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EDIBLE INFRASTRUCTURES:
EMERGENT ORGANIZATIONAL PATTERNS FOR THE PRODUCTIVE CITY

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ABSTRACT

Edible Infrastructures is an investigation into a projective mode of urbanism that considers food as an integral part of a city's metabolic infrastructure. Working with algorithms as design tools, we explore the generative potential of such a system to create an urban ecology that provides for its residents via local, multiscalar, distributed food production, reconnects urbanites with their food sources, and decouples food costs from fossil fuels by limiting transportation at all levels, from source to table.

The research is conducted through the building up of a sequence of algorithms, beginning with the "settlement simulation," which couples consumers to productive surface area within a cellular-automata-type computational model. Topological analysis informs generative operations, as each stage builds on the output of the last. In this way we explore the hierarchical components for a new Productive City, including the structure and programming of the urban circulatory network, an emergent urban morphology based around productive urban blocks, and opportunities for new architectural typologies. The resulting prototypical Productive City questions the underlying mechanisms that shape modern urban space and demonstrates the architectural potential of mathematical modeling and simulation to address complex urban spatial and programmatic challenges.

1 INTRODUCTION

"Wisdom I take to be the knowledge of the larger interactive system—that system which, if disturbed, is likely to generate exponential curves of change. Lack of systemic wisdom is always punished." —Gregory Bateson, *Steps to an Ecology of Mind (1972)*

The year 2011 saw the world's population surpass 7 billion people. Since 2008, over half of us live in cities, and that percentage is growing, set to exceed 68.7 percent by 2050 (UNFPA 2011). As cities grow, agricultural production is driven farther from urban consumers while claiming more and more of our forests and natural habitats. Increasingly, our food is produced in distant lands relying on cheap labor and imported using relatively cheap fossil fuels. The UN estimates that by 2050 the population of the world's cities will double, requiring an additional land area the size of Brazil to feed the new urbanites.

The estrangement of urban populations from their food sources has had considerable social, environmental, and economic ramifications, which, until recent times, were overlooked as the economies of the global food system produced increasing convenience and lower prices. However, the effects of climate change, peak oil, and the global population explosion threaten an impending collapse of this spatially dissociated system.

Current schemes for urban agriculture in western cities are limited in their potential performance by being reactive and discrete, working as interventions within a post-industrial urban organizational structure. This structure prioritized private development, and presumed that urban growth was unlimited and that food would be forever imported from an infinite countryside using mechanized transportation.

If urban agriculture is to effectively make an impact in feeding our future cities, urban organization must be reconsidered from a systemic perspective, considering the city as a closed loop of production, consumption, and waste. This is not a new idea. There is a long history of agriculture benefiting from the ecology of the pre-industrial city (Steel 2009). However, the complexity of the contemporary city requires new design tools for meeting this challenge. Our research employs algorithms, mathematical modeling, and simulation to explore emergent spatial organizations for the realization of such a system.

2 SYSTEM DEVELOPMENT

Agriculture, and subsequently cities, arose from a very basic tendency of life to organize itself into ever increasing complexity, taking advantage of the increasing cost-benefits of cooperation (Weinstock 2010). Our system attempts to model this process of cooperative settlement while putting in place controls to explore the effects of changes to certain parameters.

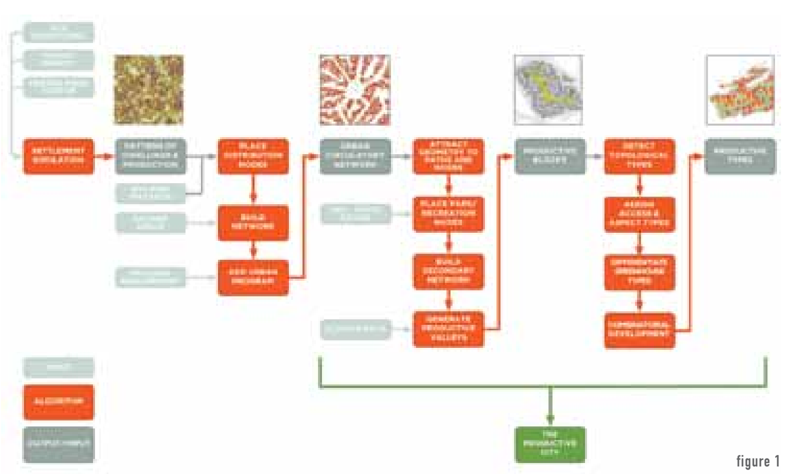

figure 1

figure 1

Hierarchical components for the Productive City are generated via a series of generative and analytic algorithms, each building on the output of the last.

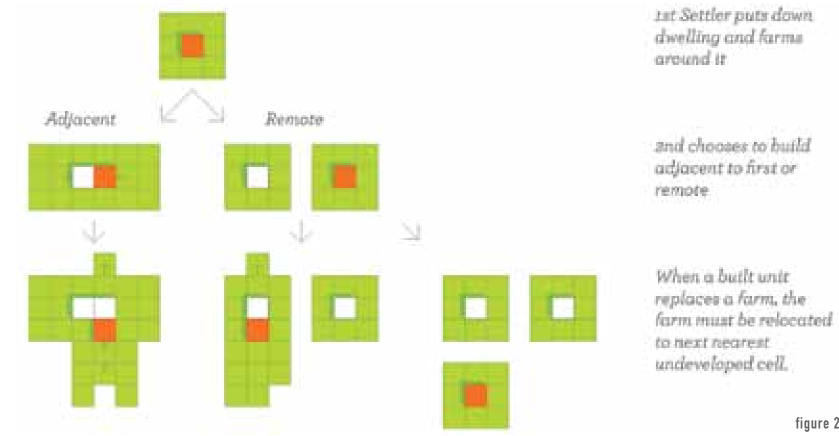

figure 2

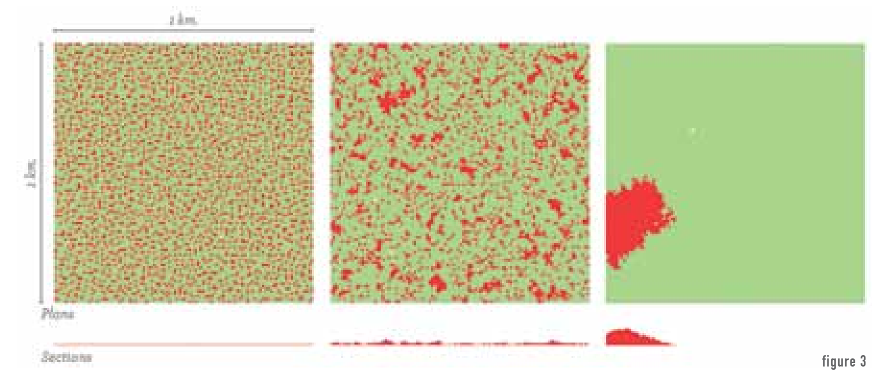

figure 3

We begin by coupling productive area to consumers and limiting the extent to which they can be separated. With these relationships in place, we can experiment with population density and production intensity levels and explore the resulting settlement patterns.

2.1 Settlement Simulation

The settlement simulation is a computational model based on multistate cellular automata. The model uses simple behavioral rules to recreate the aggregation logic of dwellings and small subsistence farms in a given field via a self-organizing "vernacular" methodology. The goal of the simulation is to investigate the sorts of distributions and collective form that might result while still meeting the fruit and vegetable requirements of the population. We work with fruits and vegetables for the time being, as historically they are hardest to transport and benefit most from urban environments (Steel 2009). Grains and livestock are more suitable to larger, peri-urban plots and require additional processing before consumption. Strategies for these will be explored in future development.

Rules:

The simulation begins with a "settler" arriving on a 1 km2 site, placing his or her dwelling, and farming the land around it. The dwelling has a footprint of 72 m2, based on a typical urban townhouse and household size of 2.59 persons (based on New York City's average) (US Census Bureau 2000). The baseline "productive" area is based on a conservative 100 m2/person (Viljoen 2005).

figure 2

Settlement simulation rules.

figure 3

F=0 (left) results in a homogenous distribution, while F=1(right) generates a single dense dwelling cluster surrounded by farms.

figure 4

Tissues generated with three Density (D) and three Friendliness (F) settings, showing the effects on local clustering and continuous farm sizes.

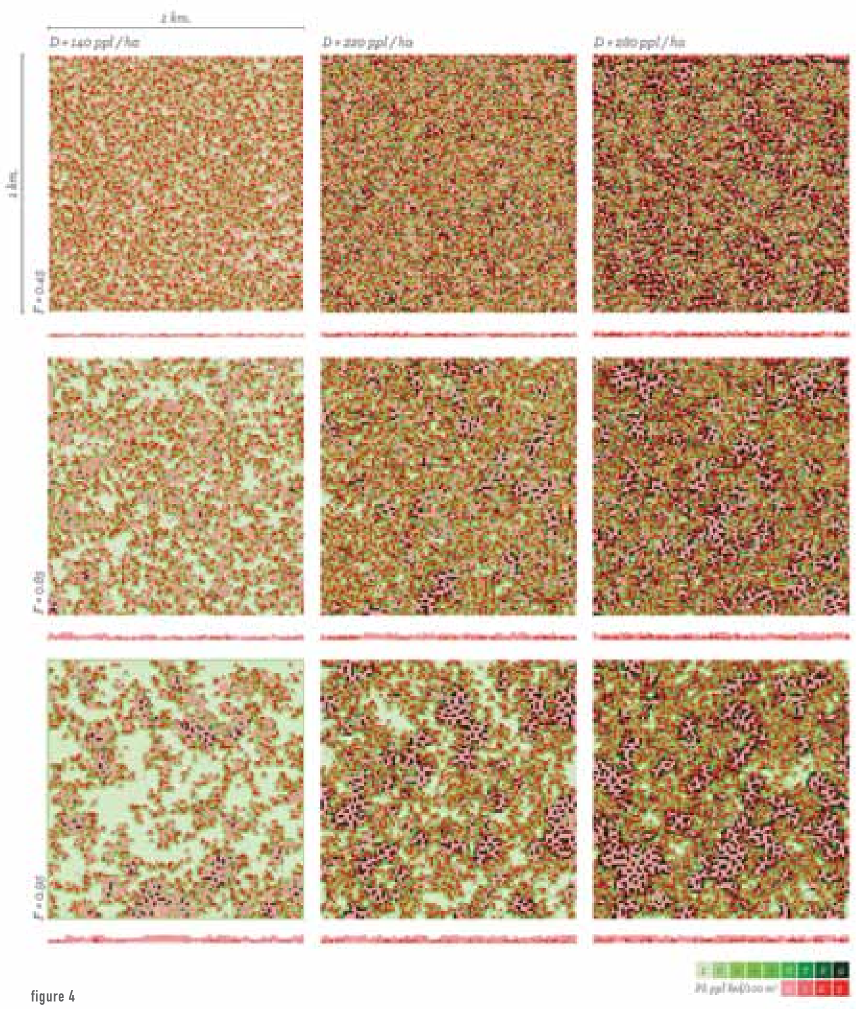

figure 4

A second settler arrives and "randomly" chooses to build either adjacent to or remote from the first settler. Should they build adjacent, they need to relocate any farmland displaced by their dwelling. If remote, they will begin a new settlement cluster (Figure 2). This process is repeated until the target population density is met for the given field.

Dwellings and farms are broken into modular units, with each dwelling equal to one cell. With every one dwelling placed, three productive units are placed.

Friendliness:

The likelihood that a new settler will build remote or adjacent is weighted by a Friendliness Factor (F), a number between 0 and 1. F=0 means that all units will try to build remote, while F=1 means that all units will try to be attached. An F of 0.6 results in a 60 percent chance that a unit will be built adjacent (Figure 3). Vertical growth is triggered when a settler "chooses" to build on an existing dwelling in a settlement cluster which has surpassed the user-specified local density threshold.

Density and Production Intensity:

In order to achieve higher population densities, Production Intensity of a given plot must be increased. Higher productivity/unit area can be achieved in a number of ways, from innovative coplanting techniques (low energy/investment) to multistory artificially lit/heated aqua/aeroponic greenhouses

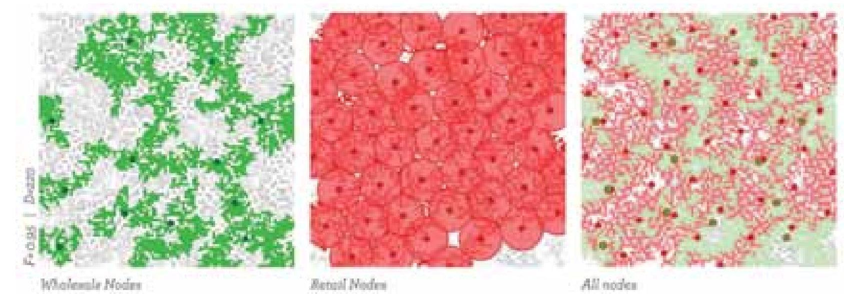

figure 5

figure 5

Wholesale (W) and retail (R) nodes are located based on distributions of dwellings and farms.

figure 6

A larger detour (branching) angle results in longer individual trips but a shorter overall network.

(high energy/investment) and a variety of methods in between. The system conserves energy by keeping production intensity minimal, stepping it up only as needed.

When the field is full, the algorithm allows agents to increase the production intensity of existing productive cells (Figure 4). Therefore, a settler's productive needs must be met in one of two ways: an increase of yields from an existing plot; or production incorporated by a neighboring dwelling, introducing "hybrid" types. Production Intensity (PI) is allowed to increase in steps of one, corresponding to the number of people whose annual fruit and vegetable needs are met per 100 m2. Therefore a cell having PI =3 means three people are provided for on that 100 m2 plot.

2.2 Network

With producer and consumer cells distributed, the resulting pattern is analyzed to inform a network topology that will facilitate the movement of food with minimal energy expenditure.

Two distribution node types are generated: wholesale nodes (on-site farm shops) and retail nodes (small grocers located throughout the dwelling clusters).

Nodes are dispersed so as to minimize travel distances and encourage walking and biking. Wholesale nodes are located on large continuous productive areas (minimum 1–2 hectares). Retail nodes are distributed throughout dwelling clusters such that any dwelling should be within a one-minute walk, or 83 m at 5 km/hour (Figure 5).

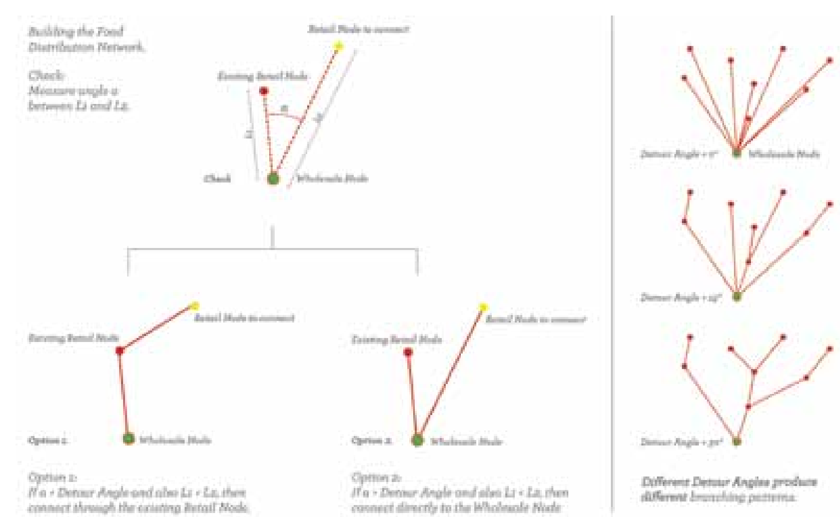

figure 6

figure 7

Individual distribution trees are joined to nearest neighbors to facilitate social movement.

figure 7

In order to connect the retailers back to their sources, a branching network is generated with the wholesale node at the root and retail nodes at the branching junctions. The angle between the branches controls the amount of detour in the network, and allows the designer to weigh energy expenditure resulting from inversely related metrics of average path (trip) length (consumer trips) versus total network length (infrastructure expenses and maintenance) (Figure 6).

The resulting network structures are "trees," emphasizing "producer to consumer" routes. However, a healthy city must facilitate the social movement of people as well; therefore an Overlap Range (Ov) is implemented, which connects terminal nodes of trees to adjacent trees within the specified range, introducing continuity and circuitry (the possibility for loops) into the urban circulatory network (Figure 7).

3 SPATIAL DEVELOPMENT

While in the development of the system the primary concern was the distribution and networking of producer and consumer cells, the subsequent steps explore the spatial potential of the generated data sets at different scales, using a 1km2 sample with parameters D=220, F=0.95, d=30°, Ov=0.7.

3.1 The Productive Network

The previously generated network edges will become the primary urban circulation paths and will need to support the full complement of public urban programs including social mixing (retail, entertainment, institutions, and workspaces), transportation, and recreation/gathering (urban squares and green spaces).

Topological analysis informs the program types and area assigned to each network component. Highly connected nodes and paths serve larger volumes of traffic and are stronger attractors for social mixing programs such as retail, food, drink, and entertainment uses.

Wholesale and Retail Nodes:
Wholesale and retail are categorized according to the number of connections from W/R1 to W/R6 and classified as "minor hubs" (W4), "major hubs" (W5+), "local nuclei" (R4), and so on (Figure 8).

Program space is allocated accordingly. Highest connected nodes are designated a total open space of 10,000 m2, comparable to Leicester Square, London (8000 m2). This area is further broken down into circulation, production, outdoor eating/drinking, and unprogrammed open space. These programs are then scaled for each node type/rank. (Semi)private space for social mixing programs is allocated in the surrounding storefronts below dwellings, ensuring mixed use, and density is maintained (Figure 9).

Network Paths:
Paths are analyzed and ranked by their integration value, which measures the likelihood of a path to

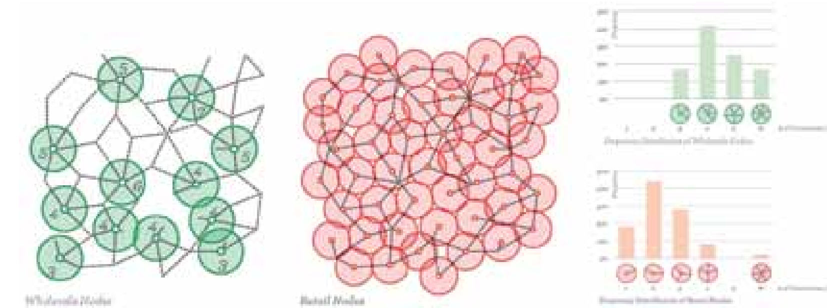

figure 8

figure 8

Nodes are identified and ranked according to the number of connections.

figure 9

Public program types and areas are allocated according to node connectivity.

figure 10

Paths are analyzed for connectivity and integration, and ranked from 0 percent to 100 percent.

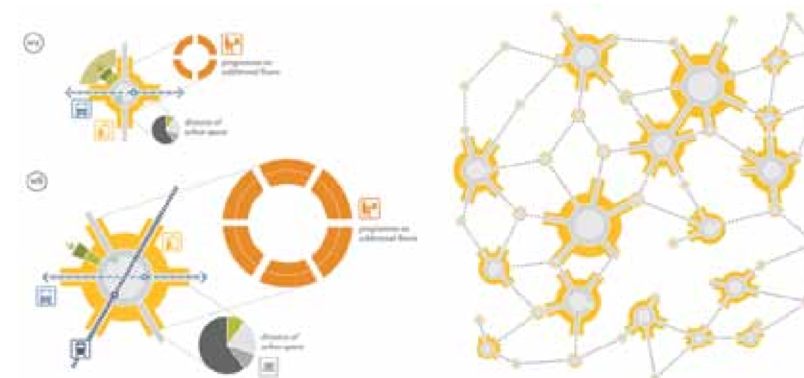

figure 9

be a destination for trips within the network (Figure 10). Highly integrated paths are most likely to be intensely trafficked, therefore they become market streets with retail frontages and farmers' markets. Low integrated paths will be quieter, tending toward residential uses and small corner grocers.

Each path is allocated space, in section, for four types of program zones:

- Public/private transition
- Pedestrian paths
- Infrastructure (both traditional and edible)
- Transport/transit

These will later be populated from a library of sectional program components. The range of widths and relative location of the zones is determined by the path integration ranking: low, medium, and high (Figures 11 and 12).

With program space assigned to paths across the tissue, a distinct hierarchy of streets becomes evident. The highly integrated paths suggest a market street or neighborhood retail core. Lower integrated streets generate less intense and narrower streets, suggesting lower intensity, primarily residential streets.

With public space and programming of the circulatory network allocated, the built morphology must respond accordingly. Dwelling cells are cleared from nodes and paths and then attracted back in a series of recursive "packing" steps, creating contiguous streetscapes and defined urban void spaces (Figure 13).

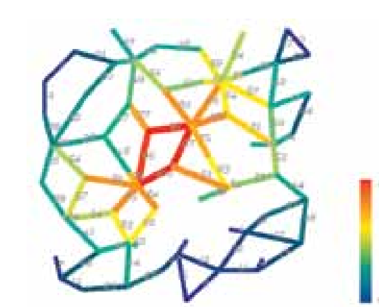

figure 10

3.2 The Productive Block

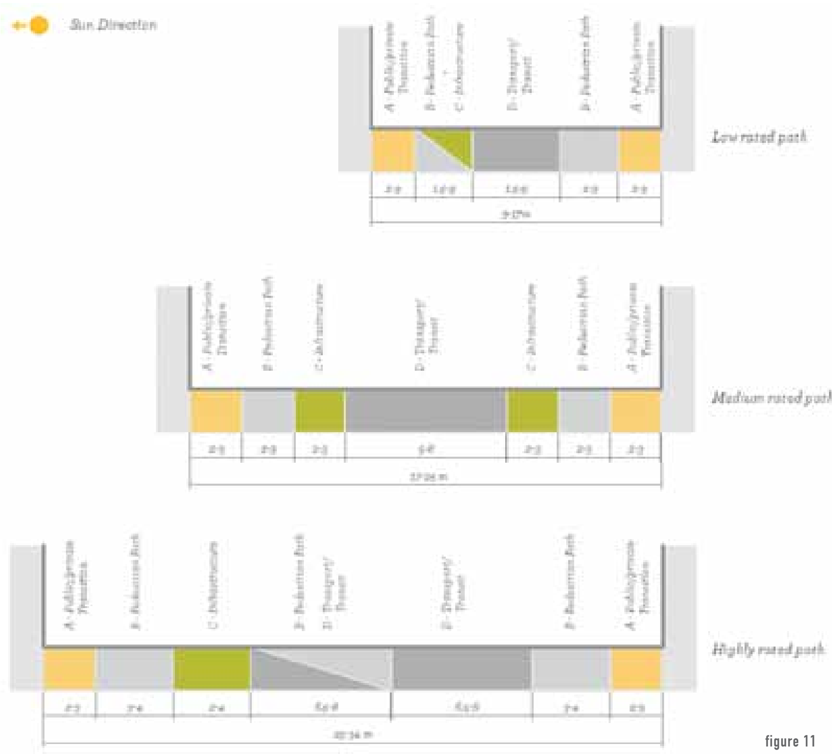

figure 11

figure 12

figure 11

Typical program zones assigned by integration rating.

figure 12

Path components applied on a highly integrated path (typical).

From the summation of these previous steps, the basic form of organization of our urban tissue emerges: the Productive Block. The section reveals three layers of spatial experience: Productive Commons on the interior, Urban Corridors around the edges, and a permeable zone of dwellings, greenhouses, and public mixing spaces, delimiting the two (Figure 14).

Block Analysis:

Comparing our block to a Manhattan block reveals some essential differences between the urban fabric generated by our food-driven system and that of the modern land ownership model. A typical New York block is 270 m x 80 m. The long thin rectangle maximizes perimeter length (storefront exposure) at the sacrifice of interior area. Our generated block in comparison is similar in area to two to three New York blocks, but with much less surface area devoted to circulation. Instead of maximizing street frontage, our system generates largely convex polygonal blocks, concentrating productive open space within (Figure 15).

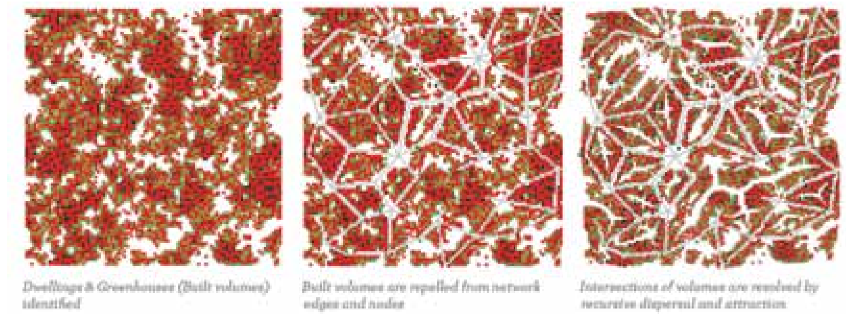

figure 13

figure 15

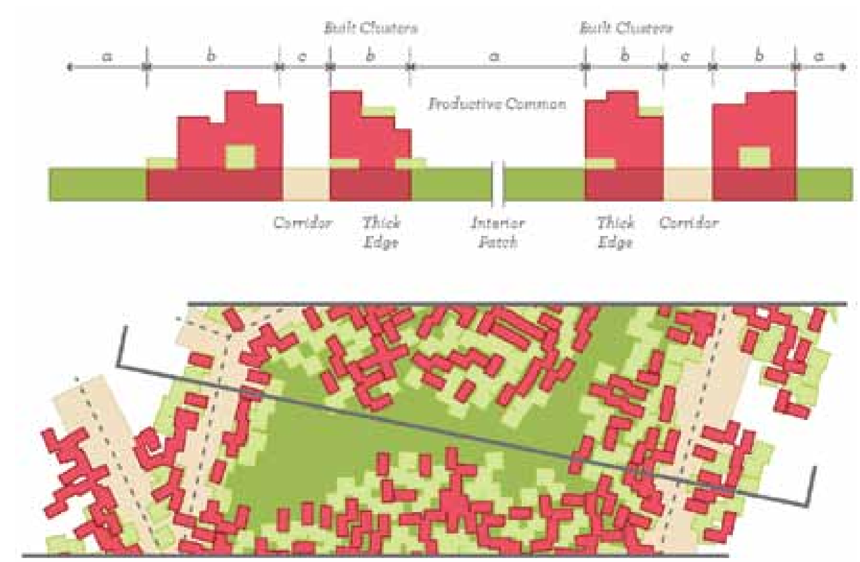

figure 14

Recreational Network:

In order to link the commons back to the city's network of public spaces, parks/recreational nodes are allocated within the productive commons based on block size and number of residents. These are then linked together with new paths through the built clusters and primary paths, resulting in a quieter secondary circulatory network, as well as shared green space for residents of each block (Figure 16).

Having identified clear concentrations of production, these areas can then be prioritized for solar exposure by introducing a postprocessing algorithm that limits building heights relative to proximity to productive area. The effect is a terracing of rooftop spaces around the commons, with the tallest volumes lining the edges/streetscapes (Figure 17).

Solar analysis before and after shows the change in solar exposure resulting from our redistribution algorithm. Analysis was run for two dates, April 1 and June 21, using London as the location (Figure 18).

Results are mapped to the three solar categories of crops (Mollison 1991):

- Zone 1: Full sun (8+ hours)—tomatoes, peppers, most vegetables

figure 13

Network paths are first cleared according to program area, then become attractors for built units.

figure 14

The Productive Block, showing three distinct spatial zones.

figure 15

A developer-driven block (New York City) versus the Productive Block.

figure 16

Recreational nodes connect Productive Commons into a secondary network.

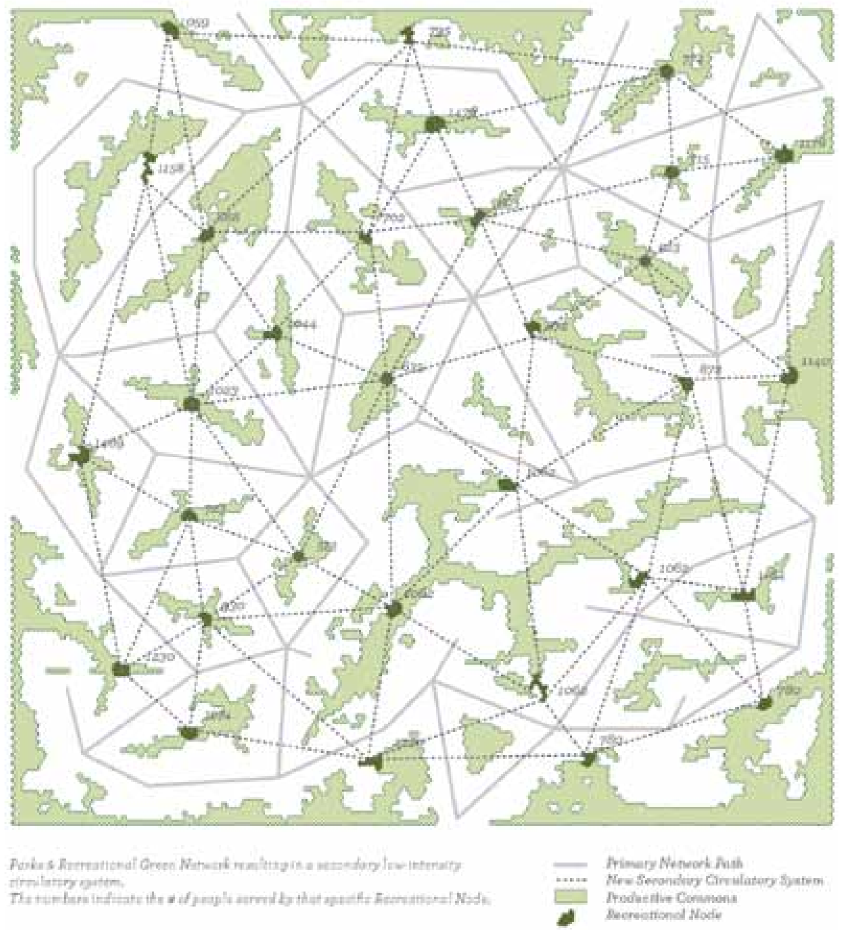

figure 16

- Zone 2: Partial sun (6–8 hours)—root vegetables
- Zone 3: Partial shade (3–6 hours)—leafy greens

Results show a dramatic 157 percent increase of full sun in April and an 87 percent increase in June.

3.3 Productive Typologies

Our built clusters display unique internal and external characteristics. Internally, within the clusters, are dwellings, greenhouses, and mixed spaces in a gradient of public/privateness. Externally, the clusters are situated uniquely between two distinct networks, urban and agricultural. The unique configuration suggests new architectural typologies.

Cluster Analysis:

Topological analysis, at the cellular level, informs components and rules for a new type of collective form. Adjacent dwellings and greenhouses are detected and sorted in clusters. Inside the clusters, connections are made between the units, saved into lists, and further organized by their topological types (Figure 19).

Base Components:

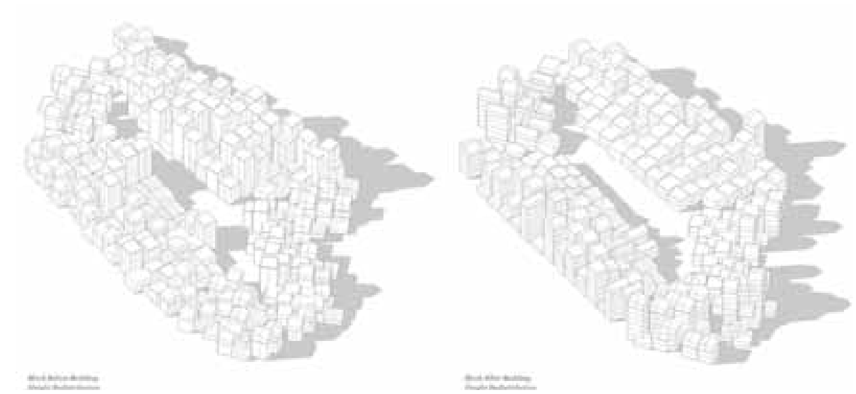

figure 17

figure 18

figure 17

The building height algorithm further differentiates the spatial character of the interior and exterior of the productive block.

figure 18

Solar exposure before and after height redistribution.

figure 19

Topology of dwellings and greenhouse clusters.

Topological types inform the differentiation of dwellings into base components, related to familiar dwelling types found in urban environments. Linear chains suggest individual direct access and dual aspect, resembling a row-house type. Double chains provide access through internal corridors with single-aspect units, such as those found in apartment/block buildings. Loops suggest a courtyard type, which can be further differentiated as single or dual aspect arranged in a courtyard configuration (Figure 20).

The relationship of these base components to productive units further differentiates them. Productive units can be public, communal (semiprivate), or private based on scale, topology, and adjacency to networks.

In section, topology suggests differing types of vertical circulation, new communal spaces, and tall public/semipublic atriumlike greenhouse volumes (Figure 21).

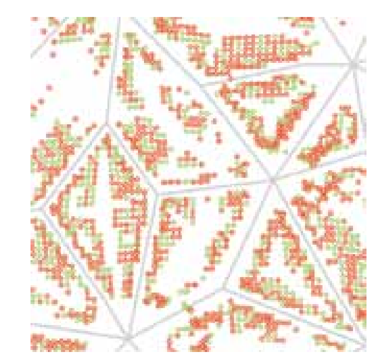

figure 19

4 PROJECTS

Over the course of development of the system, two test cases were explored to evaluate the performance of the model on real sites and inform further development of the tool. The first tested how we might deploy at a neighborhood scale into an existing urban fabric, while the second was a proposal for a new city, a satellite to an existing urban region. In both cases data retrieved from the

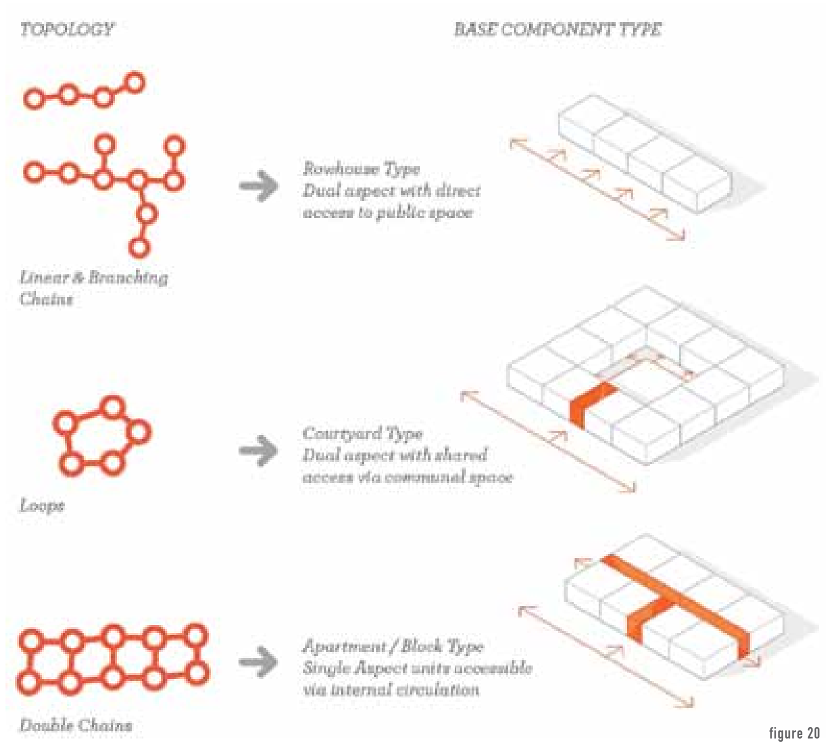

figure 20

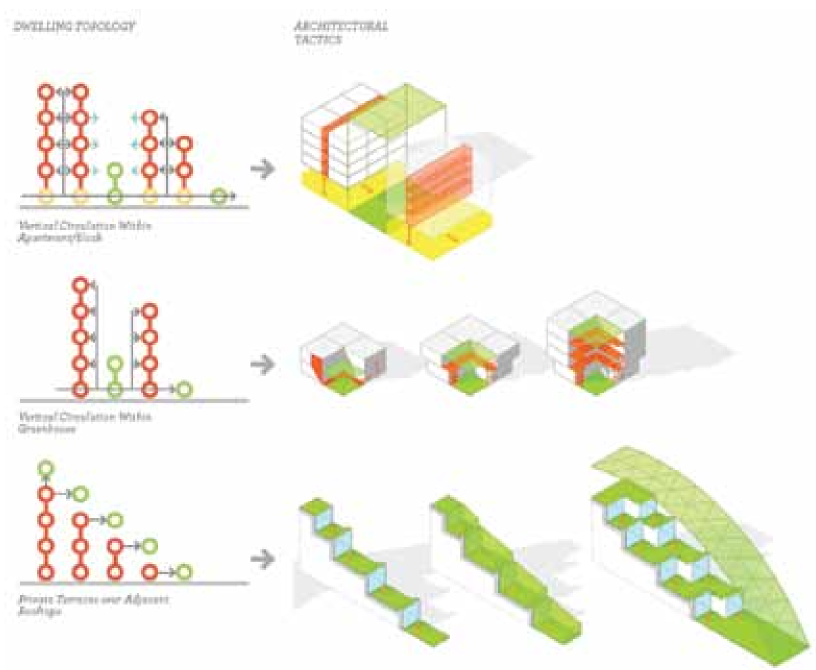

figure 21

figure 20

Dwelling cluster topology is translated into familiar base component types.

figure 21

Vertical topology informs sectional opportunities.

sites informed new inputs and confirmed previous experiments on virtual tissues.

4.1 Brooklyn Navy Yard, Brooklyn, NY

The project proposes a new productive neighborhood on a 34 hectare (83 acre) site in Brooklyn, NY, which sits between three desirable neighborhoods and at a critical junction in networks, easily accessible from Manhattan, Brooklyn, and the rest of New York City. Adjacency to the converted Navy Yard provides easy access to workspace for small businesses and new food-related jobs. The York Street subway stop (linking directly to downtown Manhattan) is located at the western end of the site, within a five-minute walk from the center of the new neighborhood.

Initialization of the model for a real site required new inputs, including boundary conditions and connections to existing networks. Surrounding commercial areas were input as attractors, and network flows into and through the site informed how the internal network connects back out to the city at large.

The simulation was run with D=200 ppl/ha (derived from neighborhoods in the area), but with several (F) Friendliness settings (Figure 22). Tissues were evaluated, checking for heterogeneity of density distribution, OSRs comparable to reference tissues, and the ability of the pattern to produce viable large-scale (>1 ha) commercial farms while maintaining a continuous urban fabric. D=200 / F=0.90 was selected and fed into the network builder.

Clusters were detected, continuous productive plots >1 ha were identified, and wholesale nodes placed. Retail nodes were located throughout the dwelling clusters, based on (W) maximum walking distance (Figure 23). From wholesale nodes, distribution networks were built, testing several detour angles as inputs; 40 degrees was selected for its balance of low trip time and low overall network cost. Individual distribution trees were connected with an overlap of 30 percent, and external network links were connected to their nearest retail nodes, creating a continuous urban fabric (Figure 23). With the network in place, built morphology was allowed to respond to the network paths forming the urban corridors and productive commons.

figure 22

figure 23

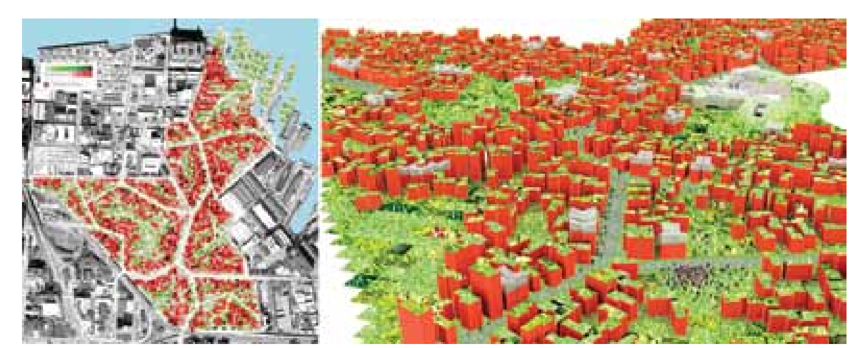

figure 24

figure 22

Tissues generated with D=200 ppl/ha and F=0.3, F=0.8, F=0.97.

figure 23

Wholesale and retail nodes are placed. Food distribution and social movement networks are generated.

Figure 24

Generated neighborhood plan (left). Overview of neighborhood (right) showing cultural center, retail corridor, and wholesale farm shop.

figure 25

The resulting neighborhood would be home to 6,164 people, with 2,380 dwellings and 18.57 hectares of productive area. A new market street and retail corridor connects north-south between adjoining neighborhoods DUMBO and Fort Greene (Figure 26). A Center for Urban Farming is proposed to anchor the neighborhood, acting as an attractor for visitors from the rest of the city and providing agricultural education and training to urbanites (Figure 24). Inhabitants would have a choice of either growing their own food or purchasing food grown commercially within the neighborhood boundaries.

4.2 Kungsängen, Sweden (Stockholm Region)

Stockholm is enacting policies to both mitigate and prepare for the effects of climate change, including a goal to be fossil fuel free by 2050 and the adaptation of building codes for a warmer, wetter climate. Within 20–30 years, Stockholm is expecting 150,000 new residents, and within 50 years, a 4–6 degrees Celsius increase in average temperature (comparable to Barcelona today) and a growing season extended by 1–2 months.

We proposed to build a new city for 150,000 people on an agricultural peninsula near Kungsängen, 30 minutes from Stockholm by commuter rail. The new community would serve as a prototype, mixing urban commuters from Stockholm and climate refugees with agrarian skills, creating a working model for a new Productive City.

Simulation:
Initialization of the Kungsängen site involved identifying landscape components as developable, protected, and/or attractors. The proposed site is 9 km2, bounded on the north by a commuter train line/station and the existing town (attractors). The eastern boundary is waterfront (attractor), while south and west are primarily wooded waterfront (protected).

The settlement simulation was built for a 1 km2 field, so for this site a scaling strategy was developed, in which the site is built up in sequential 1 km2 tiles, taking initialization data from the boundary of each previous tile (Figure 25). Tiles were assigned different Density (D) and Friendliness (F) values, providing residents a choice in varying spatial characters citywide.

Network:
As the Kungsängen site will serve as a satellite city to Stockholm, the commuter link is of prime importance in the network strategy. Therefore, once wholesale and retail nodes were located, a transit spine was placed, linking our site to the commuter train station with nodes every 400 m (5 minute walks). Transit nodes checked for nearby wholesale nodes, and if within range, they were merged (Figure 26). Additionally, a waterfront path was input with nodes for public space. All nodes were subsequently linked, nodes and paths analyzed and ranked (Figure 26), and public program area assigned.

Blocks across the different tiles exhibit much more variation in size than in our 1 km2 tissue, resulting from the different combinations of Density and Friendliness. Larger blocks are also lower in population density, providing a different urban character than those within our denser, more central tiles (Figure 27).

The natural features of the site were integrated into the recreational network by allowing recreational nodes within the blocks to connect to protected forests and public waterfront.

Typologies Informed by Climate:
In a colder climate with a shorter growing season, it is expected that there will be a heavier reliance on greenhouses. We proposed, for Kungsängen, a Greenhouse Block type, enclosing the commons and dwellings around the block perimeter (Figure 30).

figure 25

Kungsängen growth is simulated in tiles, as a lower resolution cellular automata.

5 CONCLUSION

We have shown how, by putting in place a framework of simple rules relating key parameters, we can generate urban tissues that exhibit gradients of concentration of various properties, meeting

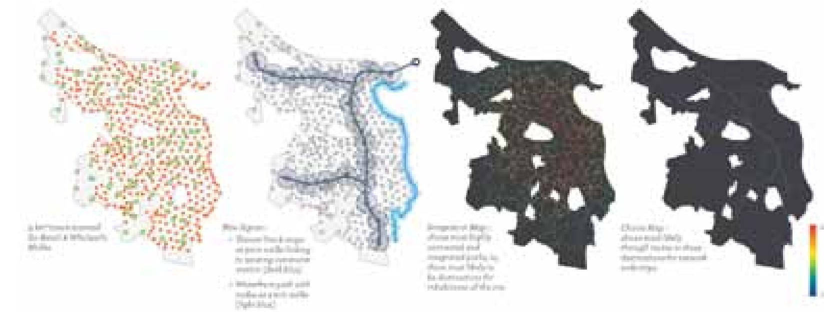

figure 26

figure 27

figure 26

Wholesale and retail nodes were placed; distribution network was generated; paths are analyzed for integration and in-between-ness, and ranked from 0 percent to 100 percent.

figure 27

A network of productive public spaces (left). Greenhouse Block type (right).

urban and productive metrics. We have also seen how analysis of these patterns can inform spatial translation, including urban programming, organization, and typologies.

In evaluating the generated tissues, we once again compare to physical-world metrics to make fitness evaluations. Certain criteria are fairly rigid. Existing agricultural techniques, for example, have limits to productivity per area while remaining economically viable. We can set this relationship as a constant for the time being and adjust it in the future as economic conditions and technologies evolve.

Others are in the realm of value judgments and have sociopolitical consequences. For example, as the "fineness" of the grain of our urban tissue increases in response to raising the (D) Density and lowering the (F) Friendliness settings, the maximum size of productive plots decreases and the continuous space desired by commercial growers is squeezed out. This allows us to find the threshold at which a community can expect to rely on commercial growers within a certain type of urban morphology. Beyond this point, the community must be prepared to increasingly "grow their own" or become part of a collective that contributes back into the local food system.

These possibilities are allowed for within the framework of the system, and it is through analysis of the particular social and political context that the designer would determine the fitness of each scheme. What remains constant is the ecological footprint of the community, which remains within the limits established in the system.

This type of procedural approach opens up questions as to the role of the designer and degree of control. As we built up the computational model, we consciously made an effort to avoid deterministic tendencies, trying instead to set up the boundaries of a system within which solutions could emerge.

We are interested in the changes this has introduced into our mode of operation. There is a temptation to believe that by setting up the most precise set of inputs and rules extracted from the design problem, the algorithm would offer an obvious "solution"; however, it has been our experience that even in this framework, there are decisions that remain firmly in the realm of the designer.

We see potential application of our work as an interactive planning tool. Ultimately, the deliverable would be not a 2D drawing or 3D model, but an interactive solver, which guides development while maintaining strategic relations and is adaptable to changing urban conditions. The tool is not complete, of course, but we believe it will be enriched by experimental deployment in a variety of contexts and territories.

Much work remains in the tailoring of a diverse catalog of inputs for adaptation to new environments and in the growth/phasing strategy. How do you seed a new city? And how do you change the "plan" according to the actual growth that materializes and the unexpected changes that arise? Some of these changes may be due to changing climate, population and cultural changes, changes in the flows of people and materials between neighboring cities, and new technologies in agriculture and energy production.

A primary obstacle to implementation of such a system is the current political-economic value system, which prioritizes land speculation and private development and downplays the actual cost of natural resources. This kind of myopic thinking has long driven the separation of our cities and farmlands, and has only been accelerated by industrial technologies.

It will take visionary municipalities to question the value of their land as it is currently framed, repositioning it as a vital energy source worth harnessing and managing. We have demonstrated one prototype for how this aim might be achieved. We hope we have shown that it is not only feasible, but a novel and provocative future for cities and city dwellers.

ACKNOWLEDGMENTS

Edible Infrastructures was developed as a master's thesis at the Architectural Association in the Emergent Technologies and Design Program. We are sincerely grateful to Mike Weinstock, George Jeronimidis, Wolf Mangelsdorf, Toni Kotnik, Suryansh Chandra, and countless others.

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A WEB-BASED GEOGRAPHIC VIRTUAL ENVIRONMENT FOR THE DELIBERATION OF URBAN PROJECTS FOR BRUSSELS

ABSTRACT

In this paper, we discuss the potentials of affordable GeoWeb 2.0 applications to support the deliberation of urban projects. We first introduce the conceptual design of a web-based geographic virtual environment specifically developed for the Brussels–Capital Region in the framework of a long-term postdoctoral research project. Then, we present two alternative open-source prototypes for the implementation of this conceptual design and compare their usability with experts. Furthermore, we share our experiences from two field applications in the form of a brief case study and discuss the potentials of the proposed prototypes with a focus on their usability and supported forms of design empowerment.

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