Interactive Design and Visualization of Urban Spaces using Geometrical and Behavioral Modeling

Carlos Vanegas[1,4,5] Daniel Aliaga[1]
Bedřich Beneš[2] Paul Waddell[3]

[1]Computer Science, Purdue University, USA
[2]Computer Graphics Technology, Purdue University, USA
[3]City and Regional Planning, UC Berkeley, USA
[4]Chair for Information Architecture, ETH Zürich, Switzerland
[5]Procedural Inc., Switzerland

Objective and Applications

Objective

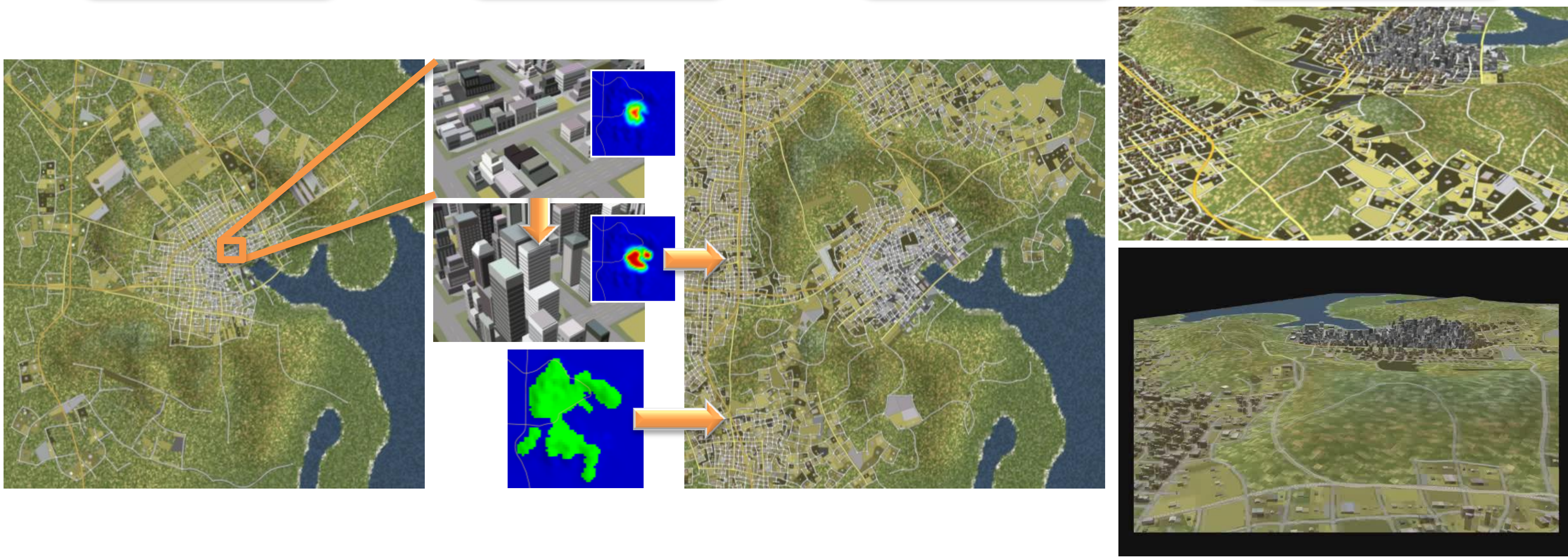
- Fast generation of 3D urban models that reflect the behavior of real-world cities

Applications

- Urban planning
- Urban visualization
    - Policy evaluation and education
- Content generation for games and movies

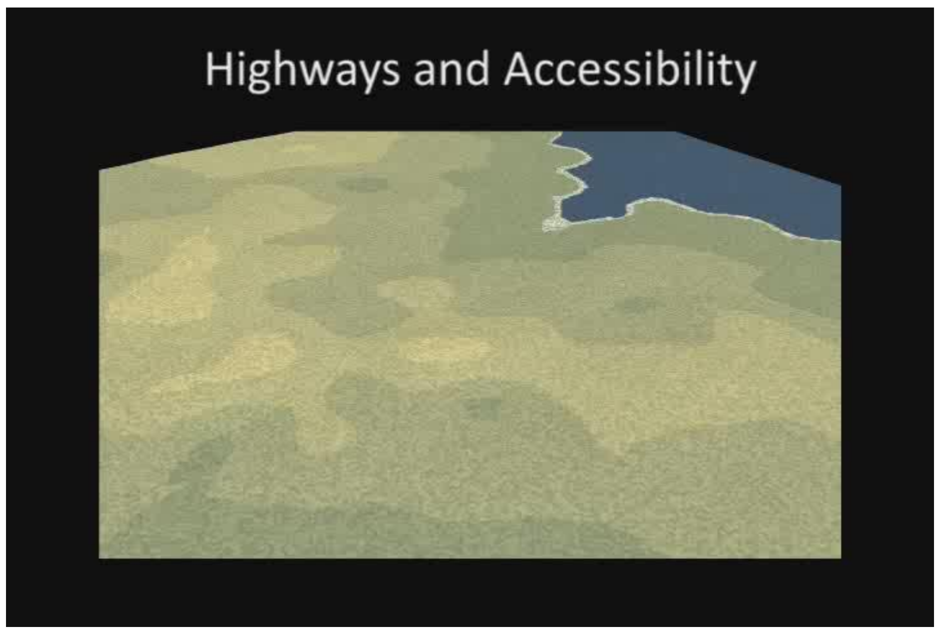
Examples (1)

- Designer increases height of buildings in downtown
- Number of jobs increases
- Population increases
- New housing appears in accessible areas

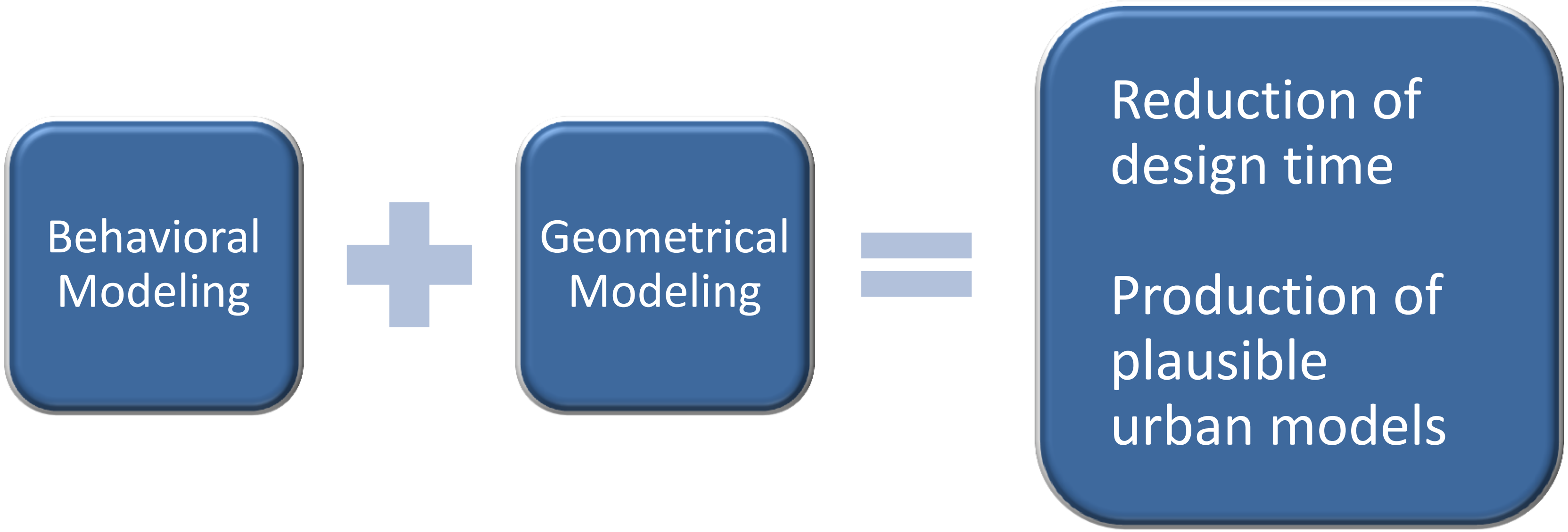


Examples (2)

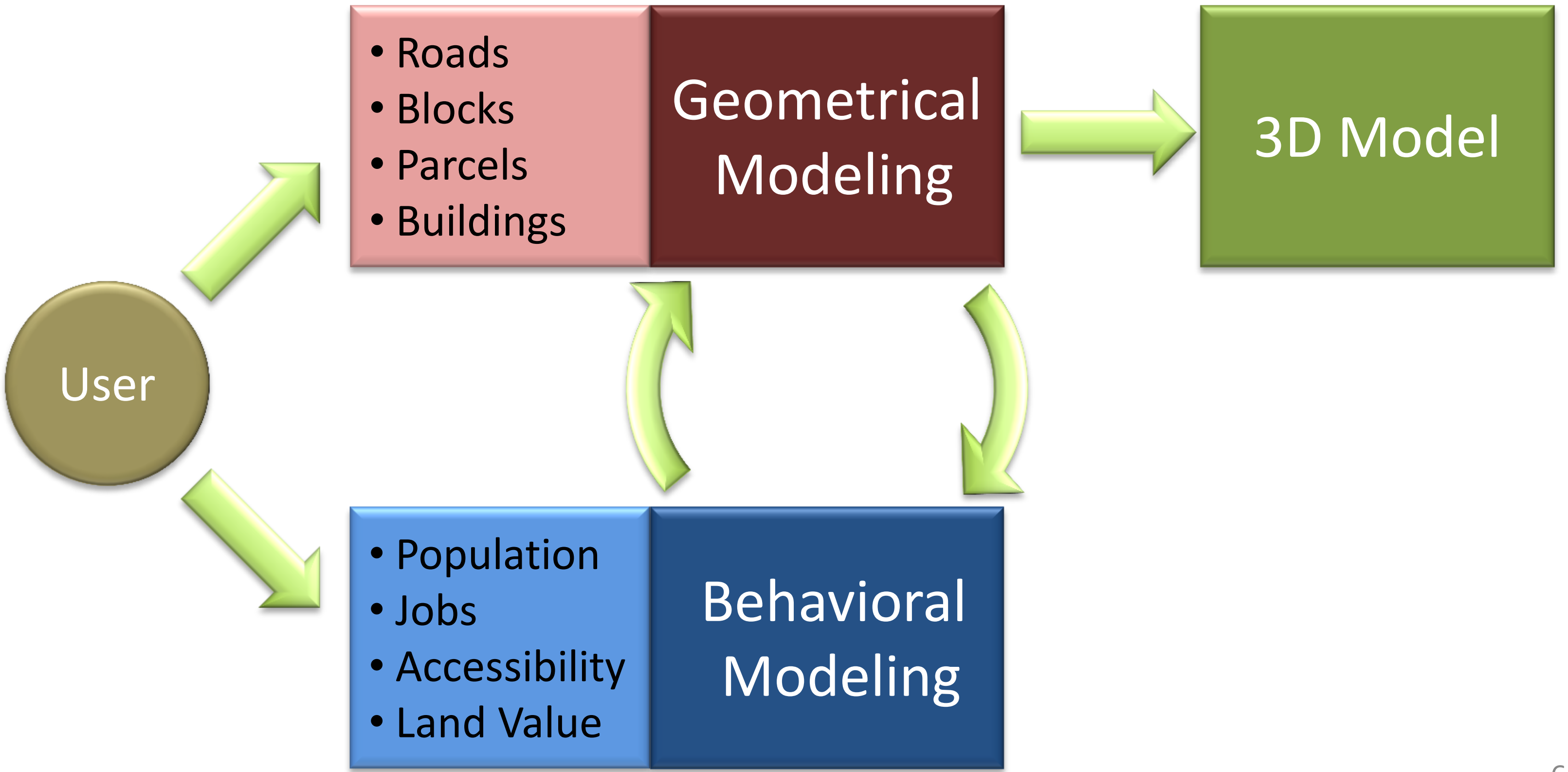
Designer inserts a highway into the model → Accessibility increases in formerly remote areas → Population redistributes → Location of jobs, houses, and buildings changes



Observation

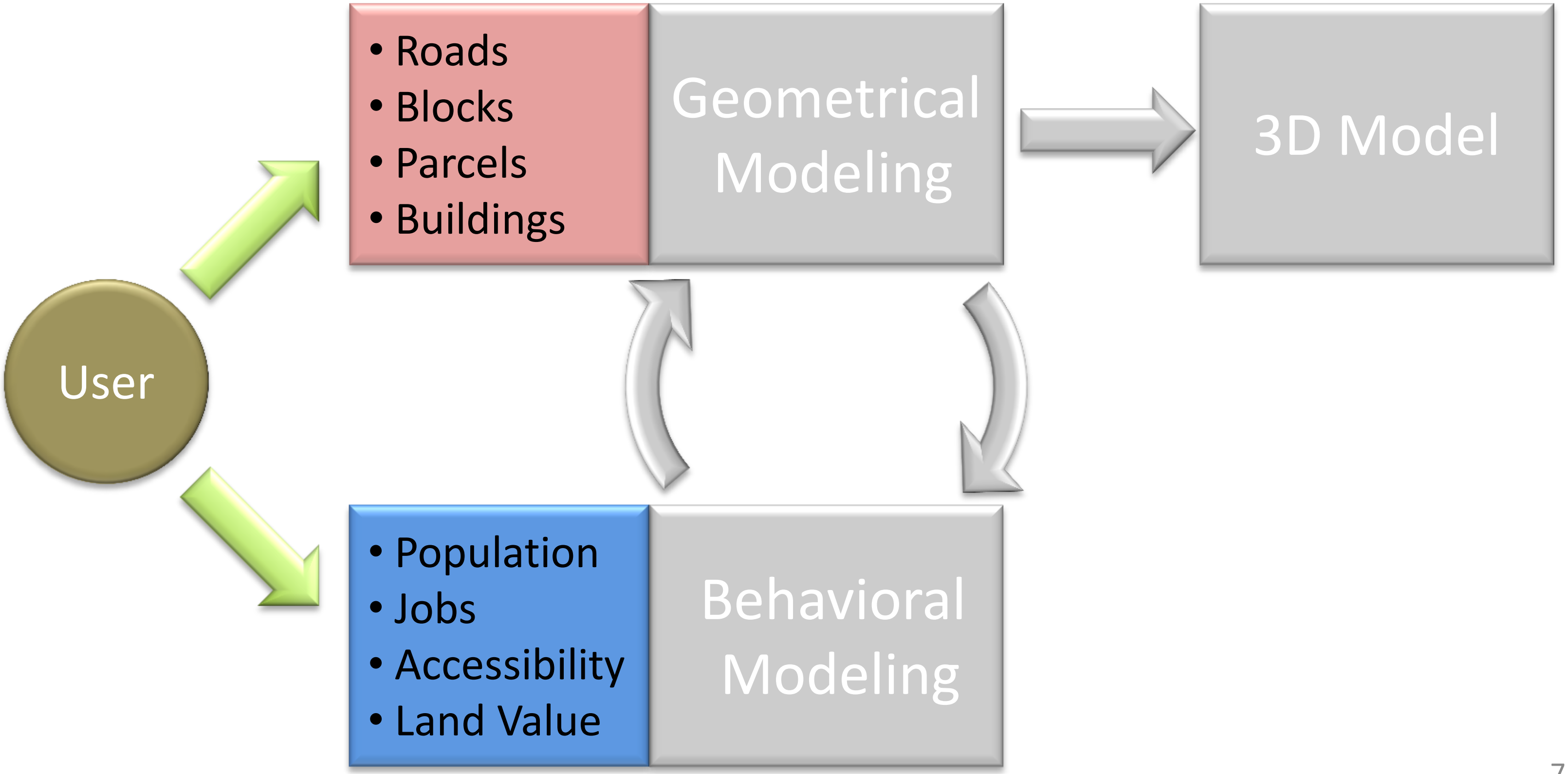


System Overview



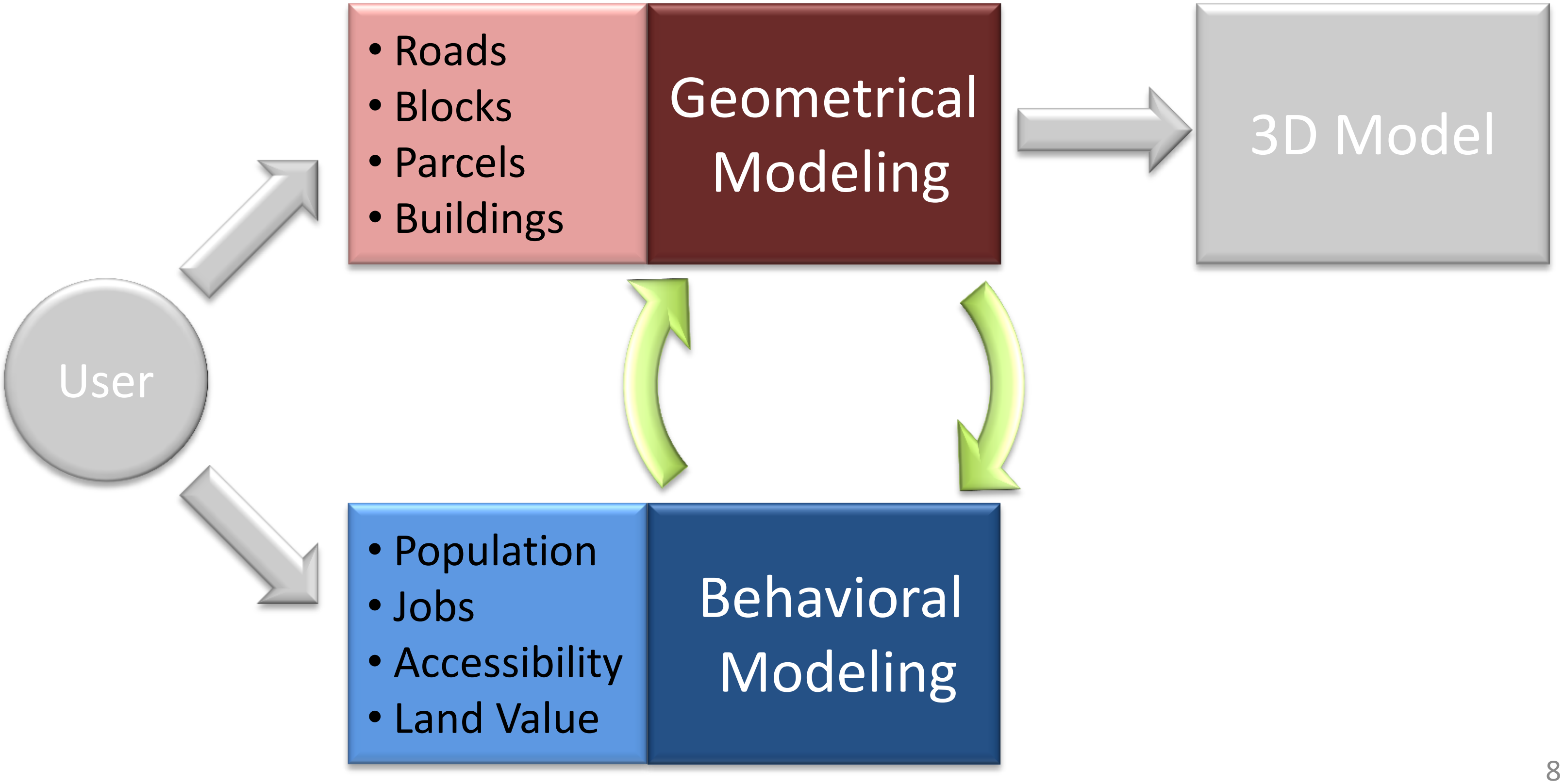
System Overview

- **Input**: Interactive design interface to change and constrain values of simulation variables



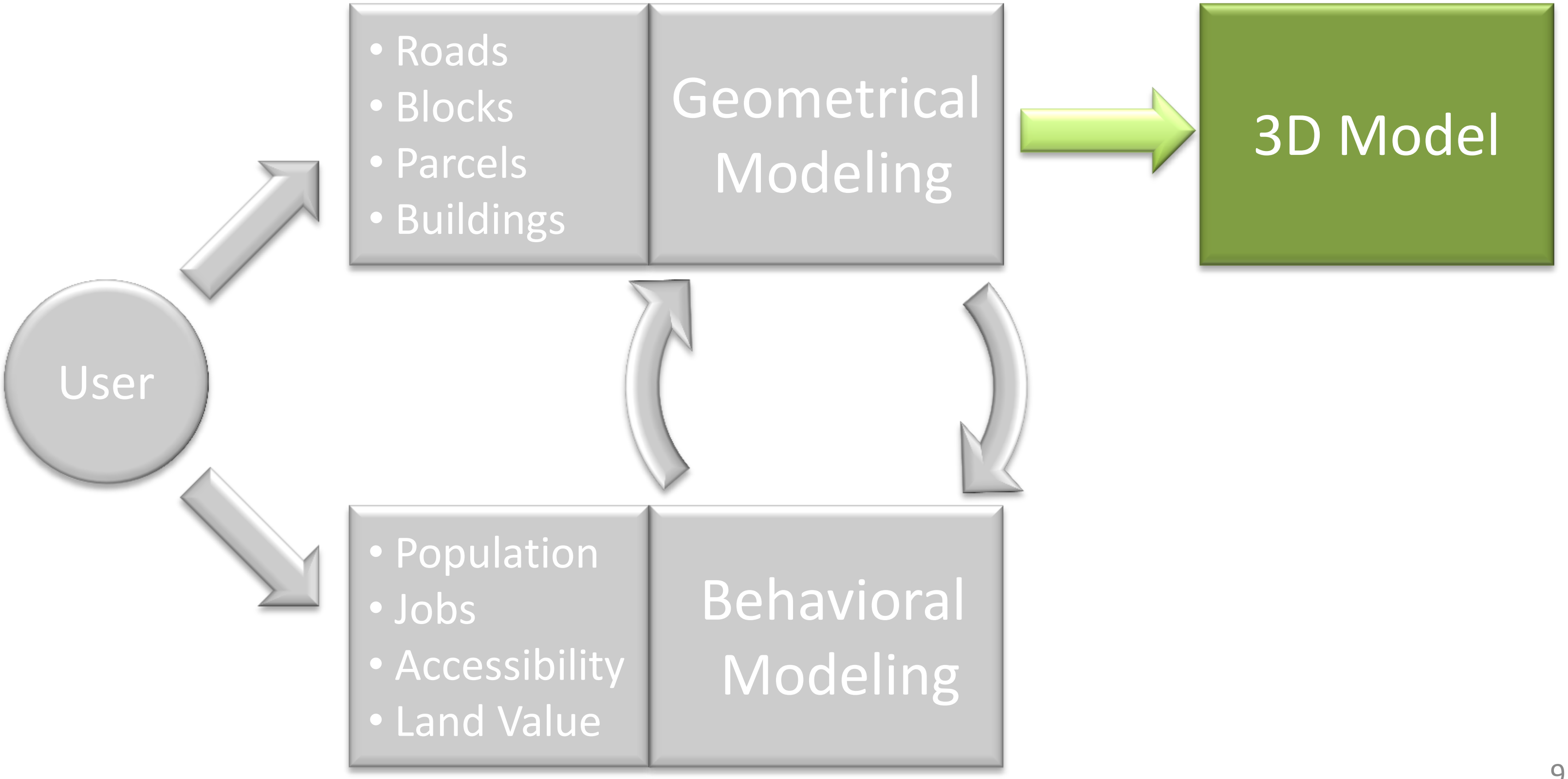
System Overview

- **Process**: Interactions between the variables are continually simulated to bring the system back into equilibrium



System Overview

- **Output**: Procedurally generated 3D urban model (based on the state of the system)



Related Work

Geometrical Modeling

- **Procedural Modeling of Cities, Buildings, Facades, Streets**
  - Müller et al., 2001, 2006
  - Wonka et al., 2003
  - Chen et al., 2008
  - Aliaga et al., 2008

Behavioral Modeling

Related Work

Geometrical Modeling

Behavioral Modeling

in Graphics

- **Large crowd modeling**
  - Sung et al., 2004
  - Treuille et al., 2006
- **Flocking and animal behavior modeling**
  - Reynolds., 1987
  - Tu and Terzopoulos., 1994

Related Work

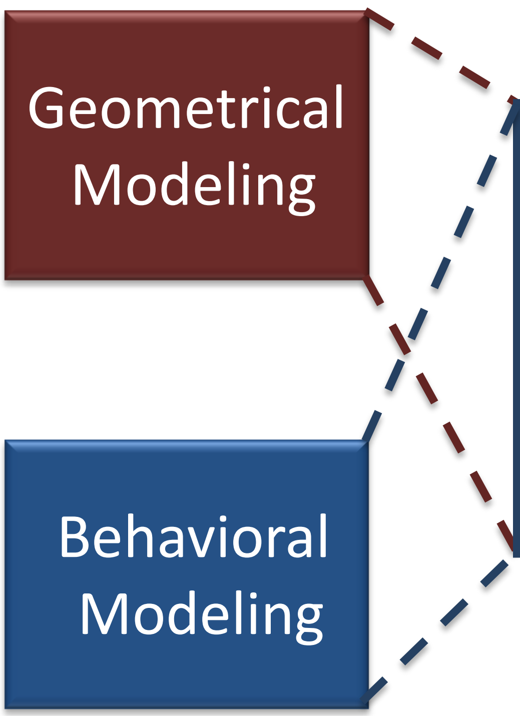
Geometrical Modeling

Behavioral Modeling

in Urban Simulation

- **Cellular automata, Agent-based**
- **Microsimulation**
  - Uses discrete-choice models
  - Uses agents that make decisions to locate and move within urban space
  - e.g., UrbanSim [Waddell et al., 2002]

Related Work



Integration

- **Interactive geometric simulation of cities over time**
  - Weber et al., 2009
- **Visualization of Simulated Cities**
  - Vanegas et al., 2009

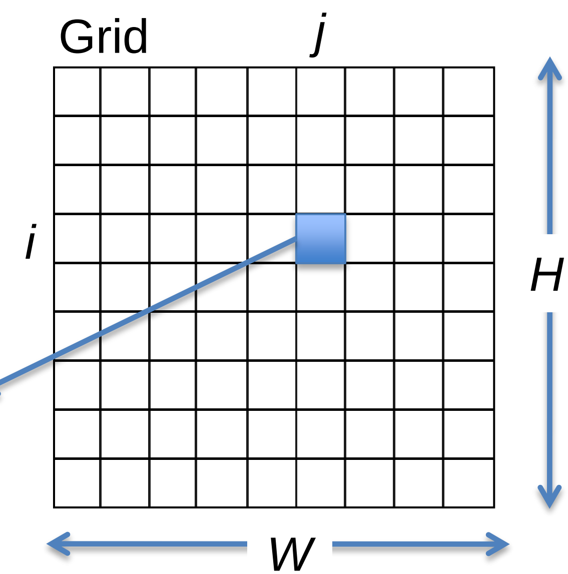
Do not focus on producing interactive design/editing time and ensuring plausible 3D urban models

Contents

- Introduction
- Urban Design as a Dynamical System
- Behavioral Modeling
- Geometrical Modeling
- Results
- Applications

Urban Design as a Dynamical System

- **System**
  - Consists of N variables defined over a spatial domain
  - Each variable sampled over a 2D spatial grid $\boldsymbol{G}$ of size $W \times H$
  - $v_k(i,j)$ denotes the value of k-th variable at grid cell (i,j)



$$v_0(i,j),\ v_1(i,j),\ \ldots,\ v_N(i,j)$$

Urban Design as a Dynamical System

- **Minimal set of design variables used in our system**
  - Population count
  - Job count
  - Accessibility
  - Land value
  - Road length
  - Building volume
  - Average tortuosity
  - Terrain elevation

Urban Design as a Dynamical System

- **Variable modeling**
  - The change in each variable $v_k(i,j)$ is represented as a differential equation

$$\dot{v}_k(i,j) = f_k(v_1, v_2, \dots v_N)$$

  - If the user changes a variable, the system iteratively updates all other variables in order to return to a state of **equilibrium**

$$|\dot{v}_k(i,j)| \leq \varepsilon$$

Urban Design as a Dynamical System

- **Iterative System** (a classical formulation)

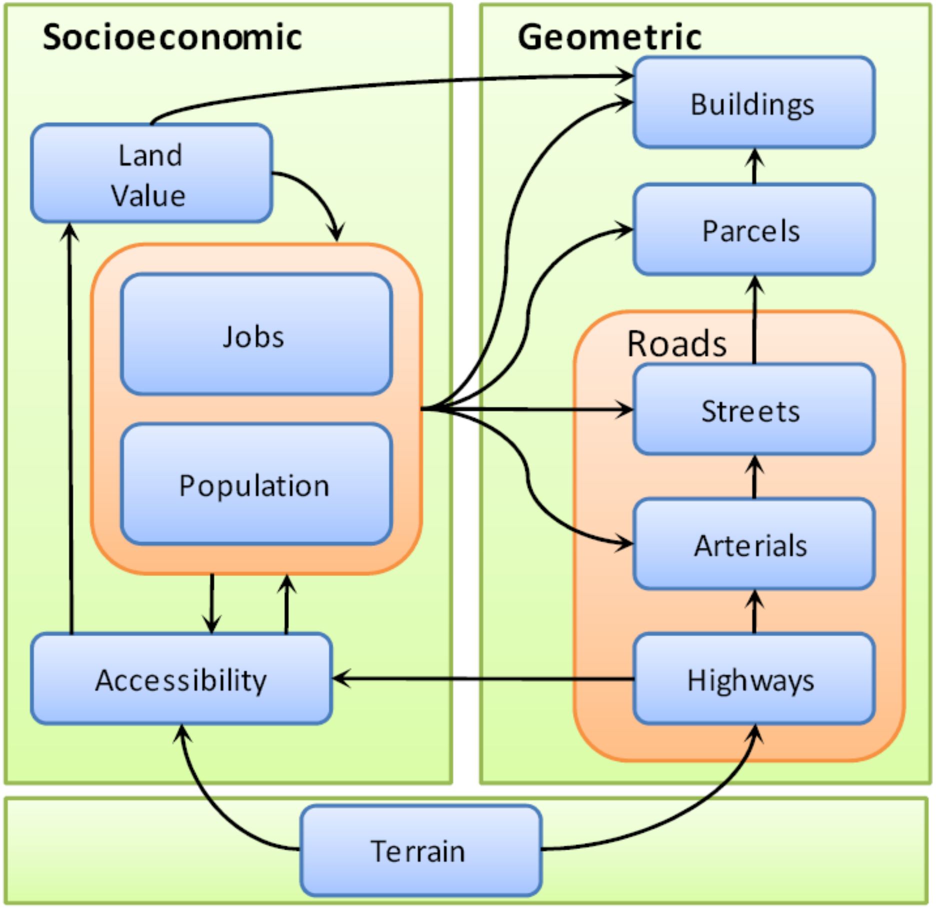
$$v_k^{n+1}(i,j) = v_k^n(i,j) + \dot{v}_k(i,j)$$

In urban design, the term $\dot{v}_k(i,j)$ is difficult to express symbolically due to widespread dependencies

Instead, we propose algorithms for computing $v_k(i,j)$ or $\dot{v}_k(i,j)$

Urban Design as a Dynamical System

- Actual dependencies between variables are:
- The system contains algorithms for modeling variables:



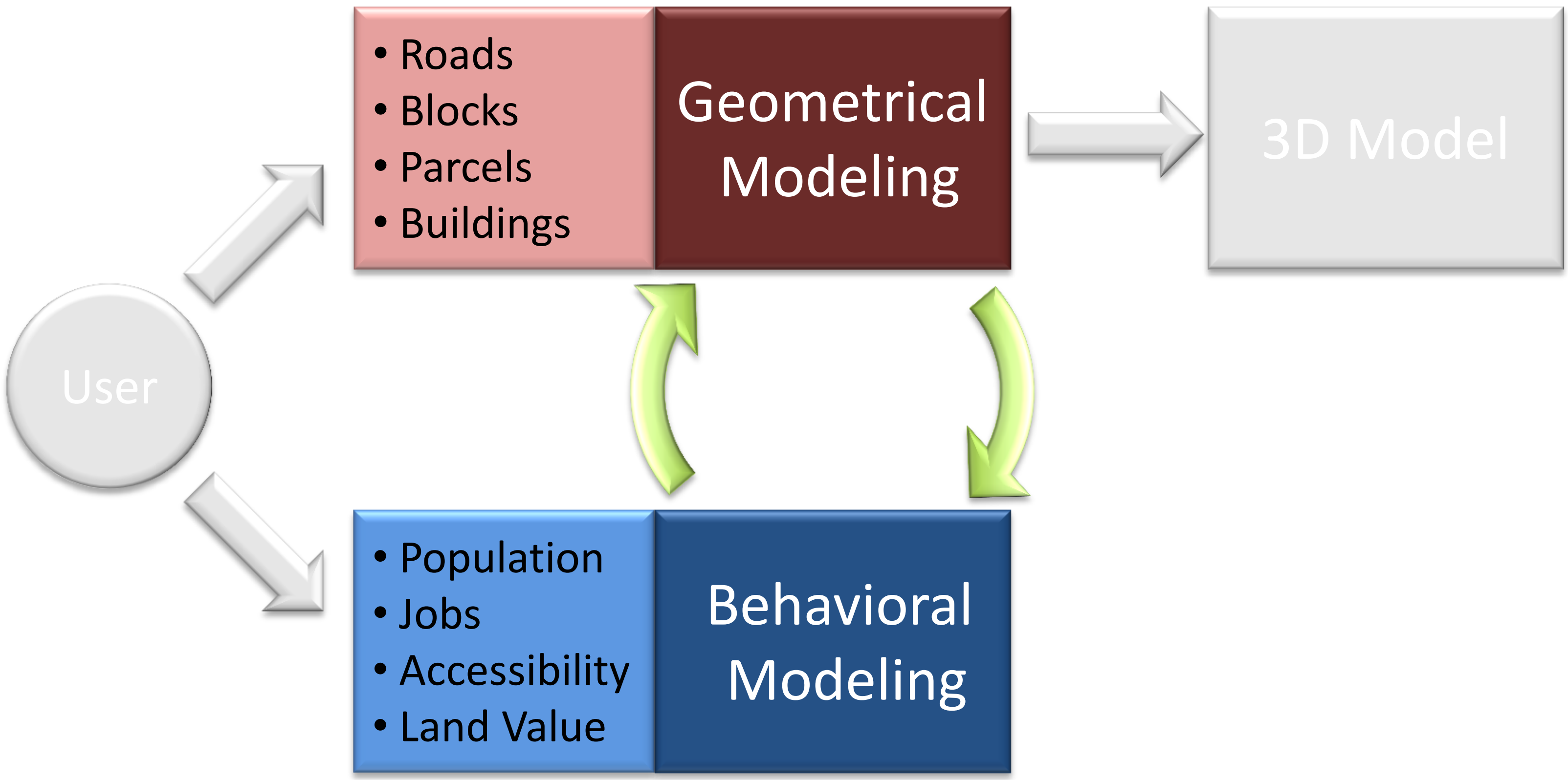
Urban Design as a Dynamical System

- **Variable Modeling:** The system considers these dependencies and for each variable:
    - Simulates its change $\dot{v}_k(i,j)$ as a function of other variables (behavioral variables)

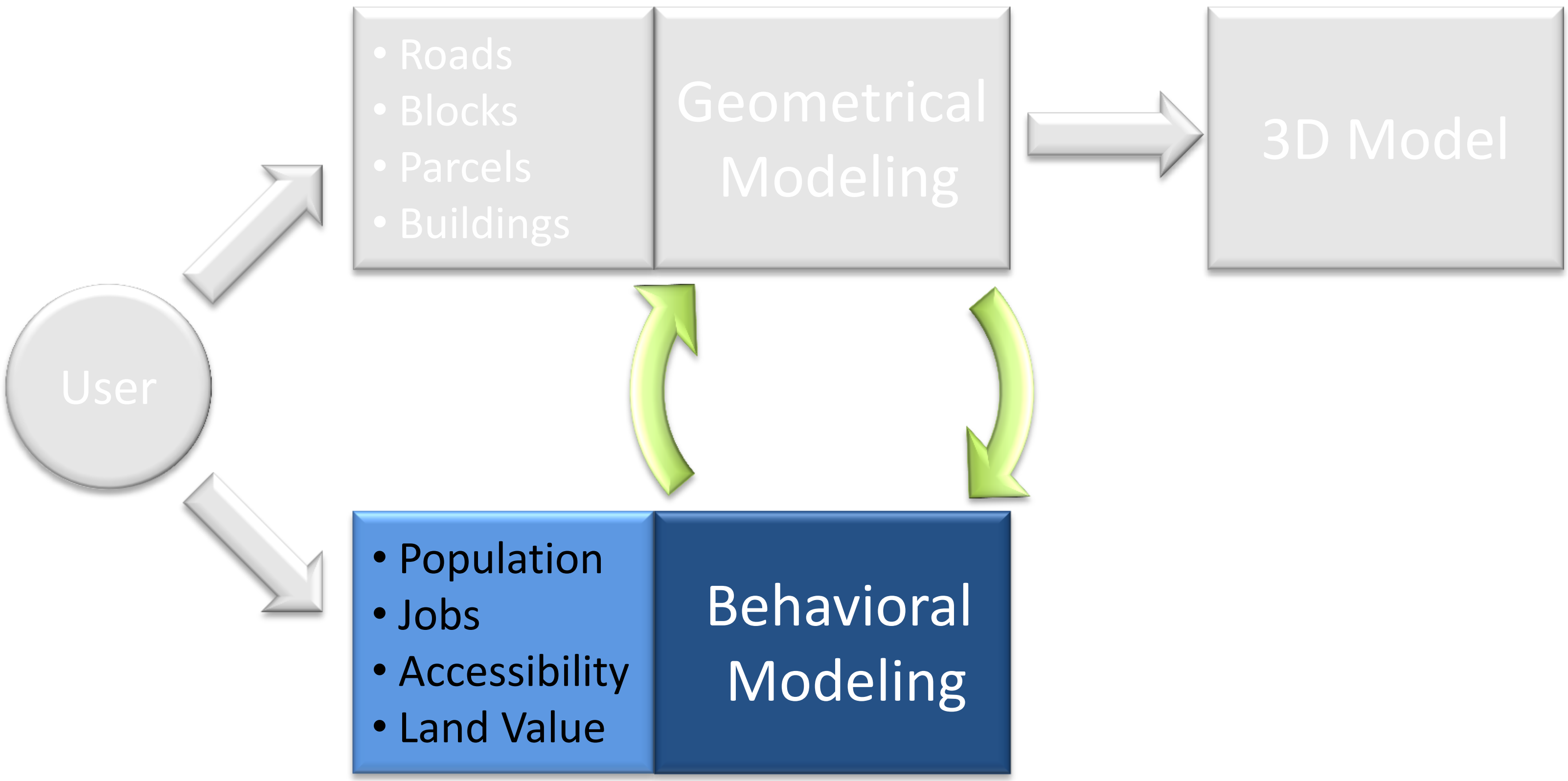
  OR

    - Calculates its target value $v_k(i,j)$ as function of other variables, and procedurally generates the geometry that matches the target values (geometrical variables)

System Overview



Behavioral Modeling



Behavioral Modeling

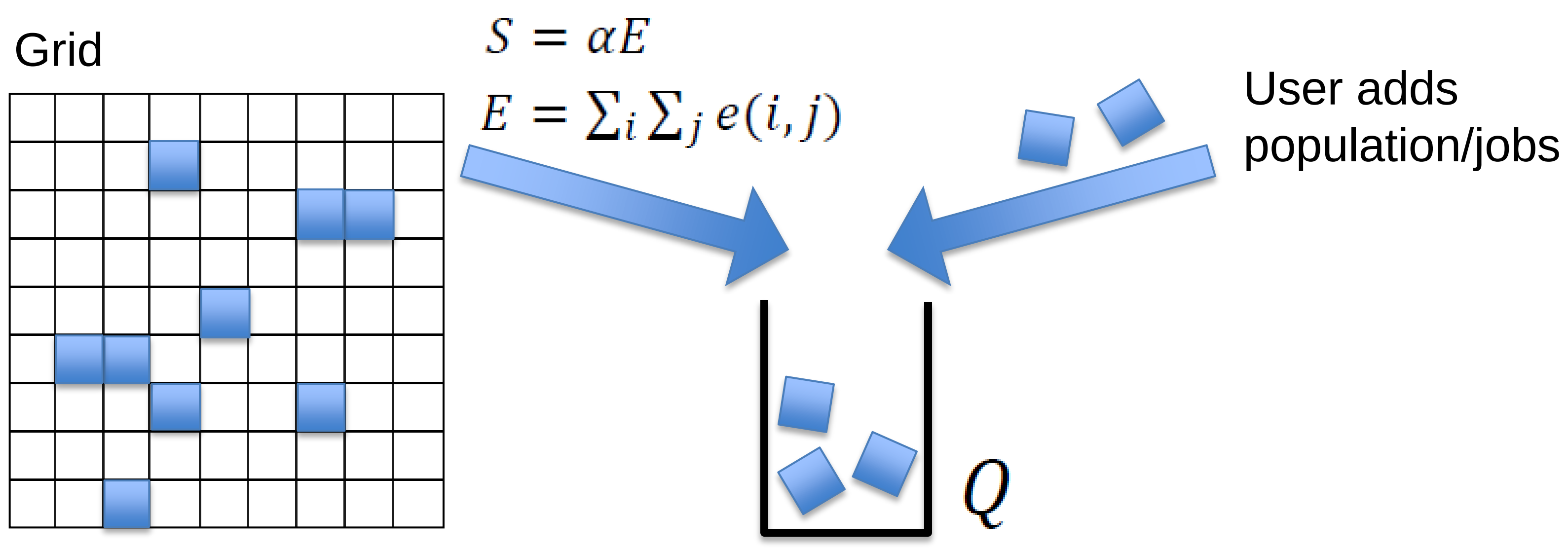
- **Variables**
  - Population count
  - Job count
  - Accessibility
  - Land value

Behavioral Modeling

- **Population and Jobs count**
  - Operations:
    - Remove a fraction of population/jobs from their current location (**Mobility** algorithm)
    - Locate population/jobs to predicted locations (**Location choice** algorithm)
  - Each unit of population/jobs is referred to as an **agent**

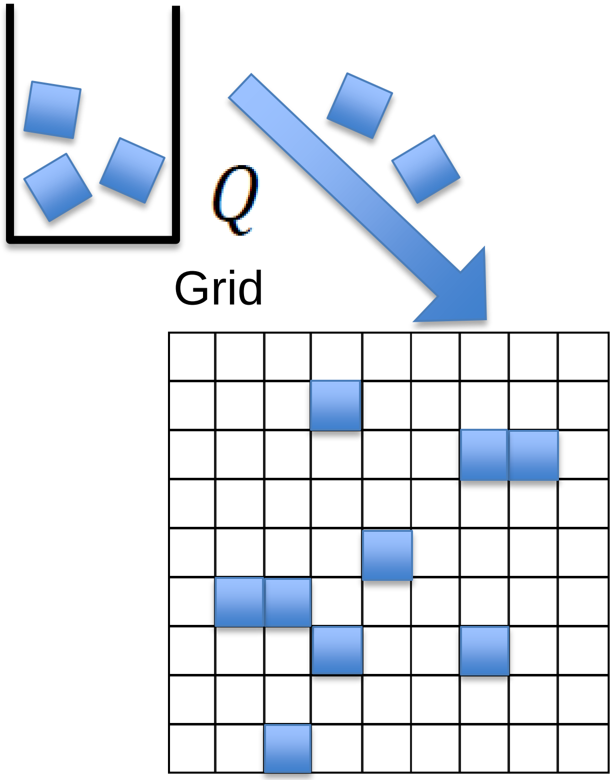
Behavioral Modeling

- **Operation**: **Remove agents** (Mobility Algorithm)
  - Agents de-located from grid are moved to queue $\boldsymbol{Q}$
  - Agents added by user are moved to queue $\boldsymbol{Q}$



Behavioral Modeling

- **Operation**: **Locate agents** (Location Choice Algorithm)
  - Agents from queue are placed back in the grid



Behavioral Modeling

- **Operation**: **Locate agents** (Location Choice Algorithm)
  - Uses weighted attractiveness measure as a probability
  - The probability q_{st} that an agent e_s will locate at the grid cell (i_t, j_t) is given by

$$q_{st} = (w_a a_t + w_b l_t)/T_s$$

a_t : **accessibility** at the grid cell
l_t : **land value** at the grid cell
T_s : total count of the agent throughout the entire grid

Behavioral Modeling

- **Accessibility**
  - Measure of access that a grid cell has to jobs and to the rest of the population
  - Intuitively
    - Decreases with increasing terrain slope
    - Increases with higher road connectivity and nearby population/jobs

Behavioral Modeling

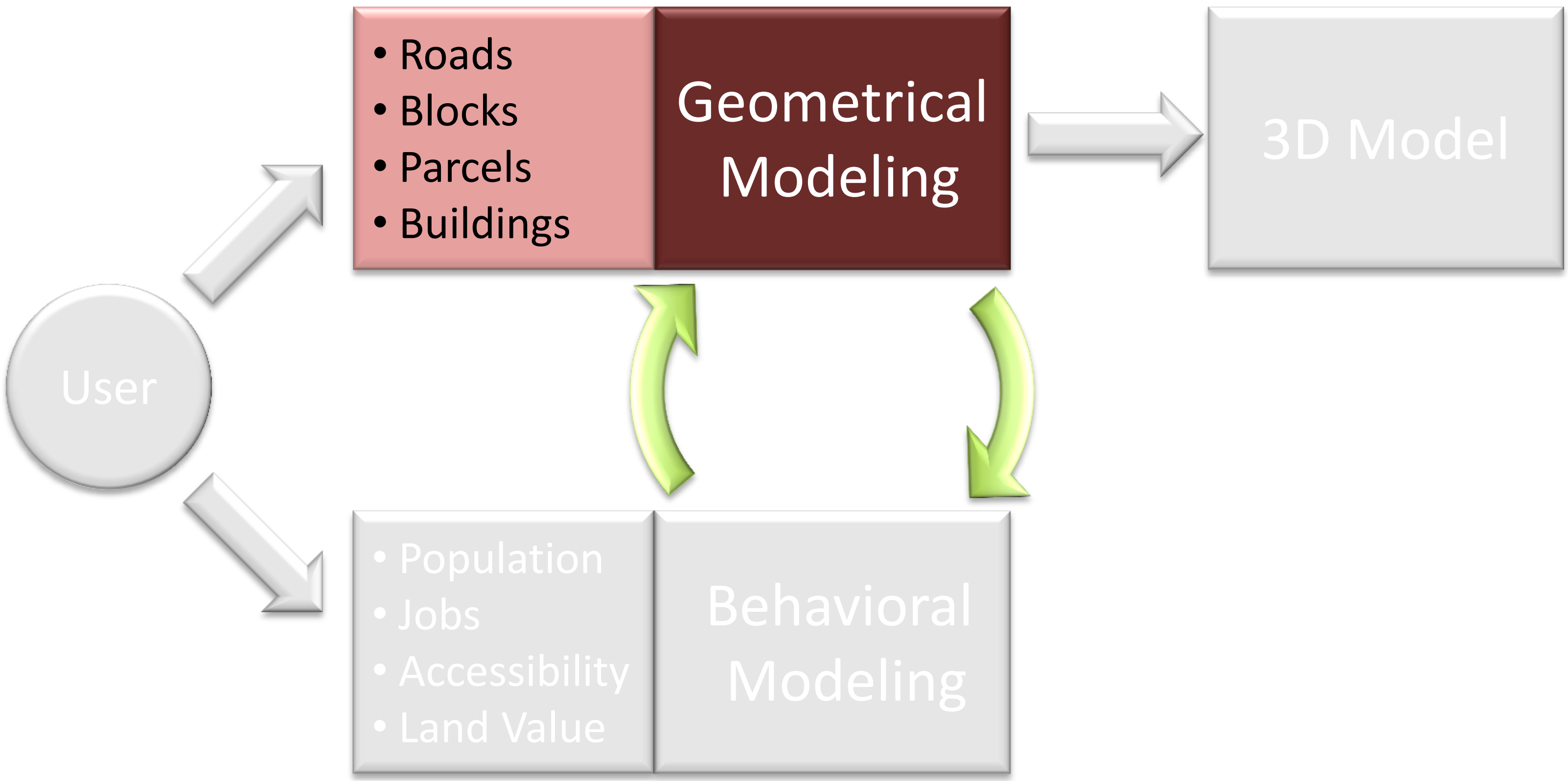
- **Accessibility**
  - Represented by logistic function $a(i,j) = \frac{1}{1 + e^{-z(i,j)}}$

$$z(i,j) = \beta_0 + \beta_1 u_1(i,j) + \beta_2 u_2(i,j) + \beta_3 u_3(i,j)$$

  - u_1: proximity to highways, arterials and streets
  - u_2: local slope of the terrain
  - u_3: Distance-normalized measure of activity level at (i,j)

$$u_3(i,j) = \sum_r \frac{D_{i_r j_r}}{d_{ij,i_r j_r}}$$

Geometrical Modeling



Geometrical Modeling

- **Variables**
  - Road length
  - Average tortuosity
  - Building volume
  - Terrain elevation at grid cell (user-controlled)

Geometrical Modeling

- **Road length**
  - Total length of roads in grid cell

$$r^{n+1}(i,j) = \min\left(w_{pr}p^{n}(i,j) + w_{br}b^{n}(i,j), r_{max}\right)$$

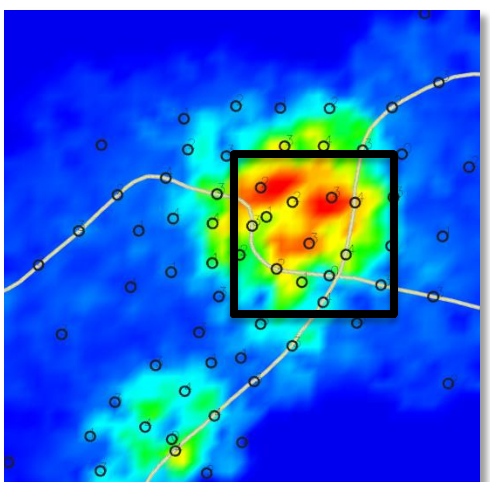
  - Two types: Arterials and Streets

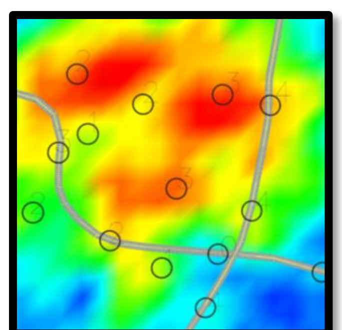
- **Average Tortuosity**
  - Ratio between road segment length and distance between segment endpoints

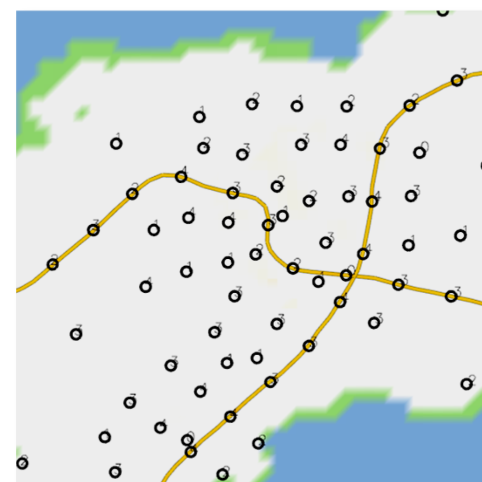
$$\tau^{n+1}(i,j) = 1 + k\left(1 - \frac{p^{n}(i,j)+b^{n}(i,j)}{p_{max}+b_{max}}\right)$$

Geometrical Modeling

- **Arterials and Streets: Seeds**
  - To connect the main population clusters a set of seeds is generated considering the population/jobs distribution and the location of highways

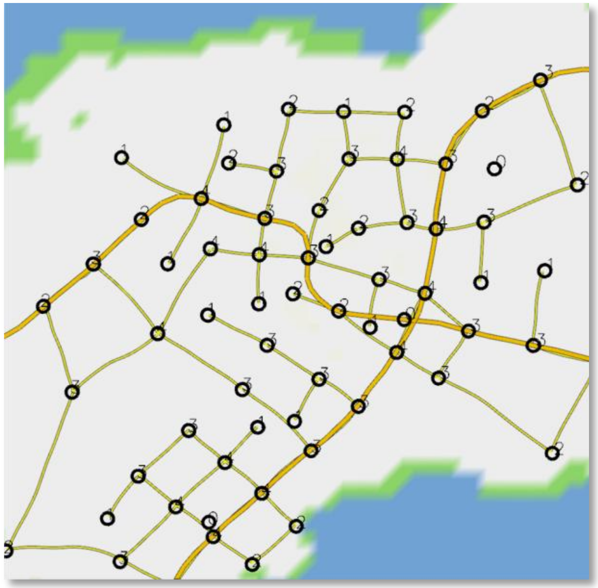






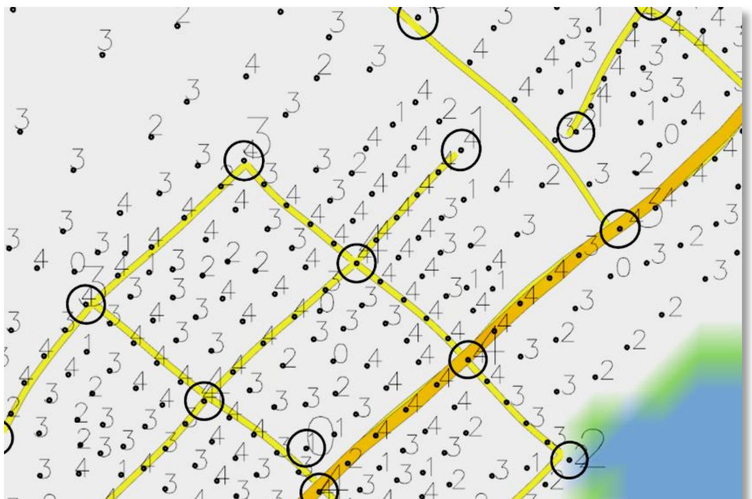
Geometrical Modeling

- **Arterials and Streets: Expansion of Arterials**
  - Each seed is used as an intersection of the arterial roads network and used to generate arterial segments



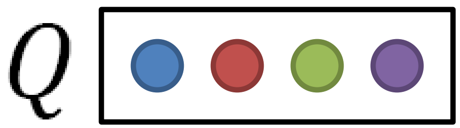
Geometrical Modeling

- **Arterials and Streets: Expansion of Streets**
  - Street seeds are generated along arterial road segments and used to create streets



Geometrical Modeling

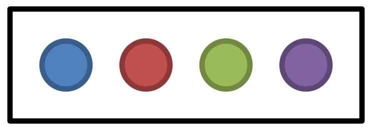
- **Arterials and Streets: Expansion Algorithm**
  - Using the seeds positioned according to population/jobs and/or along arterials, we generate road segments using a breadth-first expansion method
  - These seeds are placed into a queue



Geometrical Modeling

- **Arterials and Streets: Expansion Algorithm**

Q



Geometrical Modeling

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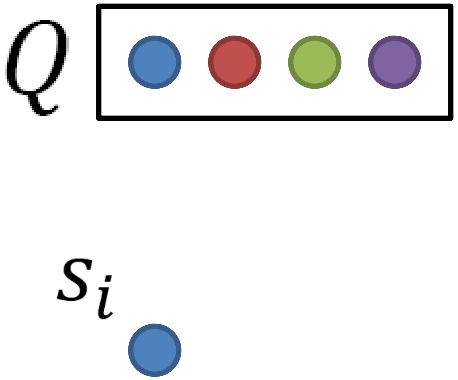

Geometrical Modeling

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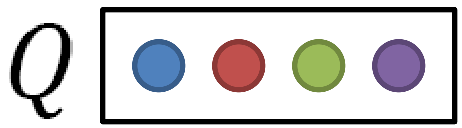
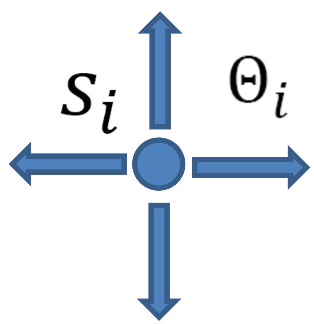


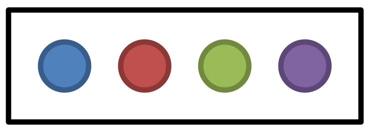


$$\Theta_i = \{\theta_0, \theta_1, \dots, \theta_{m-1}\}$$

Geometrical Modeling

- **Arterials and Streets: Expansion Algorithm**

Q

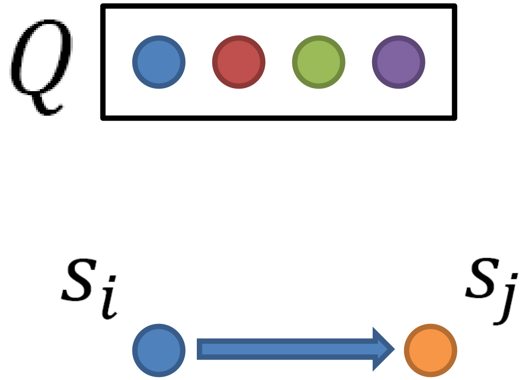


s_i

$$\int_{C_{ij}} p(x)dx = \rho$$

Geometrical Modeling

- **Arterials and Streets: Expansion Algorithm**



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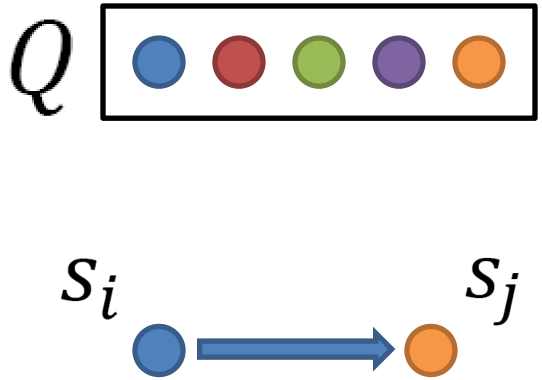
Geometrical Modeling

- **Arterials and Streets: Expansion Algorithm**



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Geometrical Modeling

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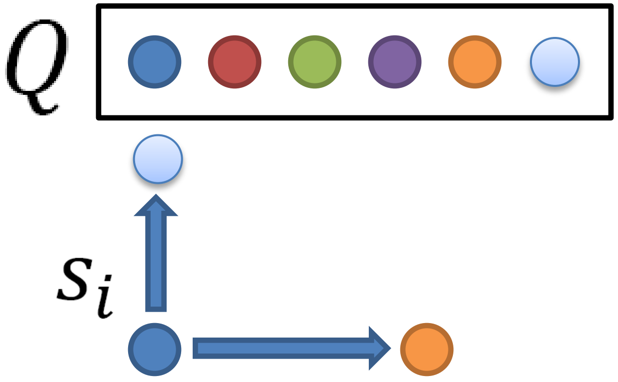

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Geometrical Modeling

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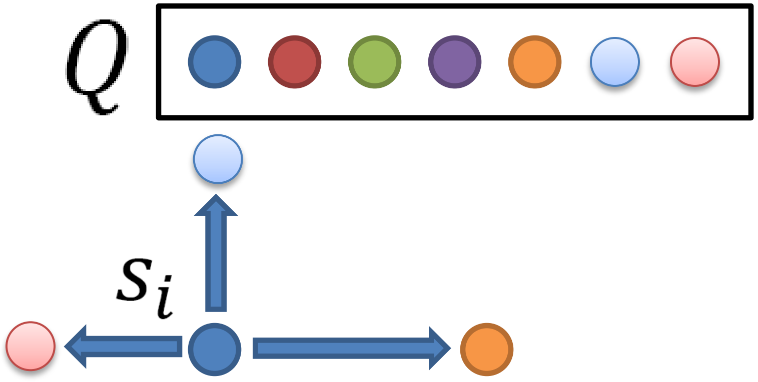

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Geometrical Modeling

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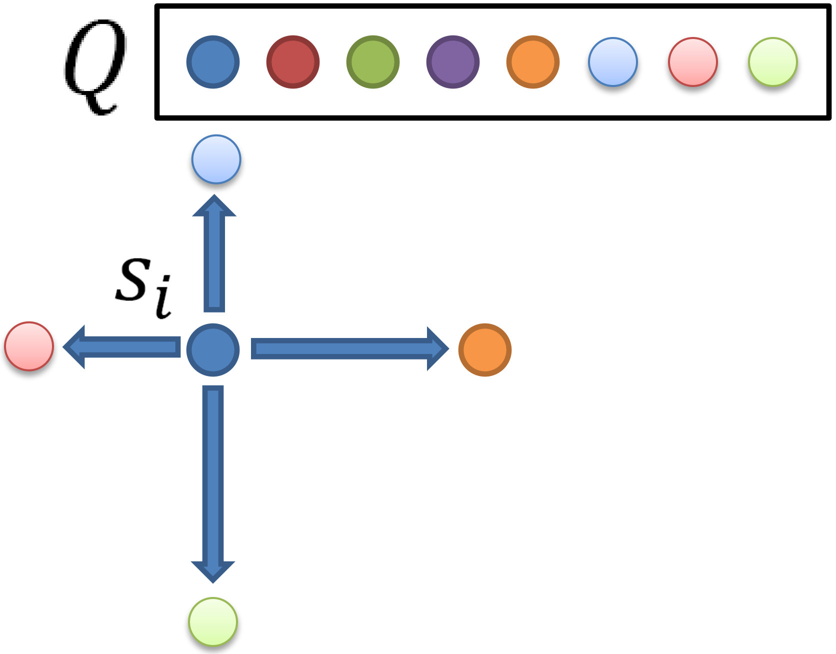

Geometrical Modeling

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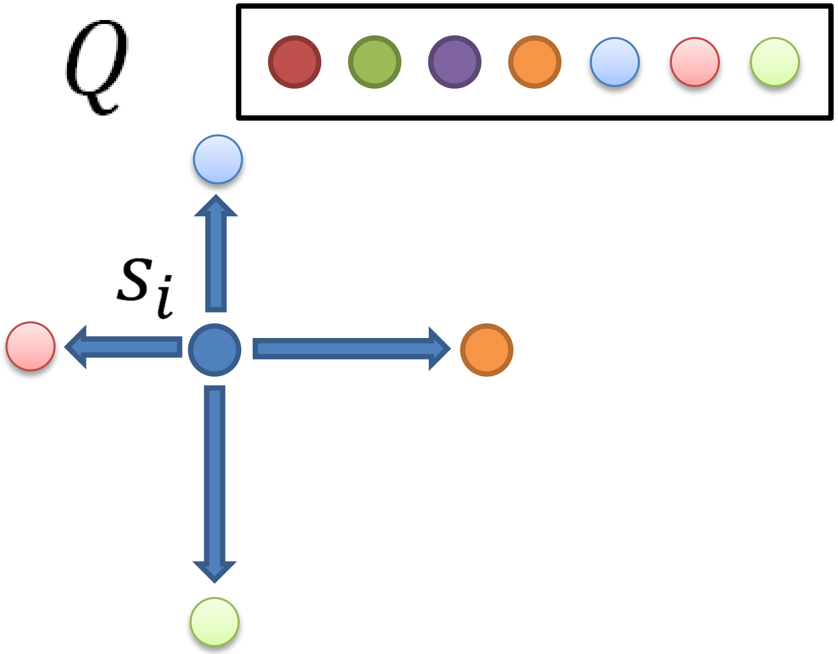
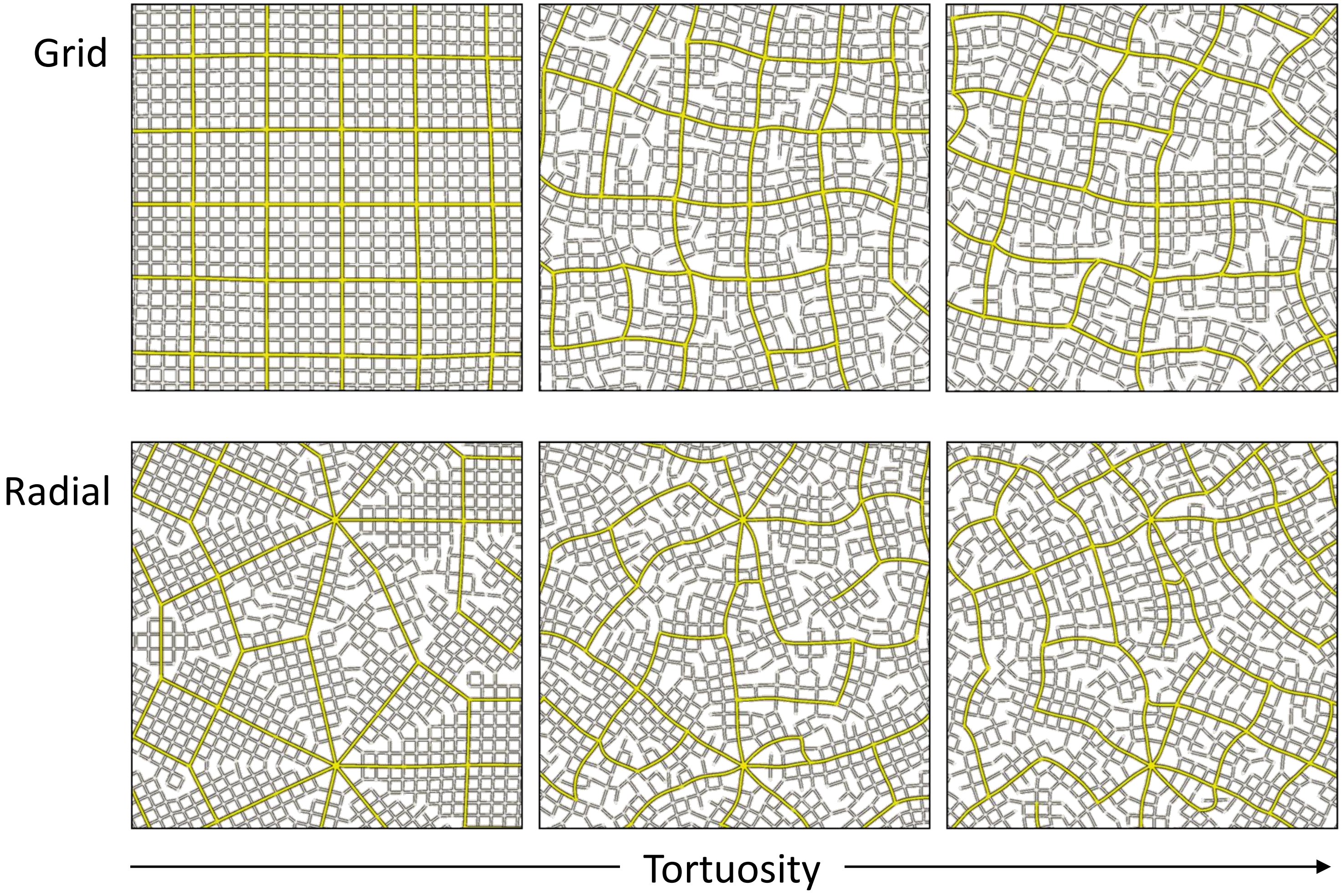


Geometrical Modeling



Geometrical Modeling

- **Building volume**
  - Total volume of all the buildings in grid cell

$$m^{n+1}(i,j) = w_{pm}p^n(i,j) + w_{bm}b^n(i,j)$$

  - Computed as a function of population and jobs

- To generate a building geometry that matches the volume, we first generate parcels and building footprints

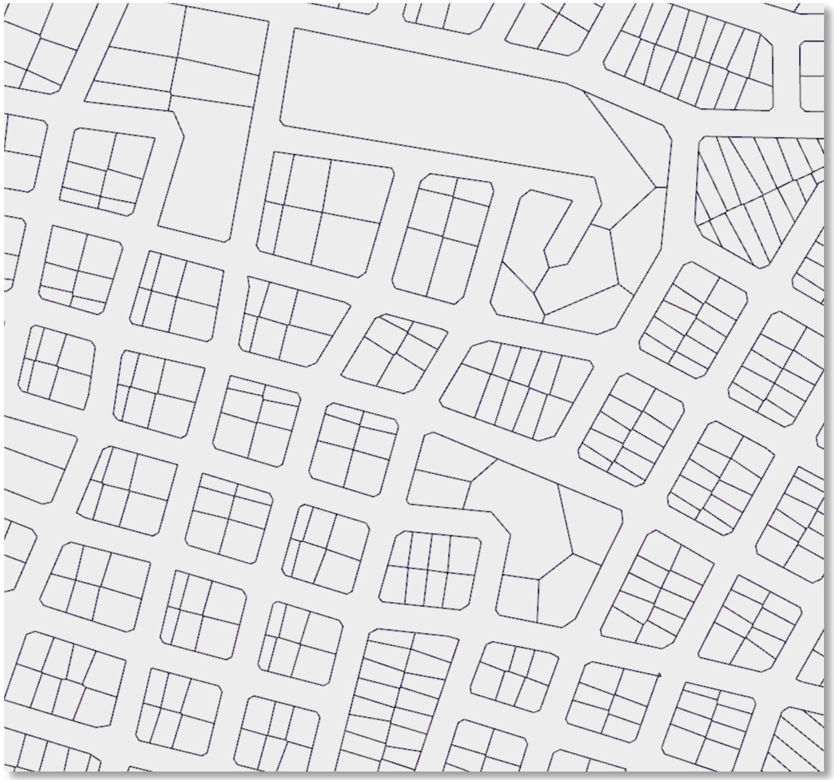
Geometrical Modeling

- **Parcels**
  - Blocks are extracted from the road network and partitioned into parcels
  - The number of parcels in the block is proportional to the product of the area of the block and the count of population/jobs in the grid cells inside the block

Geometrical Modeling

- **Parcels**

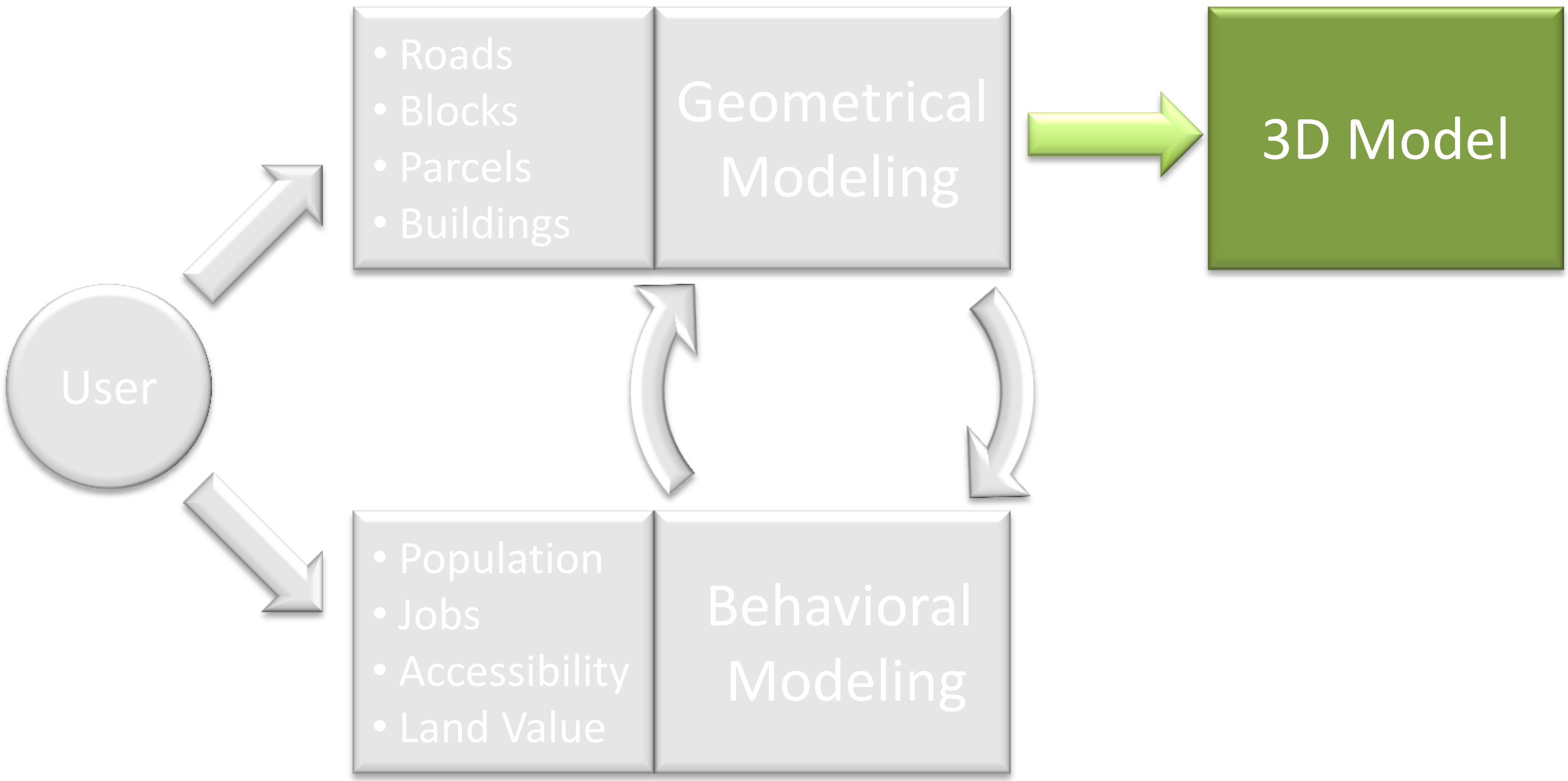
Close up view



Geometrical Modeling

- **Buildings**
  - Procedurally generated inside each parcel based on the socioeconomic information of the area
  - Process:
    - Calculate geometry of the building footprint
    - Calculate building height
    - Use procedural rules to generate 3D geometry that matches these attributes

Results

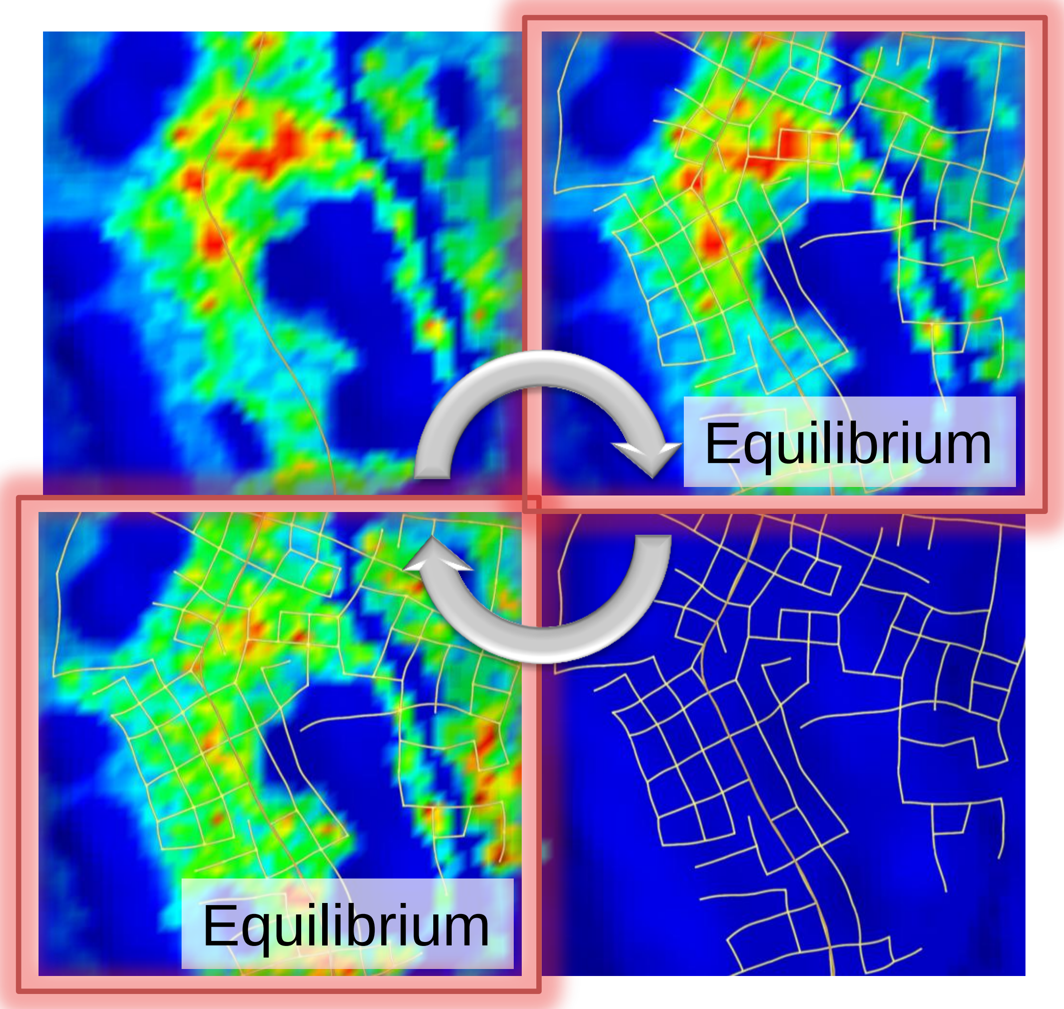


• Roads
• Blocks
• Parcels
• Buildings
Geometrical Modeling
3D Model
User
• Population
• Jobs
• Accessibility
• Land Value
Behavioral Modeling

Results: System Specs

- Dimensions:
  - Grid-cell size 0.1x0.1 km
  - Grid size up to 50x50 km in our experiments
- Time:
  - Update time step during editing:
    - <0.3 seconds for small grid (5x5 km)
    - <4 seconds for large grids (15x15 km)
  - **Total Design Time:**
    - <5 minutes for any of our examples

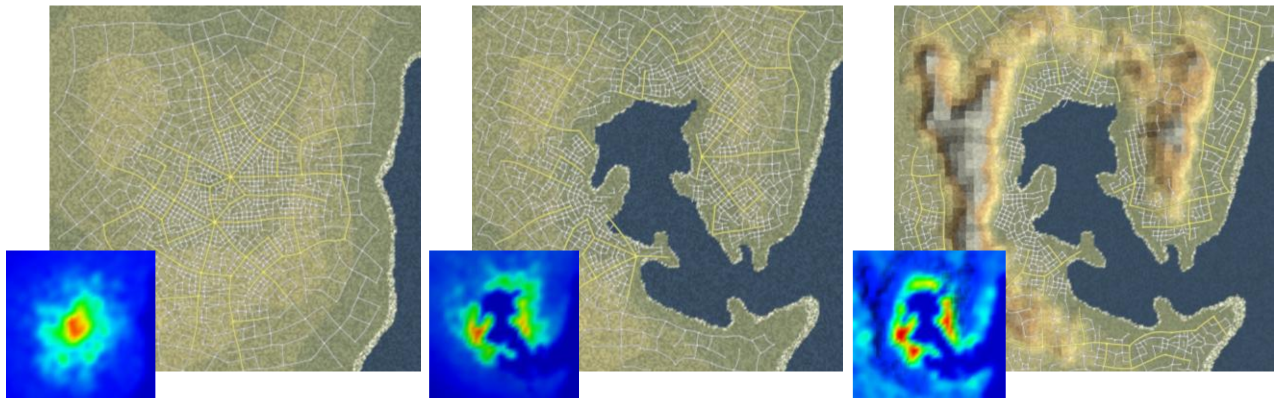
Results: Stability



Terrain and Roads

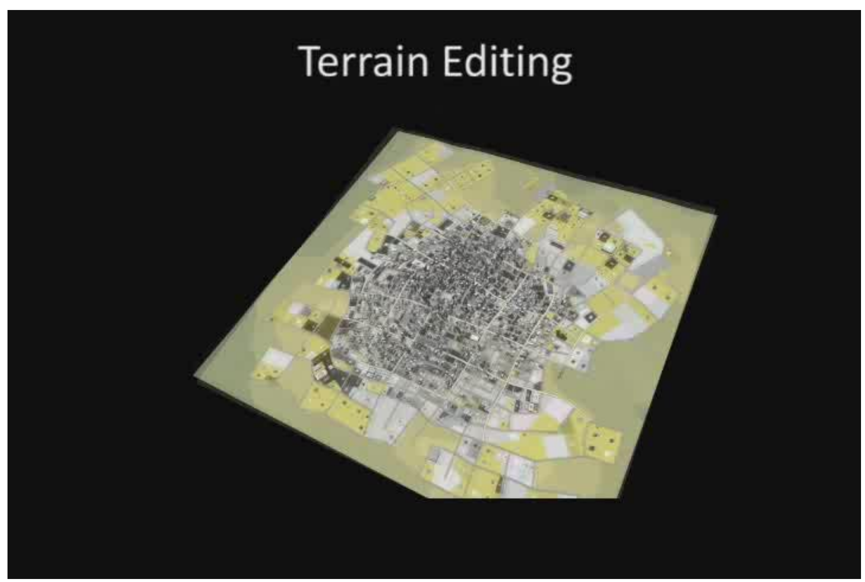
Results: Terrain Editing

Example 1

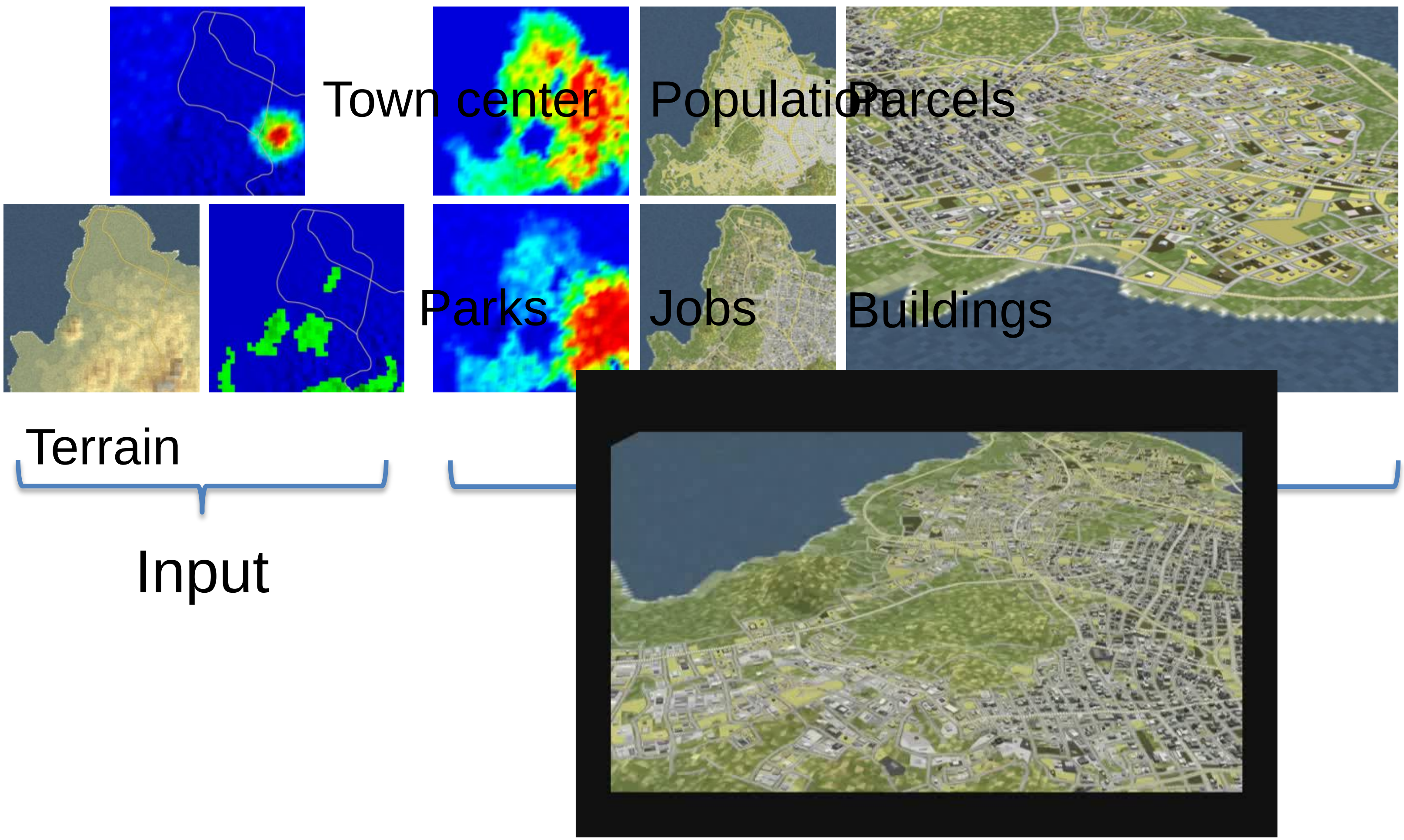


Initial Lake Mountains

Example 2



Results: Completion and Validation (1)



Results: Completion and Validation (2)

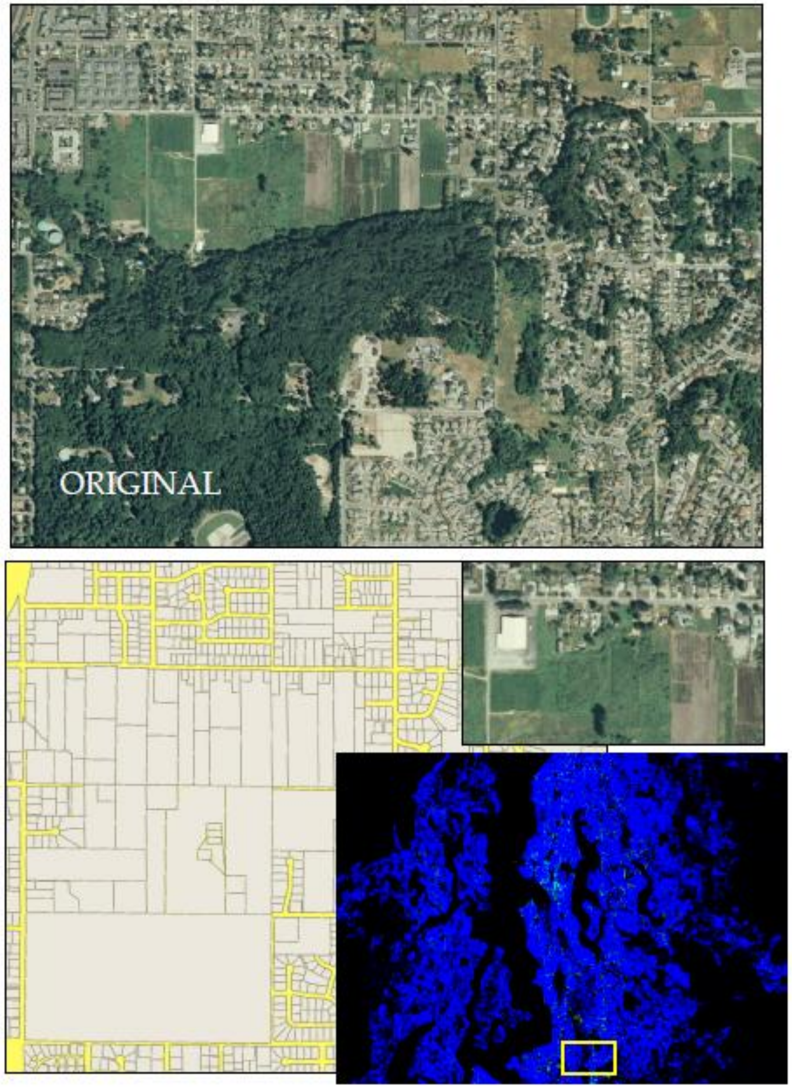
Applications

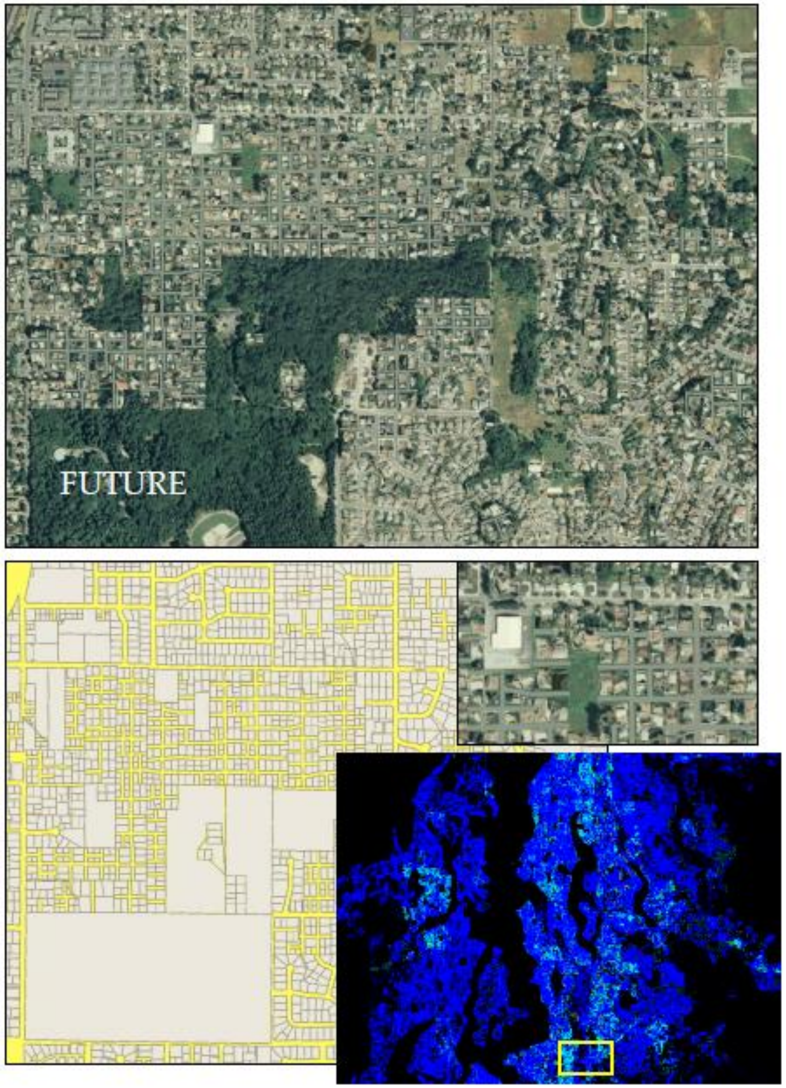
- Urban Visualization
- Weather Simulation

Urban Visualization

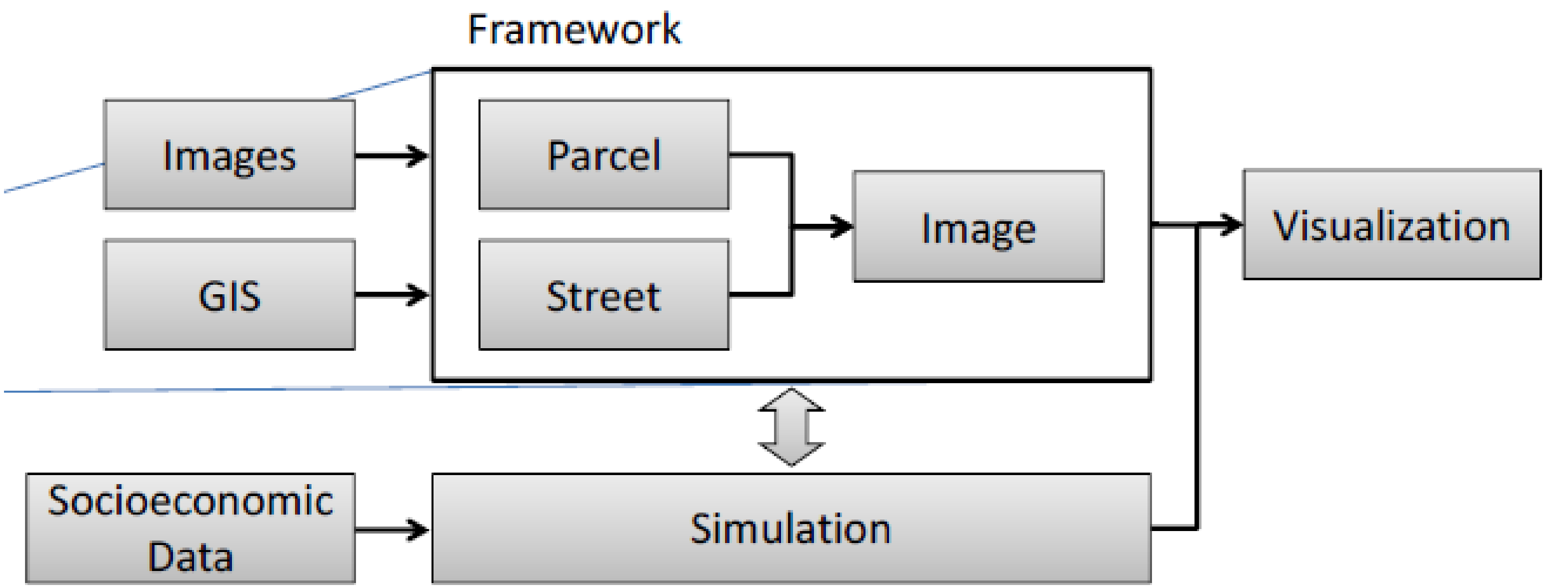
- Urban Visualization

Urban Visualization





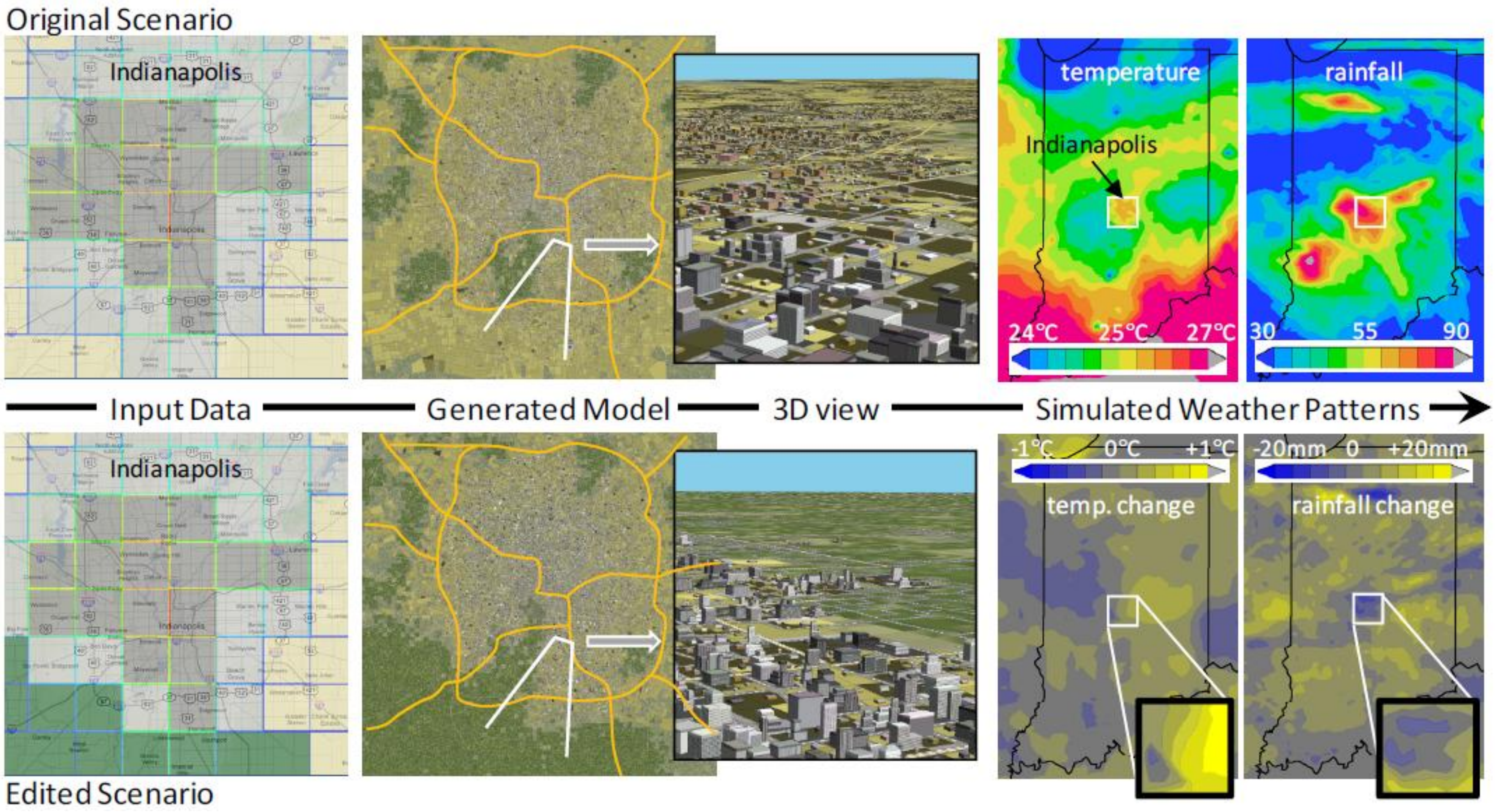
Urban Visualization



Urban Visualization

Weather Simulation

- Weather Simulation



Conclusions

- We have presented an interactive system to design and edit 3D urban models
- Our key inspiration is to close the loop between behavioral modeling and geometrical modeling producing a single dynamical system that assists a designer in creating urban models

Conclusions

- Limitations
  - Stochastic component that does not allow behaviors and geometries to be exactly repeatable
  - Over-constraining the system can lead to unfeasible urban models

Future Work

- Including additional elements of behavioral modeling, such as a more sophisticated accessibility/land value model

- Adding methods to generate more complex geometric structures using socioeconomic data (e.g., additional building details such as facades)

Acknowledgements

- Purdue Research Foundation for partially funding this work
- Aaron Link for his help with exporting models
- Students from the Computer Graphics and Visualization Lab at Purdue for their feedback
- Reviewers for their valuable comments and suggestions

Related Publications

- Carlos A. Vanegas, Daniel G. Aliaga, Bedrich Benes, Paul Waddell *“Interactive Design of Urban Spaces using Geometrical and Behavioral Modeling”*, ACM Transactions on Graphics (also in Proceedings SIGGRAPH Asia), 2009.

- Carlos A. Vanegas, Daniel G. Aliaga, Bedrich Benes, Paul Waddell, "*Visualization of Simulated Urban Spaces: Inferring Parameterized Generation of Streets, Parcels, and Aerial Imagery*", IEEE Transactions on Visualization and Computer Graphics, 2009.

- Daniel G. Aliaga, Carlos A. Vanegas, Bedrich Benes, “*Interactive Example-Based Urban Layout Synthesis*”, ACM Transactions on Graphics (also in Proceedings SIGGRAPH Asia), 2008.

More Information

- Questions, ideas, suggestions:

  www.cs.purdue.edu/homes/cvanegas

  (or Google "Carlos Vanegas")

  Email: cvanegas@purdue.edu

Thank you!


area 225 km², created in less than four minutes,
real-time render