Trade-offs between sustainable development goals in systems of cities

J. Raimbault[1,2,3,4] and D. Pumain[4]
juste.raimbault@ign.fr

[1]LASTIG, Univ Gustave Eiffel, IGN-ENSG
[2]CASA, UCL
[3]UPS CNRS 3611 ISC-PIF
[4]UMR CNRS 8504 Géographie-cités

ERSA 2022 - TRSA ABC
August 23rd 2022

Cities and SDGs

SDG 11: "Make cities and human settlements inclusive, safe, resilient, and sustainable" [Nations, 2015]

→ Cities as a transition state? [Batty, 2018] Incubators of social change and innovation, both the source and solution to sustainability issues? [Pumain, 2010]

→ Environmental Kuznet Curve hypothesis [Dinda, 2004, Stern, 2004]: inverted U-shaped relationship between environmental impact and income per-capita; not validated empirically [Harbaugh et al., 2002]

→ Trade-offs between SDGs in urban systems [Viguié and Hallegatte, 2012]

Bi-objective trade-offs

Journal of Urban Management
Volume 11, Issue 2, June 2022, Pages 237-245

Research Article

Trade-offs between sustainable development goals in systems of cities

Juste Raimbault [a, b, c, d], Denise Pumain [d]

Show more

Add to Mendeley   Share   Cite

https://doi.org/10.1016/j.jum.2022.05.008

Research objective

$\rightarrow$ More dimensions and SDGs with trade-offs?

$\rightarrow$ Several models introduced with the evolutionary urban theory [Pumain, 2018] tackle complementary dimensions (see [Raimbault et al., 2020a] for a benchmark)

Research objective:

Couple several models for complementary dimensions of urban dynamics (innovation, economic exchanges, infrastructure) into a multi-model for the dynamics of urban systems at the macroscopic scale, to explore trade-offs between SDGs in synthetic systems of cities.

Innovation diffusion and urban dynamics

Exploration of trade-offs with two dimensions: urban evolution model [Raimbault and Pumain, 2022]

→ **Innovation diffusion** is a crucial process in artificial life evolutionary systems and open-ended evolution [Bedau et al., 2000]

→ Artificial societies used to study the dynamics of innovation [Zenobia et al., 2009]

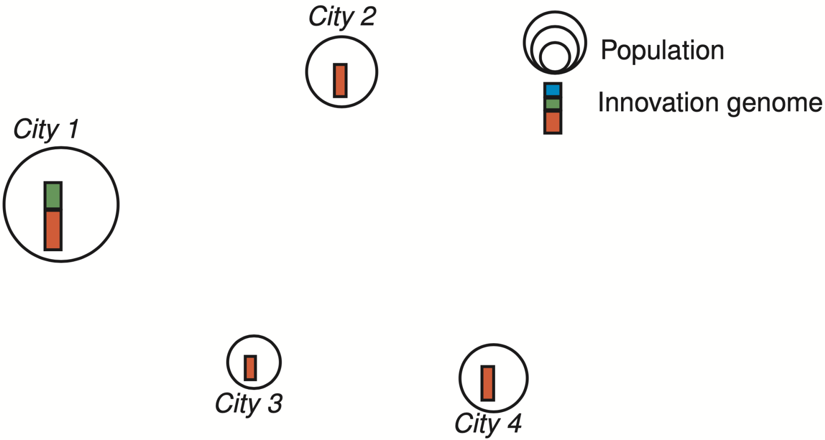
→ Innovations diffuse hierarchically in systems of cities [Hagerstrand, 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

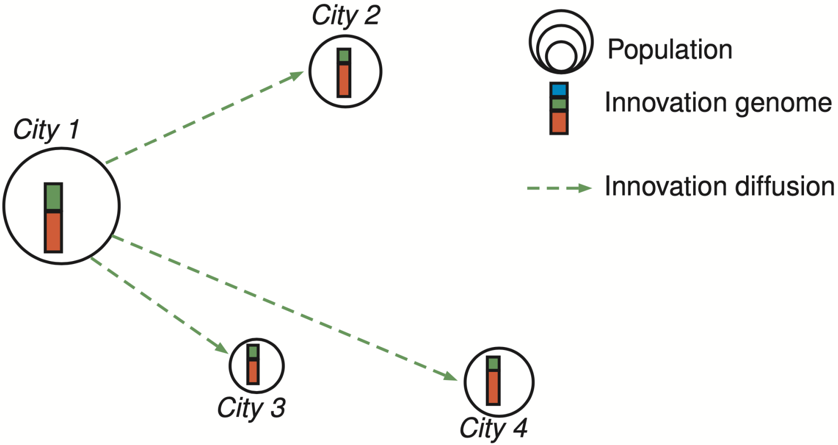
Model rationale

- Agents are cities, macroscopic scale (regional, country, continental) and long time scales (century)
- Cities characterised by their size in terms of population; genome as adoption proportions of innovations (social or technological) for each city (one single dimension to simplify)
- Following [Favaro and Pumain, 2011], attractivity of cities due to level of innovation drive their population growth through spatial interactions; innovation diffuse through an other spatial interaction model [Fotheringham and O'Kelly, 1989]
- Mutations occur in cities as new innovations appear

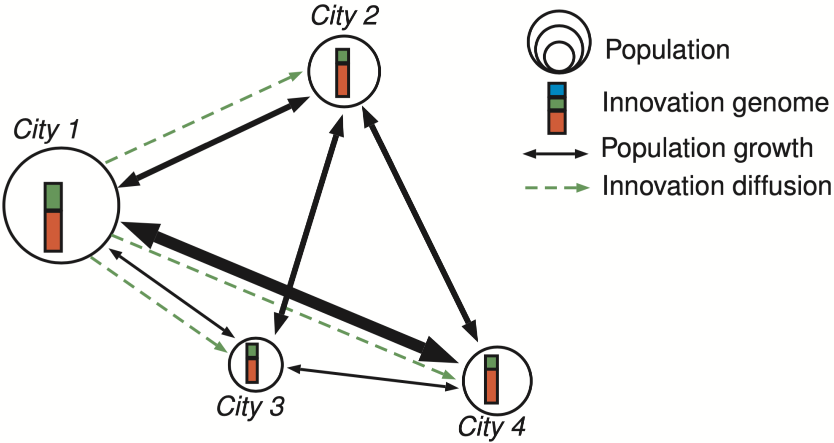
Model description



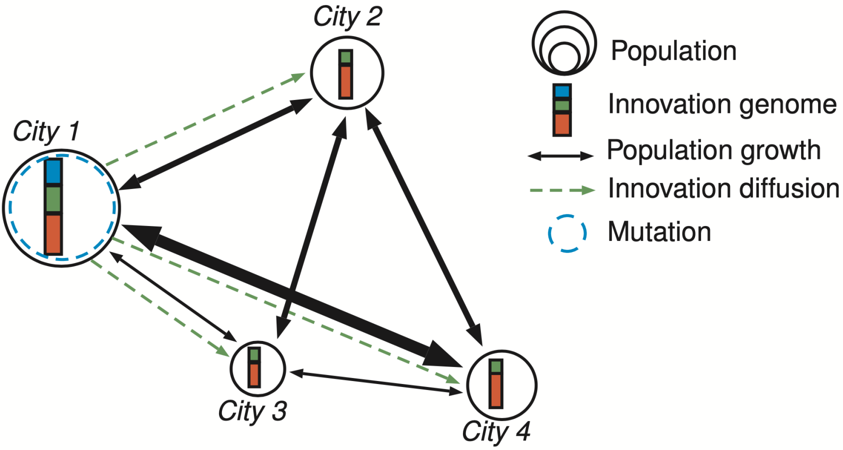
Model description



Model description



Model description



Model formalisation

At each time step, with $P_i(t)$ population, $\delta_{c,i}(t)$ genome, u_c utility of innovation, $p_{c,i,t}$ share of total population adopting innovation c in city i

1. Crossover through the diffusion of innovations

$$\delta_{c,i,t} = \frac{\sum_j p_{c,j,t-1}^{\frac{1}{u_c}} \cdot \exp\left(-\frac{d_{ij}}{d_I}\right)}{\sum_c \sum_j p_{c,j,t-1}^{\frac{1}{u_c}} \cdot \exp\left(-\frac{d_{ij}}{d_I}\right)}$$

2. Population growth through spatial interactions
   $P_i(t) - P_i(t-1) = w_I \cdot \sum_j \frac{V_{ij}}{<V_{ij}>}$ with

$$V_{ij} = \frac{P_i(t-1) \cdot P_j(t-1)}{\left(\sum_k P_k(t-1)\right)^2} \cdot \exp\left(-\frac{d_{ij}}{d_G}\right) \cdot \prod_c \delta_{c,i,t}^{\phi_{c,t}}$$

   and $\phi_{c,t} = \sum_i \delta_{i,c,t} \cdot P_i(t-1) / \sum_i P_i(t-1)$
3. Mutations with innovations introduced with probability $\beta \cdot (P_i(t) / \max_k P_k(t))^{\alpha_I}$ and an initial penetration rate r_0; new utility u_c randomly distributed (normal or log-normal) with average current average utility and standard deviation a given parameter σ_U

Synthetic configurations

Model applied on synthetic systems of cities (so that conclusions are independent of geographical contingencies [Raimbault et al., 2019]):

- random positions and rank-size hierarchy $P_i(0) = \frac{P_{max}}{i^{\alpha_0}}$ with $\alpha_0 = 1.0$ and $P_{max} = 100,000$
- regional urban system scale: $N = 30$ cities
- simulated for $t_f = 50$ macroscopic time steps (order of magnitude of a century)

Model parameters for the innovation model

Parameter	Not.	Process	Range	Def.
Number of cities	N	Spatial scale	$[10; 100]$	30
Initial hierarchy	α_0	System of cities	$[0.5; 2.0]$	1
Initial population	P_{max}	System of cities	$[10^4; 10^7]$	10^5
Simulation steps	t_f	Temporal scale	$[10; 100]$	50
Growth rate	w_I	Pop. growth	$[0.001; 0.01]$	0.005
Gravity range	d_G	Crossover	$[0; 2]$	1
Innovation range	d_I	Crossover	$[0; 2]$	1
Innovation rate	β	Mutation	$[0; 1]$	0.5
Innovation hierarchy	α_I	Mutation	$[0; 2]$	1
Innov. utility std.	σ_U	Mutation	$[0.7; 2]$	1
Penetration rate	r_0	Mutation	$[0.1; 0.9]$	0.5
Utility type	-	Mutation	{n;ln}	ln

Implementation

Model implemented in `scala`; relatively large parameter space; integration into the `spatialdata` scala library for spatial sensitivity analysis [Raimbault et al., 2020b]

→ integration into the OpenMOLE model exploration open source software [Reuillon et al., 2013]

Enables seamlessly (i) model embedding; (ii) access to HPC resources; (iii) exploration and optimization algorithms

`https://openmole.org/`

Trade-offs between SDGs

$\rightarrow$ *Which trade-offs between innovation (SDG 9: innovation) and emissions (SDG 14: climate) in systems of cities?*

Application of the urban evolution model, optimising with NSGA2 for conflicting objectives in synthetic systems of cities:

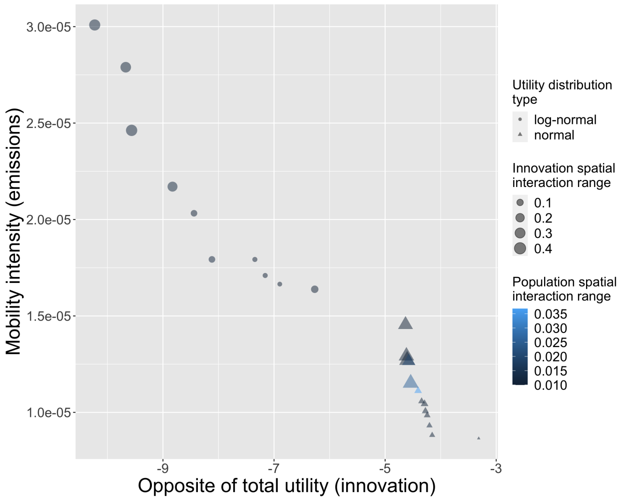
1. total utility of innovations

$$U = \sum_{t,i,c} \delta_{t,i,c} \cdot u_c$$

2. gravity mobility flows as proxy for emissions

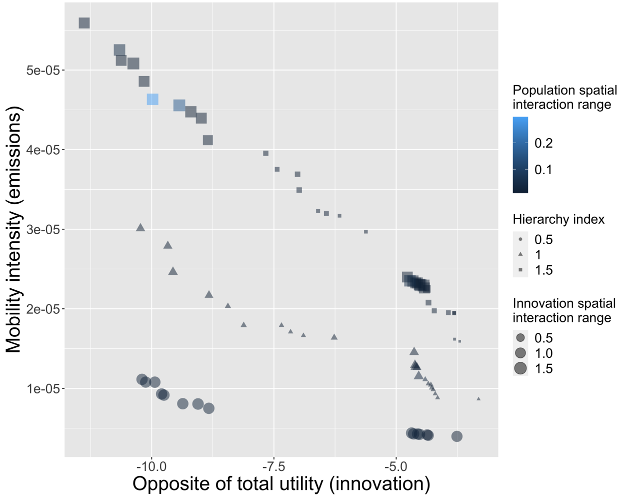
$$E = \sum_{t,i,j} \frac{P_{t,i} P_{t,j}}{P_t^2} \cdot \exp\left(-d_{ij}/d_G\right)$$

Trade-offs between SDG9 and SDG14



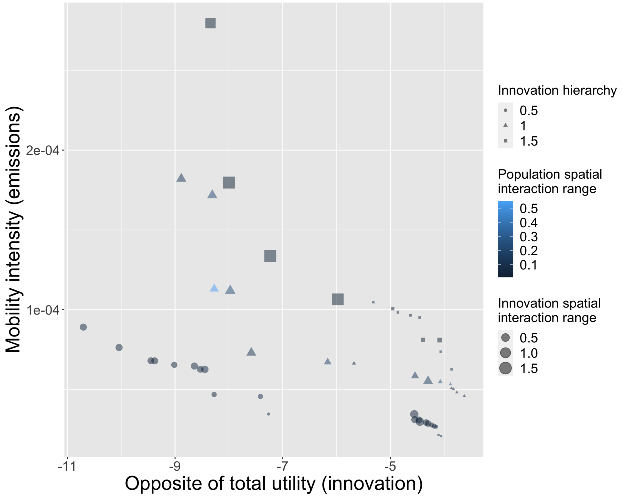
Pareto front confirms the existence of a trade-off

Influence of urban hierarchy



Higher inter-urban inequalities yield stronger trade-offs

Influence of innovation hierarchy



More balanced innovation yield higher utilities and less emissions (dominating Pareto front)

Generic multi-model of urban dynamics

Other dimensions benchmarked by [Raimbault et al., 2020a] to fit population dynamics on several large urban systems

Models integrated:

- Innovation diffusion urban evolution model [Raimbault and Pumain, 2022]
- Marius model for economic exchanges [Cottineau et al., 2015]
- Co-evolution model for cities and infrastructure networks [Raimbault, 2021]

"Semi-weak" coupling of submodels:

$$S_0 \rightarrow \left[S_1^{(0)} = M_0(S_0) \rightarrow \ldots \rightarrow S_1^{(K-1)} = M_{K-1}(S_1^{(K-2)}) = S_1 \right] \longrightarrow \ldots$$
$$\longrightarrow \left[S_T^{(0)} = M_0(S_{T-1}) \rightarrow \ldots \rightarrow S_T^{(K-1)} = M_{K-1}(S_T^{(K-2)}) = S_T \right] \quad (1)$$

Remarks: strictly weak coupling does not capture dynamics nor synergies; stronger coupling may exist to better capture interdependencies processes (here no specific coupling ontology, only population and distance matrix are shared between submodels)

Economic exchanges model

MARIUS family of models [Cottineau et al., 2015]:

Initial wealth as a power law of population (exponent α_W)

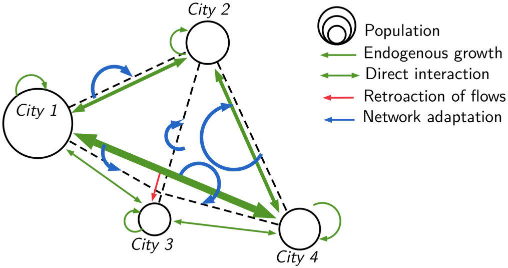
1) Update supply and demands as super-linear functions of population (exponents α_S, α_D)

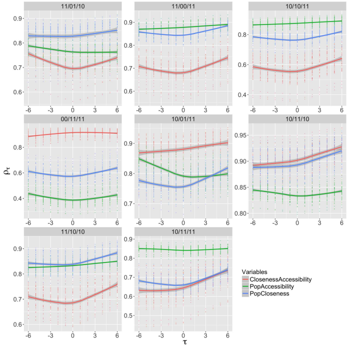
2) Exchange goods according to a gravity potential of interaction (distance decay d_M), supplies and demands; update wealth accordingly

3) Update population such that population difference is a power law of wealth difference (economic multiplier e_M and exponent α_P)

Infrastructure co-evolution model

System of cities interaction model including network evolution.





Raimbault, J. (2020). Indirect evidence of network effects in a system of cities. Environment and Planning B: Urban Analytics and City Science, 47(1), 138-155.

Raimbault, J. (2021). Modeling the co-evolution of cities and networks. In Handbook of Cities and Networks (pp. 166-193). Edward Elgar Publishing.

Raimbault, J. (2020). Hierarchy and co-evolution processes in urban systems. Forthcoming in Hierarchy in infrastructure networks, J. Fen-Chong, ed. ISTE Editions.

Optimised objectives

Proxies for SDGs:

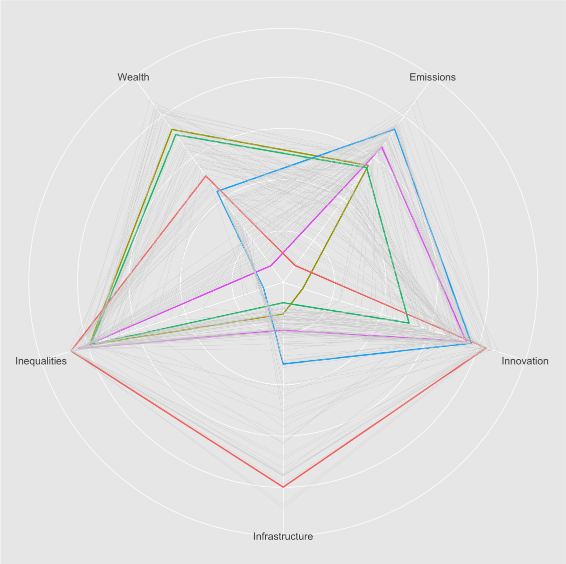
- Total utility of innovations (SDG 9 “Innovation”)
- Total spatial interaction flows across submodels (SDG 13 “Climate”)
- Average distance between cities (SDG 9 “Resilient infrastructure”)
- Economic inequalities (SDG 10 “Inequalities”)
- Total wealth of cities (SDG 8 “Economic Growth”)

Optimisation parameters: fixed synthetic urban system parameters but random configurations (10 repetitions); 8 parameters for innovation; 6 parameters for economic exchanges; 6 parameters for co-evolution

Optimisation results

Scatterplots of the 5D Pareto front. Color level: Gini economic wealth.

Optimisation results



Radar plot for the many-objective optimisation (colour: best solution along each dimension)

Discussion

Parametrisation on case studies:

→ Patent data as a proxy for innovation: geolocation of inventors not straightforward [Bergeaud and Verluise, 2021] [De Rassenfosse et al., 2019]; which technological (sub-)classes? Model with one dimension (extension with a matrix genome?); semantic content to better capture innovation diffusion? [Bergeaud et al., 2017]

→ Emissions: inter-urban mobility emissions difficult to capture (need an additional transport model?)

→ Historical infrastructure networks data?

Work in progress

→ Many-objective optimisation: NSGA3 algorithm

→ Empirical stylised facts on possible trade-offs in systems of cities

Future work

→ Towards multi-scale models: quantifying goal 11 (sustainable cities and communities) implies in some cases intra-urban dynamics (mobility, segregation, e.g.)

→ Transfer to policies and planning? Models with multiple functions? [Varenne, 2018] (towards companion modeling and stakeholder involvement)

Conclusion

→ Towards an integrative urban and territorial science applied to sustainable planning at multiple scales

→ Transfer to decision-making, policies and governance? *e-team* of the CSDC campus

To use OpenMOLE (free and open software) and contribute:
`https://openmole.org`

Model code and results open source at
`https://github.com/JusteRaimbault/SDGTradeoffs` and
`https://github.com/openmole/spatialdata`

References I

Batty, M. (2018).
Inventing future cities.
MIT press.

Bedau, M. A., McCaskill, J. S., Packard, N. H., Rasmussen, S., Adami, C., Green, D. G., Ikegami, T., Kaneko, K., and Ray, T. S. (2000).
Open problems in artificial life.
Artificial life, 6(4):363–376.

Bergeaud, A., Potiron, Y., and Raimbault, J. (2017).
Classifying patents based on their semantic content.
PloS one, 12(4):e0176310.

Bergeaud, A. and Verluise, C. (2021).
Patentcity: A century of innovation: New data and facts.

References II

Cottineau, C., Reuillon, R., Chapron, P., Rey-Coyrehourcq, S., and Pumain, D. (2015).
A modular modelling framework for hypotheses testing in the simulation of urbanisation.
Systems, 3(4):348–377.

De Rassenfosse, G., Kozak, J., and Seliger, F. (2019).
Geocoding of worldwide patent data.
Scientific data, 6(1):1–15.

Dinda, S. (2004).
Environmental kuznets curve hypothesis: a survey.
Ecological economics, 49(4):431–455.

Favaro, J.-M. and Pumain, D. (2011).
Gibrat revisited: An urban growth model incorporating spatial interaction and innovation cycles.
Geographical Analysis, 43(3):261–286.

Fotheringham, A. S. and O'Kelly, M. E. (1989).
Spatial interaction models: formulations and applications, volume 1.
Kluwer Academic Publishers Dordrecht.

Hagerstrand, T. (1968).
Innovation diffusion as a spatial process.
Chicago, USA: Univ. Chicago Press.

Harbaugh, W. T., Levinson, A., and Wilson, D. M. (2002).
Reexamining the empirical evidence for an environmental kuznets curve.
Review of Economics and Statistics, 84(3):541–551.

Nations, U. (2015).
17 goals to transform our world: United nations sustainable development 2015.
United Nations Press: New York, NY, USA.

References IV

Pumain, D. (2010).
Une théorie géographique des villes.
Bulletin de la Société géographie de Liège, 55(2):5–15.

Pumain, D. (2018).
An evolutionary theory of urban systems.
In *Rozenblat C. Pumain D. Velasquez E. (eds.), International and transnational perspectives on urban systems*, pages 3–18. Singapore, Springer Nature, Advances in Geographical and Environmental Sciences.

Pumain, D., Paulus, F., Vacchiani-Marcuzzo, C., and Lobo, J. (2006).
An evolutionary theory for interpreting urban scaling laws.
Cybergeo: European Journal of Geography.

References V

Raimbault, J. (2020).
Indirect evidence of network effects in a system of cities.
Environment and Planning B: Urban Analytics and City Science, 47(1):138–155.

Raimbault, J. (2021).
Modeling the co-evolution of cities and networks.
In *Handbook of Cities and Networks*, pages 166–193. Edward Elgar Publishing.

Raimbault, J. (2022).
Hierarchy and co-evolution processes in urban systems.
Forthcoming in Hierarchy in infrastructure networks, J. Fen-Chong, ed. ISTE Editions.

References VI

Raimbault, J., Cottineau, C., Le Texier, M., Le Nechet, F., and Reuillon, R. (2019).
Space matters: Extending sensitivity analysis to initial spatial conditions in geosimulation models.
Journal of Artificial Societies and Social Simulation, 22(4).

Raimbault, J., Denis, E., and Pumain, D. (2020a).
Empowering urban governance through urban science: Multi-scale dynamics of urban systems worldwide.
Sustainability, 12(15):5954.

Raimbault, J., Perret, J., and Reuillon, R. (2020b).
A scala library for spatial sensitivity analysis.
GISRUK.

Raimbault, J. and Pumain, D. (2022).
Trade-offs between sustainable development goals in systems of cities.
Journal of Urban Management.

Reuillon, R., Leclaire, M., and Rey-Coyrehourcq, S. (2013).
Openmole, a workflow engine specifically tailored for the distributed exploration of simulation models.
Future Generation Computer Systems, 29(8):1981–1990.

Stern, D. I. (2004).
The rise and fall of the environmental kuznets curve.
World development, 32(8):1419–1439.

Varenne, F. (2018).
Théories et modèles en sciences humaines: le cas de la géographie.
Éditions Matériologiques.

Viguié, V. and Hallegatte, S. (2012).
Trade-offs and synergies in urban climate policies.
Nature Climate Change, 2(5):334–337.

Zenobia, B., Weber, C., and Daim, T. (2009).
Artificial markets: A review and assessment of a new venue for innovation research.
Technovation, 29(5):338–350.