A Stochastic Method for the Generation of Optimized Building Layouts Respecting Urban Regulations

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CONCEPTION OBJET ET GÉNÉRALISATION
DE L'INFORMATION TOPOGRAPHIQUE

Outline

- Context, Motivation and Goal
- Proposed Method
- Case Studies

Context: project e-PLU

- Financed by European Regional Development Fund
- Aiming at transforming the paper urban planning documents into digital urban development services through a 3D simulation platform that estimates the legal building possibilities according to morphological and urban criteria

Context: French urban planning rules

- French local urban planning scheme: PLU (Plan Local d'Urbanisme)
  - Zoning plan;
  - Regulations for each zone type, including all or some of the 16 articles;
  - Each article describes a fixed theme, e.g.
    - Article 1: prohibited land use
    - Article 13: open space and plantation
    - Article 16: electronic communication infrastructures and network

- This work focuses on the PLU rules that regulate the spatial aspects for building development at the scale of a parcel:
    - Article 6: building position in relation to public roads,
    - Article 7: building position in relation to separative limits,
    - Article 8: building position in relation to other buildings,
    - Article 9: building footprint,
    - Article 10: building height,
    - Article 14: floor area ratio.

Motivation and Goal

- Motivation:
  - To better understand urban planning rules (provided in text and/or with graphic illustration)
  - To assess the impact of the rules
  - To help preliminary design and presentation of new construction projects

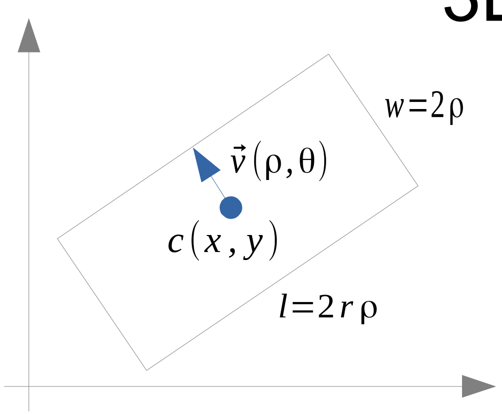
- Goal:
  - To automatically generate 3D buildings on a parcel, complying with local urban planning rules, and of optimized urban indicators (e.g. floor area ratio)

Outline

- Context, Motivation and Goal
- Proposed Method
  - Stochastic model
  - Optimization
  - Energetic modeling
- Case Studies

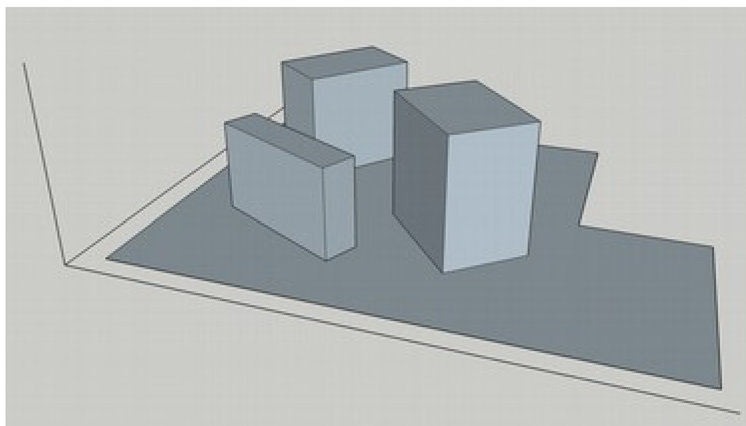
Proposed Method: Stochastic Model (1)

- Model the problem by a stochastic process: marked point process (MPP)
  - An object can be parameterized into a point (e.g its center) and its mark (all other geometric parameters)
  - In our problem, a building is represented by a 3D box with 6 parameters $(x, y, \rho, \theta, r, h)$
    - Footprint center $c(x, y)$
    - Footprint semi-minor axis vector $\vec{v}(\rho, \theta)$
    - Footprint aspect ratio (length/width) $r = l/w$
    - Height h



Proposed Method: Stochastic Model (2)

- Model the problem by a stochastic process: marked point process (MPP)



  - A building layout is a configuration of an arbitrary number of buildings with different geometry.
  - It can be considered as a realization of MPP of 3D box.

  - A MPP is defined by a probabilized space (Ω, π)

    $$\Omega = \bigcup_{n=0}^{\infty} K^n$$

    - K: the set of possible values of a single object
    - n: the number of objects

  - For our problem

$$K = \overbrace{\underbrace{[0,1] \times [0,1]}_{c_i'}}^{point} \overbrace{\times \underbrace{[\rho_{min}, \rho_{max}] \times [0, \pi]}_{\vec{v_i}} \times \underbrace{1, [r_{max}]}_{r_i} \times \underbrace{[h_{min}, h_{max}]}_{h_i}}^{mark}.$$

Proposed Method: Stochastic Model (3)

- Model the problem by a stochastic process: marked point process (MPP)
  - Probability distribution π of a MPP X can be defined by Gibbs measure:

    $\pi(X) = Z^{-1} e^{-E(X)}$, where $Z = \int_X e^{-E(X)} d\mu(X)$

    - Z is the normalization factor, with $\mu(.)$ as the distribution of the reference process (eg. Poisson process)
    - E(X) is the energy component which reflects the quality of a configuration: compliance with the PLU rules and optimization degree.
    - Thus, the optimal building layout $\widetilde{X}$ can be found by maximizing the probability: $\widetilde{X} = argmax\, \pi(.)$

Proposed Method: Optimization

- Optimization approach: Simulated annealing
  - Problem: direct sampling from π is not possible!
  - Solution: coupling with RJMCMC (Reversible Jump Markov Chain Monte Carlo) sampler

Algorithm 1 Optimization: simulated annealing coupled with RJMCMC sampler.

Construct an initial configuration X_0
Define a temperature schedule $S(.)$
repeat
  Sample $i \sim q(.|X_t)$ //select a reversible kernel Q_i
  Sample $X_t^{'} \sim Q_i(.|X_t)$ //propose a new configuration
  $R_\infty \leftarrow \frac{\mu(X_t^{'})Q_i(X_t^{'}|X_t)}{\mu(X_t)Q_i(X_t|X_t^{'})}$ //compute Green ratio of the reference process
  $R \leftarrow R_\infty e^{-\frac{\Delta E}{T}}$ //metroplis acceptance parameterized by delta energy and temperature
  $a \leftarrow min(1,R)$
  With probability $\begin{cases} a & X_{t+1} \leftarrow X_t^{'} \\ 1-a & X_{t+1} \leftarrow X_t \end{cases}$
  $T \leftarrow S(T)$ //Decrease T according to schedule
until EndTest=true

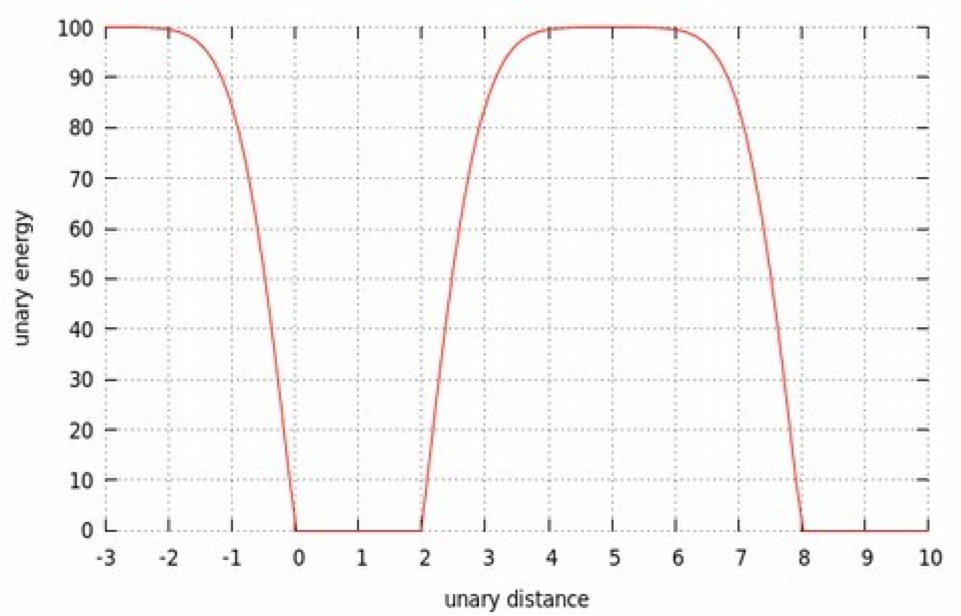
Proposed Method: Energetic Modeling (1)

- Studied PLU articles
  - Article 6: building position (e.g. distance, angle) in relation to public roads (front borders)
  - Article 7: building position in relation to separative limits (side and back borders)
  - Article 8: building position in relation to other buildings (e.g. distance between buildings)
  - Article 9: building footprint (e.g coverage ratio)
  - Article 10: building height (e.g. height limits, height difference between buildings)
  - Article 14: floor area ratio
- Grouped into 2 types of rules
  - Rule A: needs energetic modeling
  - Rule B: can be directly configured into geometric parameters
- Urban rules to energy terms or to parametric constraints
  - Rule A1: distance to parcel borders → unary distance energy
  - Rule A2: distance between buildings → binary distance energy
  - Rule A3: height difference between buildings → binary height energy
  - Rule A4: lot coverage ratio → global coverage energy
  - Rule A5: floor area ratio → global builtup energy
  - Rule B1: angle to parcel borders → constraint on parameter ρ
  - Rule B2: building height limits→ constraint on parameter h

Proposed Method: Energetic Modeling (2)

- The total energy is the sum of finite weighted energy terms, each of which is formed according to a specific rule.
- An example of energy formulation
  - If the distance from the i^{th} building to the j^{th} border d_{ij} should satisfy $0 \leqslant d_{ij} \leqslant 2m \| d_{ij} \geqslant 8m$
  - The unary border energy of the i^{th} building to the j^{th} border $E_{ij}^{u_d}$ can be defined by using Gaussian error function *erf(.)*:

$$E_{ij}^{u_d} = \begin{cases} -a * erf(d_{ij}) & d_{ij} \in [-\infty, 0) \\ 0 & d_{ij} \in [0, 2] \\ a * erf(d_{ij} - 2) & d_{ij} \in (2, 5] \\ -a * erf(d_{ij} - 8) & d_{ij} \in (5, 8) \\ 0 & d_{ij} \in [8, +\infty) \end{cases}$$



Proposed Method: Implementation

- Developed an open source tool:

  BuildUP (Building generator for local Urban Planning)
  https://github.com/IGNF/BuildUP

  - Automatic generation of buildings (as 3D boxes) on a target parcel, complying with local urban planning rules, and of optimized urban indicators
  - Automatic energetic modeling of common French PLU rules
  - Optimization is realized using the open source c++ library librjmcmc https://github.com/IGNF/librjmcmc which provides a framework for stochastic optimization using RJMCMC sampler and simulated annealing

Outline

- Context, Motivation and Goal
- Proposed Method
- Case Studies
  - Two case studies are conducted under the cooperation with our project partner QuelleVille? and evaluated by their urban planning experts

Case Study A

The PLU rules to obey:

- Article 6(1): dFront>3m
  6(2): $\theta_{bldg} = \theta_{front}$
- Article 7:
  dSide1=0 & dSide2=0 || dSide1=0 & dSide2≥max(6, h) || dSide2=0 & dSide1≥max(6,h)
  dBack >4m
- Article 8: dPair>6m
- Article 9: lot coverage ratio <=0.6
- Article 10(1): 6m<=h<=18m
  10(2): hDiff <= 6m
- Article 14: floor area ratio <=4

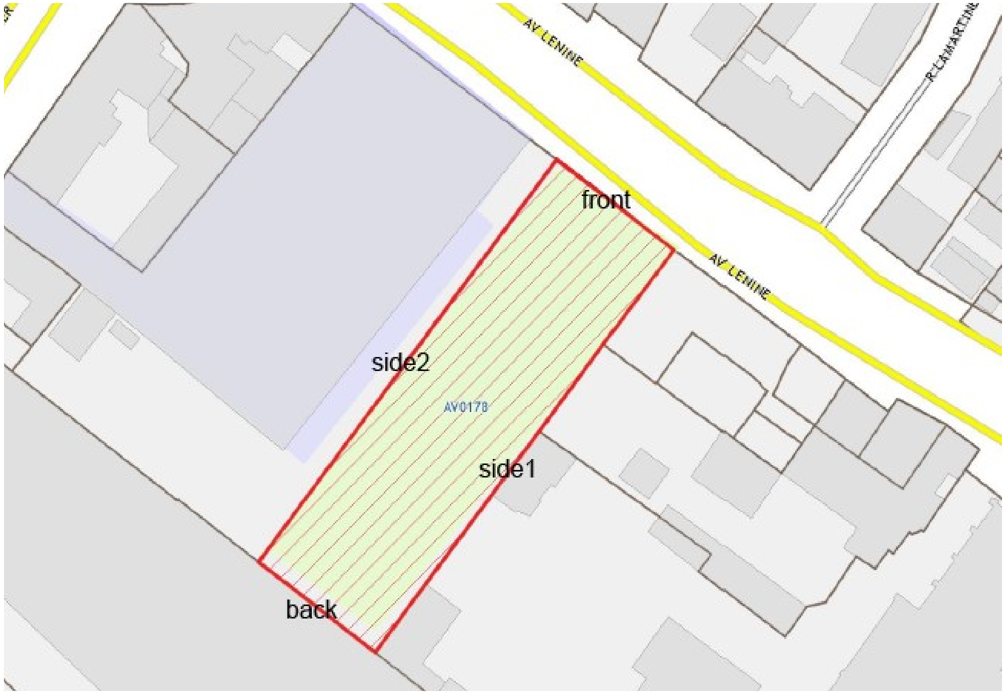
Additional constraints:

- Width of each building fixed to 5m or 10m
- Height limit varies by width

e.g. h<=6m if w=5m; h<=18m if w=10m

Optimization goal:

Maximize floor area ratio (FAR)



12 avenue Lénine, La Courneuve, France

This case study is a bit different than the one presented in the paper
(with additional constraints and modified rules)

Case Study A

Energy function: $E = 30E^{u_d} + 20E^{b_d} + 20E^{b_h} + 20E^{g_c} + 50E^{g_f}$

Unary border energy E^{u_d}

Binary distance energy E^{b_d} Binary height energy E^{b_h}

Global coverage energy E^{g_c} Global buildup energy E^{g_f}

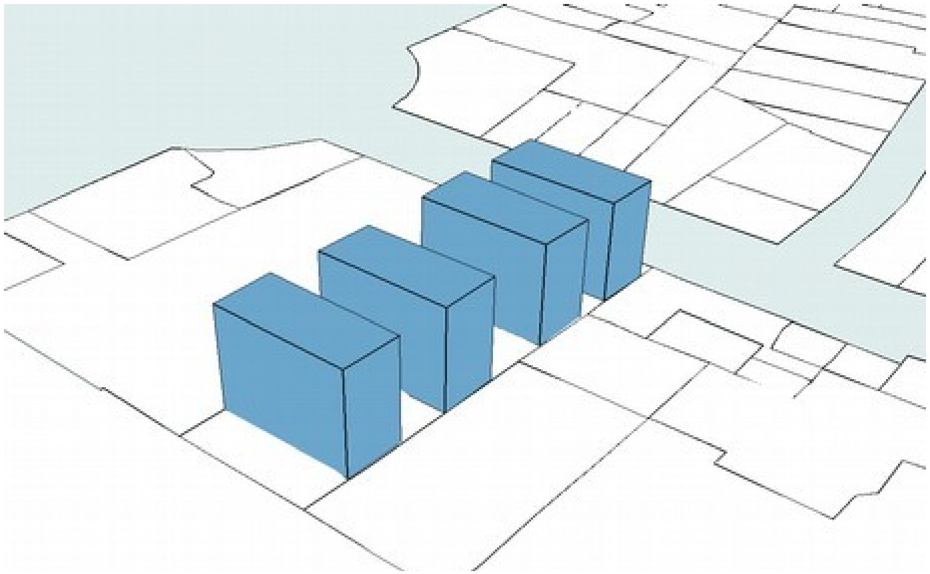
- Test environment: 32 bit Linux (Ubuntu 14.04); HP workstation Z210 with 3.3GHz dual core CPU (Intel Core i5-2500) and 8 GB memory
- 100 experiments with 1.5 million iterations per experiment for simulated annealing
  - 32 optimal results (FAR>=2.8 && no big violation of the rules)
  - 68 good results (2.8>FAR>=2.0 && no big violation of the rules)
  - 0 bad results (FAR<2.0 || big violation of the rules)
  - ~ 56 seconds/experiment

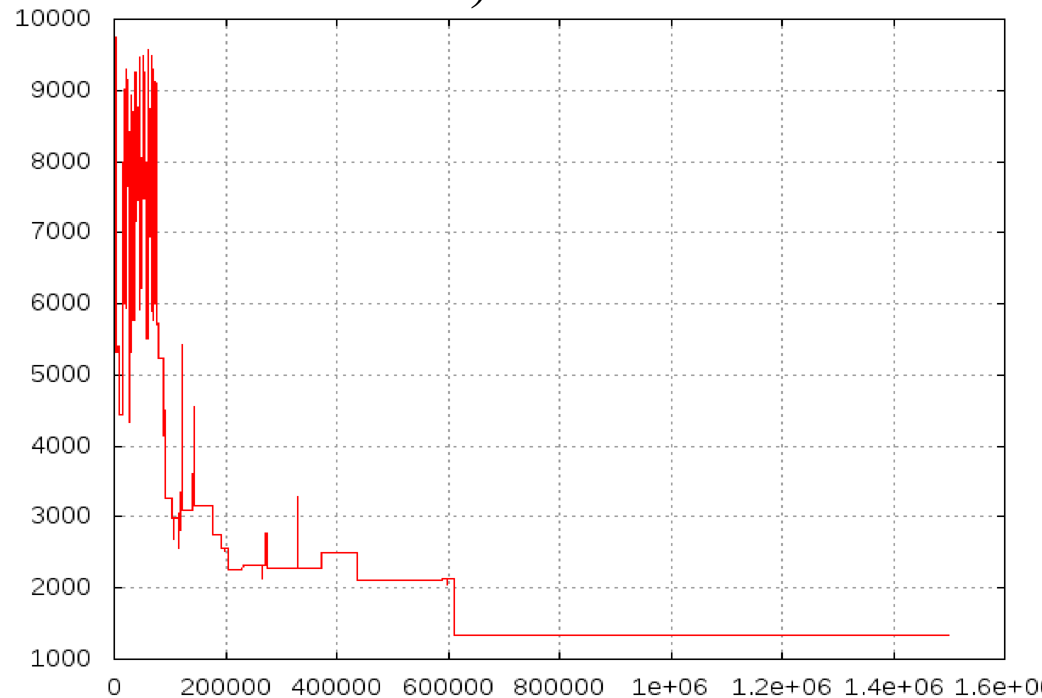
Statistics of 100 experiments

floor area ratio			lot coverge ratio			CPU time (ms)		
min	max	average	min	max	average	min	max	average
2.11511	3.02159	2.44782	0.352518	0.503598	0.40797	55892.4	58101.5	56413.4

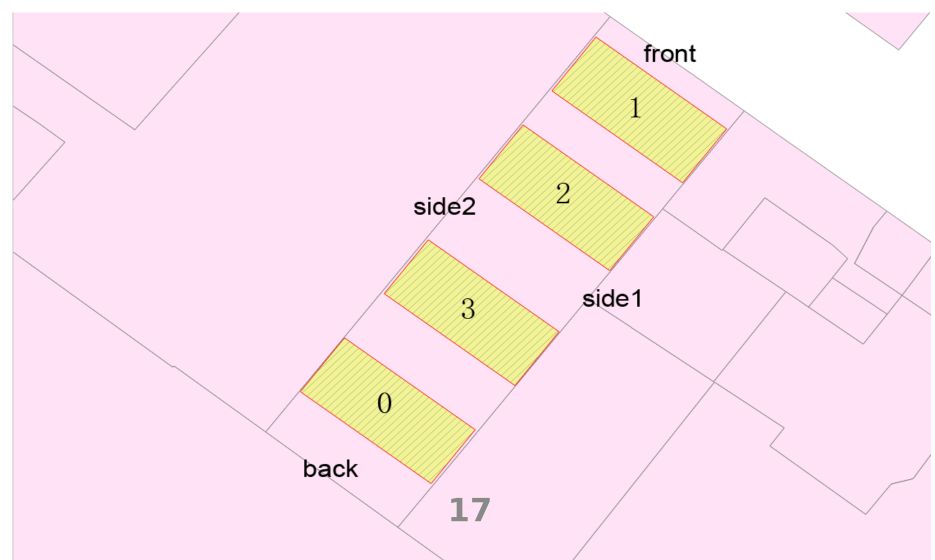
Case Study A

Best optimization result (with highest floor area ratio)



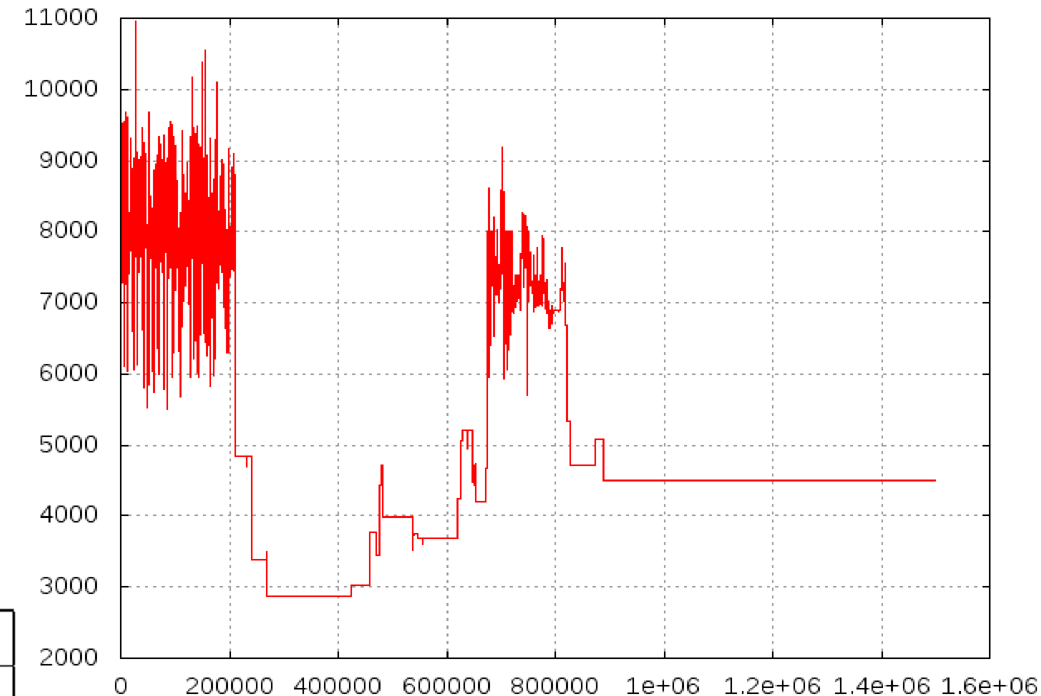


	dFront	dSide1	dSide2	dBack	height
$bldg_0$	59.892	0.349779	0.0719926	7.62962	18
$bldg_1$	3.58819	0.17575	0.290706	63.9367	18
$bldg_2$	19.989	0.14313	0.0129	47.5358	18
$bldg_3$	41.3897	0.0846339	0.348109	26.1356	18
Binary distance					
d^b_{01}	d^b_{02}	d^b_{03}	d^b_{12}	d^b_{13}	d^b_{23}
46.309	29.798	8.569	6.360	27.802	11.435
Lot coverage ratio = 0.503598					
Floor area ratio = 3.02159					
Energy					
$30E^{u_d}$	$20E^{b_d}$	$20E^{b_h}$	$20E^{g_c}$	$50E^{g_f}$	total energy
863.867	0	0	0	478.647	1342.51

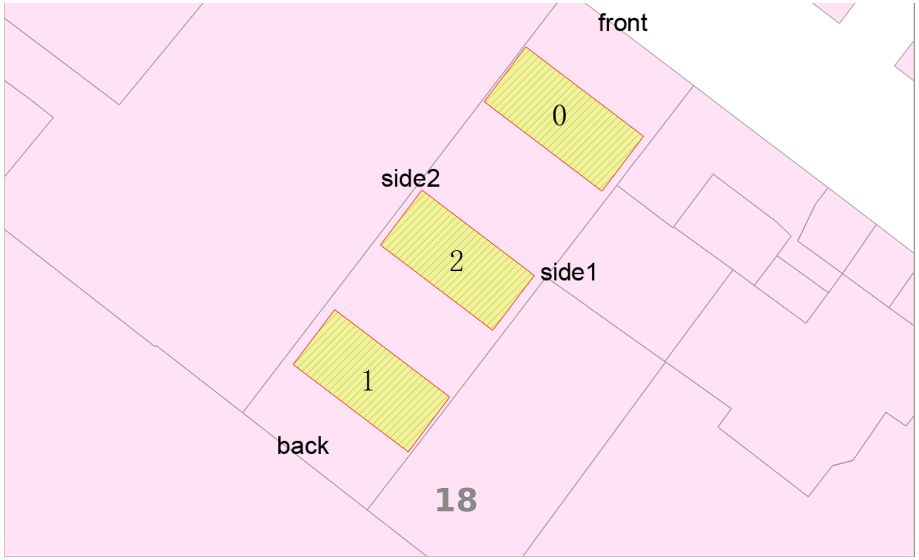


Case Study A

Worst optimization result (with lowest floor area ratio and highest energy)



	dFront	dSide1	dSide2	dBack	height
$bldg_0$	10.2911	1.18468	0.271806	57.2335	18
$bldg_1$	57.4885	0.453683	1.49288	10.0512	18
$bldg_2$	35.9913	1.44529	0.982767	31.5421	18
Binary distance					
d^b_{01}	d^b_{02}	d^b_{12}			
37.283	15.627	11.524			
Lot coverage ratio = 0.352518					
Floor area ratio = 2.11511					
Energy					
$30E^{u_d}$	$20E^{b_d}$	$20E^{b_h}$	$20E^{g_c}$	$50E^{g_f}$	total energy
2720.69	0	0	0	1776.41	4497.1



Case Study B

The PLU rules to obey:

- Article 6(1): (dFront1=0 || dFront1>2.5m) && (dFront2=0 || dFront2>2.5m)
- Article 6(2): $\theta_{bldg}=\theta_{front}$
- Article 7:
  dSide1>=max((h-3)/2,3) && dSide2>=max((h-3)/2,3)
  dBack >4m
- Article 8: dPair >max(hMax/2, (hMax-3), 8)
- Article 9: no rule on lot coverage ratio
- Article 10(1): 3.2m<=h<=24m
- Article 10(2): hDiff <= 6m
- Article 14: floor area ratio <=4

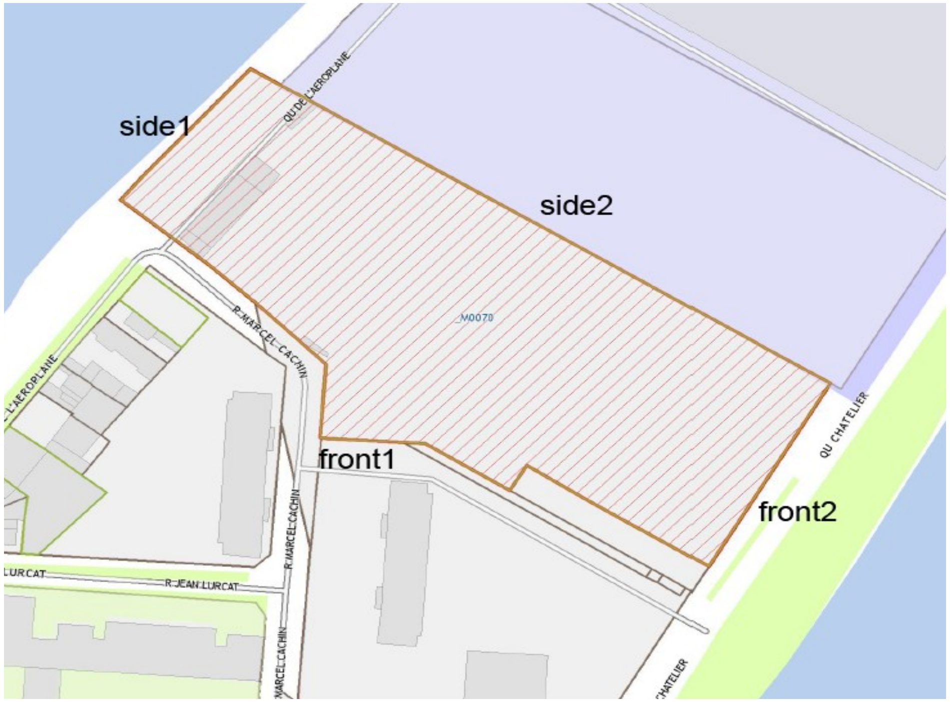
Additional constraints:

- Width of each building fixed to 5m or 10m
- Height limit varies by width

e.g. h<=6m if w=5m; h<=18m if w=10m

Optimization goal:

Maximize the floor area ratio



Quai de l'aéroplane chatelier, L'Île-Saint-Denis, France

This case study is not presented in the paper

Case Study B

Energy function: $E = 30E^{u_d} + 20E^{b_d} + 20E^{b_h} + 20E^{g_c} + 50E^{g_f}$

Unary border energy E^{u_d}

Binary distance energy E^{b_d} Binary height energy E^{b_h}

Global coverage energy E^{g_c} Global buildup energy E^{g_f}

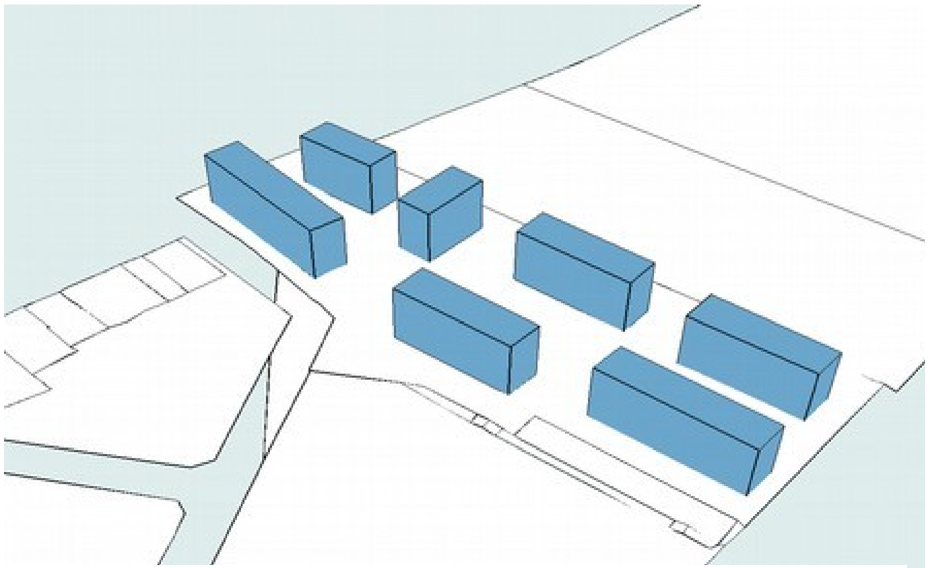
- Test environment: 32 bit Linux (Ubuntu 14.04); HP workstation Z210 with 3.3GHz dual core CPU (Intel Core i5-2500) and 8 GB memory
- 100 experiments with 1.5 million iterations per experiment for simulated annealing
  - 76 optimal results (FAR>=1.0 && no big violation of the rules)
  - 24 good results (1.0>FAR>=0.8 && no big violation of the rules)
  - 0 bad results (FAR<0.8 || big violation of the rules)
  - CPU time ~ 115 seconds

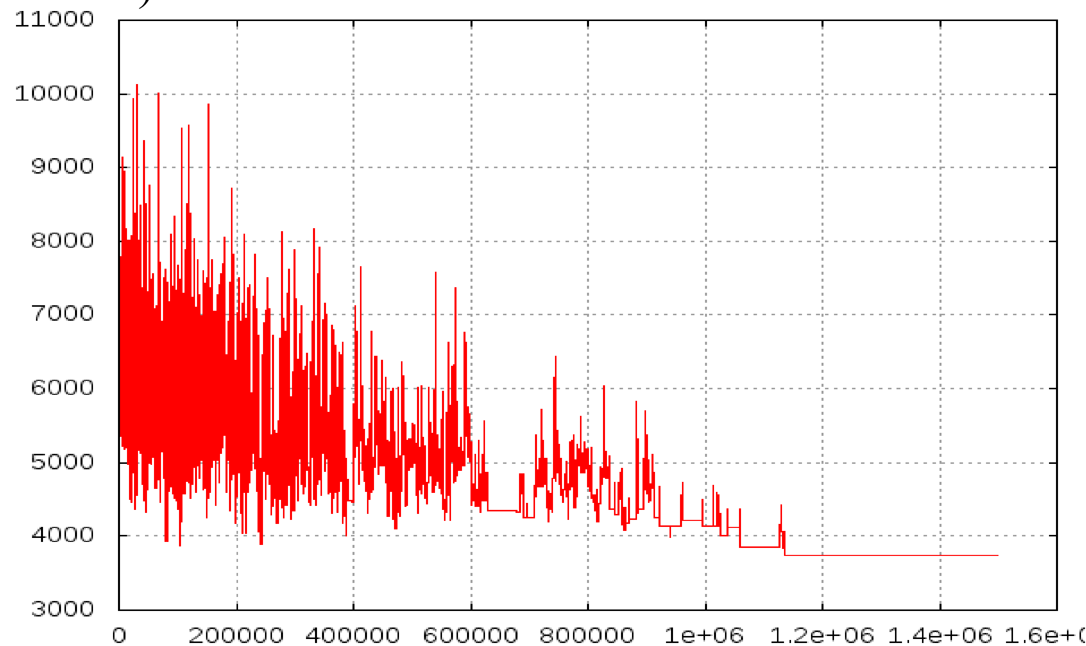
Statistics of 100 experiments

floor area ratio			lot coverge ratio			CPU time (ms)		
min	max	average	min	max	average	min	max	average
0.816634	1.26306	1.05065	0.136106	0.21051	0.175109	113133	116516	115078

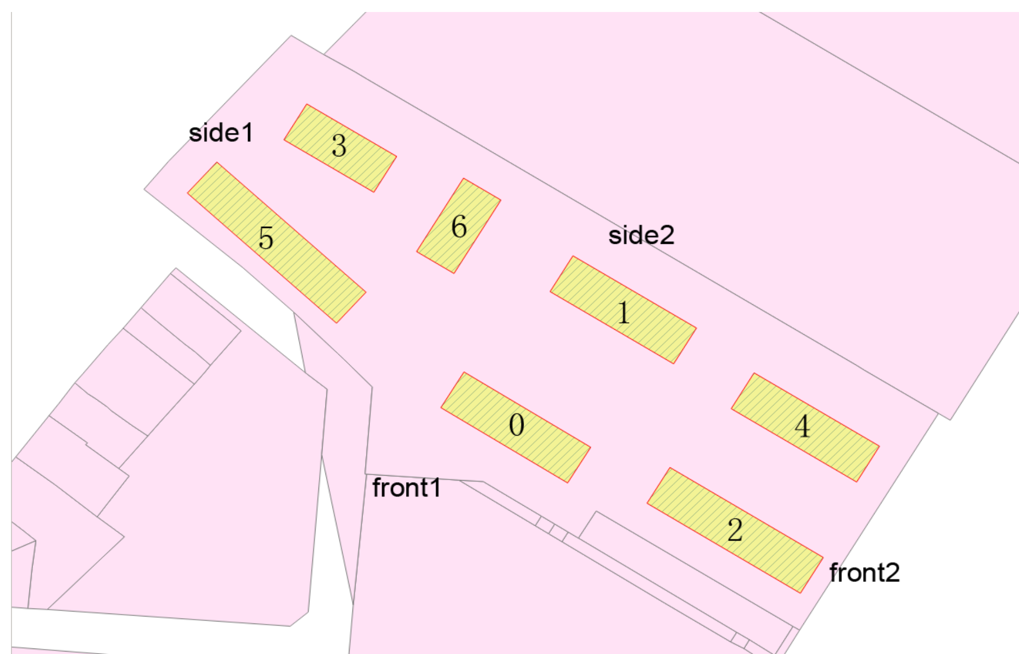
Case Study B

Best optimization result (with highest floor area ratio)



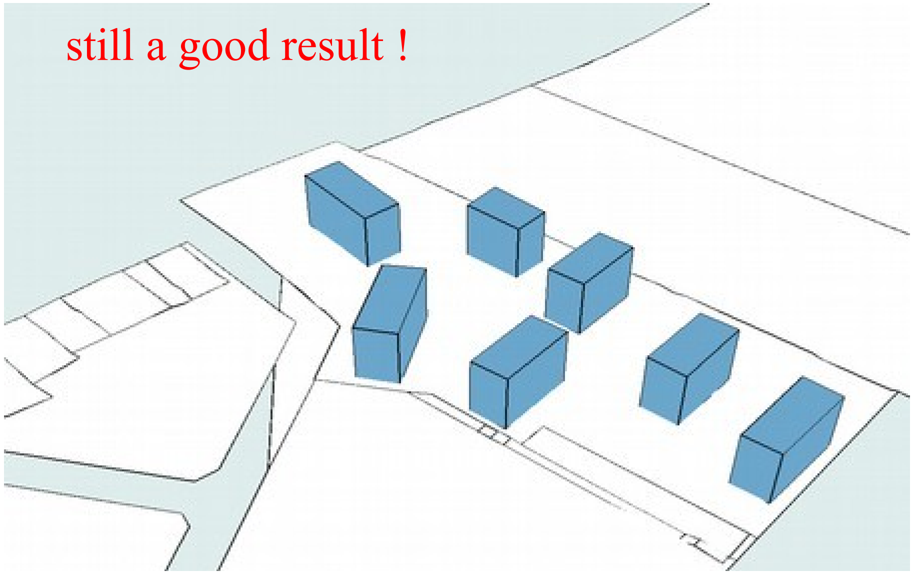


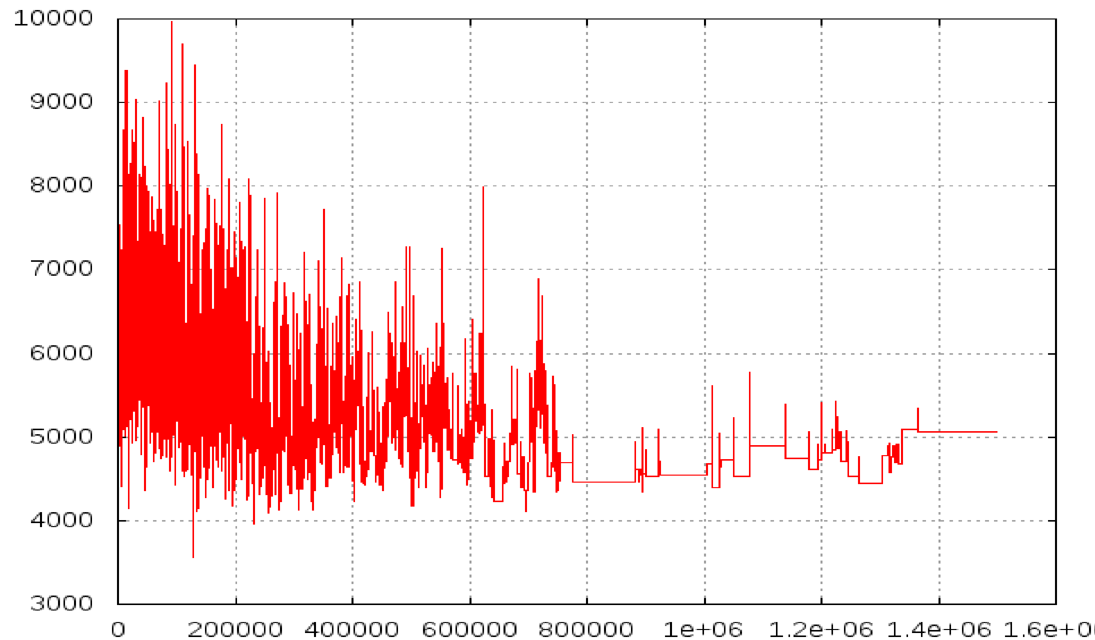
	dFront1	dFront2	dSide1	dSide2	height
$bldg_0$	9.85336	63.3457	83.449	47.9744	18
$bldg_1$	36.4654	57.6205	82.763	11.4325	18
$bldg_2$	7.60716	4.43858	133.293	42.9113	18
$bldg_3$	29.4159	137.227	13.7346	12.1943	18
$bldg_4$	36.8309	7.35529	131.968	13.6948	18
$bldg_5$	4.59922	126.305	8.17203	34.6657	18
$bldg_6$	29.9015	111.54	51.9139	8.68311	18
Binary distance: no violation					
Binary height difference: no violation					
Lot coverage ratio = 0.21051					
Floor area ratio = 1.26306					
Energy					
$30E^{u_d}$	$20E^{b_d}$	$20E^{b_h}$	$20E^{g_c}$	$50E^{g_f}$	total energy
0	0	0	0	3745.42	3745.42



Case Study B

Worst optimization result (with lowest floor area ratio)





	dFront1	dFront2	dSide1	dSide2	height
$bldg_0$	9.18388	88.1194	73.6874	47.2649	18
$bldg_1$	10.1186	3.05827	161.652	25.8945	18
$bldg_2$	6.07522	60.0734	109.678	45.5575	18
$bldg_3$	14.1849	68.2293	94.4153	9.07669	18
$bldg_4$	19.0516	31.9352	132.365	20.9724	18
$bldg_5$	18.5779	122.827	30.3905	25.1989	18
$bldg_6$	41.7577	93.6583	64.31	9.94434	18
Binary distance: no violation					
Binary height difference: no violation					
Lot coverage ratio = 0.136106					
Floor area ratio = 0.816634					
Energy					
$30E^{u_d}$	$20E^{b_d}$	$20E^{b_h}$	$20E^{g_c}$	$50E^{g_f}$	total energy
0	0	0	0	5066.91	5066.91

Conclusion and Future Work

- Preliminary case study and test results are satisfying
  - Optimal/good solution can always be obtained
  - Fast computation

    ~ 1 minute for a 1787.14 m2 parcel and ~ 2 minutes for a 11020.9 m2 parcel (time is not linear to the area due to the difference of applied urban rules)
- Future work
  - Try to increase the probability of generating optimal solutions, not just good ones
  - Conduct more case studies to evaluate the robustness and generality of our approach
  - Study more complex rules (e.g. concerning windows and roofs)
  - How to handle the diversity of urban rules?
  - How many rules can it support?

  ...

A Stochastic Method for the Generation of Optimized Building Layouts Respecting Urban Regulations

Thank You for Your Attention

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