

Identification of causalities in spatio-temporal data

J. Raimbault^{1,2}

`juste.raimbault@parisgeo.cnrs.fr`

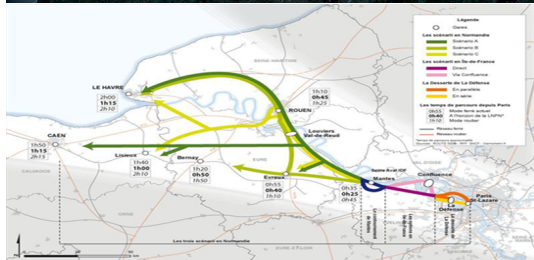
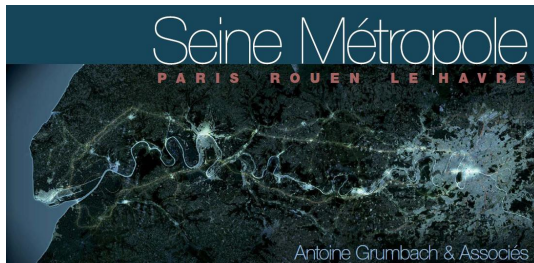
¹UMR CNRS 8504 Géographie-cités

²UMR-T IFSTTAR 9403 LVMT

Sageo 2017 - Rouen

November 7th 2017

Spatio-temporal complexity



Source : [Arnaud et al., 2013]

The myth of structuring effects

From [Bonafous and Plassard, 1974] to [Offner, 1993]: do transportation infrastructures structure territories ?

- Existence of co-evolutive processes [Bretagnolle, 2009]
- At large scale, existence of structural urban system dynamics [Offner et al., 2009]
- The question of circular causalities arises at all scales (e.g. metropolitan scale and mobility [Cerqueira, 2017]) and in various fields (knowledge spillovers and innovation [Audretsch and Feldman, 1996])

Causality in Geography

- Classical geography already investigated causal links in space [Loi, 1985]
- [Claval, 1985] : beyond reductionist causality in systemic analysis
- Systemogenesis introduced by [Durand-Dastes, 2003] focuses on dynamics and path-dependency
- Towards a complex approach to causality ? [Morin, 1976]

Existing approaches in spatio-temporal causality

Transportation Networks and Territories

- Lagged correlations : [Levinson, 2008] London population and network connectivity ; [Gargi Chaudhuri and Keith C Clarke, 2015] historical data in North Italy
- Instrumental variables : [Duranton and Turner, 2012] US highways and employment ; [Berger and Enflo, 2017] clear effect of swedish railway on cities trajectories

Spatio-temporal correlations

- Matching method for traffic flows [Liu et al., 2011]
- Generalized granger causality in neuroscience [Ke et al., 2007]
- Spatio-temporal correlations in Computer Vision [Ke et al., 2007]

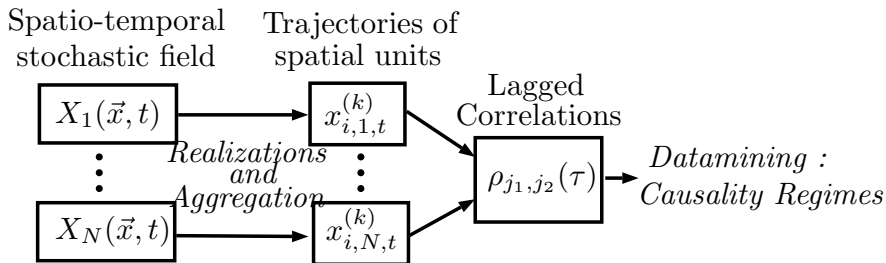
Research objective

- Genericity and operationality of existing approaches ?
- Grasp complexity in a simple way ?
- At the interface of knowledge domains (methodology, modeling and empirical) [Raimbault, 2017]

Research objective :

Explore a generic method based on patterns of spatio-temporal lagged correlations : notion of Granger causality ; validation on synthetic data and application to a case study.

Method: Rationale



Method: Formalization

Correlation estimator $\hat{\rho}$ applying in time, space and repetitions, i.e. covariance is estimated by $\widehat{\text{Cov}}[X, Y] = \hat{\mathbb{E}}_{i,t,k}[XY] - \hat{\mathbb{E}}_{i,t,k}[X]\hat{\mathbb{E}}_{i,t,k}[Y]$

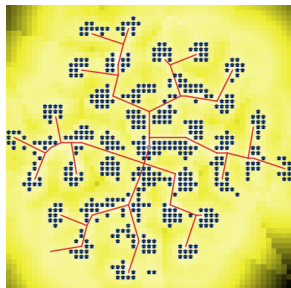
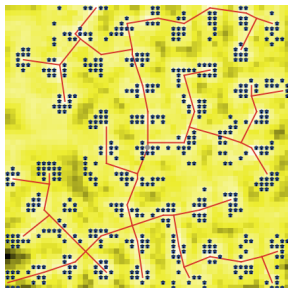
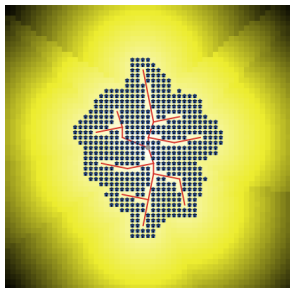
Lagged Correlation defined by

$$\rho_{\tau}[X_{j_1}, X_{j_2}] = \hat{\rho} \left[X_{i,j_1,t-\tau}^{(k)}, X_{i,j_2,t}^{(k)} \right] \quad (1)$$

Patterns of $\operatorname{argmax}_{\tau} \rho_{\tau}[X_{j_1}, X_{j_2}]$ or $\operatorname{argmin}_{\tau} \rho_{\tau}[X_{j_1}, X_{j_2}]$ (assumed clearly defined : e.g. statistical significance, minimal value) capture the sense of causality between j_1 and j_2

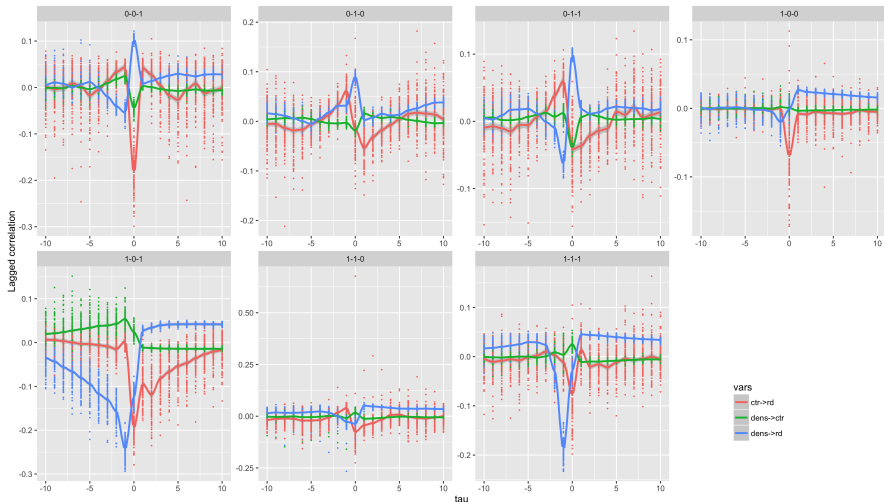
→ Datamining on ρ_{τ} (possibly parametrized values as $\rho_{\tau}^{(\omega)}$) to understand causality patterns.

Validation: Synthetic Data



Synthetic urban configurations generated by an hybrid morphogenesis model from [Raimbault et al., 2014]

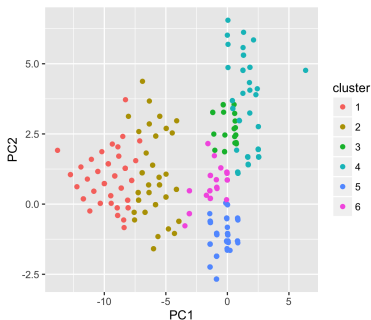
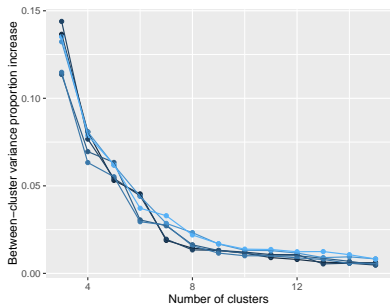
Profiles of lagged correlations



Values of ρ_τ for all couples of three explicative variables (density, distance to center, distance to roads), for 8 extreme parameter points

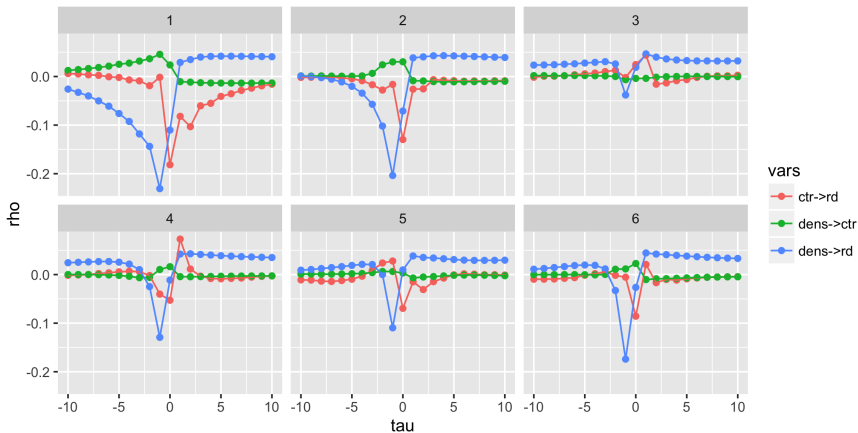
Unveiling Endogenous causality regimes

Intensive exploration of model parameter space (1000 parameters points x 100 repetitions) with OpenMole software [Reuillon et al., 2013]



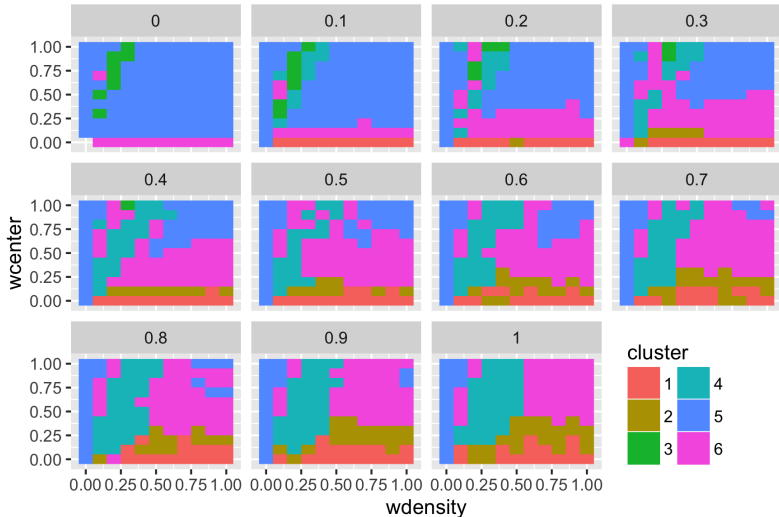
Unsupervised classification (robust k-means) on τ_{min}, τ_{max} features: (Left) Derivative of clustering coefficient for number of clusters k ; (Right) PCA visualisation of classification for “optimal” k

Consistence and interpretation of regimes



Values of cluster centers in terms of ρ_τ

Consistence and interpretation of regimes

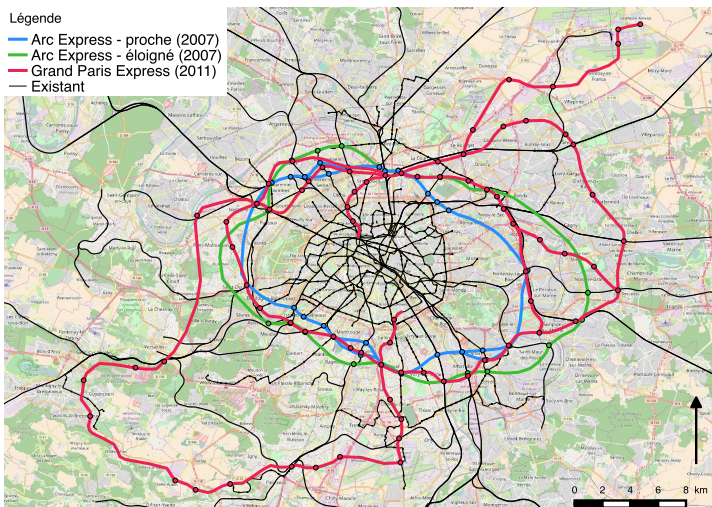


Position of clusters in the parameter space w_i

Application: Case study

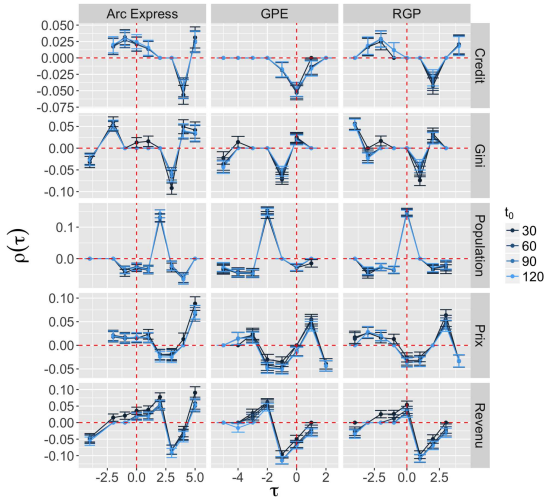
Légende

- Arc Express - proche (2007)
- Arc Express - éloigné (2007)
- Grand Paris Express (2011)
- Existant



Successive projects for the Grand Paris new transportation infrastructure

Application: Results



Values of ρ_τ for the different projects (columns) and different variables (rows), with accessibility differentials

Discussion

Implications

- Lagged correlation patterns on real data to investigate “structuring effects” in complex systems
- The operational concept of *Causality Regimes* introduces a novel way to look at co-evolution in models of simulation

Developments

- Characterisation of spatio-temporal diffusion : testing the spatial diffusion of innovation and the evolutive urban theory [Pumain, 2010]
- Optimal spatial scales for stationarity : link with GWR ? [Brunsdon et al., 1998]

Conclusion

- A method validated on synthetic data and showed operational on a real system
 - At the interface of knowledge domains : theory, modeling, empirical, methodological
 - At the interface of disciplines : spatial analysis, statistics, datamining
-
- Code, data and results available at <https://github.com/JusteRaimbault/CityNetwork>
 - Paper on arXiv at <https://arxiv.org/abs/1709.08684>
 - Acknowledgments : We thank the *European Grid Infrastructure* and its *National Grid Initiatives* (*France-Grilles* in particular) to give the technical support and the infrastructure.

Reserve Slides

Granger causality

Granger causality test based on VAR processes :

$$X(t) = \sum_{0 \leq \tau \leq \tau_Y} b_\tau Y(t - \tau)$$

If there exists b_τ such that $|b_\tau| > 0$ significantly, then Y Granger-causes X .

We have then $\rho_\tau(Y, X) > 0$.

Morphogenesis

Morphogenesis (*Oxford dictionary*)

- 1 *Biology* : The origin and development of morphological characteristics
- 2 *Geology* : The formation of landforms or other structures.

History of the notion

→ Started significantly with embryology around 1930 [Abercrombie, 1977]

→ Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics

→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion* ?

Defining Morphogenesis

Meta-epistemological framework of imbricated notions:

Self-organization \supsetneq Morphogenesis \supsetneq Autopoiesis \supsetneq Life

Properties:

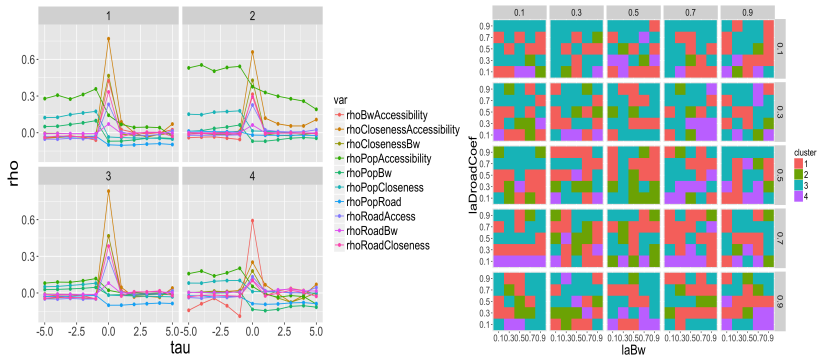
- Architecture links form and function
- Emergence strength [Bedau, 2002] increases with notion depth, as bifurcations [Thom, 1974]

Definition of Morphogenesis : *Emergence of the form and the function in a strongly coupled manner, producing an emergent architecture [Doursat et al., 2012]*

Causality Regimes in a model of co-evolution

Unsupervised learning on lagged correlations between local variables unveils a diversity of causality regimes in a model co-evolving urban form and network topology

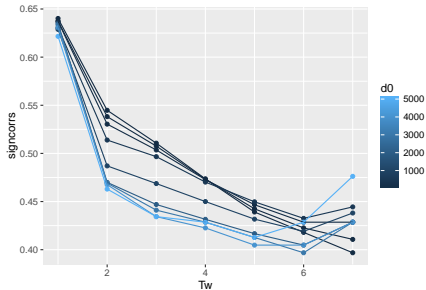
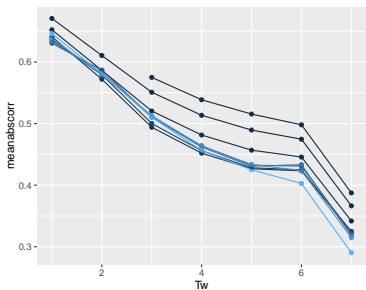
→ Link between *co-evolution regime* and morphogenetic properties of the urban system



(Left) Lagged correlation profiles of cluster centers; (Right) Distribution of regimes

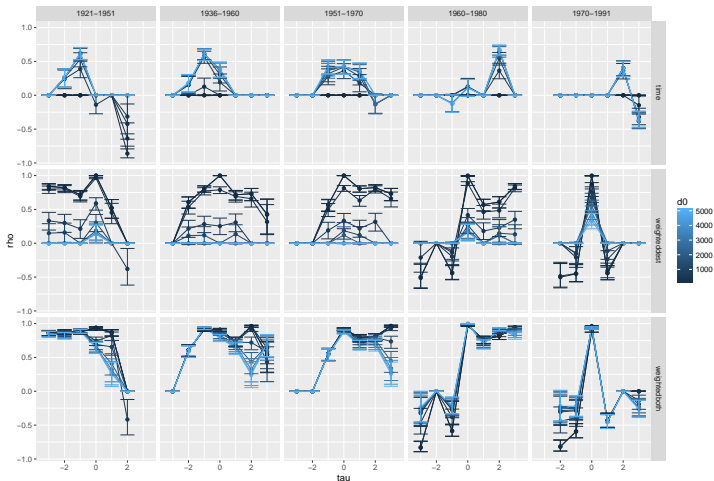
Application to South Africa : Stationarity scales

Optimal estimation time window and spatial range for accessibility



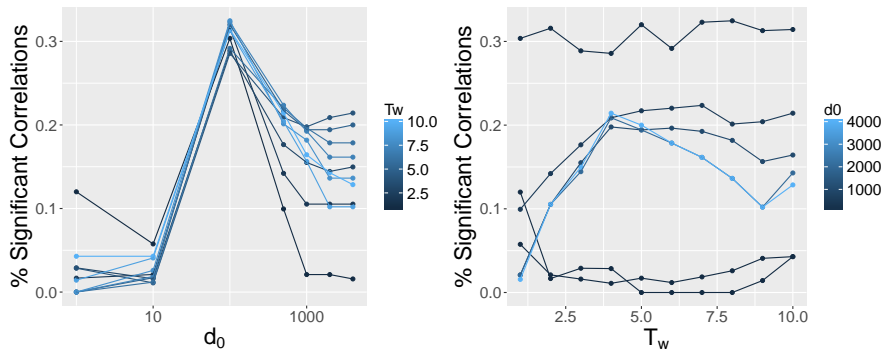
Application to South Africa : Causality Patterns

Clear inversion of the sense of Granger causality suggests a structural segregation effect of the apartheid laws

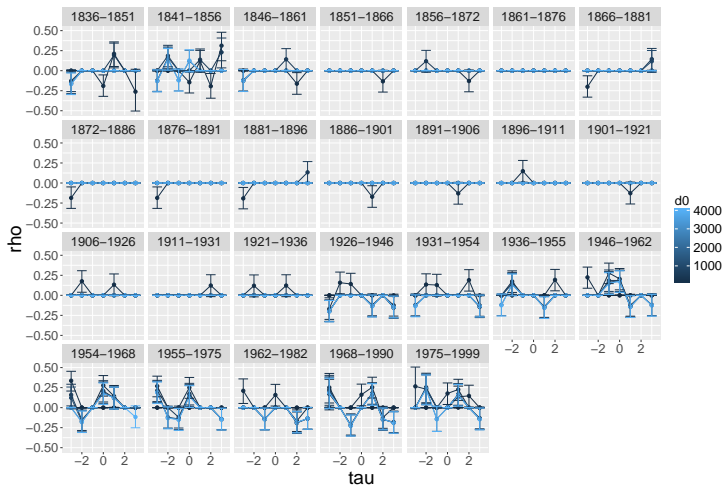


Application to France : Stationarity scales

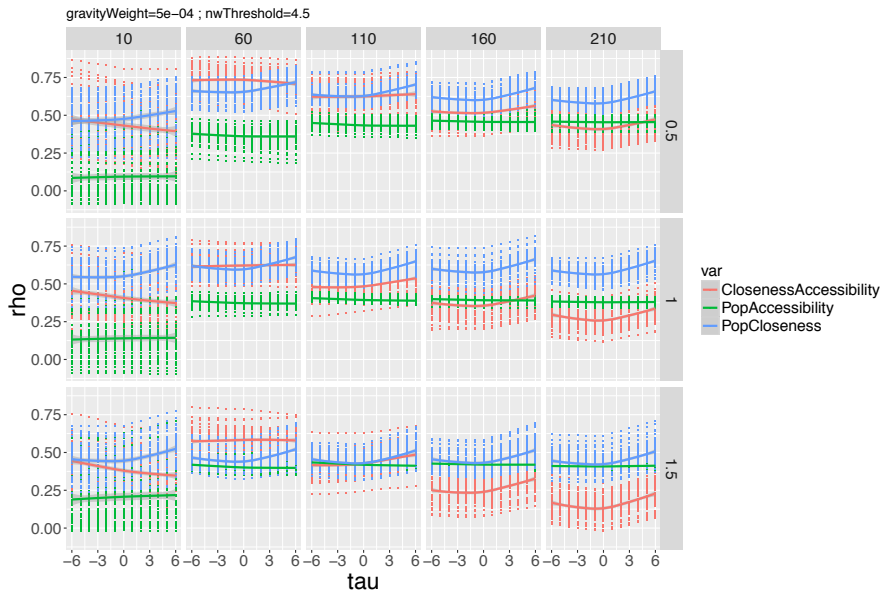
Optimal estimation time window and spatial range for accessibility







Application to France : No significant correlation






Macroscopic co-evolution : Correlation Patterns






References I

-  Abercrombie, M. (1977).
Concepts in morphogenesis.
Proceedings of the Royal Society of London B: Biological Sciences,
199(1136):337–344.
-  Arnaud, B., Bussi, M., and Guermond, Y. (2013).
Le grand paris et l'axe seine.
Métropoles, (13).
-  Audretsch, D. B. and Feldman, M. P. (1996).
R&d spillovers and the geography of innovation and production.
The American economic review, 86(3):630–640.
-  Bedau, M. (2002).
Downward causation and the autonomy of weak emergence.
Principia: an international journal of epistemology, 6(1):5–50.





References II

-  Berger, T. and Enflo, K. (2017).
Locomotives of local growth: The short-and long-term impact of
railroads in sweden.
Journal of Urban Economics, 98:124–138.
-  Bonnafous, A. and Plassard, F. (1974).
Les méthodologies usuelles de l'étude des effets structurants de
l'offre de transport.
Revue économique, pages 208–232.
-  Bretagnolle, A. (2009).
Villes et réseaux de transport : des interactions dans la longue durée,
France, Europe, États-Unis.
Hdr, Université Panthéon-Sorbonne - Paris I.

References III

-  Brunsdon, C., Fotheringham, S., and Charlton, M. (1998). Geographically weighted regression. *Journal of the Royal Statistical Society: Series D (The Statistician)*, 47(3):431–443.
-  Cerqueira, E. V. (2017). Les inégalités d'accès aux ressources urbaines dans les franges périphériques de belo horizonte (brésil): quelles évolutions? *EchoGéo*, (39).
-  Claval, P. (1985). Causalité et géographie. *Espace géographique*, 14(2):109–115.


References IV


-  Doursat, R., Sayama, H., and Michel, O. (2012).
Morphogenetic engineering: toward programmable complex systems.
Springer.
-  Durand-Dastes, F. (2003).
Les géographes et la notion de causalité.
-  Duranton, G. and Turner, M. A. (2012).
Urban growth and transportation.
The Review of Economic Studies, 79(4):1407–1440.
-  Gargi Chaudhuri and Keith C Clarke (2015).
On the Spatiotemporal Dynamics of the Coupling between Land Use
and Road Networks: Does Political History Matter?
Environment and Planning B: Planning and Design, 42(1):133–156.


References V

-  Ke, Y., Sukthankar, R., and Hebert, M. (2007).
Spatio-temporal shape and flow correlation for action recognition.
In Computer Vision and Pattern Recognition, 2007. CVPR'07. IEEE Conference on, pages 1–8. IEEE.
-  Levinson, D. (2008).
Density and dispersion: the co-development of land use and rail in london.
Journal of Economic Geography, 8(1):55–77.
-  Liu, W., Zheng, Y., Chawla, S., Yuan, J., and Xing, X. (2011).
Discovering spatio-temporal causal interactions in traffic data streams.
In Proceedings of the 17th ACM SIGKDD international conference on Knowledge discovery and data mining, pages 1010–1018. ACM.




References VI

 Loi, D. (1985).
Une étude de la causalité dans la géographie classique
française.[l'exemple des premières thèses régionales].
Espace géographique, 14(2):121–125.




 Morin, E. (1976).
La méthode: la nature de la nature.
Le Seuil.

 Offner, J.-M. (1993).
Les "effets structurants" du transport: mythe politique, mystification
scientifique.
Espace géographique, 22(3):233–242.

References VII

-  Offner, J.-M., Beaucire, F., Delaplace, M., Frémont, A., Ninot, O., Bretagnolle, A., and Pumain, D. (2014).
Les effets structurants des infrastructures de transport.
Espace Geographique, (42):p–51.
-  Pumain, D. (2010).
Une théorie géographique des villes.
Bulletin de la Société géographie de Liège, (55):5–15.
-  Raimbault, J. (2017).
An applied knowledge framework to study complex systems.
ArXiv e-prints.

References VIII

-  Raimbault, J., Banos, A., and Doursat, R. (2014).
A hybrid network/grid model of urban morphogenesis and optimization.
In Proceedings of the 4th International Conference on Complex Systems and Applications (ICCSA 2014), June 23-26, 2014, Université de Normandie, Le Havre, France; M. A. Aziz-Alaoui, C. Bertelle, X. Z. Liu, D. Olivier, eds.: pp. 51-60.
-  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.
-  Thom, R. (1974).
Stabilité structurelle et morphogénèse.
Poetics, 3(2):7–19.

References IX



Turing, A. M. (1952).

The chemical basis of morphogenesis.

Philosophical Transactions of the Royal Society of London B: Biological Sciences, 237(641):37–72.