

Modelling growth of urban firm networks

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Role of firm networks in urban systems:

- Cities as cross-overs of socio-economic interactions [Castells, 1996]
- Networks as the new social morphology of societies [Castells, 2000], giving rise to network economies [Sassen, 1991]
- Emergence of an interconnected world city network as a crucial feature of globalisation [Taylor, 2001]
- Interurban interactions between firms as one of the most representative of economic trends [Martinus and Sigler, 2018]

Relevance of dynamics urban network evolution models:

- Evolutionary Theory of Urban Systems [Pumain, 1997]
[Pumain, 2006]
- Adaptive cycles and diffusion of innovation [Hagerstrand, 1968]
- Path dependence [Martin and Sunley, 2006] [Pumain, 2012]
- Selection and emerging structures of systems
- Evolutionary models for urban systems dynamics:
[Favaro and Pumain, 2011] [Cottineau et al., 2015]
[Schmitt et al., 2015] [Raimbault, 2018] [Raimbault, 2020]
[Raimbault et al., 2020]

Main geographical processes considered:

- Metropolisation & internationalisation effects
- Specialisation-driven factors and drivers of innovation
- Macroeconomic exogenous chocs and resilience of urban systems

→ *How can we capture geographical and economic processes within urban networks of firms with a generative model?*

Advantages of the model introduced:

- Indirect inference on processes
- Multiple complementary factors driving inter-urban links
- Includes path-dependency

We examine the interactions of European cities within firm linkages defined by corporate ownership links and introduce

- an empirical analysis of the firm ownership urban network in the European Union, based on the Bureau Van Dijk's AMADEUS database;
- a generative network model to simulate the growth of such linkages at urban areas scale;
- the model allows us to compare the effect of different factors on the final network structure, which is extensively studied through model sensitivity analysis and exploration;
- we calibrate the model on the empirical network and apply it to stylized economic shock scenarios.

→ Cities are defined by their GDP and their profile regarding the proportion of firms in the different sectors. Links between cities are created in an iterative way, taking into account:

- geographical proximity (distance or effective accessibility)
- geopolitical proximity (belonging to the same country or single market → application to Brexit)
- city size (economic size as GDP)
- economic similarity (e.g. cosine distance between sector proximity as done in [Cottineau and Arcaute, 2019])
- previous linkages

Formalization

Cities characterised by economic size E_i (GDP) and economic structure S_{ik} (probability distribution of firms within K sectors)

Starting from an initial network, at each time step, add a fixed number of links randomly, following a probability as a generalised Cobb-Douglas function

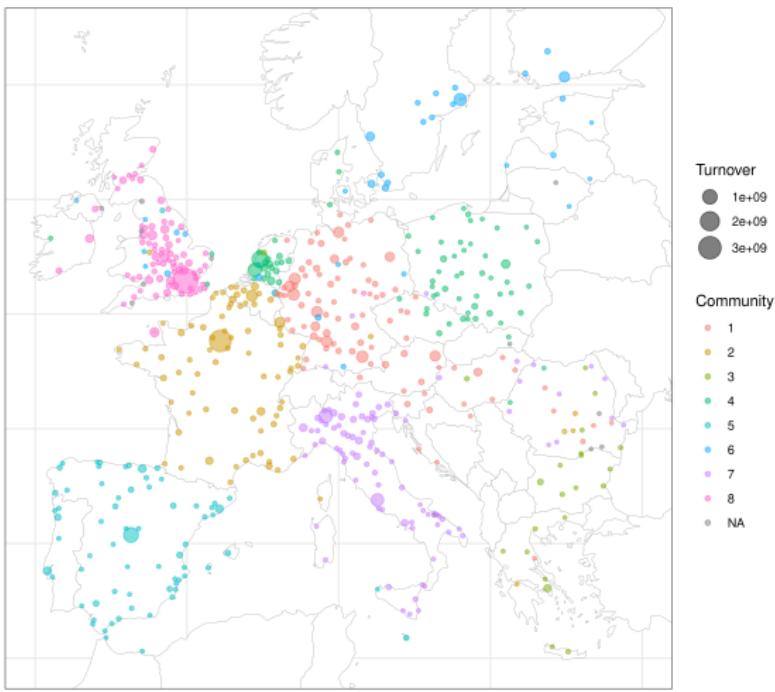
$$p_{ij} \propto \left(\frac{E_i}{E}\right)^{\gamma_O} \cdot \left(\frac{E_j}{E}\right)^{\gamma_D} \cdot \left(\frac{w_{ij}}{W}\right)^{\gamma_W} \cdot s(S_{ik}, S_{jk})^{\gamma_S} \cdot \exp\left(-\frac{d_{ij}}{d_0}\right) \cdot \exp\left(-\frac{c_{ij}}{c_0}\right)$$

where $E = \sum_k E_k$, $W = \sum_{i,j} w_{ij}$, s is a proximity measure given by cosine similarity, d_{ij} euclidian distance, and c_{ij} a socio-cultural distance

Model parameters: $\gamma_O, \gamma_D, \gamma_W, \gamma_S, d_0, c_0$

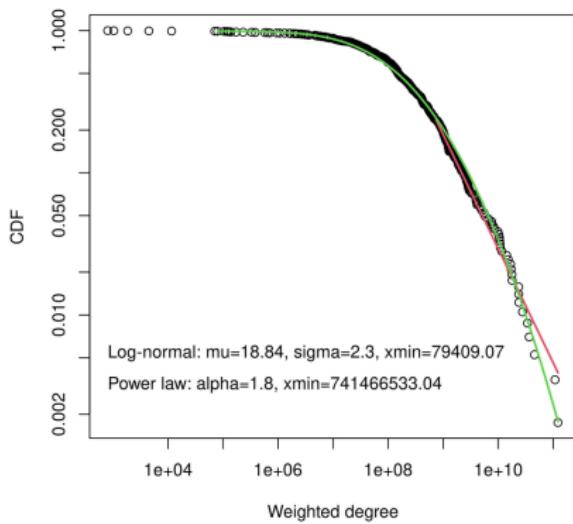
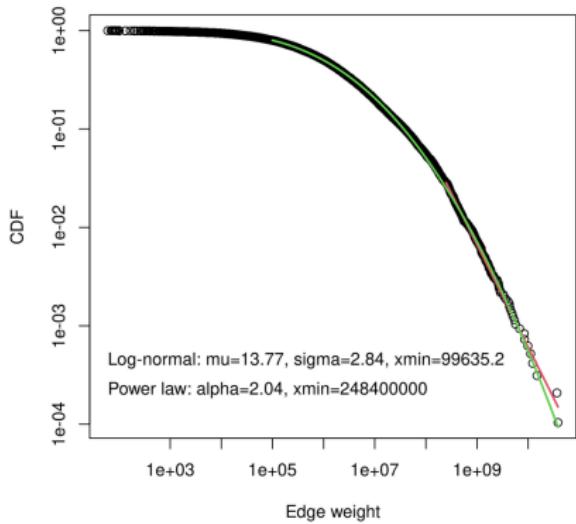
Model indicators: internationalisation (modularity of countries in the network), metropolisation (correlation between weighted degree and city size), optimal modularity, average community size

Empirical data



Map of network communities obtained by modularity maximisation (European ownership network between Functional Urban Areas, constructed from the AMADEUS database).

Empirical network properties



Empirical distribution of network properties, with log-normal and power law fits

Statistical models

Most general spatial interaction model with fixed effects:

$$\log w_{ij} = \log d_{ij} + \log T_i + \log T_j + \log s_{ij} + \alpha_{c_i, c_j} + \varepsilon_{ij} \quad (1)$$

Model	(1)	(2)	(3)	(4)	(5)
$\log(d_{ij})$	-0.06** (0.03)	-0.11** (0.05)	-0.41*** (0.02)	-0.35*** (0.04)	-0.26*** ($5 \cdot 10^{-6}$)
$\log(T_i)$			0.56*** (0.01)	0.56*** (0.01)	0.79*** ($2 \cdot 10^{-6}$)
$\log(T_j)$			0.39*** (0.01)	0.39*** (0.01)	0.66*** ($1.5 \cdot 10^{-6}$)
$\log(s_{ij})$				0.19*** (0.07)	0.53*** ($9 \cdot 10^{-6}$)
Countries		28.3%		26.5%	100%
R^2	0.00059	0.17	0.21	0.31	0.56
MSE	7.75	6.84	6.10	5.33	8.72
AIC	44304	43578	42131	41917	

Zero-inflated and Hurdle models: [Details](#)

- ① Simulation on synthetic systems of cities [Raimbault et al., 2019]: generation of a continent-scale urban system with stylized order of magnitude corresponding to Europe (urban hierarchy, countries, industrial sector distributions - [Details](#))
- ② Simulation on the European system of cities, setup with AMADEUS data at FUA level ([Details](#))

Implementation and experiments

Implementation

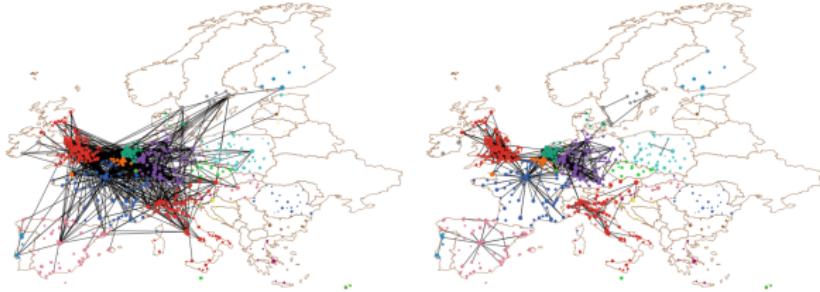
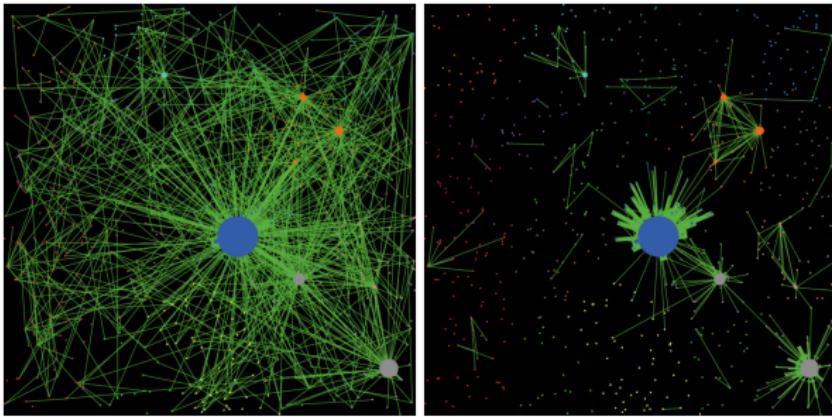
- Model implemented in NetLogo (good compromise interactivity / ergonomy), with fast data structures (matrix/table extensions)
- Integrated seamlessly into OpenMOLE [Reuillon et al., 2013] for model exploration <https://openmole.org/>



Experiments

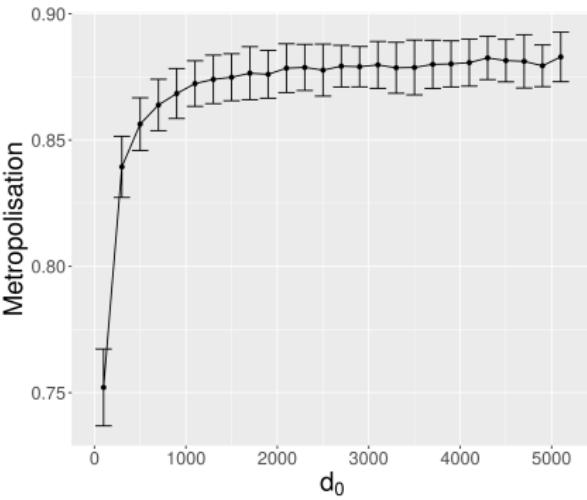
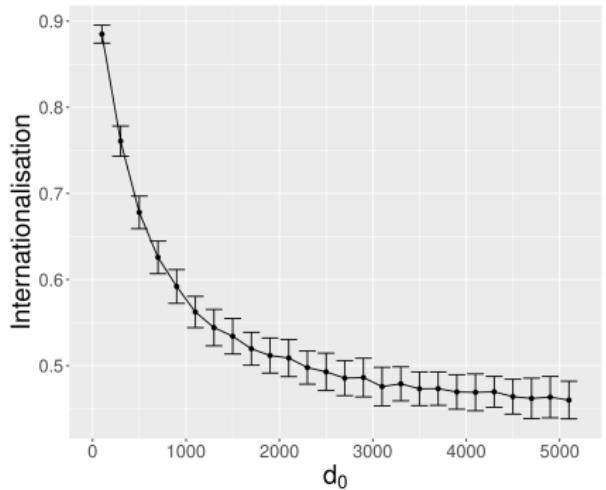
- One-factor sampling with 100 repetitions to assess statistical properties (good convergence, average sharpe ratios for indicators all larger than 5)
- Grid sampling with 20 repetitions for model behavior
- Targeted experiment on impact of synthetic hierarchy
- Global Sensitivity Analysis [Saltelli et al., 2008]
- Calibration on real setup with a Genetic Algorithm
- Application to economic shocks scenarios

Simulation of urban networks



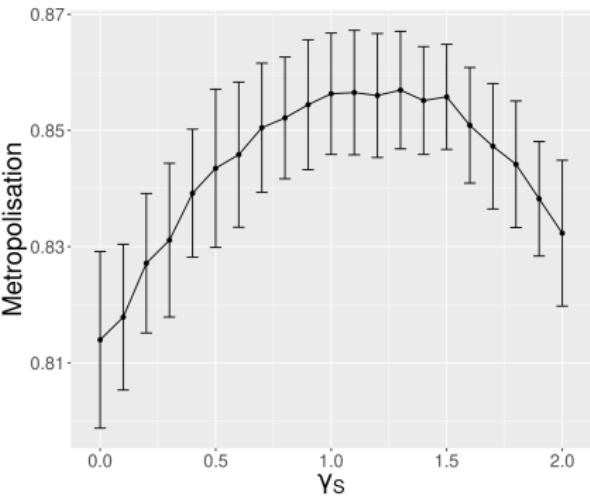
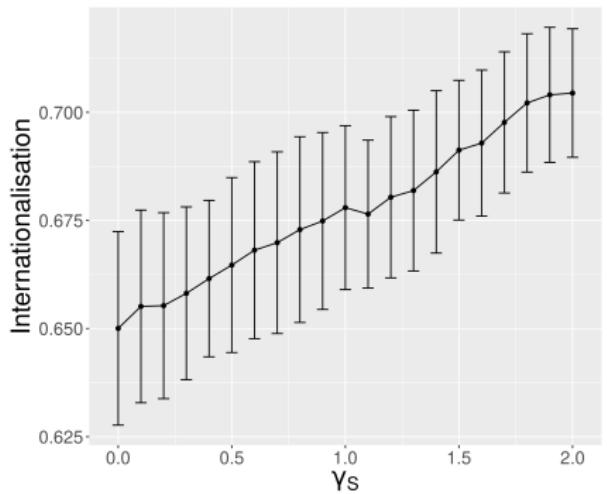
Simulated networks in a synthetic setup (top) and real setup (bottom), for a large (resp. low) interaction range d_0 (left, resp. right).

Effect of interaction decay



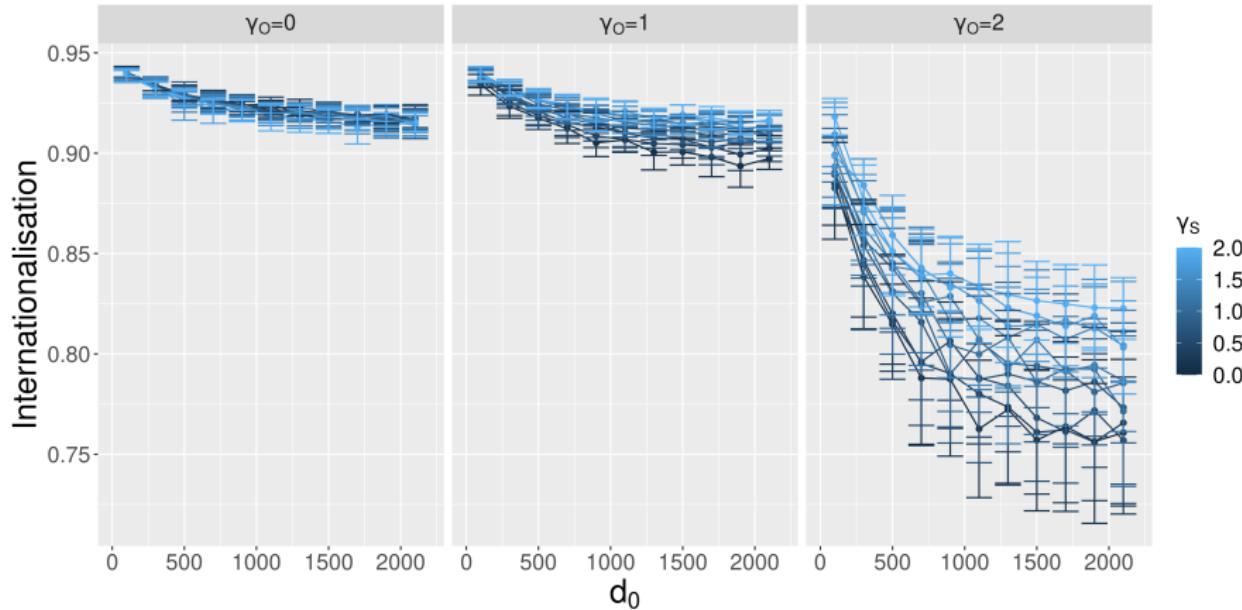
(Left) Internationalisation index decreases exponentially with gravity decay; (Right) metropolisation also shows a progressive transition from a local to a global regime.

Effect of sector proximity



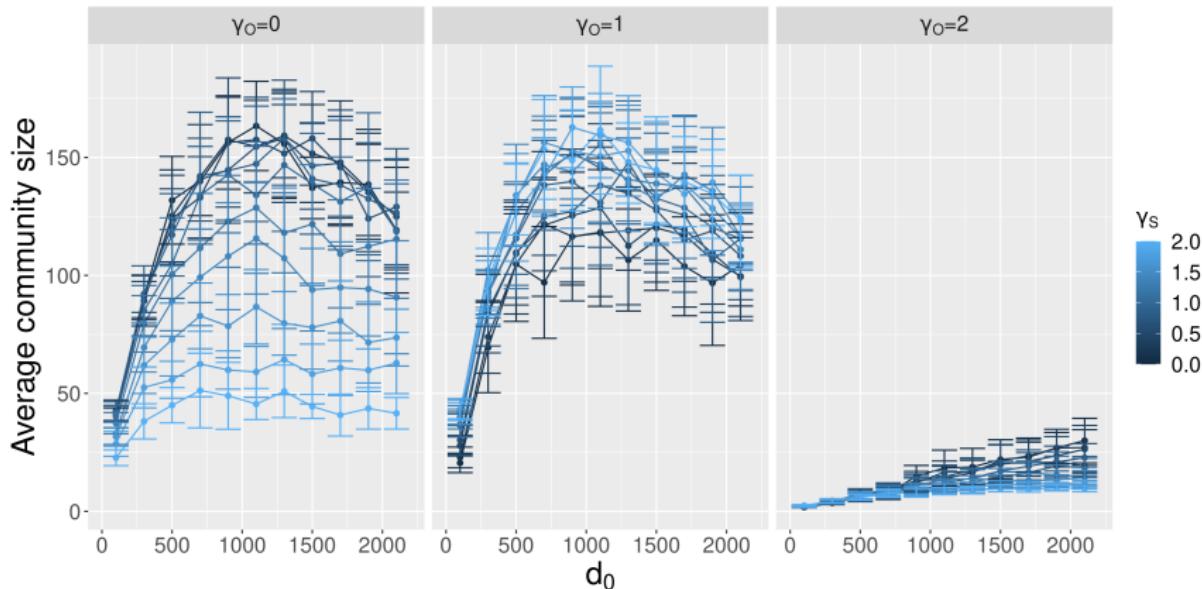
(Left) Internationalisation varies linearly with sector proximity γ_s ; (Right) metropolisation witnesses an intermediate regime where size is the most important

Grid exploration: internationalisation



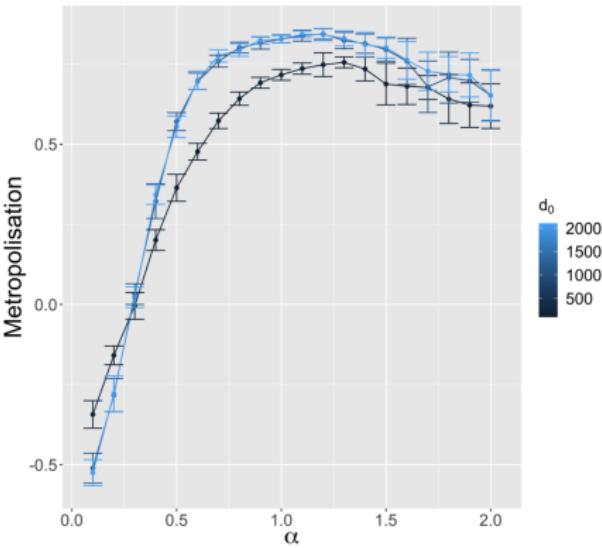
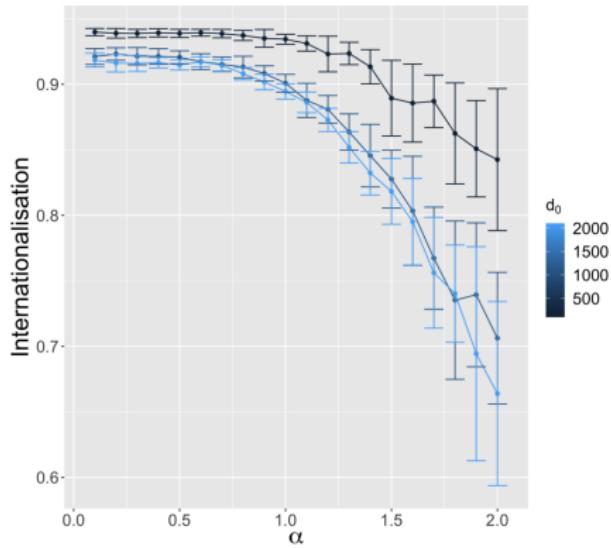
The transition as a function of interaction range depends on the influence of origin size γ_F ; sector proximity γ_S plays a role only for a large influence of the origin.

Grid exploration: community size



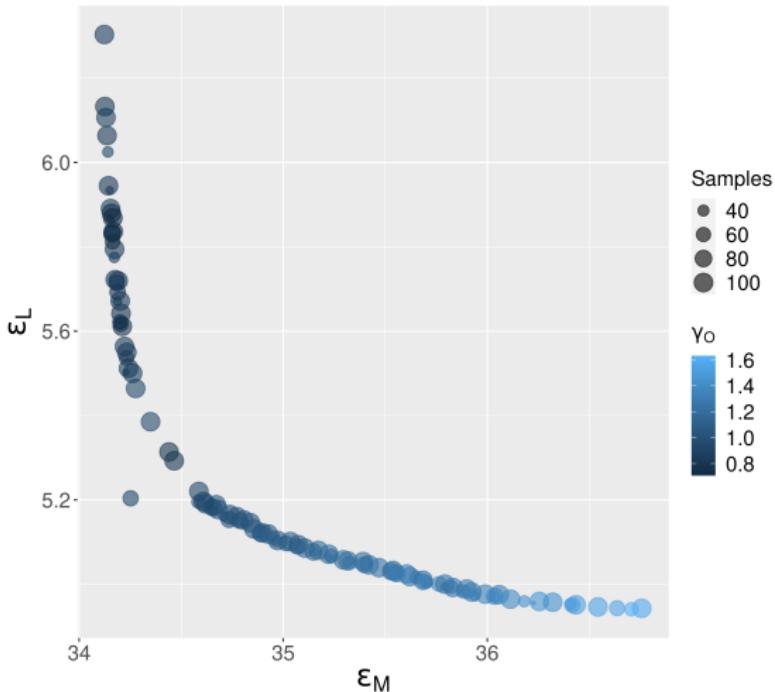
- Maximal integration in term of community size is achieved at an intermediate value of d_G : emergence of a regional regime
- Maximal size depends on the role of sectors γ_S , in a decreasing way when origin size is deactivated, and increasing way when $\gamma_F = 1$
- This regime disappear when origin size influence is too large

Role of urban hierarchy



Impact of urban hierarchy on model indicators in synthetic systems of cities: existence of a maximum for metropolisation at intermediate hierarchies.

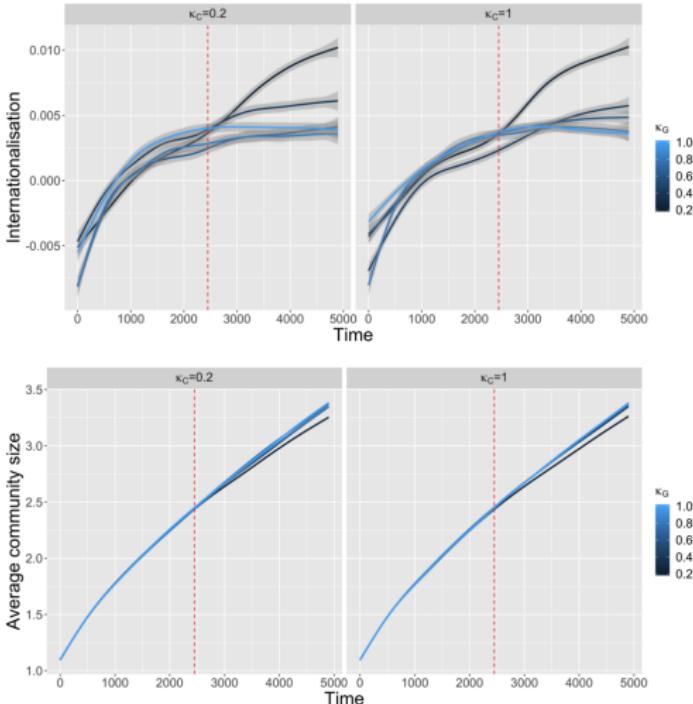
Calibration on the European urban network



Pareto front obtained for the bi-objective model calibration using a NSGA2 algorithm (outperforms statistical models that have a MSE of 5.33).

Details on the calibration procedure

Economic shock scenarios



Although the system is resilient to moderate shocks, strong restrictions have an important impact on internationalisation and thus can be expected to have a detrimental effect on UK economy due to these foreign ownership links.

Practical applications

- Potential application to public policy issues;
- Effect of exogenous shocks on specific economic sectors mostly dependent on foreign ownership links (extraction of crude petroleum, manufacture of tobacco & basic pharmaceutical goods, activities of head offices).

Developments

- co-evolution model (evolution of city sizes) [Raimbault, 2021];
- a model with firm agents (multi-scale ABM) [Raimbault, 2019];
- targeted study of path dependency;
- other formulation of the combination of factors or multi-objective optimisation depending on sectors using Pareto fronts.

Conclusion

- A generative model to understand processes of economic network emergence
- Crucial role of model exploration to validate and extract knowledge from such a simulation model

Preprint at <https://arxiv.org/abs/2009.05528>

Open repository for model and results at
<https://github.com/JusteRaimbault/ABMCitiesFirms>

Simulation data at <https://doi.org/10.7910/DVN/UPX23S>

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Reserve slides

- ① Generate $N = 700$ cities with size following a power law $E_i = E_0 \cdot i^{-\alpha}$ with $E_0 = 10^{11}$ and $\alpha = 1.1$ (computed on Europe for GDP with cities larger than 50.000 inhabitants)
- ② Distribute them randomly in space ([Simini and James, 2019] vs [Banos et al., 2011])
- ③ Create countries with k-means clustering ($C = 30$)
- ④ Distribute sectors such that (i) smaller cities are more specialised and (ii) larger cities are more knowledge-based, with a one dimensional axis to position sectors $1/K \dots 1$ where the density $f(k)$ follows a log-normal with (μ, σ) such that $\sqrt{\text{Var } f} = K/2$ for the largest, $\sqrt{\text{Var } f} = 1/K$ for the smallest

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Real configuration setup

Urban areas (FUAs) positions, economic size initialised from the GHSL database, sector composition from the Amadeus database using classification of firms and aggregating

Initial dummy network ($w_0 = 1$)

Socio-cultural distance c_{ij} : fixed effects coefficients

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
-2.327	1.440	2.451	2.538	3.447	11.797	339

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Global sensitivity analysis

	d_0		c_0		γ_s		γ_w		γ_o		γ_d	
	F	T	F	T	F	T	F	T	F	T	F	T
Internationalisation	0.2	0.3	0.7	0.7	0.001	0.008	$5 \cdot 10^{-4}$	0.007	0.03	0.04	0.02	0.04
Metropolisation	0.02	0.04	0.02	0.04	0.02	0.3	0.002	0.01	0.2	0.7	0.2	0.7
Modularity	0.3	0.4	0.6	0.6	$5 \cdot 10^{-4}$	0.02	0.002	0.02	0.007	0.03	0.003	0.03
Avg. com. size	0.004	0.1	0.01	0.1	0.003	0.07	0.001	0.04	0.3	0.6	0.3	0.6
Degree entropy	0.003	0.03	0.002	0.03	0.008	0.04	0.003	0.03	0.5	0.6	0.5	0.6
Weight entropy	0.04	0.2	0.03	0.2	0.002	0.1	0.001	0.1	0.5	0.6	0.5	0.6

First order and total sensitivity indices [Saltelli et al., 2010], for all parameters and indicators.

Zero-inflated and Hurdle statistical models

Accounting for zeros with specific models: same qualitative results

Model	Zero-inflated		Hurdle	
	Count	Zero-infl.	Count	Zero-hurdle
$\log(d_{ij})$	-0.28*** (7e-4)	0.88*** (0.01)	-0.29*** (8e-6)	-0.75*** (0.01)
$\log(T_i)$	0.74*** (4e-6)	-0.74*** (7e-3)	0.74*** (5e-6)	0.67*** (5e-3)
$\log(T_j)$	0.64*** (4e-6)	-0.52*** (7e-3)	0.64*** (4e-6)	0.48*** (5e-3)
$\log(s_{ij})$	0.46*** (2e-5)	-0.33*** (3e-2)	0.45*** (2e-5)	0.27*** (0.02)
R^2	0.1607		0.1661	
AIC	5.85e10		5.85e10	

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Model calibration

To avoid overfitting: $c_0 = 0$ to deactivate the mechanism

Calibration objectives:

$$\varepsilon_L = \frac{1}{N^2} \sum_{i,j} (\log w_{ij} - \log \hat{w}_{ij})^2$$

$$\varepsilon_M = \log \left(\frac{1}{N^2} \sum_{i,j} (w_{ij} - \hat{w}_{ij})^2 \right)$$

On macro indicators? Too much solutions, equifinality

Rescale flows: w_0 is arbitrary, so is optimised with rescaling:

$$\varepsilon_L(k_0) = \frac{1}{N^2} \sum_{i,j} (\log w_{ij} - \log (k_0 \cdot \hat{w}_{ij}))^2$$

what yields

$$k_0 = \exp \left[\frac{1}{N^2} \sum_{i,j} \log w_{ij} - \frac{1}{N^2} \sum_{i,j} \log \hat{w}_{ij} \right]$$