Explaining foreign direct investment patterns: a testable micro-macro gravity model for FDI

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Abstract:
This paper proposes a stand-alone model for explaining international foreign direct investment (FDI) patterns, including zero flows. The model provides a micro foundation for FDI decisions at firm level that supports a structural gravity model. The FDI supply push depends on the relative abundance of proprietary knowledge assets of firms, which in turn depends on knowledge creation by the public sector. The demand pull for inward FDI depends on market size and the relative knowledge gap of countries. Firms self-select into FDI if their productivity is high enough to overcome the fixed costs of an international headquarter and the setup costs of a foreign subsidiary. Both types of fixed costs increase in the level of bilateral FDI frictions (physical and policy-related). Aggregated at country level, the model explains the occurrence of zero FDI flows between countries. The model is generalised to a *n*-country model, which includes the effects third-country policies. The latter affect the relative FDI start-up costs of all other countries, depending on the size and distance of the third countries. The paper derives testable predictions from the model. The model implications have high potential policy relevance.

JEL codes: D23, D25, F23 , G32, L1, O34

Keywords: foreign direct investment, firm behaviour, decision model, structural gravity, zero FDI flows, policy implications

Explaining foreign direct investment patterns: A testable micro-macro gravity model for FDI

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1. Introduction

This paper proposes a new stand-alone model for explaining bilateral foreign direct investment (FDI) patterns. The model is based on decisions of individual firms, takes into account knowledge-capital conditions in origin countries, and FDI-affecting policies in destination countries. The model supports a structural gravity model of FDI patterns, but it also explains behaviour at the extensive margin of foreign direct investment, including zero FDI flows.

A much-cited review article on the determinants of FDI concludes that a gravity model specification tends to provide a reasonably good fit for actual cross-country FDI data (Blonigen, 2005). However, the same author complains that: "*Ideally, the FDI literature would have an established model and empirical specification that lays out the primary long-run determinants of FDI location. [...] However, there is no [...] paper that lays out a tractable model that specifically identifies gravity variables as the sole determinants of FDI patterns*".

The gravity model has often been used in empirical studies of FDI without a theory that explains the gravity-conform pattern.[1] The other side of the spectrum is formed by complex and large models that integrate FDI, trade, differentiated FDI motives, economic growth, and innovation.[2] Each of these models is too complex and too data-demanding to be falsifiable by empirical testing with current data (cf. Markusen, 2021; Lewbel, 2019). Their authors often resort to calibrated numerical exercises (sometimes called 'guestimating' or 'estibrating') in order to demonstrate the plausibility of the model. Despite the interesting and inspiring perspectives that such papers may provide, none of them provides a stand-alone explanation of the world's bilateral FDI patterns.

We propose testable and falsifiable stand-alone theory of bilateral FDI patterns. It builds on behaviour of individual firms setting up foreign subsidiaries and changing the latter's activity levels in response to changes in their competitive environment. This process feeds and shapes FDI patterns at country level. That is where economic mass starts to count as the basis for the patterns that gravity models invariably find.

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[1] Cf. Kleinert and Toubal (2010); Davies and Kristjandottir (2010); Brainard (1997), Braconier *et al.* (2005); Egger and Pfaffermayr (2004).
[2] Cf. Bergstrand and Egger (2007); Anderson *et al*. (2019); Ramondo and Rodríguez-Clare (2013); Allen *et al.* (2014); Arkolakis *et al*. (2018).

Economic mass (say GDP) is important as attractor of FDI, because it creates larger markets where more foreign product varieties in larger volumes can find their ways to consumers. But economic mass is also important for outward FDI pressure, because larger countries tend to have more firms, increasing the absolute probability that some of these firms develop unique knowledge assets that can also be exploited in other countries via FDI. Moreover, larger economic mass (country size) makes it possible spend more on public knowledge creation that can be encapsulated and converted to firm-specific knowledge assets that domestic firms use as basis for engaging in foreign FDI. The demand pull for inward FDI depends on market size and the relative knowledge gap of countries. Analogue with Newton's gravity model, we distinguish a number of FDI friction factors that may countervail the attractive forces of economic mass. Friction factors may stem from man-made policies (that facilitate or discourage bilateral FDI), cultural differences, language, and physical factors such as spatial distance. We have one problem less than Newton had, because we know that firm behaviour carries the operation of FDI gravity, while Newton just accepted the physical gravity force without knowing what 'carried' it.[3]

The present paper expands on earlier work by offering a better micro foundation for firm-level and country-level FDI drivers. The model includes the insights from recent work on testing the Markusen's knowledge-capital model of FDI (Kox, 2022).

The paper makes several contributions to the literature. The first contribution is a micro-economic model that explains FDI decisions of firms in a way that is consistent with the classic gravity model. The micro-economic model combines a self-selection mechanism with the knowledge-capital model (Markusen, 2002) in the presence of the market-mediated attraction forces of economic mass. Secondly, the model distinguishes different policy-related economic friction factors that weaken or countervail the economic gravity forces. It shows that the friction factors have an impact on the self-selection process of firms. Thirdly, the paper explains the stylised fact that not all countries have bilateral FDI with all other countries, based on the self-selection process of firms. Only the most productive firms can absorb the FDI friction costs. This yields a result that is comparable to the Melitz (2003) paper on self-selection into export activity. Fourthly, the n-country version of the model derives FDI-specific multilateral resistance terms. They reflect relative FDI friction costs for all countries, weighted by the economic scales of the origin and destination country. Fifthly, we discuss the methodology for testing our stand-alone FDI gravity model using state-of-the-art econometric insights. Finally, the paper is policy-relevant by showing that the FDI-specific multilateral resistance terms form a rich quantitative information source for evaluating the impact of unilateral, bilateral or multilateral policies on FDI patterns.

The structure of the paper is as follows. In Sections 2-4 we stepwise develop the gravity-based FDI model at the country-pair level. Section 2 models the country-level push factors of outward FDI, based on a new version of the knowledge-capital

[3] Despite Einstein's general relativity theory, gravity still has many mysteries. A graviton as physical 'carrier' of the gravity force still has not been identified and gravity's interaction with other fundamental forces is still object of research and debate (cf. Panek, 2019; Zee, 2018; Wilczek, 2015, 2021; Bernhard Cohen, 1981).

interpretation of FDI. Section 3 models the country-level pull factors of inward FDI in host countries and how these, together with the push factors in FDI origin countries, create the basic drivers for bilateral FDI in a world without FDI frictions. Section 4 introduces two types of FDI friction factors for bilateral FDI. Section 5 provides a micro-economic foundation for the decision of firms to engage in bilateral FDI. It shows that bilateral FDI frictions increase the fixed costs for firms with FDI ambitions. The micro model quantifies the cut-off productivity level that is necessary to absorb the up-front fixed costs of bilateral FDI. Section 6 expands the model to an *n*-country world, by taking on board the effect that developments in third countries may have on relative FDI friction costs. The latter affect the selection of FDI destination countries (viewed from the multinational firm's perspective). Section 7 evaluates the micro-macro interaction in the model and derives testable predictions from the model, together with a number of ideas for testing the model. Section 8 summarises the findings and concludes.

2. Push factors: FDI supply based on firm-level knowledge-capital

When applying gravity analysis to economic interactions we take it that a country's GDP represents its economic mass (Tinbergen, 1962; Linnemann, 1966). A larger mass potentially attracts more economic transactions from neighbouring countries. Physical distance weakens this attractive force, but other friction sources between countries, like legal, language-related and policy-related obstacles work out in the same way.

Taking the present and past distribution of country's GDP size as exogenous inputs, we concentrate on the FDI process itself. The model will be developed stepwise, starting with the 2-country case without economic frictions, then adding FDI frictions, and finally extending it to a world FDI model.

FDI is a bundled concept, which includes aspects of *ownership* (economic control, international management hierarchy, equity versus debt financing), *location* (international capital flows, greenfield investment, mergers or acquisitions, tax routing, market seeking, resource seeking, production networks, global value chains), and *internalisation of transactions* (headquarter services, intra-firm knowledge assets, transaction costs, intra-company finance flows).[4] Taking all these aspect on board in a single economic model that explains international patterns of bilateral FDI is next to impossible. We opt for a stripped, but clear-cut version of the FDI concept using the knowledge-capital interpretation of FDI.[5] The knowledge-capital (KC) model assumes that firms own unique knowledge assets like patents, in-house know-how, blueprints, procedures, technology networks, reputations and trademarks. Many of such assets are geographically separable from the firm's original production site. They may be applied elsewhere at low or zero additional costs, as intra-firm 'free goods' without decreasing the original value of these assets. If the firm uses such assets in foreign subsidiaries, it increases the returns to these assets. They form a source of firm-level scale economies.

[4] Cf. Dunning (2001); Feenstra (2004); Head and Ries (2008).
[6] Markusen, 2002, 2001, 1984; Carr *et al*., 2001; Markusen and Maskus, 2003. The concept of knowledge capital is also used by, *inter alia*, Benhahbib *et al.* (2017); McGrattan and Prescott (2009, 2010); Holmes, *et al*. (2011).

The KC model regards this process as the core of foreign direct investment.[6] In line with the IMF definition we speak only of FDI if the firm uses its knowledge assets for equity-controlled foreign production. A necessary corollary of the KC model is that countries with large outward FDI stocks should have a relative abundance of proprietary KC assets.[7]

Before presenting our formal model we motivate the main choices that we made regarding the interaction between public knowledge systems and the proprietary knowledge assets of firms. Though firms are the main commercializing agents of national knowledge capital, their competitive edge partly rests on the knowledge products from the public and semi-public sector. Public institutions like universities, national institutions for technology transfer, and scientific publications form a constant source of new ideas. Effectively, most knowledge products from the public and semi-public sector can be characterised as non-proprietary and outside the market domain. It is rare that the public sector itself commercially exploits public-held patents.[8] Often, such patents are, before expiration, given away to national firms, or are sold via auctions.[9] Hence, the public knowledge sector tends to be generous with its products. The public knowledge system therefore forms an important source of free knowledge externalities, by generating and disseminating innovations and discoveries via publications, congresses, staff mobility, intermediary supplier networks, and education-related activities.[10] By contrast, firms work almost exclusively on the basis of proprietary knowledge capital. After absorbing free knowledge produced by the public and semi-public sector, firms encapsulate and recombine these input elements with firm-specific knowledge, thus creating marketable products, technologies, brands, and even new business models. In what follows, we first model the public knowledge creation and subsequently the creation of firm-level proprietary knowledge.

We regard the public knowledge system as an input-output process. Its input side accounts for dedicated human and material resources that are used for creating new knowledge and reactivating 'older' knowledge. It has a throughput and processing phase where efficiency, concentration, and incentives for creativity matter. And it has an output side where knowledge products, educated persons, technologies, and a learning-oriented institutional environment 'pop out'.

Let M_{pit} be the active public KC stock of country i in year t; it is a product of current and past efforts. "Active" emphasizes that knowledge from the past forms a perishable 'good', requiring constant refreshment, re-education, reappropriation, re-transfer, documentation and dissemination actions by the current generation, otherwise it decays and becomes dead knowledge. Public knowledge creation is supposed to be fully financed from tax receipts, and hence depends on GDP size. Knowledge is a multi-

[6] Burstein and Monge-Naranjo (2009) argue that the international mobility of managerial know-how constitutes the kernel of 'firm-embedded productivity'.
[7] Cf. Kox (2022) for an empirical proof of this corollary of the KC model.
[8] Cf. Agrawal and Henderson, 2002; Calderini *et al*., 2007; Perkmann *et al*., 2013.
[9] Cf. Mazzucato, 2014; Arundel *et al*., 2013; Escalona Reynoso, 2010; Maskus and Reichman, 2004; Boyle, 2003a, 2003b; Carlsson and Fridh, 2002; Cohen *et al*., 2000; Henderson *et al*., 1998.
[10] Cf. van Elk *et al*., 2019; Gerbin and Drnovsek, 2016; Audretsch and Stephan, 1996, 1999; Arundel *et al*., 2013; Breschi and Catalini, 2010; Toole and Czarnitzki, 2010; Verhoogen, 2021; Keller, 2004.

dimensioned entity, but can be defined in terms of costs as a GDP fraction. At any time t, M_{pio} defines the older, path-dependent vintages of publicly created knowledge. We use a simple production function for M_{pit}:

$$M_{pit} = v_{it} \left[\varepsilon_{it} M_{pio} + \beta_{it}\right] Y_{it} \tag{1}$$

in which $\beta_{it} > 0$ is country i's coefficient for knowledge development activities in year t, expressed as a fraction of GDP. We assume that β_{it} also includes the costs for attracting new foreign knowledge products. Similarly, $\varepsilon_{it} > 0$ is the GDP fraction spent for keeping 'old' knowledge stock M_{io} fresh and active. Parameter $v_{it} > 0$ measures national throughput efficiency, representing a mix of knowledge-absorption capabilities, creativity incentives, connectivity, legal and institutional framework, labour productivity, and overall national efficiency.[11] Countries may differ considerably as to these throughput aspects.

The lagged knowledge component M_{pio} has a vintage structure, in which $\beta_{i,t-\theta}\, Y_{i,t-\theta}$ represents the newly create knowledge in year $t-\theta$, and $0 < \delta_{it-\theta} \leq 1$ is the depreciation rate with which the knowledge vintage is annually depreciated until year $t-\Theta$ in which a one-shot discarding of the oldest knowledge cohort follows.[12] So, the aggregation is restricted to only $\Theta - 1$ years. The lagged component M_{pio} thus aggregates over a finite time horizon:

$$M_{pio} = \sum_{\theta=1}^{\Theta-1} \frac{\beta_{i,t-\theta}}{(1-\delta_{i,t-\theta})^{\theta}}\, Y_{i,t-\theta} \quad with\ \ 0 < \delta_{i,t-\theta} < 1\, ;\ \delta_{i,t-\Theta} = 1 \tag{2}$$

M_{pio} is only related to GDP of preceding years. The ratio $\beta_{it}/(1-\delta_{it})$ thus determines the speed of annual knowledge-rejuvenation. Competition and creative destruction increase the depreciation rate, and shorten the renewal cycle. Higher renewal rate gives a younger stock of knowledge capital.[13]

For private knowledge creation by firms we set up a similar production function, but with two important differences. Firstly, firm-level knowledge production partly depends on the public knowledge inputs in their headquarter country i. A second difference is that individual firms are heterogeneous with respect to their innovativeness, management capabilities and overall efficiency. Let M_{sit} be the proprietary knowledge stock of firm s ($s \in 1,..,S$) in country i at time t. We assume that the total number of firms in a country (S) has a constant relation with GDP size, in order to prevent that S could form a separate source of economic mass.

The production of M_{sit} depends on three activities: internal creation of new private knowledge assets; absorbing and encapsulation of public knowledge inputs; and re-

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[11] The throughput efficiency is assumed to be a dimensionless scalar, implying that the value of the knowledge outputs is a function of its input costs. For model simplicity and transparency, we assume v_{it} to be identical for all sub-processes of a national knowledge system.

[12] The annual cohorts of country i's stock of knowledge capital can be consistently aggregated by the constant elasticity of substitution (CES) vintage aggregator proposed by Benhabib (2019): $M_{io} = [a_1 M_{it-1}^{1-\varepsilon} + a_2 M_{it-2}^{1-\varepsilon} + \ldots + a_n M_{it-(\Theta-1)}^{1-\varepsilon}]^{1/1-\varepsilon}$, in which $\varepsilon > 1$ is the elasticity of substitution and $a_1 \ldots a_{\Theta-1}$ the size shares of the annual knowledge stock cohorts, which sum to 1.

[13] Note that having a relative young public knowledge stock may form a quality-ladder asset for FDI partner countries.

activation of a firm's older private knowledge stocks. All firm-level costs of knowledge creation are expressed as fraction of country i's GDP to obtain a uniform value dimension:

$$M_{sit} = (v_{it})^{z_s} \, [\alpha_{sit} + \omega_{sit}. M_{pi,t-1} + \varepsilon_{sit}. M_{sio}] \, . Y_{it} \qquad with \; s = 1, .., S \qquad (3)$$

in which v_{it} is again national throughput efficiency, but mitigated by the firm-specific and time-invariant fixed effect z_s with range $[-1, +1]$.[14] Parameter $\alpha_{sit} > 0$ represents the firm's costs of own knowledge-creation activities (hiring of in-house or outside specialists, firm-level R&D, development of new product varieties, marketing concepts or business models). Parameter $\omega_{sit} > 0$ stands for the costs of absorbing public knowledge products through networking activity, setting up internal learning projects, or the hiring of specialists to master new knowledge areas.[15] It also includes the costs of recombining the public knowledge inputs with firm-internal knowledge, and the costs of turning the mixed knowledge products into excludable private assets, e.g. through patenting or secrecy measures.[16] Note that firms use not the very latest public knowledge, but a lagged knowledge cohort ($M_{pi,t-1}$) as input.[17] Finally, parameter $\varepsilon_{sit} > 0$ represents firm-level costs for keeping the firm's 'old' knowledge stocks M_{sio} fresh and active.[18] When we assume that firms only capitalise the new knowledge that they have fully developed internally, M_{sio} has a vintage structure that is the same as for the public sector:

$$M_{sio} = \sum_{\theta=1}^{\Theta-1} \frac{\alpha_{si,t-\theta}}{(1-\delta_{si,t-\theta})^{\theta}} \, Y_{i,t-\theta} \qquad with \;\; 0 < \delta_{si,t-\theta} < 1 \, ; \; \delta_{si,t-\Theta} = 1 \qquad (4)$$

Let $M_{fit} = \sum_s M_{sit}$ be total active knowledge stock in year t of all firms in country i. This must be considered as a gross total, because knowledge creation is here calculated by input costs (GDP fraction). It is possible and even likely that the individual knowledge-creation efforts of firms result in duplications that still have to prove their value in the market.[19]

The equations (1-4) offer a stylised description of knowledge flows between the public and private sector, as dimensioned by economic mass. The equations may generate a rich array of dynamics. Both private M_{fit} and public M_{pit} contain lagged components. Decision patterns from the past and the time variance of GDP create a path dependency that affects current knowledge stocks. In order to clarify the basic dynamics over time, we assume that public and private sector have the same depreciation method (Θ, δ) and

[14] Micro-econometric studies show that firms with multinational activities typically have a productivity that is higher than exporting firms, and substantially higher than firms that operate solely in the domestic market. Cf. Wagner, 2012; Kox and Rojas, 2010; Bernard et al., 2018, 2013; Helpman et al., 2004.
[15] Cf. Lind and Ramondo, 2022.
[16] Cf. Crouset et al., 2022.
[17] Not only because it is plausible, but also because it prevents endogeneity loops within the model.
[18] This relates to issues like internal courses for new employees, writing protocols and procedure, documentation, company 'how to ..." handbooks, internal refreshment courses, and HR management.
[19] Firms synchronously use the same inputs from public knowledge creation. This increases the probability of duplication (being new to the firm is quite different from being new to the market). In public-sector knowledge creation duplication also happens, but because these efforts are more open, the risks of duplication are probably lower than holds for firm-level innovation, where innovation efforts are commonly more subject to strategical secrecy measures.

we take out the time variance of the main parameters (ε_i , β_i , v_i , ε_{si} , α_{si} and ω_{si}). This allows us to obtain a reduced-form expression that is only defined by ratio parameters and national economic mass (GDP).

Proposition 1: *If behavioural parameters are time invariant, the development of proprietary knowledge stocks of firms (M_{fit}) has the following dynamics over time*:[20]

$$M_{fit} = v_i^{z_s-1}\, Y_{it} \sum_{s=1}^{S} \left\{ \alpha_{si} + \omega_{si}\, \varepsilon_i\, \beta_i\, A_i + \omega_{si}\, \beta_i\, Y_{it-1} + \frac{\varepsilon_{si}}{v_i} B_i \right\} \tag{5}$$

in which two complex, lagged and GDP-related terms are abbreviated for shortness as $A_i = \sum_{\theta=1}^{\Theta-1}(1-\delta)^{\theta-1}\, Y_{i,t-(\theta-1)}$ and $B_i = \sum_{\theta=1}^{\Theta-1}\, \alpha_{i,t-\theta}\, Y_{i,t-\theta}(1-\delta)^{\theta}$.

Equation (5) depicts the magnitude of a country's stock of firm-owned knowledge assets that can potentially serve as basis for FDI. Firms exploit their KC first in their domestic market, but potentially also abroad when the KC is separable from the original production location in the origin country, and if it increases their returns to these firm-owned knowledge stocks. The firms' willingness to supply FDI is unbounded, provided that these two conditions are met. This potential FDI supply must therefore be regarded as a vector force.

FDI activities could extend to all $j \in [1,2,..,J]$ potential destination countries. FDI_{ijt}^{sup} expresses a firm's potential KC supply for setting up foreign subsidiaries.

$$FDI_{sijt}^{sup} = \begin{cases} q_{si}\,(M_{sit})^h & if \sum_{s=1}^{S} R_{sijt} \geq 0 \\ 0 & otherwise \end{cases} \qquad \forall \;\; i,j \tag{6}$$

in which $q_{si} = [0,1]$ is a firm-specific parameter that reflects separability of proprietary knowledge assets, and h>0 is a parameter for supply elasticity. R_{sijt} is firm-level expected profitability of using M_{sit} for creating up or expanding a foreign subsidiary in country *j*. The conditionality of equation (6) will be formulated more precisely after dealing with the implications of self-selection by heterogeneous firms. Potential FDI supply depends via M_{sit} on economic mass (Y_i), and hence reflects a potential gravity force. Aggregated to country level, the vector of potential total bilateral FDI supply amounts to:

$$\overrightarrow{FDI_{ijt}^{sup}} = \sum_{s=1}^{S} FDI_{sijt}^{sup} \qquad \forall \;\; i,j \tag{7}$$

3. Pull factors: forces attracting inward FDI

Bilateral FDI is not only driven by a supply push, but also by a demand pull. The potential overall market size of country *j* is determined primarily by its economic mass. Firms from country *i* are attracted by the potential of taking their share in the market of country *j*, and this demand pull potential is proportional to country *j*'s economic mass. Subsidiaries in a foreign market where individual consumers have a preference for

[20] The Annex provides the proof of Proposition 1.

more product variety will always find product demand, proportional to its GDP size. Traditional gravity models of FDI mostly confirm this.[21]

There is a second potential demand pull factor that can be identified as a separate cause. If country *j* has a positive knowledge gap with country *i*, this may induce active policies from public authorities or merger bids from firms in country *j* to attract FDI from country *i*. Foreign FDI forms an access road to desired knowledge capital. Larger economies may absorb more foreign commercial technology than smaller countries, but that effect is already captured by overall market size. Quantifying a real knowledge gap requires a correction for differences in GDP size of both countries. We propose the following procedure for calculating a bilateral real knowledge gap (ΔM^*_{fijt}), based on firm-owned private knowledge assets:[22]

$$\Delta M^*_{fijt} = \frac{1}{Y_{jt}}\left[\frac{M_{fit}}{Y_{it}/Y_{jt}} - M_{fjt}\right] \qquad \forall\, i,j \tag{8}$$

In the presence of a positive real knowledge gap ($\Delta M^*_{fijt} > 0$), governments develop active investment-attracting policies. They wish to maximise FDI-related domestic learning externalities that raises labour productivity and organisational efficiency, and that may open new sectors in the domestic economy (e.g. Lu *et al.*, 2017; Tao and Wang, 1998; Amighini *et al*., 2017; Vujanović *et al.*, 2022), or may increase domestic wage incomes (e.g. Setzler and Tintelnot, 2019).[23] For analytical clarity about the bilateral FDI vector forces, we should identify the separate FDI-attracting role of a real knowledge gap. This being said, we must immediately add that the knowledge gap at the aggregate level is just a proxy. The forces of technological attraction may differ by industry, comparable with the role of intra-industry traffic in international trade. Hence, the role of the real bilateral knowledge gaps for bilateral FDI traffic will in most cases play some role, rather than being a binary (on-off) force. ΔM^*_{fijt} is related to economic mass in both countries, but in a complex and indirect way. Sub-national regions and individual industries have their own path-dependence, in which catching-up and falling-behind processes may play a role.

Based on the preceding analysis we propose that the pulling force on inward FDI has the following form at the bilateral level:

$$\overrightarrow{FDI^{dem}_{jit}} = \phi_j \left[Y_{jt}\right]^{\gamma} + \zeta_{jt}\, \Delta M^*_{fijt} \qquad \forall\, i,j \tag{9}$$

[21] Cf. Tanaka, 2009; Kleinert and Toubal, 2010; Blonigen and Piger, 2014. In more recent structural gravity models of FDI (like Anderson *et a*l., 2019; Kox and Rojas, 2020), the time-variant GDP impact on inward FDI is fully absorbed in the set of estimation dummies (origin-time, host-time).

[22] Earlier FDI gravity tests (cf. Blonigen and Piger, 2014) often used the bilateral GDP gap between two countries to explain inward FDI, but what they actually estimated was probably the effect of a mix of the scale-corrected bilateral knowledge gap $\Delta M f_{ijt}{}^*$ and the bilateral GDP gap strictu sensu.

[23] Positive learning externalities may be channelled through the employment relation (learning by observing, staff mobility), through the channel of domestic intermediary suppliers (e.g. standards with regards to product quality, delivery and transport, packaging and labelling), and through the channel of new products and technologies (Ghodsi and Jovanovic, 2022; Verhoogen, 2021; Keller, 2004).

in which $\phi_j > 0$ is a country-specific proportionality constant, $\gamma > 0$ is the elasticity of inward FDI with respect to market size, and $\zeta_{jt} \geq 0$ reflects country *j*'s reaction parameter to a real bilateral knowledge gap.

So far, we identified the push and pull factors shape bilateral FDI that goes from country *i* to country *j*. $\overrightarrow{FDI_{ijt}^{sup}}$ reflects the potential outward push forces of origin country *i* and $\overrightarrow{FDI_{jit}^{dem}}$ represents the potential inward pull forces from country *j*. Both mutually reinforce each other and they can be presented in a multiplicative way, as in Newton's gravity equation. In a world without frictions and external influences, actual bilateral FDI amounts to:

$$FDI_{ijt}^{nofric} = g_{ij} \left(\overrightarrow{FDI_{ijt}^{sup}} . \overrightarrow{FDI_{jit}^{dem}} \right) \qquad (10)$$

in which g_{ij} is the proportionality factor between potential and actual bilateral FDI. The push and pull factors shape bilateral FDI that goes from country *i* to country *j*. It is important to note that this is not a *net* flow, but that there may synchronously also be a non-zero reverse flow (FDI_{jit}^{nofric}) that goes in opposite direction. This is due to the fact that countries are no homogeneous entities, but may have sectors, industries and even large multinational corporations whose strengths and weaknesses are differently distributed, also with respect to their knowledge-capital assets. The procedure for deriving the reverse flow is the same as the one described before, but with flipped country suffices.

4. Introducing FDI friction forces.

Physical distance is the sole factor that weakens gravity in Newton's analysis. In applying the gravity model to international trade, Tinbergen (1962) and Linnemann (1966) noticed —not unexpectedly— that the explanatory power of their models increased strongly by adding tariffs as a further source of trade frictions. Later empirical work accounted for the trade-costs obstacles that arose due to cultural, legal and policy-made differences between countries. For FDI we propose two types of bilateral friction sources.[24]

The first category is formed by bilateral obstacles ($\pi_{ij} \geq 0$) that are time-invariant and unrelated to current policies. Examples are: physical distance, time zone difference, having different legal systems, having a different language, not sharing a border, and not having a common cultural history and comparable institutions. These friction sources are symmetric in both directions ($\pi_{ij} = \pi_{ji}$). They hamper bilateral FDI in a way that resembles Newtonian frictions: they weaken the gravity force.

The second category of bilateral frictions (ω_{ijt}) is policy-related and time variant. As a rule, such frictions are non-symmetric ($\omega_{ijt} \neq \omega_{jit}$) with elements like discriminatory

[24] A third, non-bilateral form of obstacles exists, formed by policies that have the consequence of increasing investment costs for all investors (domestic and foreign) in a particular country. If such policies differ strongly between origin and destination country, it may lead to cost duplication and thus create an additional FDI obstacle. For expository reasons, we leave out this category of barriers.

provisions for specific (potential) foreign investors. Examples are statutory prohibitions of FDI in particular industries or regions, economic needs tests for foreign investors, or operational, or nationality requirements, or additional administrative obstacles for specific origin countries. The ω_{ijt}-type frictions often have a composite 'gamut' nature, with different policy rules for different industries or regions. Also 'negative frictions' (liberalisation policies, subsidies) are possible for specific FDI domains. Bilateral or multilateral cooperation agreements like preferential trade and investment agreements often apply positive discrimination for member-state firms, thus lowering ω_{ijt} symmetrically for member countries.

The friction indices (π_{ij}, ω_{ijt}) may have different dimensions, but when they are normalised with the international average value we obtain dimensionless ratios that ensure continuous quantification and international comparability. After such modification, we may include the frictions in a Newton-like FDI gravity equation:

$$FDI^{*}_{ijt} = \frac{\mathcal{G}_{ij}\ \ FDI^{nofric}_{ijt}}{(1+\pi_{ij})(1+\omega_{ijt})} \qquad \forall\, i, \forall j \qquad (11)$$

in which $\pi_{ij} > 0$ represents the time-invariant bilateral FDI frictions that are not dependent on current policies, and $\mathcal{G}_{ij}$ is the friction-adapted proportionality constant. FDI^{*}_{ijt} is the bilateral FDI from country *i* that enters country *j* in a situation where no other country pairs are considered. Note that FDI^{*}_{ijt} will always be strictly positive if FDI^{nofric}_{ijt}>0. However, equation (11) is a provisional bilateral result that will be generalised once the model is adapted to a *n*-country world and the presence of self-selection by firms.

5. *Micro-foundation of FDI decisions*

The micro model is based on heterogeneous firms that only produce with labour. Firms only differ with respect to their labour productivity λ_{si}.[25] Following Jovanovic (1982), each firm obtains an unobservable, random draw (λ_{si}) from a Pareto-shaped domestic productivity distribution. This is in line with empirical evidence and the productivity literature.[26] The cumulative distribution function $G(\lambda_{si})$ and the corresponding probability density function $g(\lambda_{si})$ have, respectively, the following forms:[27]

$$G(\lambda_{si}) = 1 - \left(\frac{\lambda_m}{\lambda_{si}}\right)^{\alpha} \ \ , \ \ g(\lambda_{si}) = \frac{\alpha\ (\lambda_m)^{\alpha}}{(\lambda_{si})^{\alpha+1}} \qquad \forall s \in (1, ..S) \qquad (12)$$

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[25] In terms of equation 3, it holds that λ_{si}=$(v_i)^{z_s}$, in which v_i is national average productivity and z_s is a fixed effect, specific for firm *s*.
[26] For empirical studies, see Aoyama *et al*. (2008) and Axtell (2001, 2006). Studies on trade by firms with heterogeneous productivity often assume a Pareto-shaped productivity distribution (Helpman *et al*., 2004; Melitz and Redding, 2014; Bekkers and Francois, 2018; Kleinert and Toubal, 2010).
[27] The mean productivity level of this distribution is $\overline{\lambda_i} = \alpha.\lambda_m/(\alpha-1)$ and the median is $\lambda_{i,med} = \lambda_m \sqrt[\alpha]{2}$. The distribution has support $\lambda_{si} \in [\lambda_m, +\infty]$.

in which $\lambda_m > 0$ is the minimum productivity level, used for normalisation of productivity performance, and $\alpha > 1$ is a distribution-shape parameter. To keep the model tractable and applicable across countries, we assume λ_m to be identical for all countries. With a productivity level $\lambda_{si} < \lambda_m$, a firm drops out.

Firms with productivity levels $\lambda_{si} > \lambda_m$ are able to make a profit in the domestic market, but a higher productivity level is required for firms that aspire to become a multinational corporation. This is due to the fixed costs that must be absorbed up-front, when becoming a multinational. First, setting up and running a headquarter that monitors, communicates, and supervises foreign subsidiaries requires overhead labour tasks c_{ijo}. The second fixed-cost barrier is formed by a fixed one-off labour task f_{ijo} for setting up a foreign subsidiary (e.g. preparation, market prospecting, organising financial start-up conditions, setting up logistics and local suppliers, learning to deal with foreign institutions, and complying with local regulations). The wage costs of both overhead tasks depend on the firm's labour productivity level λ_{si}. With wage level W_i the costs of running a headquarter and setting up a foreign subsidiary become, respectively, $H_{sij} = W_i\ (c_{ijo}/\lambda_{si})$ and $F_{sij} = W_i\ (f_{ijo}/\lambda_{si})$. These fixed-cost expenses also hold in a situation that there are no bilateral frictions for FDI. The setup costs form an investment that firms want to recoup in τ years by equal annual amounts, so that the annualised fixed setup costs amount to H_{sij}/τ and F_{sij}/τ. A 'new multinational' has to absorb both amounts, while it is only F_{sij}/τ for just adding a new foreign subsidiary.

The effect of bilateral frictions (ω_{ijt}, π_{ij}) is that they increase both fixed costs barriers.[28] For brevity we define $\varphi_{ijt} \equiv (1 + \pi_{ij})(1 + \omega_{ijt})$. The effective fixed annual setup costs for the headquarter and a foreign subsidiary in the case of bilateral FDI frictions become, respectively, $\varphi_{ijt}H_{sij}/\tau$ and $\varphi_{ijt}F_{sij}/\tau$. It is now possible to derive the cut-off productivity rate λ^*_{ijt} that is minimally required for a positive FDI decision at firm level, for the case that a firm has to absorb both types of fixed investment costs.

Let a firm's expected sales revenues for a new subsidiary $(\tilde{R}_{sijt})$ be proportional to the lagged GDP (Y_{jt-1}) of country *j*, using proportionality factor r_j and a parameter $\mu_{sij} > 0$ that reflects the firm's self-assessment of its competitive strength in the new market:

$$\tilde{R}_{sijt} = \mu_{sij}\, r_j Y_{jt-1} \qquad \forall\, s, j, i \tag{13}$$

Disregarding variable costs, a firm's expected gross profits (PR_{sijt}) from starting FDI activities in country *j* amount to:

$$PR_{sijt} = \tilde{R}_{sijt} - \frac{\varphi_{ijt}}{\tau}\left[C_{sijt} + F_{sijt}\right] \qquad \forall\, s, j, i \tag{14}$$

and in reduced form:

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[28] More differences in distance, language, cultural and legal systems or more discriminatory regulatory provisions tends to increase the fixed setup costs of a subsidiary and the headquarter costs. Formally, we assume that $(dc_{ijo}/d\omega_{ijt}) > 0$; $(df_{ijo}/d\omega_{ijt}) > 0$; $(dc_{ijo}/d\pi_{ijt}) > 0$; $(df_{ijo}/d\pi_{ijt}) > 0$.

$$PR_{sijt} = \mu_{sij}\, r_j Y_{jt-1} - \frac{\varphi_{ijt}}{\tau\, \lambda_{si}}\left[W_i\left(c_{ijo} + f_{ijo}\right)\right] \qquad \forall\, s, j, i \tag{15}$$

Using the first-order condition for profit maximalisation to equation (15) yields the cut-off productivity at which a domestic firm with productivity rate λ_{ijt}^* breaks even if it becomes a multinational:

$$\lambda_{ijt}^* = \frac{\varphi_{ijt}}{\tau\, \mu_{sijt}\, r_j}\left(\frac{W_i\left[c_{ij0} + f_{ij0}\right]}{Y_{jt-1}}\right) \tag{16}$$

Only firms with a productivity draw $\lambda_{si} > \lambda_{ijt}^*$ will engage in profitable FDI activities in country *j.* Equation (16) shows that the cut-off productivity rate increases with the friction term φ_{ijt}, but decreases with the market size (Y_{jt-1}) of the destination economy. Firms decide on a country-by-country basis to engage in bilateral FDI. An important result is that λ_{ijt}^* is strictly country-specific and may differ by country pair. Having said that, we apply Ockham's razor and generalise the conclusion. We only keep the essentials of eq. (16) by assuming that $\mu_{sijt} = \mu_{ij}$, $W_i = W$ and $r_j = r$:

$$\lambda_{ijt}^* = \frac{\varphi_{ijt}}{\tau\, \mu_{ij}\, r}\left(\frac{W\left[c_{ij0} + f_{ij0}\right]}{Y_{jt-1}}\right) \tag{16a}$$

An attractive property of the Pareto distribution is that its shape has a fractal, self-similar structure. This implies that the truncated distribution of domestic firms with $\lambda_{sit} > \lambda_{ijt}^*$ has a similar structure as the full productivity distribution. It means that the subset of firms with non-zero FDI is drawn from the following truncated distribution:[29]

$$G\left(\widetilde{\lambda_{sit}}\right) = 1 - \left(\frac{\lambda_{ijt}^*}{\lambda_{sit}}\right)^{\alpha}, \quad g\left(\widetilde{\lambda_{sit}}\right) = \frac{\alpha\left(\lambda_{ijt}^*\right)^{\alpha}}{\left(\widetilde{\lambda_{sit}}\right)^{\alpha+1}} \qquad \forall s \in (1, .. S) \tag{17}$$

A non-trivial condition for the existence of this distribution is that the subset $\lambda_{sit} > \lambda_{ijt}^*$ is not empty. The empirics of worldwide bilateral FDI patterns shows however an overwhelming presence of zeros.[30] This effectively means that distribution $G\left(\widetilde{\lambda_{si}}\right)$ must be empty in many cases. Given the fundamental willingness of firms to lease their knowledge assets (M_{sit}) to other countries in the form of FDI, the conclusion in the context of the present model must be that their firm-level productivities sometimes are insufficient to overcome the FDI friction costs, and that the size of country *j*'s market is not always sufficient to compensate for that.

We define $u_{sit,\lambda_{si}t>\lambda_{ijt}^*}$ as the fraction of all domestic firms u_{si} that have a productivity high enough to invest profitably in FDI activity in country *j*. The extensive FDI margin ψ_{ijt} is then defined as:

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[29] Note that the truncated distribution partly varies with time-variant friction components, so that a time suffix is required. The mean of this truncated productivity distribution $G\left(\widetilde{\lambda_{sit}}\right)$ is $\bar{\lambda_i} = \alpha.\lambda_{ijt}^*/(\alpha - 1)$, and the median is $\lambda_{i,med} = \lambda_{ijt}^* \sqrt[\alpha]{2}$. The distribution has support $\widetilde{\lambda_{sit}} \in \left[\lambda_{ijt}^*, +\infty\right]$.

[30] Cf. Helpman et al. (2004).

$$\psi_{ijt} = \frac{\sum_s^S u_{sit,\lambda_{si}t>\lambda^*_{ijt}}}{\sum_s^S u_{\lambda_{\text{sit}}}} \tag{18}$$

The results of this Section are comparable to the large trade literature on the extensive margin with heterogeneous firms and fixed costs that followed the seminal paper by Melitz (2003). There is still another parallel with the trade literature, in particular the papers that predict a positive country-size effect on bilateral trade, e.g. Melitz and Ottaviano (2008), Chaney (2008) and Melitz and Redding (2014). Many studies with firm-level trade data confirm a self-selection behaviour among firms. This is also what our model predicts with respect to FDI. Micro-econometric studies report that firms with FDI activities normally have a significant productivity premium over non-FDI domestic firms.[31]

Implications for the bilateral model. With the results of the micro model it is now possible to refine the micro-economic conditionality of the bilateral FDI equation (11). As long as $\psi_{ijt} > 0$, we expect some positive amount of bilateral FDI^*_{ijt} (however small it is), and otherwise it will be zero. The contribution of the micro model is that it that it explains ψ_{ijt}, and hence, the many zeros that can be observed in the world matrix of bilateral FDI, especially for outward FDI:

$$FDI^*_{ijt} = \begin{cases} \dfrac{\mathcal{G}_{ij} \,.\, FDI^{nofric}_{ijt}}{(1+\pi_{ij})(1+\omega_{ijt})} & \text{if } \psi_{ijt} > 0 \\ 0 & otherwise \end{cases} \tag{19}$$

6. Structural FDI gravity model for the *n*-country world

World FDI patterns form a closed system, if only because at least some multinational companies apply a global perspective in their investment decisions. Strategic decisions are driven by expectations on market outlooks and relative FDI costs. An increase (or lowering) of the FDI friction costs in country *Z* could cause a cascade of investment-substitution decisions. Policy changes in nearby large economies may send out stronger and more geographically extended 'ripples of change' than similar policies in remote small island states would do. So changes in country Z may change the relative attractiveness of countries X and Y, without the latter having changed their own friction-related policies.

Until quite recently, economic gravity studies of bilateral FDI patterns largely ignored such effects for third countries. Anderson and Van Wincoop (2003) were the first to explicitly model and quantify these effects with regard to international trade. Already a few years later, neglecting of such general equilibrium effects was labelled the "gold medal error" in estimation (Baldwin and Taglioni, 2006). A number of empirical papers show that ignoring third-party effects of trade policies leads to substantial biases in the results (cf. Head and Mayer, 2014; Fally, 2015; Yotov *et al*., 2016). The key problem is

[31] Cf. Bekes and Muraközy (2016); Wagner (2017); Kox and Rojas (2010); Bernard et al. (2005, 2018)

that actual trade patterns are affected by both absolute and relative trade frictions. Relative trade costs reflect the opportunity costs of directing bilateral trade to other countries. This issue has a full parallel in regard to global direct investment choices for firms with a multinational action perspective. The role of relative investment costs for FDI has only been analysed very recently.[32] Baltagi *et al*. (2007) found that third-country effects also occur in relation to FDI. Structural FDI gravity analysis explicitly deals with such general-equilibrium effects.

Anderson and Van Wincoop (2003) found a way to deal with third-party effects by expressing relative trade costs via what they call *multilateral resistance* (MR) terms; these terms aggregate relative trade costs in a consistent way. We apply their method and most[33] of their suggestions to model bilateral FDI patterns in an *n*-country world ($n \in 1,,2,..,J$). A comprehensive FDI analysis should regard the full set of country pairs with their relative FDI friction costs and their relative market sizes.

The direct frictions between a country pair are grasped by the values of ω_{ijt} and π_{ij}. However, the indirect or relative FDI friction costs must be normalised by the average economic mass and the average friction costs of all country pairs. The MR terms do so by aggregating from two perspectives, for outgoing FDI (origin country perspective), and for incoming FDI (perspective of the host/destination country). The outward MR term P_{it} measures —from the perspective of origin country *i*— the relative attractiveness of each potential destination country[34] as a combination of the direct friction costs, the relative friction costs for entering that market, and the country's potential FDI absorption capacity (proxied by relative GDP size):

$$P_{it} = \left[\sum_{j=1}^{n} \left\{\frac{(1+\omega_{ijt})(1+\pi_{ij})}{\Pi_{jt}}\right\}^{1-\sigma} \cdot \left(\frac{Y_{jt}}{Y_t}\right)\right]^{\frac{1}{1-\sigma}} \qquad \forall\, j,i \qquad (22)$$

The way in which third-country effects are taken into account is by normalising the direct FDI friction costs (ω_{ijt}, π_{ij}) with the average inward MR terms of each partner country (Π_{jt}). In this way we measure relative outward friction costs, represented by the first term behind the summation sign in equation (22). The second term measures the relative FDI absorption capacity of each potential partner country as proxied by its share in world GDP ($Y_t = \sum_j Y_{jt}$). All destination-country alternatives are made comparable with a constant substitution elasticity ($\sigma > 1$) that is assumed to be equal for all countries.[35] Relative friction costs increase in the direct FDI friction costs in country *j* (ω_{ijt}, π_{ij}), but decrease in average inward friction costs elsewhere (Π_{jt}).

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[32] Cf. Anderson, Larch and Yotov (2019); Kox and Rojas (2020, 2019).

[33] The assumption by Anderson and Van Wincoop (2003) that bilateral frictions between partner countries should be fully symmetric is redundant and overly simplifying. As shown in equation (11) our model of bilateral FDI friction also includes direction-specific friction costs ($\omega_{ijt} \neq \omega_{jit}$).

[34] Cf. Anderson (2011).

[35] The $\sigma > 1$ constant substitution elasticity expresses that countries have a preference for variety with respect to foreign knowledge or technology capital in the form of FDI.

When the world FDI pattern is considered as an integrated system, friction costs on each side of the national border must be considered. This also holds for the frictions that hinder outgoing FDI of each origin country. Seen from the perspective of the FDI-receiving country, it will be easier to attract FDI from countries with low policy-related obstacles for outgoing FDI. The inward MR term Π_{jt} is consistently aggregated by evaluating different FDI origin alternatives, as the mirror image of equation (22):

$$\Pi_{jt} = \left[\sum_{i=1}^{n} \left\{\frac{(1+\omega_{ijt})(1+\pi_{ij})}{P_{it}}\right\}^{1-\sigma} \cdot \left(\frac{Y_{it}}{Y_t}\right)\right]^{\frac{1}{1-\sigma}} \qquad \forall\, i,j \qquad (23)$$

The direct pairwise friction costs (ω_{jit}, π_{ij}) that affect incoming FDI are now normalised with the average outward MR term P_{it} of each origin country, thus expressing relative friction costs that affect incoming FDI.

Together, equations (22) and (23) map worldwide relative FDI friction costs for all countries. The MR terms form an inseparable module of the *n*-country model. It is evident that equations (22) and (23) refer to each other, which could hint to fixed-point problems and non-unique solutions. However, it has been proven that unique solutions exist for the Π_{jt} and P_{it} vectors.[36]

We may now present the *n*-country version of the FDI gravity equation (eq. 11 was provisional) with a correction for market-size-weighted relative friction costs:

$$FDI_{ijt} = \left[\frac{\Pi_{jt} \,.\, P_{it}}{(1+\omega_{ijt})(1+\pi_{ij})}\right] \overrightarrow{FDI}_{ijt}^{nofric} \qquad \text{for } \psi_{ijt} > 0\,;\ \forall\, i,j \qquad (24)$$

When the direct bilateral frictions term in the denominator increase relative to the averaged MR terms $(\Pi_{jt}. P_{it})$, this will decrease bilateral FDI going from country *i* to country *j,* and vice versa in the opposite case. The eventual bilateral FDI supply remains conditional on the extensive FDI margin $(\psi_{ijt} > 0)$ from the micro-economic model.

Finally, for the consistency of the world FDI matrix, and also for ensuring that the world FDI system is treated as a closed system, the following accounting condition must hold:

$$Z = \sum_{i=1}^{J} FDI_{ijt} - \sum_{j=1}^{J} FDI_{jit} = 0 \qquad \forall\, i,j \qquad (25)$$

The accounting condition (25) ensures that the world FDI matrix is square. This means not only that all origin and destination countries must be included, but also that the main diagonal of the matrix (i.e. FDI_{iit}, FDI_{jjt}) of domestic investments must be filled.

[36] Here we may learn from inputs outside the international economics literature. In 1772, Joseph-Louis Lagrange solved the *n*-body gravity problem for celestial objects by taking mass-weighted triangulation averages (root mean square of all relative distances, weighted by the total mass of all objects) of distances between all tuplet configurations (cf. Barbour, 2020). Dealing with an analogue problem in input-output analysis, Dietzenbach and Miller (2009) prove that the equivalent of the MR terms have unique solutions relative to a neutral normalising constant. Translating their results to FDI, it requires: (a) all countries are represented in the world FDI matrix; (b) all countries invest in their own economies (elements on main matrix diagonal are strictly positive); and (3) there is no group of countries that operates in FDI-autarky or in FDI--isolation (matrix can not be made block diagonal). Poissonnier (2019) even argues that it would suffice to satisfy condition (c) only.

This is necessary to account for the general equilibrium effects caused by changes in market sizes (GDP) and in relative FDI friction costs, including intra-national friction costs for investment.[37]

Anderson *et al*. (2019) presented a FDI gravity equation as part of a larger general equilibrium model that also explains bilateral trade. This prevents testing of their model as a stand-alone model. Their MR terms are exclusively based on the bilateral trade-costs frictions, and they assume that these hold as well for FDI. However, in our model we explicitly concentrate on FDI-related (MR terms).[38] Moreover, our model also allows for non-symmetric FDI frictions between partner countries.

Finally, given the result of equation (24), we may calculate the average intensive FDI-margin at firm level κ_{ijt} by dividing total bilateral FDI with the number of firms that have a productivity that is sufficiently high to absorb the bilateral friction costs:[39]

$$\kappa_{ijt} = \frac{FDI_{ijt}}{\psi_{ijt}} \qquad \text{for } \psi_{ijt} > 0 \; ; \; \forall \, i,j \qquad (26)$$

7. A stochastic model, but basis for testable predictions

In the Sections 2-6 we have proposed a stand-alone deterministic model that explains bilateral FDI patterns. It shows what would happen if all decision makers had access to all relevant information. The prime function of the micro-model is to explain the extensive FDI-margin at firm level, explaining the zeros in the world system of bilateral FDI from a self-selection process among a country's firms. This provides the main conditionality for non-zero bilateral FDI. Worldwide, many bilateral FDI flows still are zero flows, so the contribution of the micro model is utterly relevant. After the self-selection process, the average intensive FDI margin (κ_{ijt}) per firm forms the factor that accommodates bilateral frictions.

The assumption that all decision makers have access to all relevant information is of course a simplifying assumption; its holds for most economic models. At the micro-level, decision makers never have the full world information at their disposal. Therefore, equation (24) works only stochastically, through the law of mass action, through trial and error, across many cases of over-shooting or under-estimation errors. Firms take FDI decisions on a country-by-country basis, sometimes by comparing a limited set of potential destination countries. Firms assess their own FDI capabilities, based on private knowledge of their own labour productivity and the available knowledge on foreign FDI friction costs. The gravity model works through the self-

[37] Cf. Agnosteva et al. (2019), Anderson et al. (2019, 2020), Yotov et al. (2016), Olivero and Yotov (2012).

[38] Bergstrand and Egger (2007, 2010) argue that bilateral trade and FDI flows are driven by a similar process. In forthcoming empirical research, we will show that relative trade and FDI friction costs may differ considerably.

[39] A Pareto-distributed random variable like the productivity variable ($\lambda_{si}, \lambda^*_{ijt}$) has the convenient property that all power functions derived from this random variable are also Pareto-distributed themselves. This also holds for κ_{ijt} so that it could provide testable predictions on the productivity distribution of the firms from country *i* that firm that actually provide outward FDI to country *j*.

selection behaviour of firms, even though the behaviour is driven by incomplete knowledge. However, the gravity forces are quite strong and may even beat host country policies.[40] The friction externalities of third countries (Π_{jt}, P_{it}) play an important role, especially through the role of large firms with a real global FDI horizon. The model is still a partial equilibrium model, because it takes the current and past distribution of economic masses (GDP) as an exogenous input.[41]

This paper presents a model for explaining worldwide bilateral FDI patterns at the most general level. It means that we disregard idiosyncrasies, e.g. behavioural FDI elements that are peculiar to specific sectors or FDI types (vertical, export-platform, global value chains). For the intensive FDI margin (κ_{ijt}) at firm level, such elements may be crucial. Some elements could be built in easily[42], but it leads away from the general gravity mechanism and it is non-essential from the perspective of Ockham's razor.

The model is falsifiable, because it yields a set of testable predictions:

- Parameters of the relative economic masses (GDP) of origin and destination country should have positive and significant signs.
- Parameters for estimated FDI friction costs (physical distance, lacking a common language, lacking a common border, lacking common institutions or history, having different regulations, policy-made obstacles to bilateral FDI) should have significant and negative signs.
- A negative correlation should exist between the incidence of zero outward FDI flows (either *i→j* or *j→i*) and the relative productivity performance of a country.
- A positive correlation should exist between the relative magnitude of outward FDI flows and the parameters that measure a country's relative abundance of proprietary knowledge stocks (cf. equation 5).
- A negative sign is expected for estimated parameters that measure relative bilateral distance, 'language distance', 'cultural distance', 'distance between legal systems', and the incidence of relative inward 'FDI-closedness' policies.
- A positive sign is expected for being members of the same preferential trade agreements, and for being members of the same bilateral investment agreement, because the latter are expected to lower bilateral FDI frictions.

For empirical testing, we propose a stepwise identification strategy that starts from a very general specification of the regression model with almost only fixed effects for time, for individual countries and for country pairs. The fixed effects absorb all country-

[40] Baltagi *et al*. (2007) find evidence for US manufacturing FDI that the impact of FDI-facilitating policies by potential host countries on bilateral FDI patterns is undermined by the host country's remoteness from main consumer markets (and by weaknesses in local skilled-labour supply).
[41] Olivero and Yotov (2012) elaborate how the economic mass of countries converges or diverges through changes in their policy-based friction costs and through endogenous changes in FDI and trade.
[42] An obvious option that is compatible with the Eaton and Kortum (2002) model, would be to link the host country's productivity and wage levels to incoming FDI. Brainard (1997) found that the presence of trade obstacles positively affects the choice for FDI as international expansion strategy. Also, vertical FDI motives in upstream or downstream foreign expansion activities remain outside the scope of this paper (e.g. Markusen, 2002; Carr *et al.*, 2004)). Country pairs with large bilateral trade or FDI flows are more likely than others to engage in joint preferential trade agreements (part of ω_{ijt}), while countries with an insecure investment climate are more likely to sign bilateral investment agreements (e.g. Cezar *et al.*, 2020).

and country-pair differences, including time variation in direct friction costs and economic mass (GDP), plus any non-modelled or unobservable differences. After this comprehensive assessment, different strategies can be applied to 'peel off' more specific information from the general results. The crux in econometric testing of this model is whether it remains standing despite the non-modelled, non-observed, or even non-observable impacts on world bilateral FDI patterns. This gives a range of challenges that must be dealt with in the econometric testing of the model:

- impact of non-specified factors (sectors, fiscal motives) for bilateral FDI at the level of individual country pairs;
- non-observed or even unknown impact factors that are relevant at the firm or/or country level, such as tax routing;
- time-related regional or worldwide shocks;
- any confounding impact factor that affect both the dependent variable (FDI_{ijt}) and some or all of the explanatory variables ($Y_{it}, Y_{jt}, \omega_{ijt}, \omega_{jit}$) and may lead to biased econometric results.

With regard to econometric testing of gravity models, Yotov *et al.* (2016) and Head and Mayer (2014) provide valuable toolkits and 'cookbooks'.[43] The recent literature suggests that the Pseudo-Poisson Maximum Likelihood (PPML) estimator is a good first start. It has the advantage that it effectively deals with zero bilateral FDI flows, and also with situations in which the variance of the error term depends on at least one of the explanatory variables (Santos Silva and Tenreyro, 2006, 2011; Correia et al., 2020). Both characteristics are important for the FDI data.

Zeros are overwhelmingly present in the world bilateral FDI matrices, and their incidence at lower aggregation levels (e.g. by sector) will even be stronger than our micro-model predicts. A sharp distinction has to be made between real zero FDI and missing (or non-reported, suppressed) data. Recent FDI data sets of IMF, OECD, Eurostat and UNCTAD identify non-reported, confidential FDI flows. Heteroskedastic error terms are caused by the large differences in relative size of countries. The structure of the data variables should therefore be a co-determinant for the choice of a particular estimator, while robustness tests with different estimators are advisable.[44] If most reported bilateral FDI data are from large countries with the most detailed statistics, this issue should not be much of a problem.

For adequately capturing the impact of third-country externalities on bilateral FDI, it is important that accounting condition (25) is satisfied. This is something that must be done in the data preparation phase. The available bilateral FDI data are improving in the last few years, but statistical reporting of FDI is still insufficiently coordinated

[43] See also Kox and Rojas (2020) for a review of best practices in testing structural FDI gravity models.
[44] PPML assumes a constant variance-to-mean ratio (dispersion index), whereas Gamma PML assumes a constant coefficient of variation. PPML puts more emphasis than Gamma PML on observations with large expected FDI. Head and Mayer (2014) and Martínez-Zarzoso (2013) recommend controlled tests with different types of Monte-Carlo generated databases. An often suggested alternative for PPML is the Gamma PML. Camarero *et al*. (2019) use the Negative Binomial PML, but according to Head & Mayer (2014) this estimator cannot perform correctly in the presence of many zeros. A test on the adequacy of the estimator is easy to apply.

internationally, resulting in different reporting of the same bilateral flow by origin and destination country, partly reported origin or destination countries, and anomalies such as dimensional mistakes and negative FDI stocks. Because of statistical deficiencies, it may be necessary to define a rest-of-world category, specific for each origin and destination country, to capture unspecified or unreported bilateral FDI, based on mirror data of bilateral FDI partners. The literature suggests that there is more under-reporting than over-reporting of FDI, so that the use of mirror data from partner countries is a relatively easy first step towards achieving the $Z=0$ condition of eq. (25).[45] Negative bilateral FDI stocks can be explained by the vintage structure of bilateral FDI stocks and the way in which these past flows were financed. Old vintages of FDI assets within a particular host country may be subject to local changes in accounting systems, local valuation changes and local changes in the structure of asset financing. These actions take place outside the explanatory scope of the bilateral FDI gravity model and they are not necessarily related to the knowledge capital of the origin country or even to knowledge assets leased from the origin country's firms. The model explains semi-positive current FDI stocks and FDI decisions by firms, and not the ex-post valuation changes in existing FDI stocks. So, reported negative stocks are best set to zero.

Finally, the estimation process of the model generates also quantitative estimates for the multilateral resistance (MR) terms, both inwards (Π_{jt}) and outwards (P_{it}).[46] The inward MR terms form a rich information source for secondary analysis. One may use regression analysis to quantify the impact of different types of domestic policies on a country's inward MR terms. Similarly, one may use the outward MR terms for analysis that quantifies the impact of domestic policies in the origin countries have on the magnitude of outgoing FDI flows. Whether bilateral or multilateral policies like preferential trade agreements, WTO, regional integration pacts, or bilateral investment agreements are effective between member countries can be assessed using the FDI-related MR terms (for the relevant country sample) as quantitative indicator (cf. Kox and Rojas, 2019).

8. Conclusions

The paper develops a stand-alone gravity model to explain international patterns of foreign direct investment (FDI). Using Ockham's razor, we opt for the smallest possible model that could explain worldwide FDI patterns. The model is based on the knowledge-capital interpretation of FDI and uses a vector interpretation of gravitational forces that shape the push and pull factors behind international FDI patterns. Most push and pull factors are directly or indirectly linked to GDP, which represents a country's economic mass. The model provides a micro-economic foundation for the bilateral extensive FDI margin, i.e. the decision whether an individual firms does or does not set up a new subsidiary in another country. When aggregated over all national firms, self-selection explains the existence of zero outward FDI flows.

[45] It may not be enough. If still holds that $Z > 0$, the difference might be added to a fictive ROW 'country' of the least-reporting world aggregate (either $\sum_{i=1}^{J} FDI_{it}$ or $\sum_{j=1}^{J} FDI_{jt}$), while adding a similar, but empty ROW 'country' to the other world aggregate.

[46] Cf. Correia et al. (2020); Weidner and Zylkin. (2021).

Physical and policy-made friction costs factors explain why only a small selection of firms effectively engages in FDI activities. The model is generalised to a n-country world by also accounting for the externalities caused by third-country effects. The FDI-based multilateral resistance terms quantify the relative FDI friction costs of all countries, weighted by the size of their markets. They vary by year and country pair. The FDI-based multilateral resistance terms may be considered as a fluctuating gravity field, in which firm-level FDI decisions are being taken. The model allows for different types of FDI friction costs, including policy-related country-specific or pair-specific costs.

The model provides several policy-relevant outcomes. It shows the impact of public knowledge-creation policies on outward FDI. The model quantifies the impact of policy-made FDI frictions on expected bilateral FDI. Moreover, as a secondary output the model yields quantitative values for the multilateral FDI resistance terms. The latter may be used to evaluate the FDI impact of both national and international policies on bilateral and worldwide FDI flows.

Annex Proof of Proposition 1

If public and private sector have the same depreciation method (Θ, δ) and we take out the time variance of the main parameters (ε_{it} , β_{it} , v_{it} , ε_{sit} , α_{sit} and ω_{sit}), the equations (1-4) reduce to:

$$M_{pit} = v_i \left[\varepsilon_i \, M_{pio} + \beta_i\right] Y_{it} \qquad (1a)$$

$$M_{pio} = \sum_{\theta=1}^{\Theta-1} \beta_i \, Y_{i,t-\theta} \, (1-\delta)^{\theta} \qquad with \;\; 0 < \delta < 1; \; ; \; \delta_{t-\Theta} = 1 \qquad (2a)$$

$$M_{sit} = (v_i)^{z_s} \left[\alpha_{si} + \omega_{si}.M_{pi,t-1} + \varepsilon_{si}.M_{sio}\right].Y_{it} \qquad with\; s = 1,..,S \qquad (3a)$$

$$M_{sio} = \sum_{\theta=1}^{\Theta-1} \alpha_{i,t-\theta} \, Y_{i,t-\theta} (1-\delta)^{\theta} \qquad with \;\; 0 < \delta < 1 \, ; \; \delta_{t-\Theta} = 1 \qquad (4a)$$

Starting from aggregation of all firm-level knowledge creation effort, we get equation A1, in which:

$$M_{fit} = \sum_{s=1}^{S} (v_i)^{z_s} \left[\alpha_{si} + \omega_{si}.M_{pi,t-1} + \varepsilon_{si}.M_{sio}\right].Y_{it} \qquad (A1)$$

This rewrites as:

$$M_{fit} = (v_i)^{z_s} \, Y_{it} \sum_{s=1}^{S} \alpha_{si} + \omega_{si}.M_{pi,t-1} + \varepsilon_{si}.M_{sio} \qquad (A2)$$

And using eq. (1a), $M_{pi,t-1}$ can be written as $M_{pi,t-1} = v_i \left[\varepsilon_i \, M_{pio,t-1} + \beta_i\right] Y_{it-1}$. After substituting this into (A2) and some rearrangement, this yields:

$$M_{fit} = v_i^{z_s-1} \, Y_{it} \sum_{s=1}^{S} \alpha_{si} + \omega_{si}\left[\varepsilon_i M_{pio,t-1} + \beta_i Y_{it-1}\right] + \frac{\varepsilon_{si}}{v_i}.M_{sio} \qquad (A3)$$

From equations (2a) and (4a) the lagged knowledge stocks M_{sio} and $M_{pio,t-1}$ may be substituted into (A3):

$$M_{fit} = v_i^{z_s - 1}\, Y_{it} \sum_{s=1}^{S} \left\{ \alpha_{si} + \omega_{si}\, \varepsilon_i\, \beta_i \left[\sum\nolimits_{\theta=1}^{\Theta-1} Y_{i,t-(\theta-1)}\, (1-\delta)^{\theta-1} \right] + \right.$$
$$\left. +\ \omega_{si}\, \beta_i\, Y_{it-1} + \frac{\varepsilon_{si}}{v_i} \left[\sum\nolimits_{\theta=1}^{\Theta-1} \alpha_{i,t-\theta}\, Y_{i,t-\theta} (1-\delta)^{\theta} \right] \right\} \qquad QED\ \blacksquare$$

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