A Hybrid Network/Grid Model of Urban Morphogenesis and Optimization

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A beautiful place...

...well planned and designed?

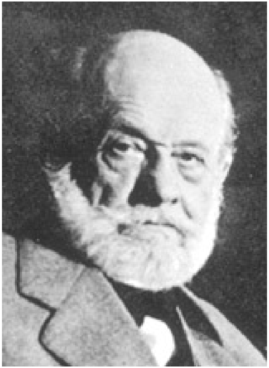


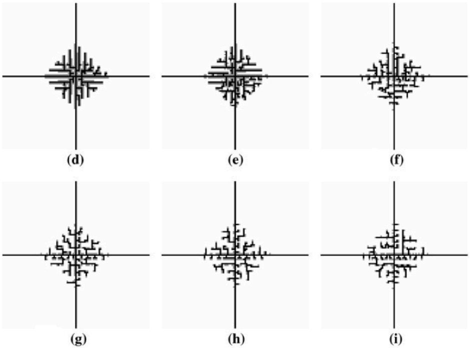
Figure: Auguste Perret (1874–1954). One of the founders of modern architecture.

Figure: Le Corbusier (1887–1965). Greatly influential through his buildings and writings. Theory of Urbanism, partially modeled and simulated by our work.

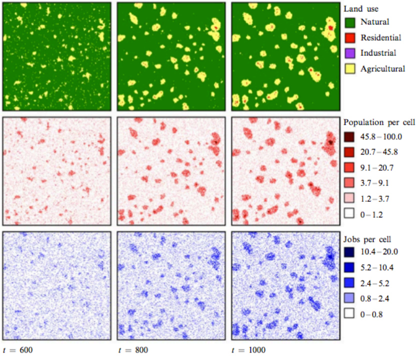
Research question and objective

- What is the influence of proximity on urban form? Proposition of modeling transportation network coupled with a Cellular Automaton in [Moreno et al., 2007, Moreno et al., 2009].
- We generalize and extend this model: from morphological to functional properties of the urban environment. We couple a Cellular Automaton with an evolving network.
  Research question: Is it possible to reproduce patterns of urban form with a model of urban development taking into account both transportation network and city scape, including form and function ?
- Our objective is to apply the model to a real case, by proposing a method for the optimization of planning on all possible functional configurations.

Examples of uses of CA in Urban Planning



(a) Microeconomic model of sprawl, [Caruso et al., 2011]



(b) Land use simulations, [van Vliet et al., 2012]

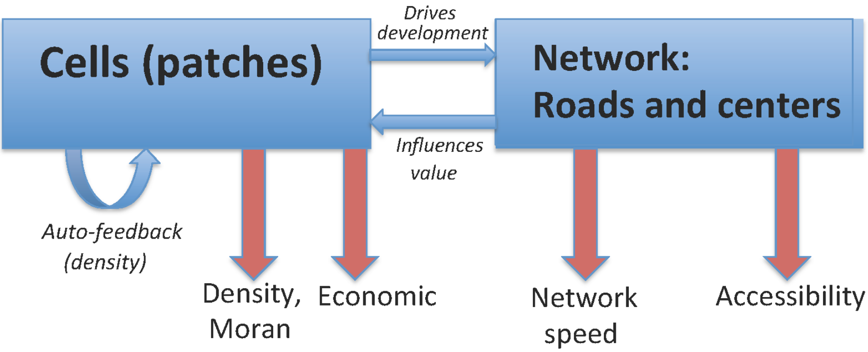
Cellular Automata and Urban Planning

- First introduction for reproduction of fractal urban form and land-use patterns in [White and Engelen, 1993, Batty, 1997].
- Since then, numerous applications, e.g. coupling with GIS in quantitative geography, calibration on real land-use configurations (review in [Iltanen, 2012]).
- Examples: [Caruso et al., 2011] micro-economic model of sprawl; [Peeters and Rounsevell, 2009] 1D CA to show path-dependence of settlements patterns; [Wu, 1996] real-time rules for sustainable development.

Settings and agents

- Fixed agents: cells in a square lattice $(L_{i,j})_{1\leq i,j\leq N}$, occupied or not (function $\delta(i,j,t) \in \{0,1\}$)
- Evolving euclidian network $G(t) = (V(t), E(t))$, including fixed city centers $C_0 \subset V(0)$ for each an activity $a \in \{1, \ldots, a_{max}\}$ is defined (functional properties of the urban scape).
- Heterogeneous explicative variables $(d_k)_{1\leq k\leq K}$ defined on cells, with associated weights $(\alpha_k)_{1\leq k\leq K}$ (main parameters of the model), that are:
  - d_1 the density around the cell (in a fixed radius r)
  - d_2 the distance to the nearest road
  - d_3 the distance to the nearest town center through the network
  - $d_4(i,j,t) = \left(\frac{1}{a_{max}} \sum_{a=1}^{a_{max}} d_3(i,j,t;a)^{p_4}\right)^{1/p_4}$: integrated accessibility of activities

Model workflow



Evolution rules

At each time step:

- Sprawling of occupied urban structure. The best N cells according to the value $v(i,j,t) = \frac{1}{\sum_k \alpha_k} \sum_{k=1}^{K} \alpha_k \frac{d_{k,max}(t) - d_k(i,j,t)}{d_{k,max}(t) - d_{k,min}(t)}$ are built.
- Adaptation of the network: when a new cell is built, if $d_2 > \theta_2$, the cell is connected to the network by a new perpendicular road.

Evaluation functions

Objective Morphological indicators

- Integrated local density

$$D(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum^{N}{}_{\substack{i,j=1 \\ \delta(i,j,t) \neq 0}} d_1(i,j,t)^{p_D} \right)^{1/p_D}$$

- Moran index (` `polycentric" character of a distribution of populated cells, [Tsai, 2005, Le Néchet and Aguilera, 2011]): world decomposed in a grid of size M ($1 \ll M \ll N$), $(P_i)_{1 \leq i \leq M}$ are populations in each part of the grid, then

$$I(t) = \frac{M^2}{\sum_{\mu \neq \nu} 1/d_{\mu\nu}} \frac{\sum_{\mu \neq \nu} (P_\mu - \overline{P})(P_\nu - \overline{P})/d_{\mu\nu}}{\sum_{\mu=1}^{M^2} (P_\mu - \overline{P})^2}$$

Evaluation functions

Performance indicators

- Network speed ([Banos and Genre-Grandpierre, 2012])

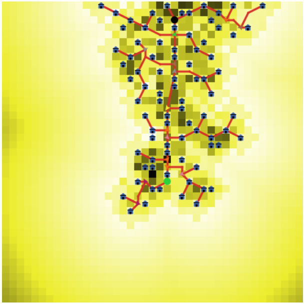
$$S(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum^{N}_{\substack{i,j=1 \\ \delta(i,j,t)\neq 0}} \left(\frac{d_3(i,j,t)}{e_3(i,j,t)} \right)^{p_S} \right)^{1/p_S} \quad \text{with } e_3(i,j,t)$$

  euclidian distance to nearest center
- Normalized functional accessibility

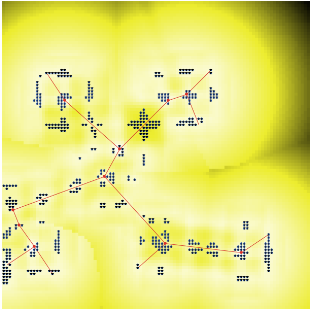
$$A(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum^{N}_{\substack{i,j=1 \\ \delta(i,j,t)\neq 0}} \left(\frac{d_4(i,j,t)}{d_{4,max}(t)} \right)^{p_A} \right)^{1/p_A}$$

- Socio-economic segregation potential: run on the generated configuration of an economic residential ABM dynamics ([Schelling, 1969], [Benenson, 1998]), which is strongly sensitive to spatial structure according to [Banos, 2012], calculation of the final spatialized segregation index E.

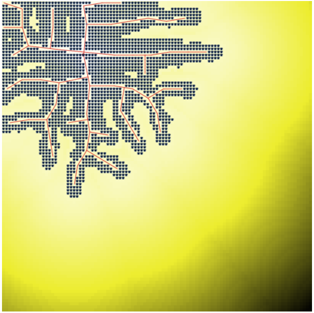
Examples of generated shapes



(a) ``A city can be a tree'', [Alexander, 1964]

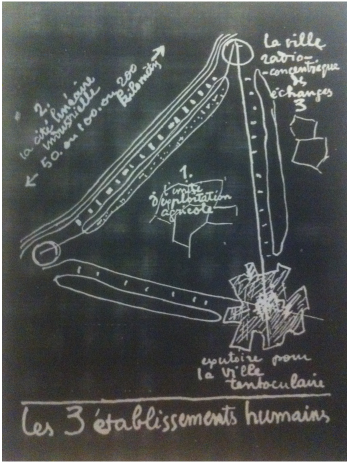


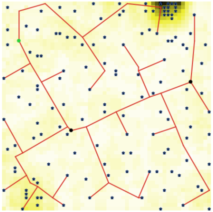
(b) Intermediate shape

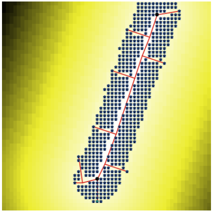


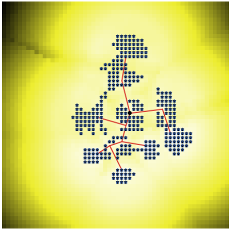
(c) One center, no density

Typology of structures



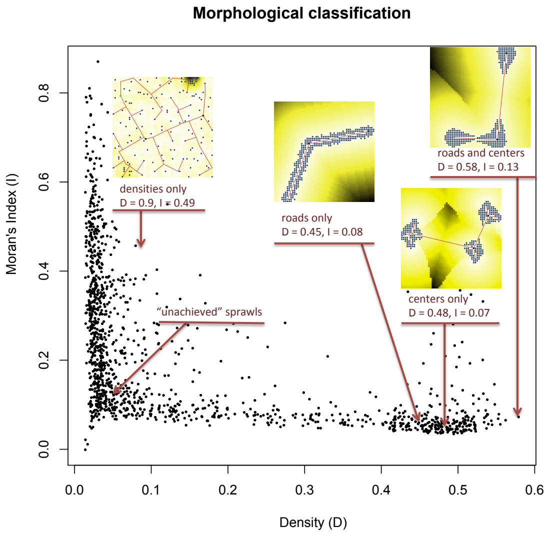






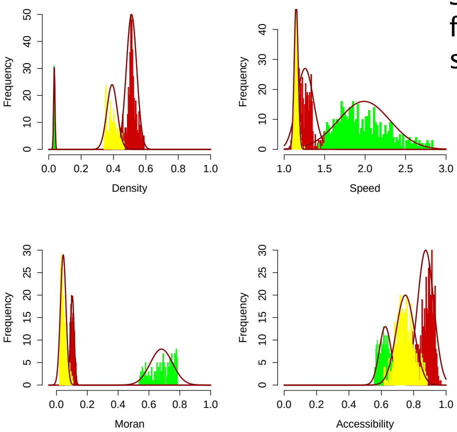
Parallel between Le Corbusier's typology of « human settlements » and some generated structures

Morphological classification



Projection in the morphological plane of indicators; classification of some structures.

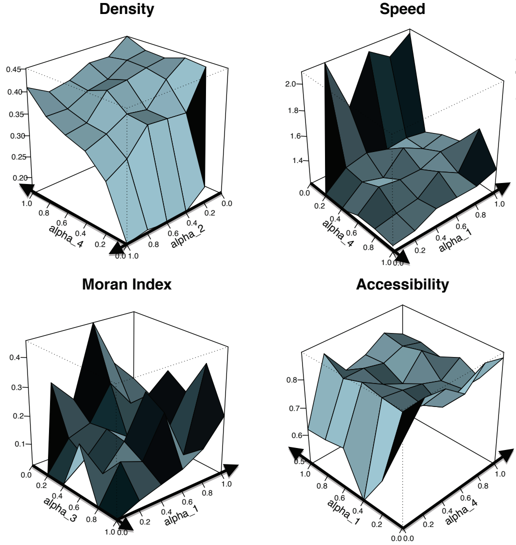
Statistical analysis



Statistical distributions of outputs for different points in parameter space.

- Statistical study of the behavior of the model: is the output sensitive to initial spatial configurations?
- Internal robustness of the model
- Number of repetitions needed : $n = (2\sigma \cdot 1.96/0.05)^2 \simeq 60$ repetitions for 95% confidence interval of width 0.05

Exploration of the parameter space



Sample surface plots of the evaluation functions.

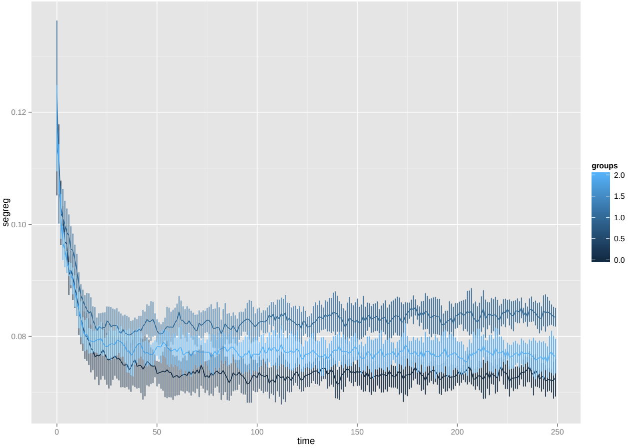
- Finer exploration of the (α_k) parameter space: 4D-grid of step 0.2, what gives 1295 points.
- Expected results regarding speed and density.
- Emergent behavior: local competition between agents does not lead to the most efficient structure.

Why are these explorations useful?

- Demonstration of the robustness of the model and of the possibility to compare runs on different initial configurations (involving calculations on stochastic repetitions), behavior of outputs along moves in the parameter space. According to Banos [Banos, 2013], one of the requirements of quantitative simulations.

- Other necessary points that we explored: influence of update type, size of the grid for Moran index, behavior of the economic ABM.

Economic ABM

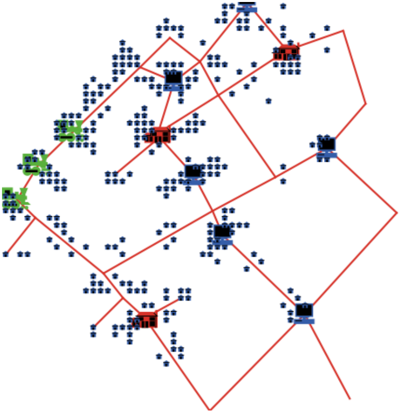


Time series of segregation index during a run of the economic ABM for different configurations.

Practical application: method

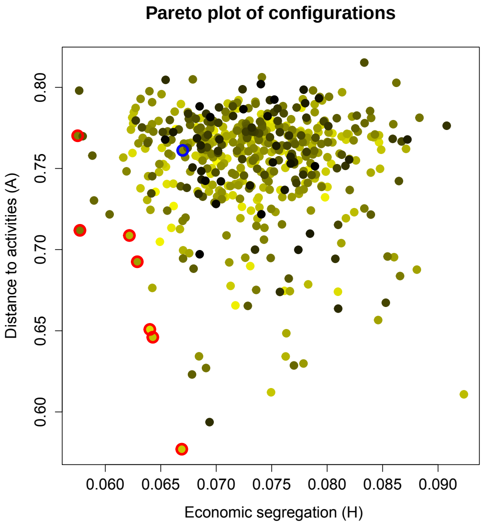
- Fixing the spatial initial structure and the parameters, optimize on the possible distribution of activities among centers. Choice of parameters is crucial.
- Importation of real GIS data: centers correspond to centroids of zones in a district, initial network to main roads. Some centers have fixed activity (stations), other can be 2 different ones (residential or tertiary).
- Exploration of all possible configurations (possible here, $2^8 = 256$ configurations), Pareto-plot of economic performance and accessibility.

Practical application



Practical application. Optimizing the distribution of activities over urban centers.

Application : Pareto optimization



Scatterplot of all configurations in the (H, A) morphological plane. Real situation in blue, Pareto front in red. Color gradient follows level of heterogeneity from low (black) to high (yellow). It suggests the performance of functional heterogeneity, often recommended by planners today.

Discussion

- Many questions are still open: do we have the good scale of application? (although it should be scale-free), did we isolate the dominant processes? (cf [Louf and Barthelemy, 2013])
- Local scope : is the system isolated? Economic processes are implicitly taken into account.
- Towards a more operational model? Difficulty to calibrate conceptual CA models on real data [Maria de Almeida et al., 2003]
- Complex coupling with economic ABM [Varenne et al., 2013]? Compromise between complexity level and model performance always difficult to find.

Conclusion

- Interesting qualitative and quantitative results: reproduction of Le Corbusier's typology; assessment of relative performance of urban mixity [Mangin, 2004] .
- Can be seen as going in the sense of the emergence of a rigourous ``evidence-based urbanism'', or ``quantitative urbanism''
([Portugali, 2012]).