both of which are located at the beginning of production chains. Summarizing our findings, we have seen that intercountry linkages are either intra-industry or between agriculture and agro-related manufacturing, and intra-industry linkages are frequently mutual (except for industries in the early phase of a production chain).

Also for the intercountry linkages, we find that some of the APL-2 arrows are consistent with the combination of two APL-1 links, while some others are not. For example, the Belgian metal-related manufacturing is an intermediate step for the APL-2 forward dependence of the German on the French metal-related manufacturing. In several other cases in figure 2, such APL-2 linkages can be "explained" if domestic APL-1 linkages are included. Also note that the APL-3 linkage between Dutch energy and German metal-related manufacturing is consistent with sequencing three APL-1 linkages (using German energy and German other manufacturing as intermediate steps).

3.4. Extracting Countries

The graphical representation in figure 2 focused entirely on intercountry linkages, which allowed us to gain insight into the dependencies between the countries. A simple count of the incoming and outgoing arrows for each country indicates its role for the other countries. We find twenty-three for Germany and Belgium, twenty-one for Netherlands, thirteen for France, and three for Italy and for Denmark.[11] This preliminary finding suggests that Germany and Belgium are important for the dependencies between countries, whereas Italy and Denmark are not.

One way to quantify the role of a single country within the system is by means of the hypothetical extraction method.[12] The underlying idea is that each country (one at a time) is extracted from the six-country system. For example, if Germany is extracted, the remaining system consists of five countries. The imports from and exports to Germany are treated in the same way as trade with the rest of the world. That is, these flows are not considered when analyzing the

TABLE 4. The Effect of Extracting a Country on Average Propagation Lengths (APLs)

Extracted Country	*Before Extraction*	*After Extraction*	*Percent*
Germany	2.77	2.68	−3.27
France	2.78	2.75	−1.40
Italy	2.74	2.73	−0.51
Netherlands	2.80	2.76	−1.54
Belgium	2.88	2.83	−1.65
Denmark	2.80	2.80	−0.08

linkages within the five-country system. The effect of extracting a country is that the remaining five-country system shows less interactions and a lesser degree of complexity. The linkages will be weaker and fewer, thus the APLs will be smaller. The extent to which the APLs have decreased indicates the relevance of the extracted country within the original six-country system.

For our application we have used the unweighted overall average APL. In the case of extracting Germany for example, the 40×40 matrix with APLs was calculated for the remaining group of five countries (and eight industries). This yields the average APL after extraction, which is compared with the average APL before extraction. The latter is based on the original 48×48 matrix of APLs for the full six-country system. Note, however, that for reasons of comparability the average APL is determined only over the 40×40 APLs that do *not* involve Germany (i.e., the extracted country).

The results of extracting a country are given in table 4. Before we discuss the findings in more detail, it should be emphasized that the size of the average APLs are quite different from those reported in table 1. As a point of reference, the average APL as calculated from the full 48×48 matrix of APLs for the six-country system is 2.84. This is substantially larger than the value of 2.06 that was found for the aggregate in table 1. This remarkable difference is caused by the difference in size of the input–output tables, i.e., 8×8 versus 48×48. Working with the 48×48 table means that, for example, German agriculture is a different industry than French agriculture. When working with the aggregate 8×8 table in section 3.1, these industries were part of a single agriculture industry. The single link in section 3.1 between other manufacturing and energy, for example, now consists of six intra-country and thirty intercountry links. Consequently, the complexity of the production structure in terms of connections between industries is much larger, which is reflected by a much larger average APL. This also points to a potential drawback of using APLs—the results of different studies should be compared only with the greatest care whenever they have employed a different number of industries.

Table 4 shows that extracting a country lowers the average APL of the remaining five countries. The APLs within the five-country system are shortened because the linkages in which the extracted country participates are now considered as external and thus disregarded for calculating the APLs. At first sight, the results in table 4 may seem to contrast the distinction between the large countries (Germany, France, Italy) and the small ones (Netherlands, Belgium, Denmark), as reported in table 2. Consider that the average APLs in table 2 are for domestic linkages; those in table 4 are the APLs for a set of five countries. It turns out that Germany is by far the most important country in terms of its participation in the six-country system; all countries depend to some extent on German imports. Also the extraction of Belgium, Netherlands, and France (in this order) reduces the average APL considerably. The two small countries are very dependent on imports so that every other country extensively trades with them. Extracting Belgium, for example, then implies that the routes through Belgium are no longer available. The role of France is similar to that of Germany, but to a lesser extent. Extracting Italy and, in particular, Denmark has a small (respectively negligible) effect on the length of the chains. Both countries are remarkably independent.

4. Concluding Remarks

In this paper we have studied linkages between industries from the perspective of production chains, so that sequencing plays an important role. Therefore, the distance between two industries is a relevant aspect, next to the strength of the linkage. Distance was expressed by the average propagation length (APL), which was defined as the average number of steps it takes a stimulus in one industry to propagate throughout the production structure and affect another industry (or itself).

Using the 1985 intercountry input–output table for six European countries, we have presented three types of application. First, we showed how combining APLs and linkage sizes allows for a visualization of the production structure by graphing the production chains. The APLs clearly pointed to sequencing the steps in the production processes. Second, we have applied the same methodology to obtain some insight in the intercountry linkages between the industries. It was found that most of the linkages were intra-industry (with the exception of the interindustry linkages between agriculture and agro-related manufacturing). We also observed that many of these intra-industry linkages were mutual for industries located in a later phase of the production chain. Industries in the early phase of the chain (such as agriculture and energy) exhibited only one-way dependencies. Third, we have applied the hypothetical extraction method to calculate the effect on the average APL. Extracting Germany decreased the average APL of the other five countries the most, which indicates that the linkages with and within Germany are the most important for the system of the six countries. Obviously, it would be of great interest to carry out an integrated structural analysis for the entire EU with data for all separate member countries. Unfortunately, an estimate of such an intercountry input–output table is only expected in five years.

There are several directions in which the framework of average propagation lengths may be expanded. One is to incorporate the aspect of time more explicitly into this concept. For example, studying supply chains in the context of inventory control and material requirements planning, Grubbström and Ovrin (1992) use Laplace transforms to incorporate timing. In our framework, we have used the power series expansion of the Leontief inverse to distinguish between, for example, one-step, two-step, and three-step effects. Robinson and Markandya (1973) presented an input–output model in which each step takes a certain amount of time (e.g., a month). They state that "systems are more 'complex' when they require more time and transactions to reach a new equilibrium after some exogenous change" (Robinson and Markandya 1973, p. 121).

A second expansion would involve the application of the methodology to other fields. Examples would be the power structure (including relations and hierarchies) in social networks (see e.g., Burt 1992; Jackson 2006), the property structure within groups of firms that have a silent interest in each other due to cross-shareholding (see e.g., Dietzenbacher et al. 2000; Flath 1993; Turnovec 1999), or the issue of fragmentation in economic geography (see e.g., Jones and Kierzkowski 2005). A more straightforward extension would be to consider APLs in the context of extended input–output models and demo-economic models, taking interregional migration into account (see e.g., Batey and Rose 1990; Madden and Trigg 1990; Oosterhaven and Dewhurst 1990) as an example.

Finally, it should be pointed out that the results obtained from applying APLs have policy relevance. The arrows in our graphs indicate how an exogenous shock in one industry propagates and affects other industries. Suppose, for example, that the Dutch energy industry were struck by an unfortunate event that drastically reduces its capacity. The outgoing arrows in figure 2 (indicating forward dependencies) show that other manufacturing and metal-related manufacturing will be affected in each country.[13] The effects of a final demand shock can be traced similarly in a backward fashion by following the incoming arrows in the opposite direction. The advantage of considering APLs for analyzing such problems is that they provide a sequential ordering of the effects. The traditional linkage calculations provide the size of the effects, and the APLs determine the average number of steps it takes a stimulus to reach and affect its destination. So industries with low APLs will be affected first; industries with large APLs will be affected at a later stage. This is extremely important information in the case of catastrophes, because it may direct the attention to the most urgent industries first.

A further policy application arises when one particular industry is singled out, e.g., agriculture. In that case, it would make sense to calculate the results at a much more detailed level. For instance, in the context of the European intercountry application, we would have used the 150×150 matrix of intermediate deliveries based on twenty-five industries (instead of the eight aggregated industries). The table underlying figure 2 would in this case record 150 rows and columns. However, because the focus would be solely on agriculture, essentially the non-zero elements in the six rows and columns for agriculture would be of particular interest. This would allow us to analyze the position of agriculture in each country and the connections with other industries and other countries. The results of such an investigation might help in addressing agricultural or rural policy issues (see e.g., Hewings 2001). For example, the information might be relevant when decisions have to be made at the EU level about agricultural subsidies. The size of the linkages determines the magnitude of the effects, and the APLs reflect the sequencing or timing of the effects. An interesting question in this respect would be whether domestic APLs are typically smaller than intercountry APLs, also considering sectors that import and/or export.

NOTES

1. For applications of enterprise input–output models, see Polenske and Chen (1991), Tang et al. (1994), Polenske (1997), Grubbström and Tang (2000), Marangoni and Fezzi (2002), and Polenske and McMichael (2002).

2. Several approaches that use input–output tables have been proposed in the past for the purpose of visualizing the structure of production. These include graph theory, structural path analysis, network flow theory, cluster analysis, and qualitative input–output analysis (see Dietzenbacher and Lahr 2001, for an overview).

3. Within an input–output framework, this gave rise to the issue of triangularization (as developed in Simpson and Tsukui 1965). By re-numbering the industries (i.e., permuting the rows and columns), the aim is to find an ordering of industries that leads from primary products to final goods. Ideally, this yields a triangular input matrix that shows only zeros on one side of the main diagonal.

4. Recent overviews of the literature can be found in Kurz et al. (1998); Dietzenbacher and Lahr (2001); Sánchez-Chóliz and Duarte (2003); and Cai and Leung (2004).

5. Alternatively, the initial effect could be considered to have length 0. In that case, the term 0×1 needs to be added in the numerator in equation 8 and the denominator is to be replaced by l_{jj}. A consequence is that the APLs on the main diagonal of table 1 below, will become close to zero, indicating that the initial effect dominates (in size) the direct and indirect effects.

6. In the same way, it follows from $\mathbf{H}(\mathbf{I}-\mathbf{A}) = \mathbf{L}-\mathbf{I}$ that $\mathbf{H} = (\mathbf{L}-\mathbf{I})\mathbf{L}$. Using $\mathbf{L}-\mathbf{I} = \mathbf{AL} = \mathbf{LA}$ provides a set of alternative expressions for $\mathbf{H}$.

7. Although the model produced intuitively appealing results in empirical analyses, it has been heavily criticized and became regarded as theoretically implausible (see Oosterhaven 1988, 1989). Dietzenbacher (1997), however, showed that all implausibilities vanish once the model is interpreted as a price model instead of as a quantity model (which had been the typical interpretation).

8. The matrices **B** and **G** have been proposed before to reflect the forward linkages, see e.g., Beyers (1976); Dietzenbacher (1992); Jones (1976).

9. The full series of European intercountry input–output tables in current prices (for the years 1965, 1970, 1975, 1980, and 1985) can be downloaded at http://www.regroningen.nl. For the intercountry tables in constant prices, see Hoen (2002).

10. Loviscek (1982) used a weighted average of the elements of the two inverse matrices and provided an attempt at interpretation. We do not agree with that interpretation and suggest using the numbers just as an indicator for size of the linkages.

11. Note that only intercountry linkages have been counted, not the domestic linkages in figure 2. It should be emphasized that for specific purposes one might be more interested in backward linkages and thus in incoming arrows, while for other purposes outgoing arrows (indicating forward linkages) would be more appropriate. In the present case, however, we are merely interested in the existence of dependencies, no matter whether forward or backward.

12. The hypothetical extraction method was originally proposed by Paelinck et al. (1965) and Strassert (1968) for extracting industries. In a regional context, the approach was introduced by Miller (1966, 1969). Recent applications include Cai and Leung (2004); Dietzenbacher et al. (1993); Dietzenbacher and van der Linden (1997); and Duarte et al. (2002). For an excellent overview, see Miller and Lahr (2001).

13. Of course, a quantification of such effects requires a more detailed analysis and a full specification of the shock. See, for example, the contributions on "disaster input–output analysis" in Okuyama and Chang (2004).

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