Endogenizing Capital in the Value-Added Analysis of Trade

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Abstract: This paper proposes a new methodology to account for capital goods and services in the analysis of global value chains (GVCs) and trade in value-added (TiVA). In conventional inter-country input-output (ICIO) models, capital is exogenously treated, which may underestimate the actual influence of capital on trade dynamics. Our approach endogenizes capital formation and incorporates both domestic and foreign capital contributions, resulting in the development of novel indicators that more accurately reflect capital's role in trade. By constructing capital flow matrices that trace transactions between industries, we assign value-added associated with capital goods to the industries using them and devise new indicators that measure domestic and foreign capital value-added embodied in exports. Our empirical analysis highlights significant divergences in revealed comparative advantage (RCA) indices calculated with endogenized capital as compared to traditional RCAs based on gross exports or trade flows in value-added terms. The capital RCA approach reveals the export strength of major developed economies rooted in capital goods and services excellence, which traditional RCAs overlook. Comparison with standard TiVA accountings unveils systematically higher shares of value-added in intermediate versus final goods exports when capital is endogenized. This aligned with the role of capital goods in facilitating production across GVCs. Our capital-augmented ICIO framework offers a deeper insight into the interplay between capital and global production processes, thereby supporting more effective trade policy decision-making.

Keywords: Input-Output Analysis, Global Value Chains, Capital Endogenization, Revealed Comparative Advantage

1. Introduction

Fixed capital encompasses long-term physical assets that are used repeatedly in the production process for more than one year, and that were created or accumulated in previous periods (Eurostat, 2008; EC, IMF, OECD, UN & World Bank, 2009; Berrill et al., 2020). Fixed capital is integral to the continuous generation of goods and services. It underpins infrastructure, facilitates transportation and communication, and fulfills modern development and construction needs.

Despite its pivotal role, current Input-Output (IO) models and accounting frameworks for trade in value-added (TiVA) treat capital as an exogenous component in final demand, equivalent to household consumption and government expenditures. This conventional approach neglects capital's substantive contribution to the production of goods and services, potentially leading to an underestimation of its impact on output (Chen et al., 2018). Overlooking capital's crucial role in influencing the output of industries tends to oversimplify the production process.

In the realm of Global Value Chains (GVCs), this oversight becomes particularly consequential, as highlighted by Södersten, Wood and Hertwich (2018) in the context of the assessment of the carbon footprint of final consumption. As GVCs are highly fragmented and complex, with production processes distributed across multiple nations, the need for accurate representation of all contributing factors, including domestic and foreign capital, has intensified. Current accounting frameworks for the measurement of value-added in trade assume capital to be exogenous and do not account for its role in the creation of value. For example, ASML in the Netherlands is a major producer of lithography systems used in semiconductor manufacturing. While the Netherlands has no significant contribution to semiconductor production through the supply of direct intermediate inputs, the country plays a pivotal role in their production through capital goods. Traditional TiVA indicators capture domestic and foreign value-added from intermediate goods and services in exports, but cannot identify the role of the Netherlands in the semiconductors value chain. Capital goods like machinery, equipment, and infrastructure are instrumental in enabling production across GVCs. The exclusion of capital's role in these models not only misrepresents the actual value creation in trade but also limits the understanding of a country's strategic participation in global production networks, as well as interdependencies across countries in terms of capital formation.

To address these gaps, this paper introduces new techniques to endogenize capital formation in inter-country input-output (ICIO) frameworks. In the IO literature, two primary methods have been identified to endogenize capital: the augmentation technique and the flow matrix method. Although not novel, these methods have been widely used and studied (Lee, 1971; Casler, 1983; Wolff, 1985; Gowdy, 1992; Hohmeyer & Walz, 1992). The augmentation method involves adding a separate additional sector to the inter-industry flow matrix to incorporate capital. This approach creates an artificial sector with a homogeneous commodity "capital", which is used and put into production according to the gross fixed capital formation (GFCF) vector and consumed based on the row vector of capital input. In relative terms, the flow matrix method decomposes capital by assets and sectors, creating a separate capital flow matrix. This matrix is then added to the conventional inter-industry matrix to construct the total flow matrix. By doing so, the role of capital is explicitly acknowledged, and the model captures the interdependence between capital and other sectors.

Both methods have their strengths and limitations, and researchers have debated which one is more suitable for different research questions. Lenzen and Treloar (2004) examined the two methods for endogenizing capital transactions in the IO literature. They found that although the augmented method is simpler to use, it leads to systematic overestimation of low/mid-range Leontief multipliers (including capital requirements) and underestimation of high-range multipliers. The reason for this is that the allocation of different types of capital is not representative. On the other hand, the flow matrix method provides more accurate results. However, this approach presents a major challenge as it requires detailed data disaggregating capital inputs by supplying and using sectors, which are typically not available in national accounts.

This paper's contribution lies in applying these capital-endogenized approaches to the analysis of trade in value-added, uncovering potential biases in the traditional TiVA analysis. By doing so, we aim to offer a more complete and accurate depiction of global production sharing and value creation patterns, thus enriching the current understanding of GVCs. We revisit the IO literature with endogenized capital and show how the two methods proposed can be incorporated into ICIO models. This involves creating capital flow matrices that trace capital transactions between industries and incorporating them alongside inter-industry flows. The endogenized capital approach enables assigning value-added associated with capital goods to the industries that use them. We then provide a framework for the calculation of capital-endogenized TiVA indicators and illustrate with an empirical analysis based on OECD ICIO tables how these indicators can differ from traditional TiVA indicators. We focus on the calculation of Revealed Comparative Advantage (RCA) indices to highlight how relevant is this analysis for our understanding of specialization and competitiveness. But the approach can be extended to other types of TiVA indicators such as those used in the context of work on the identification of interdependencies across countries.

The rest of the paper is organized as follows. The next section (Section 2) explains how the two methods found in the literature to endogenize capital in IO models (the capital augmentation and flow matrix methods) can be implemented in the context of ICIO frameworks used for the decomposition of trade flows in value-added terms. Section 3 provides the formulas to decompose gross exports in the capital-augmented model. Section 4 illustrates such decomposition with results and new indicators. Section 5 concludes.

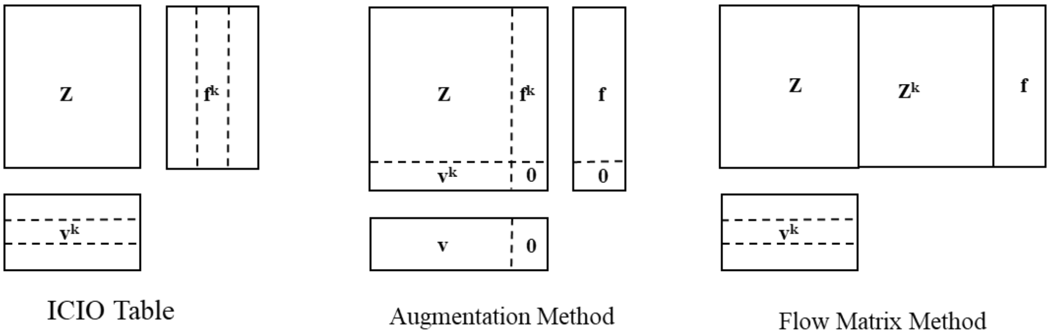
2. Methodologies to endogenize capital in ICIO and TiVA frameworks

In typical ICIO tables, such as those produced by the OECD, the ADB or coming from the WIOD project (Timmer, Dietzenbacher, Los, Stehrer, & de Vries, 2015), information on capital transactions is found in the GFCF columns that are within the final demand matrix. For each row in the table (corresponding to output in a specific country and industry), the GFCF columns indicate the value of capital goods or services produced within this industry and used (as part of gross fixed capital formation) in the countries identified in the columns of the final demand matrix (including the domestic economy and foreign economies). As such, these tables provide a capital matrix in the country-industry of origin and using country dimensions. What are not known are the industries that use the capital goods and services in each country.

To implement the augmentation method for the endogenization of capital, the GFCF columns $\boldsymbol{f^k}$ that are in the final demand matrix can be brought into the intermediate consumption matrix as an additional sector (Figure 1). This 'capital' sector is assumed to produce in each country a homogeneous commodity using the capital goods and services from the different supplying countries and industries that are in the rows of each country-capital column. But the way this homogeneous 'capital' commodity is consumed in each country requires creating capital rows as well that allocate capital inputs across using industries ($\boldsymbol{v^k}$). This information is not available from the ICIO tables. Capital inputs are part of the primary inputs within the value-added vector in such tables and one needs to extract from the value-added vector the contribution of capital (using additional data sources).

To endogenize capital with the flow matrix method, the capital matrix extracted from the final demand matrix needs to be split in columns according to the using industry (Figure 1). This new capital matrix $\mathbf{Z}^{\boldsymbol{k}}$ cannot be derived from existing ICIO tables and requires additional information from national accounts. Some countries have fixed capital matrices in the industry-by-industry dimension (e.g. Japan). When such matrices are not available, one possibility is to derive the information from capital accounts that have data on assets and their use in different industries.

Figure 1. Illustration of the augmentation and flow matrix methods



To build a full international fixed capital matrix in the country-industry (origin) x country-industry (using) dimensions, we need to use techniques similar to those used in the construction of ICIO tables. These techniques link the fixed capital information across countries, based on assumptions and estimation methods to fill data gaps. In this paper, we rely on such an international capital matrix that was created by the OECD (Alsamawi et al., 2020). The international capital flow matrix $\mathbf{Z}^{\boldsymbol{k}}$ is of the same size and dimensions as the inter-industry flow matrix $\mathbf{Z}$ of intermediate consumption (which is provided within ICIO tables).

Several frameworks have been suggested to decompose value added in gross exports (Koopman et al., 2014; Los et al., 2016; Miroudot & Ye, 2021; Borin & Mancini, 2023). We rely in this section on the methods based on extraction matrices developed by Los et al. (2016) and Miroudot and Ye (2021) as they are simple to implement and theoretically funded. We refer to decompositions where domestic and foreign value added are defined from the exporter perspective and provide formulas for the capital-endogenized model that are comparable with Miroudot and Ye (2022) for the conventional TiVA analysis.

The flow matrix method of value-added in trade

With this method, the idea is to use the capital flow matrix $\boldsymbol{Z}^{\boldsymbol{k}}$ and to obtain a capital requirement matrix similar to the inter-industry requirement matrix calculated as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$ (and used to calculate the Leontief inverse $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$). The capital requirement matrix is $\mathbf{K} = \mathbf{Z}^k\hat{\mathbf{x}}^{-1}$. Then, we can re-write the traditional input-output equation as: $\mathbf{x} = (\mathbf{A} + \mathbf{K})\mathbf{x} + \mathbf{y}^k$,where $\mathbf{x}$ is the output vector and $\mathbf{y}^k$ is the final demand vector $\mathbf{y}$ that excludes the GFCF part.

In the capital-endogenized ICIO model, the value of gross exports remains unchanged. We define a new Leontief inverse as $\mathbf{B}^k = (\mathbf{I} - (\mathbf{A} + \mathbf{K}))^{-1}$. To decompose gross exports in this new framework, we define extraction and identification matrices, similar to the ones described in Miroudot and Ye (2021, 2022) for the country perspective. They are expressed as $\mathbf{A}^{k*} = \mathbf{A}^* + \mathbf{K}^*$ and $\mathbf{A}^{k\mathrm{I}} = \mathbf{A}^{\mathrm{I}} + \mathbf{K}^{\mathrm{I}}$. Also, we have $\mathbf{B}^{k*}$=$(\mathbf{I} - \mathbf{A}^{k*})^{-1}$. The vector of exports can be expressed as:$\mathbf{e} = \widetilde{\mathbf{A}}^k\mathbf{e} + \tilde{\mathbf{y}}^k$, with $\widetilde{\mathbf{A}}^k = \mathbf{A}^{k\mathrm{I}}(\mathbf{I} - \mathbf{A}^{k*})^{-1}$.

The augmentation method of value-added in trade

The augmentation method involves moving the GFCF columns into the intermediate input matrix, effectively treating them as an additional sector. We can define a new augmented intermediate input matrix as $\begin{pmatrix} \mathbf{A} & \mathbf{K} \\ \mathbf{V} & \mathbf{0} \end{pmatrix}$ where $\mathbf{K}$ could in practice be a matrix directly created with the GFCF columns of the final demand matrix in the initial ICIO tables. But we can also derive the augmented intermediate input matrix with the same capital matrix $\mathbf{K}$ used before in the flow matrix method for a more precise incorporation of capital flows into the intermediate input matrix and to highlight the consistency of the two methods. In the augmented intermediate input matrix, the elements v_{ij} in matrix $\mathbf{V}$ represents the capital input from sector *i* for each dollar of output in sector *j*. We still have the output expressed as $\mathbf{x} = \mathbf{Ax} + \mathbf{Kx} + \mathbf{y}^c$ and exports expressed as $\mathbf{e} = \widetilde{\mathbf{A}}^k\mathbf{e} + \widetilde{\mathbf{Y}}^k$. The extraction and identification matrices for the decomposition of gross exports are $\mathbf{A}^{k*}$ and $\mathbf{A}^{k\mathrm{I}}$, as in the flow matrix method.

As Lenzen and Treloar (2004) noted, the flow matrix method yields more precise results since capital goods and services are also allocated across using industries. But it comes only from the way the capital information is constructed in the ICIO framework. If the augmented intermediate input matrix is derived from the same capital matrix $\mathbf{K}$ used in the flow matrix method, the two methods produce identical expressions and identical results for the decomposition of value added in exports. Therefore, we can refer to a single capital-endogenized ICIO model without further distinguishing the two methods in the rest of the section.

Capital value added in trade

In the capital-endogenized ICIO model, exports are defined as $\mathbf{e} = \widetilde{\mathbf{A}}^k\mathbf{e} + \widetilde{\mathbf{y}}^k = (\mathbf{A}^{\mathrm{I}} + \mathbf{K}^{\mathrm{I}})(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{e} + (\mathbf{A}^{\mathrm{I}} + \mathbf{K}^{\mathrm{I}})(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{y}^{k*} + \mathbf{y}^{k\mathrm{I}}$. Exports can be divided into two components: exports including capital goods used in production $\mathbf{e}^c = \mathbf{K}^{\mathrm{I}}(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{e} + \mathbf{K}^{\mathrm{I}}(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{y}^{k*}$ and exports not including capital goods $\mathbf{e}^n = \mathbf{A}^{\mathrm{I}}(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{e} + \mathbf{A}^{\mathrm{I}}(\mathbf{I} - \mathbf{A}^* - \mathbf{K}^*)^{-1}\mathbf{y}^{k*} + \mathbf{y}^{k\mathrm{I}}$. Based on the decomposition framework of Miroudot and Ye (2021), we can derive new capital indicators in the value-added decomposition of gross exports.

Domestic capital value-added in exports (for a specific country i) can be calculated as $\mathbf{CDVA} = \mathbf{v}_i\mathbf{B}^*_{ii}\mathbf{e}^c_i$. This indicator measures the domestic value added from capital goods used in the production of country i's exports ($\mathbf{v}$ is the vector of value-added coefficients**,** i.e. the share of value-added in gross output, $\mathbf{B}^*$ is the Leontief inverse based on the extraction matrix $\mathbf{A}^*$ in the conventional ICIO). Foreign capital value added in exports (for country i) is $\mathbf{CFVA} = \sum_{j\neq i}^{G}\mathbf{v}_j\mathbf{B}^*_{ji}\mathbf{e}^c_i$. This indicator can be understood as the foreign value added from capital goods and services used in other countries that is then embodied in country 's exports.

By separating the capital and non-capital components, these new indicators provide additional insight into value generation and trade from a capital perspective. The domestic capital value-added in exports represents the portion of a country's exports value that was generated domestically through capital goods and services production. For example, this would include the value added by Germany's machinery industry embodied in Germany's automotive exports. This indicator highlights the contribution of a country's capital goods and services sector in supporting export competitiveness. A higher share of domestic capital value added signals greater reliance on domestically-produced capital goods and services for exporting industries.

In contrast, the foreign capital value added in exports points to the contribution of capital generated in other countries for domestic export competitiveness. For instance, the indicator can measure Chinese value added from machinery production that ends up in US manufacturing exports (and vice-versa). A higher share of foreign capital value added implies greater dependence on imported capital goods and services to produce exports. It highlights that the provision of key capital equipment has been offshored.

By distinguishing the origin of capital, these indicators provide new insights into the contribution of capital goods and services to trade and export competitiveness. Their evolution over time can track shifts in strategic capital endowments. They complement traditional value-added measures that overlook capital contributions. Moreover, comparing capital-based measures with traditional TiVA metrics can further highlight the significance of capital for understanding trade and GVCs.

Decomposition of gross exports in the capital-endogenized ICIO framework

The decomposition of gross exports in Miroudot and Ye (2021) includes four terms: domestic value added (DVA), domestic double-counting (DDC), foreign value added (FVA) and foreign double-counting (FDC). These components are represented as follows: $\mathbf{DVA} = \mathbf{v}_i \mathbf{B}^*_{ii} \mathbf{e}_i$, $\mathbf{DDC} = \mathbf{v}_i [\mathbf{B}^* \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ii} \mathbf{e}_i$, $\mathbf{FVA} = \sum_{j \neq i}^{G} \mathbf{v}_j \mathbf{B}^*_{ji} \mathbf{e}_i$, $\mathbf{FDC} = \sum_{j \neq i}^{G} \mathbf{v}_j [\mathbf{B}^* \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ji} \mathbf{e}_i$. In these equations, $\mathbf{A}^{\mathbf{I}}$ refers to the identification matrix once exports of interest have been extracted. By merging the expression for exports in the capital-endogenized model $\mathbf{e} = \tilde{\mathbf{A}}^k \mathbf{e} + \tilde{\mathbf{y}}^k$ with these value-added terms, we can obtain similar expressions that decompose gross exports.

The above formulas ignore the sectoral dimension for simplicity. But their implementation in the context of ICIO tables that have industries is straightforward as it requires only to calculate the diagonal matrix of the vB* vectors. Similarly, decompositions from the bilateral perspective (i.e. where double counting is defined as the value added crossing the bilateral border more than once) can be easily derived by substituting the submatrices of $\tilde{\mathbf{A}}$ and $\tilde{\mathbf{B}}$ with $\tilde{\mathbf{A}}^k$ and $\tilde{\mathbf{B}}^k$, as explained in Miroudot and Ye (2022).

Finally, we provide in Table 1 the formulas matching the 8-term decomposition of gross exports (country perspective) from Miroudot and Ye (2022) where the DVA and FVA terms are further decomposed based on the destination of value added in exports (similarly to Koopman, Wang and Wei, 2014).

Table 1. Decomposition of gross exports (country perspective) for the conventional and capital endogenized IO model

	Conventional decomposition (Miroudot and Ye, 2022)	Capital endogenized decomposition
Domestic value added absorbed by foreign countries via final products (DVA_FIN)	$\sum_{j \neq i}^{G} \mathbf{v}_i \mathbf{B}_{ii} \mathbf{y}_{ij}$	$\sum_{j \neq i}^{G} \mathbf{v}_i \mathbf{B}_{ii}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \boldsymbol{y}_{ij}^{k}$
Domestic value added absorbed by foreign countries via intermediate products (DVA_INT)	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \mathbf{v}_i \mathbf{B}_{ii} \widetilde{\mathbf{A}}_{ij} \mathbf{y}_{jk}$	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \mathbf{v}_i \mathbf{B}_{ii}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \widetilde{\mathbf{A}}_{ij}^{k} \boldsymbol{y}_{jk}^{k}$
Domestic value added that returns home (DVA_RET)	$\sum_{j}^{G} \mathbf{v}_i \mathbf{B}_{ii} \widetilde{\mathbf{A}}_{ij} \mathbf{y}_{ji}$	$\sum_{j}^{G} \mathbf{v}_i \mathbf{B}_{ii}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \widetilde{\mathbf{A}}_{ij}^{k} \boldsymbol{y}_{ji}^{k}$
Domestic double-counting (DDC)	$\mathbf{v}_i [\mathbf{B}^{*} \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ii} \mathbf{e}_i$	$\mathbf{v}_i [\mathbf{B}^{*} \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ii} \mathbf{e}_i$
Foreign value added absorbed by foreign countries via final products (FVA_FIN)	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \mathbf{v}_j \mathbf{B}_{ji} \mathbf{y}_{ik}$	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \mathbf{v}_j \mathbf{B}_{ji}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \boldsymbol{y}_{ik}^{k}$
Foreign value added absorbed by foreign countries via intermediate products (FVA_INT)	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \sum_{l \neq i}^{G} \mathbf{v}_j \mathbf{B}_{ji} \widetilde{\mathbf{A}}_{ik} \mathbf{y}_{kl}$	$\sum_{j \neq i}^{G} \sum_{k \neq i}^{G} \sum_{l \neq i}^{G} \mathbf{v}_j \mathbf{B}_{ji}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \widetilde{\mathbf{A}}_{ik}^{k} \boldsymbol{y}_{kl}^{k}$
Foreign value added that returns home (FVA_RET)	$\sum_{j \neq i}^{G} \sum_{k}^{G} \mathbf{v}_j \mathbf{B}_{ji} \widetilde{\mathbf{A}}_{ik} \mathbf{y}_{ki}$	$\sum_{j \neq i}^{G} \sum_{k}^{G} \mathbf{v}_j \mathbf{B}_{ji}^{*} \widetilde{\mathbf{B}}_{ii}^{k} \widetilde{\mathbf{A}}_{ik}^{k} \boldsymbol{y}_{ki}^{k}$
Foreign double-counting (FDC)	$\sum_{j \neq i}^{G} \mathbf{v}_j [\mathbf{B}^{*} \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ji} \mathbf{e}_i$	$\sum_{j \neq i}^{G} \mathbf{v}_j [\mathbf{B}^{*} \mathbf{A}^{\mathbf{I}} \mathbf{B}]_{ji} \mathbf{e}_i$

3. Empirical illustration and discussion

This section provides illustrative results for the year 2015 for which the OECD constructed a capital flow matrix matching the 2018 edition of the OECD Inter-Country Input-Output tables. The work of the OECD is described in Alsamawi et al. (2020).

Capital VA in exports

Table 2. Capital value added in exports for selected economies and sectors

	Sectors	EXP (BN USD)	CHN	DEU	FRA	JPN	KOR	NLD	TWN	USA
CHN	26	493.1	13.76%	0.26%	0.08%	0.60%	0.98%	0.03%	0.87%	0.58%
	27	211.0	14.35%	0.16%	0.05%	0.33%	0.31%	0.02%	0.21%	0.34%
	29	58.4	28.94%	0.55%	0.11%	0.66%	0.48%	0.04%	0.26%	0.72%
DEU	26	50.8	1.19%	18.01%	0.29%	0.22%	0.14%	0.18%	0.13%	0.54%
	27	51.3	0.68%	15.95%	0.34%	0.15%	0.08%	0.17%	0.05%	0.41%
	29	223.9	0.61%	23.02%	0.56%	0.25%	0.12%	0.22%	0.05%	0.63%
FRA	26	19.3	1.24%	0.72%	20.18%	0.17%	0.13%	0.16%	0.11%	0.54%
	27	16.4	0.81%	0.96%	13.91%	0.14%	0.08%	0.14%	0.04%	0.45%
	29	38.1	0.61%	1.44%	15.64%	0.22%	0.09%	0.17%	0.04%	0.43%
JPN	26	59.8	0.80%	0.09%	0.03%	13.65%	0.13%	0.01%	0.12%	0.31%
	27	40.7	1.01%	0.12%	0.05%	17.77%	0.18%	0.02%	0.12%	0.41%
	29	129.0	1.12%	0.35%	0.08%	35.42%	0.22%	0.03%	0.10%	0.50%
KOR	26	145.8	1.88%	0.23%	0.08%	0.51%	9.86%	0.03%	0.45%	0.64%
	27	31.7	1.77%	0.33%	0.12%	0.79%	15.09%	0.05%	0.20%	0.76%
	29	73.0	2.57%	1.12%	0.20%	1.18%	29.02%	0.10%	0.23%	1.23%
NLD	26	22.4	0.92%	2.15%	1.46%	1.31%	0.15%	10.83%	0.16%	6.11%
	27	3.0	0.54%	0.77%	0.24%	0.15%	0.05%	12.20%	0.04%	0.55%
	29	5.5	0.51%	2.00%	0.54%	0.27%	0.10%	14.27%	0.05%	0.77%
TWN	26	120.8	1.15%	0.15%	0.05%	0.61%	0.29%	0.02%	10.49%	0.45%
	27	5.8	1.84%	0.24%	0.07%	1.49%	0.34%	0.04%	11.18%	0.58%
	29	6.4	2.53%	0.88%	0.16%	2.69%	0.56%	0.08%	24.38%	1.12%
USA	26	76.7	0.60%	0.07%	0.03%	0.08%	0.08%	0.01%	0.06%	18.98%
	27	26.4	0.78%	0.16%	0.06%	0.17%	0.11%	0.02%	0.06%	15.02%
	29	105.9	1.49%	0.46%	0.11%	0.55%	0.31%	0.05%	0.13%	19.53%

Notes: sector 26= ICT products; sector 27= Electrical equipment; sector 29= Motor vehicles, trailers and semi-trailers.

Table 2 shows the proportion of capital VA embedded in the exports of pivotal industries from leading economies. It underscores the dominant role of the United States and China as key capital producers. The United States and China consistently exhibit higher capital VA shares in various exporter-industry combinations compared to other foreign suppliers. For instance, US capital forms a significant component in Dutch ICT exports, while Chinese capital is prominently featured in Korean motor vehicle exports. This finding corroborates existing research that identifies the US as a global frontrunner in supplying capital equipment and intellectual property across diverse sectors

(Xing, 2020). Concurrently, it reflects China's ascent and upgrading in GVCs, marked by its increasing exports of machinery, factory equipment, and infrastructure, catering to the industrialization needs of developing countries. This evolution of China's role in global production networks, from a country mostly processing foreign intermediate inputs to a critical capital provider, has been highlighted in recent studies examining its capital goods export capabilities (Zhu, 2019; Gopalakrishnan et al., 2021*)*.

However, China's own dependence on external capital contributions, particularly in its ICT sector, is evident from Table 2. Chinese ICT exports incorporate significant capital VA from Japan, Korea, Taiwan, and the United States. This reliance is primarily on imported capital goods like electronics manufacturing equipment, semiconductor fabricating tools, and precision instruments, underscoring China's interdependency in global technology networks. Similarly, the automotive sector showcases China's substantial integration of German and Japanese capital VA, reflective of these nations' competitive advantages in auto manufacturing equipment, technologies, and engineering expertise. The high embodied foreign capital VA highlights how China relied on imported machinery, tools, and robotics to underpin the rapid development of its automotive sector.

We can also see in Table 2 that Taiwan's ICT exports are reliant on Japanese and American capital, with a relatively modest contribution from Korea. This disparity is noteworthy given Korea's specialization and strength in electronics exportation and when comparing the figure with Korea's contribution to capital VA in mainland China ICT exports.

The analysis also reveals that the Netherlands' ICT exports are highly reliant on US capital VA, supplemented by significant contributions from Germany, France and Japan. This reliance underscores the Netherlands' integration of global high-tech equipment and precision instruments in developing its unique semiconductor capabilities, exemplified by companies like ASML. Moreover, the data can also be interpreted in the context of European integration and specialization, with Germany providing advanced instrumentation, optics and automation technologies, and France supplying specialized electronics fabrication equipment. For a small open economy, reliance on foreign capital is key to participate in GVCs. By combining foreign technologies and machinery with domestic R&D and engineering excellence, the Netherlands has established leadership in key segments of the semiconductor value chain, such as lithography, nano-patterning, or metrology systems. This allows the Netherlands to further contribute through capital VA to products manufactured downstream in the ICT sector.

German automotive exports, while central to its economy, also demonstrate significant incorporation of foreign capital VA, notably from China, the US, and France. Germany's large-scale auto production for domestic use and exports markets is supported by machinery and equipment imported from China and the US. Additionally, the significant French capital VA reflects the ongoing specialization within the EU for automotive technologies. We also find significant shares of German capital VA in the exports of other automotive manufacturers, reflecting Germany’s enduring competitive advantage in the manufacturing of specialized auto production equipment, such as assembly robots and welding systems. The blend of domestic and foreign capital across countries highlights the collaborative nature of global auto manufacturing technology exchange.

Capital VA RCA indices

Table 3. Capital value-added RCA index for selected economies and sectors

	Sectors	TiVA RCA	Rank	Capital VA RCA	Rank
CHN	agg	0.10	17	0.17	15
	26	0.36	9	0.46	6
	27	0.65	1	0.55	2
	29	-0.12	25	-0.23	26
DEU	agg	0.15	8	0.46	1
	26	0.01	18	0.07	16
	27	0.36	4	0.46	4
	29	0.70	3	0.80	2
FRA	agg	-0.03	45	0.10	22
	26	-0.25	28	-0.09	20
	27	-0.14	29	0.07	16
	29	-0.09	22	-0.06	21
JPN	agg	-0.01	40	0.24	10
	26	0.08	15	-0.14	23
	27	0.17	11	0.06	17
	29	0.82	1	0.86	1
KOR	agg	0.13	10	0.45	3
	26	0.63	3	0.72	3
	27	0.58	2	0.62	1
	29	0.74	2	0.75	3
NLD	agg	0.09	18	0.13	20
	26	0.08	16	0.24	13

	27	-0.25	34	-0.12	27
	29	-0.47	33	-0.57	36
TWN	agg	0.21	5	0.30	8
	26	0.75	2	0.77	2
	27	-0.21	33	0.07	15
	29	-0.11	24	0.10	16
USA	agg	-0.13	61	-0.09	34
	26	-0.50	38	-0.16	24
	27	-0.59	50	-0.24	35
	29	-0.52	35	-0.64	38

The adoption of a capital-endogenized ICIO model facilitates the computation of a novel Revealed Comparative Advantage (RCA) index based on capital VA. This index, juxtaposed against traditional RCA metrics based on gross exports or trade in value added (TiVA), offers new insights into export competitiveness. Empirical data in Table 3 illustrates notable discrepancies between capital RCA and TiVA RCA rankings amongst developed economies. Germany's top position in capital RCA, in contrast to its 8th place in TiVA RCA, exemplifies this disparity. Similarly, the US, France and Korea display marked elevations in their capital RCA standings relative to TiVA RCAs, indicating a more profound competitive edge in capital-intensive exports. In contrast, China's modest improvement in RCA ranking reflects its ongoing reliance on imported capital for exports despite policies aimed at bolstering its indigenous capabilities.

This enhanced export competitiveness in capital VA, particularly evident in the US and France across technology-intensive sectors, aligns with their established leadership in advanced manufacturing equipment, automation systems, and technological infrastructure. The US's supremacy in high-tech engineering for electronics fabrication and France's strengths in specialized machinery and optics are reaffirmed by the capital RCA metrics. Japan, while maintaining high competitiveness in electronics as per TiVA RCA, shows a lower stance in capital RCA, suggesting a reliance on imported capital goods and technologies for domestic industrial development. For example, Japan remains dependent on critical semiconductor fabricating equipment and precision instruments from the US to maintain its competitiveness in electronics manufacturing.

The divergence between TiVA and capital RCA indexes underscores the enhanced ability of capital RCA to capture the intrinsic competitiveness of economies in terms of capital goods capabilities and specializations. This approach reveals the strategic strengths of countries like

Germany and Korea as leading suppliers of specialized machinery and technological infrastructure that are critical for global manufacturing and service sectors. Capital RCA indices provide additional insights on sources of comparative advantage and value creation in trade and can nuance the results of TiVA RCA indices that understate export competitiveness for developed economies that produce advanced capital goods.

VA decomposition of gross exports with endogenized capital

Using the equations described in Table 1, Table 4 presents the decomposition of gross exports in 2005 and 2015 for the top 10 exporting economies within the dataset, contrasting results derived from conventional and capita-endogenized ICIO models. Endogenizing GFCF within the IO framework reallocates value added across the different terms of the conventional decomposition of gross exports. This reallocation comes from the value added associated with the production of capital goods and services.

Since capital goods and services are no longer part of final demand, there is a decrease in the share of value added (domestic or foreign) absorbed by foreign countries via final goods, compensated by an increase in the share of value added absorbed by foreign countries through intermediate products. The size of this shift diverges across countries based on the prevalence of capital products in their exports. For example, Germany and Japan exhibit a comparatively higher decrease in domestic value added in final products and increase in domestic value added in intermediates (about 15 percentage points). The capital-intensive economies also influence the foreign VA terms, with higher foreign VA absorbed by foreign countries via intermediate products.

In India, Table 4 highlights a significant change in the structure of exports between 2005 and 2015 with more capital VA shifting domestic VA towards intermediate products. Moreover, some shifts can be observed in other VA terms such as the domestic returned VA that corresponds to VA embodied in exports of intermediate products that are re-imported by the exporting economy once further processed in third countries. In the capital-endogenized model, capital goods and services can also be part of this 'circular' trade. In the case of the US, we can see a significant increase in the returned domestic VA when capital goods and services are accounted for, reflecting the use of US machines and technologies in countries from which US exporters source their inputs.

Table 4. Value-added decomposition of exports in the conventional and capital endogenized IO models

	Year	EXP (TN USD)	Conventional						Capital endogenized						Difference					
			DVA_FIN	DVA_RET	DVA_INT	FVA_FIN	FVA_RET	FVA_INT	DVA_FIN	DVA_RET	DVA_INT	FVA_FIN	FVA_RET	FVA_INT	DVA_FIN	DVA_RET	DVA_INT	FVA_FIN	FVA_RET	FVA_INT
CHN	2005	0.70	34.6%	1.1%	38.7%	11.7%	0.4%	12.6%	24.6%	1.2%	48.5%	7.3%	0.5%	17.1%	9.9	-0.1	-9.8	4.5	0.0	-4.4
CHN	2015	2.20	37.8%	2.3%	42.5%	7.4%	0.5%	8.5%	26.1%	2.9%	53.6%	4.6%	0.7%	11.1%	11.7	-0.6	-11.1	2.7	-0.1	-2.6
USA	2005	1.19	42.0%	6.2%	40.4%	5.0%	0.9%	4.8%	29.6%	8.5%	50.6%	3.3%	1.3%	6.2%	12.4	-2.3	-10.1	1.8	-0.3	-1.4
USA	2015	2.02	42.1%	5.1%	42.9%	4.5%	0.7%	4.3%	29.9%	6.8%	53.3%	2.9%	0.9%	5.7%	12.2	-1.8	-10.4	1.6	-0.2	-1.4
DEU	2005	0.86	36.3%	1.9%	42.6%	8.4%	0.4%	9.6%	22.9%	2.5%	55.3%	5.2%	0.6%	12.7%	13.3	-0.6	-12.7	3.3	-0.2	-3.1
DEU	2015	1.27	35.3%	1.7%	41.3%	9.4%	0.5%	11.0%	21.3%	2.1%	54.8%	5.5%	0.6%	14.7%	14.0	-0.5	-13.5	3.8	-0.1	-3.7
JPN	2005	0.64	38.2%	1.5%	49.9%	4.0%	0.2%	5.9%	21.0%	2.3%	66.3%	2.2%	0.3%	7.7%	17.2	-0.8	-16.4	1.8	-0.1	-1.7
JPN	2015	0.73	36.9%	1.1%	48.6%	5.2%	0.2%	7.8%	18.6%	1.7%	66.3%	2.6%	0.3%	10.3%	18.3	-0.6	-17.7	2.6	-0.1	-2.5
GBR	2005	0.52	34.6%	1.5%	49.4%	6.3%	0.2%	7.7%	26.3%	1.9%	57.3%	4.4%	0.3%	9.5%	8.3	-0.4	-7.9	1.9	-0.1	-1.8
GBR	2015	0.68	35.4%	1.4%	47.9%	6.8%	0.2%	8.1%	26.1%	1.8%	56.8%	4.5%	0.3%	10.2%	9.3	-0.4	-8.9	2.2	-0.1	-2.2
FRA	2005	0.54	38.4%	1.3%	39.6%	9.8%	0.4%	10.2%	28.7%	1.7%	48.9%	6.6%	0.5%	13.3%	9.7	-0.4	-9.4	3.2	-0.1	-3.1
FRA	2015	0.65	34.9%	1.2%	42.2%	10.0%	0.3%	11.0%	25.0%	1.5%	51.8%	6.1%	0.4%	14.7%	9.9	-0.3	-9.6	3.9	-0.1	-3.8
KOR	2005	0.32	26.2%	0.4%	40.4%	11.8%	0.2%	20.5%	15.1%	0.6%	51.3%	6.7%	0.3%	25.6%	11.1	-0.1	-10.9	5.1	-0.1	-5.1
KOR	2015	0.61	26.2%	0.4%	40.5%	11.4%	0.2%	20.8%	13.4%	0.5%	53.2%	5.8%	0.3%	26.3%	12.8	-0.1	-12.7	5.6	-0.1	-5.5
ITA	2005	0.44	39.7%	1.0%	38.6%	9.8%	0.3%	10.3%	28.7%	1.3%	49.3%	6.4%	0.4%	13.6%	11.0	-0.3	-10.7	3.4	-0.1	-3.3
ITA	2015	0.52	38.4%	0.6%	38.5%	10.4%	0.2%	11.6%	26.6%	0.8%	50.1%	6.4%	0.3%	15.4%	11.8	-0.2	-11.6	3.9	-0.1	-3.9
CAN	2005	0.39	25.1%	0.9%	54.1%	7.4%	0.3%	11.8%	19.9%	1.0%	59.2%	5.6%	0.3%	13.6%	5.2	-0.1	-5.1	1.8	0.0	-1.8
CAN	2015	0.45	24.7%	0.9%	52.9%	8.5%	0.2%	12.4%	17.8%	1.1%	59.6%	5.3%	0.3%	15.5%	6.9	-0.2	-6.7	3.2	-0.1	-3.1
IND	2005	0.16	38.3%	0.3%	42.6%	8.1%	0.1%	10.5%	27.6%	0.4%	53.3%	6.2%	0.1%	12.4%	10.7	-0.1	-10.6	1.9	0.0	-1.9
IND	2015	0.41	40.9%	0.4%	39.6%	8.7%	0.1%	10.2%	26.0%	0.6%	54.3%	6.1%	0.2%	12.8%	14.9	-0.2	-14.7	2.6	0.0	-2.6

4. Conclusion

Due to constraints in data availability, capital accounting in IO models has remained elusive in the past decades. By formulating and implementing techniques to endogenize capital in an ICIO framework, we help to address this longstanding gap and provide a more comprehensive framework for understanding the intricacies of international trade and production networks. Our approach has revealed that traditional TiVA metrics often underestimate the contribution of countries to GVCs through capital, especially in developed economies that are specialized in the production of capital goods and services. The empirical analysis, utilizing our capital-endogenized IO model, demonstrates a notable shift in the perceived export competitiveness and value-added contributions of major economies.

The new perspective offered by our model holds substantial implications for policymaking. For instance, the redefined comparative advantage in capital-intensive industries can inform trade and investment policies, as well as debates on the resilience of GVCs and interdependencies through trade linkages. With the recent emphasis on economic security in the context of geopolitical tensions, we can expect the contribution of capital to GVCs to be more scrutinized. Additionally, our findings underscore the importance of capital goods and services to strengthen a country's position in global markets.

While our study represents a leap forward in acknowledging the role of capital in GVCs, it still has limitations and offers potential for extensions in future research. For example, integrating more granular capital flow data could help to refine the flow matrix method and to improve the accuracy of results. Moreover, a quasi-dynamic or full dynamic IO framework could be employed to explore temporal changes in capital endowments and the diffusion of technology through trade. With respect to indicators, the literature measuring GVC participation that started with Koopman, Wang and Wei (2014) could be revisited to account for participation through capital. For example, one could extend the concept of GVC participation to firms that export final goods without using imported intermediate inputs but that rely on foreign capital. Lastly, merging capital endogenization with environmental and social IO satellite accounts could provide more insights into the sustainability implications of global production and consumption patterns, as illustrated by the empirical analysis of Södersten et al. (2018).

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