Eco-Evolutionary Pathways Toward Industrial Cities

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Summary

Industrial location theory has not emphasized environmental concerns, and research on industrial symbiosis has not emphasized workforce housing concerns. This article brings jobs, housing, and environmental considerations together in an agent-based model of industrial and household location. It shows that four classic outcomes emerge from the interplay of a relatively small number of explanatory factors: the isolated enterprise with commuters; the company town; the economic agglomeration; and the balanced city.

Introduction

On 17 April 2013, a fertilizer production facility exploded, killing 15 people, injuring more than 160, and damaging or destroying more than 150 buildings in the adjacent town of West, Texas (Fernandez and Schwartz 2013). This poses the question as to why people chose to live so close to a dangerous site.

The location of housing near industrial workplaces is historically common. Illustratively, the local economy of Warren, Rhode Island, a New England town incorporated in 1668, was first dominated by whaling, then ship building, then textile mills, each of which required larger sites that attracted the residences of employees who needed to walk to work during the preautomobile era. Warren's largest factory site was developed in 1847. Yet, this timeline did not play out in West, Texas, which incorporated in 1892 after the railroad brought prosperity and settlers, and which only attracted the fertilizer plant in 1962.

This article investigates selected aspects of how the environmental characteristics of firms affect the evolutionary pathways of their host settlements. It explores how the sites of industrial enterprises might grow into urban agglomerations, which refer to intensively developed settlements that contain residential, commercial, and industrial facilities that enjoy economic benefits from their proximity to one another. Using agent-based modeling techniques, this article asks:

- What are the evolutionary pathways that settlements founded around industrial enterprises might follow?
- Which factors explain commonly observed settlement patterns?
- Do environmental factors play a role?

From Enterprises to Settlements

This investigation of how industrial enterprises sometimes evolve into industrial cities draws on three analytical traditions, including urban modeling, industrial symbiosis (IS), and jobs-to-housing comparisons.

Environmental Simplification in Urban Modeling

The classical traditions in location theory all employ a microeconomic logic. The land-use tradition originates with von Thünen (1966/1826) who argues that land uses in a preindustrial landscape follow a monocentric model that optimally locates dispersed agricultural production based on transport costs to a central market. Alonso (1964) updates this approach for the industrial city by determining the optimal distances of residential and commercial land uses from a central business district. Sasaki and Box (2003) replicate von Thünen's results in an agent-based model. The central-place tradition originating

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with Christaller (1933) and Lösch (1943) instead assumes centralized suppliers serving a dispersed market, so that trade areas of central places that provide a particular good or service must all be of similar size, leading a regular spacing of cities within a hierarchy. The industrial location tradition optimizes the location of enterprises based on cost minimization (Weber 1929), profit maximization (Smith 1971), optimal scale (Moses 1958), and additional factors (Isard 1956), which allows very localized consideration of both supply- and demand-related factors.

Hotelling (1929) adds a strategic, game-theoretical dimension to industrial location theory by focusing on spatial competition. Lowry (1964) refines the basis for spatial interaction using a gravity model, which posits that travel behavior and settlement patterns emerge from the combined attractive forces pulling populations together and the distance frictions that keep them apart. Wilson (1970) achieves a similar result with an entropy-maximizing model. Up until the end of the 1960s, urban modelers worked to generalize static urban structures and had difficulty forecasting (Batty 1970).

It was not until the system dynamicist, Forrester (1969), simulated temporal changes in a hypothetical city that modelers began to focus on urban dynamics. Although skeptics abounded (Lee 1973), a number of new theories and models have been developed since then to describe urban systems. Urban complexity has been examined through the lenses of catastrophe theory (Wilson 1976; Wilson 1981), fractals (Batty and Longley 1989; White and Engelen 1993), discrete choice (Landis 1995; Waddell 2002); self-organization (Portugali 2000), cellular automata (Clarke et al. 1997), and agent-based modeling (Otter et al. 2001), all of which support a view that cities emerge from the interactions of individuals with one another and their external environment, and follow idiosyncratic evolutionary paths.

In examining existing models of urban evolution, it is evident that land-use patterns have become a key focus of urban modelers. This is because land-use change is a key feature of urban evolution and is closely related to human activities, although natural forces might affect land-use change in the long term or in the case of natural disasters. From the perspective of modelers, current land-use classification systems in urban models often assume that industrial firms are homogeneous in their environmental performance.

However, as cities develop, pollution-intensive industries may follow different evolutionary pathways than green and clean firms because "dirty" industries might generate more environmental risks for nearby residents. The recent Texas fertilizer plant explosion illustrates this possibility and shows the value of isolating high-risk or pollution-intensive industries from residential areas. To protect public health, local planning authorities worldwide have adopted zoning ordinances to separate incompatible land uses. Yet, urban planners also advocate mixed-use development in which residential, commercial, and industrial land are blended in an effort to overcome the environmental and social ills of urban sprawl. In this regard, pollution-intensive industries should be considered in modeling urban dynamics and this article aims at the gap.

Sectoral Gaps in Industrial Symbiosis

In eco-industrial development (EID) research, Kalundborg still retains a place of honor, but a plethora of additional symbiosis cases have been "uncovered" (Chertow 2007). Understanding their development has highlighted the relative importance of market actors over planners as coordinating forces (Desrochers 2004; Baas 2011; Chertow and Ehrenfeld 2012), the presence of agglomeration economies in the forms of shared labor pools, nontraded inputs, and information spillovers (Marshall 1890), plus cost savings in environmental management and enhanced regional economic development (Chertow et al. 2008), and the path dependence of their evolutionary pathways (Chertow 2000; Baas and Boons 2004; Costa and Ferrao 2010; Paquin and Howard-Grenville 2012). Agent-based modeling has found use to support policy analysis and experimentation in EID (Axtell et al. 2001; Batten 2009).

Current research on EID sets priorities for industrial systems, but manifestly ignores external linkages of industrial systems. Even in the case of Kalundborg, industrial activities benefit local homeowners by providing cheap, reliable heat and power while residents act as the main human resource of production (Ehrenfeld and Gertler 1997). Similarly, environmental and economic sharing happens among firms and with adjacent residential areas in the case of Suzhou Industrial Park (Mathews and Tan 2011) and Kawasaki City (van Berkel et al. 2009). Instead of keeping external linkages of industrial systems black-boxed, industrial ecologists can scale up boundaries of systems and rethink EID from a larger perspective, which is another objective of this article.

Thus, urban modelers usually assume—very unrealistically—that industrial enterprises are homogeneous in their environmental performance. EID researchers usually focus on the internal dynamics of their symbioses and ignore key external linkages, especially the relation to housing. This article begins to fill that gap.

Jobs and Housing

Urban planners use a balanced growth metric that targets a roughly equal number of jobs and housing units within new settlements. Ewing (1996) recommends a jobs-to-housing ratio of 1.3:1.7, and Cervero (1996) recommends a nearly equivalent jobs-to-employed residents ratio of 0.8:1.2 in order to minimize commuting travel times. The mean ratio of total employment to occupied housing units for U.S. counties is currently 1.3 (standard error, 0.008; range, 0.3 to 8.0) and it is slowly dropping, according to U.S. Census data. For smaller geographic units, such as towns and cities, the jobs-to-housing ratios are more variable because bedroom communities may lie next door to industrial agglomerations. A good jobs-housing balance was more valuable before the advent of the automobile (Giuliano 1991), although current smart-growth advocates are working to make it more salient (Zhou et al. 2012). In any case, the jobs-to-housing ratio is a useful metric for studying the evolution of industrial towns.

Table 1 Typology of enterprise-housing location options

Enterprise	*Distant housing*	*Nearby housing*
Single firm	1. Isolated enterprise with commuters (e.g., mine-mouth coal-fired power plant in PA, Merck HQ or Bell Labs in NJ)	2. Company town (e.g., West TX, coal-mining towns in WV, Los Alamos National Lab, and Salem Glass Plant in Salem NJ)
Multiple firms	3. Economic agglomeration (e.g., Metropark NJ office park, Houston TX petrochemical complex, Linden NJ petrochemical complex, and Iselin NJ)	4. Well-balanced city (e.g., New Brunswick NJ, NYC, Suzhou Industrial Park in China)

Note: PA = Pennsylvania; HQ = headquarters; NJ = New Jersey; TX = Texas; WV = West Virginia; NYC = New York City.

Urban agglomerations have at least two dimensions—firms and housing—so there are at least four endpoints, as shown in table 1. It is possible to identify examples of each. In the upper-left quadrant, isolated enterprises that rely on commuters are a familiar sight in exurban areas. A mine-mouth, coal-fired power plant fits this profile. The corporate headquarters of Merck, the pharmaceutical giant, or the former AT&T Bell Labs Holmdel site, both in New Jersey, also illustrate this type. In the upper-right quadrant is the "company town" that, as with the fertilizer plant in West, Texas, or Los Alamos National Laboratory in New Mexico, has housing for workers close by. In the lower-left quadrant is a strictly economic agglomeration with commuters. Examples include the petrochemical complex in Linden, New Jersey, and the nearby Metropark office complex in Iselin, New Jersey. Finally, the lower-right quadrant represents the well-balanced city that has both jobs and housing. Examples include New Brunswick, New Jersey, or, on the other side of the world, the Suzhou Industrial Park in China. Here, we focus primarily on U.S. examples to emphasize their comparability.

Methods

Historical case studies can provide valuable and contextualized descriptive insights, but, alone, they do not allow explanatory research on how various factors interact to produce particular settlement patterns. Modeling provides a tool for investigating these "what-if" questions. This article uses agent-based modeling techniques to examine the actions and interactions of autonomous agents individually, with other groups of agents, and with the environment, and their effects on the system as a whole. For example, it simulates how firms select better locations to share resources, workers, and technology as well as how workers seek to avoid pollution and commuting costs. The agent-based model is programmed in NetLogo (Tisue and Wilensky 2004; Wilensky 1999). An overview of the simulation system is shown in figure 1. The model starts with an empty rural landscape whose 100 × 100 grid cells are highly differentiated in terms of natural resource endowments. A firm then selects its preferred site. Workers start to enter the landscape and they select sites for houses. Additional firms and workers enter the landscape, and, over time, settlement patterns emerge.

Factors that should affect location decisions include traditional economic geography concerns, such as the relative costs of natural resources, land, and transportation. Agglomeration economies should also play a role, because shared labor pools, denser knowledge-sharing networks, and investments in persistent amenities all affect location decisions. Other economic aspects that affect firms' location decisions, such as tax reductions and subsidies, are not included in the current model, but may warrant future consideration.

This model will highlight an additional concern—embodied in U.S. traditional separation-of-incompatible-uses zoning doctrine—that pollution-intensive industrial enterprises may impose environmental health risks, both chronic and acute, on nearby residents. Although there is no consensus on the definitions or standards of "dirty" or "pollution-intensive" industries globally, different regions often adopt similar standards. In Europe, industries that fall into the Seveso Directive are classified as pollution intensive (European Commissioner for the Environment 2014). In the context of U.S industries, Cole and Elliott (2005) have used the ratio of the pollution abatement operating costs of industries to their added value to identify pollution-intensive industries. Based on this framework, Kim (2009) has identified five top dirty industries: paper, chemical, petroleum, nonmetallic mineral, and primary metal industries.

Additionally, the model will highlight the claims made by eco-industrial park advocates that colocation brings economies in the forms of shared environmental management infrastructure and opportunities for productive waste exchange.

Firms

Firms have characteristics and follow decision rules.

The characteristics of firms include requirements for material inputs (percent virgin natural resources and percent substitutable resources, such as wastes of neighboring firms), land, waste disposal (valueless and value-as-substitutable-resource), and an industrial accident or environmental risk profile (acute, chronic, or negligible). These characteristics are calibrated to typical firms in specific industries.

The plant location decision is Weberian. The firm agent seeks a profit-maximizing site, but assumes a neoclassical marketplace with normal profits (firm is a price taker). Hence, the plant locates to minimize expected costs (labor costs + material input costs + land costs + waste disposal costs + industrial accident costs), where all of these variables

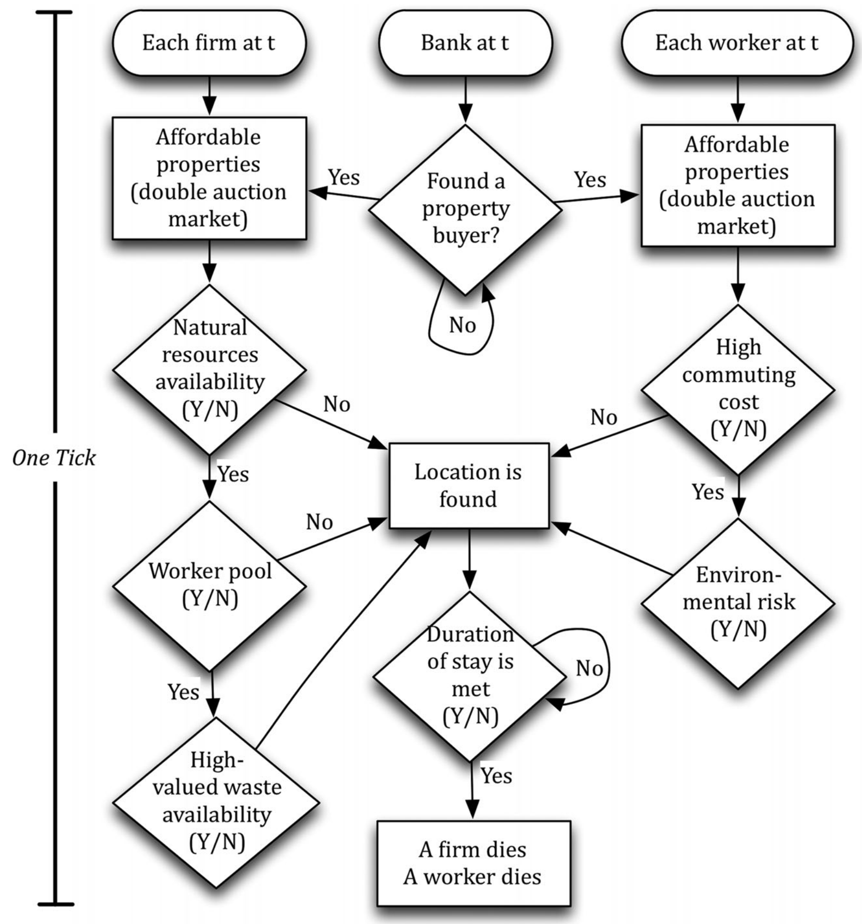

Figure 1 Modeling flowchart (time tick = 1 year).

can be stochastic. These variables are weighted and randomly generated by NetLogo (see table 2).

Ongoing operations decisions are modeled to assume that the firm operates in an efficient manner, seeking to maximize profits again assuming a neoclassical marketplace with normal profits. Hence, it operates to minimize expected costs, as discussed above.

Firms can discover colocation economies, including a shared labor pool, ability to use the wastes of one firm as feedstocks for another firm, sharing of waste disposal infrastructure, and knowledge sharing or regulation to reduce likelihood of industrial accidents.

Workers

Workers also have characteristics and follow decision rules. Their characteristics, typically, include job skills (unskilled, skilled), income (dollars per year constrained by skilled/unskilled status), knowledge of environmental risks (low, high), and willingness to endure search/research costs (low, high).

The worker's housing location decision is based on seeking a welfare-maximizing site. Hence, the worker locates to maximize income + site amenity while minimizing expected costs (rent + commuting costs + damage costs resulting from nearby industrial accidents), where all of these variables are weighted and can be stochastic, as described in table 2.

The workers' ongoing living decisions are based on seeking to maximize personal welfare on an ongoing basis. They periodically search for opportunities to increase income by changing jobs, increase site amenity by finding a larger house or better access to urban amenities, decrease rent by moving to a cheaper site, decrease commuting costs by moving closer to work, and decrease damage costs resulting from industrial accidents by moving away from dangerous firms. Search opportunities are constrained so that workers do not all move every year by incorporating a minimum search frequency (say, 1 or 5 years) and accounting for search costs (job search cost, house search cost, moving cost, commuting mode search cost, and cost to learn about industrial accident risks).

Commuting costs are exogenous and are relative to the commuting time to work. The longer the commuting time, the greater the costs workers need to pay. The modeling effort explores low and high automobile dependence. There is a schedule of cost functions (walk, bike, drive, and transit) that captures how the attractiveness of modes changes with distance traveled. Note that this model follows the economic base

Table 2 Set-up parameters and state variables of firms and workers

Attribute or variable	*Units and range*	*Description*
Firms		
Firm_type	IS industries, non-IS industries	Types of firms available for the modeling
Natural_req	Low, medium, high	Amount of water required by a firm
Hi-val-waste_req	Low, medium, high	Amount of high-valued waste or substitutable resources required by a firm
Workers_req	Low, medium, high	Number of workers required by a firm
Waste_treatment?	True or false	True if a firm has a waste treatment
Waste_rate	Low, high	Proportion of waste generated by a firm
Hiwaste_rate	Low, high	Proportion of high-valued waste generated by a firm
Utility	0 to 100	Utility value for location search
Workers		
Income	Dollars	Monthly income
Pollution-pref	Low, high	Knowledge of environmental risk
Commutingcost-pref	Low, high	Willingness to pay for commuting cost
Utility	0 to 100	Utility value for location search
Land		
Rentprice	Dollar	Land price
Wasteamount	Numbers	Amount of nonrenewable waste at one location
Hiwasteamount	Numbers	Amount of high-valued waste at one location
Naturalresamount	Numbers	Amount of natural resources at one location
Sddistance	Distance	Distance buffer from a firm to surrounding locations
Is-water-well?	True or false	True if a location is a water well
Double auction market		
Traded?	True or false	True if a property buyer makes a trade
Person_property	A property	A property owned by property owner
Best_property	A property	The best property yet found
Candidateproperties	A set of properties	Properties under consideration
Search_time	Yearly	A time length a buyer searches for a property
Annual_fee	Dollar	Amount of annual fee paid by property owners

Note: IS = industrial symbiosis.

modeling tradition of only counting "basic" export-oriented jobs, treating "nonbasic," jobs serving local needs as a scalar multiplier on export-oriented jobs that plays no role in the regional economy's dynamics (Bendavid-Val 1991).

A Bank Agent and Double Auction Market

Firms and workers also consider land rent prices in searching for sites at the beginning of every time step (see figure 1). They buy land either from private sellers (firm- and worker-owned land) or from a bank. We model this interaction between buyers and sellers using the experimental economics technique of a double auction market. In a double auction market, buyers and sellers trade for several rounds until transactions reach high levels of market efficiency. This approach introduces a new type of agent into the model, a bank. A bank owns all empty land. A bank has similar characteristics to private sellers: It makes an offer as a contribution to the overall market price. It, however, does not have an auction mechanism with buyers. Buyers buy land from a bank whenever they cannot find the desired land offered by private sellers.

The first time a buyer comes into the market, he or she forms a bid price between his or her income level, adjusted by an affordability multiplier, and zero. Meanwhile, a seller forms an ask price between the maximum reasonable market price and his or her buying price of the land. Each buyer then compares his or her bid with the best asking price. If his or her bid is above the best ask, he or she accepts the best ask and puts it into consideration along with other components in his or her search for site location. If the bid is below the best ask (or there is no best ask) and above the best bid so far, it becomes the best bid. If his or her bid is below the best bid, his or her bid is ignored. The same rule applies to each seller. If his or her ask price is below the best bid, the best bid becomes the final price tagged for the land. A buyer repeats the process until all candidate lands are appraised. A buyer and a seller that make a successful transaction are removed from future trading. The process ends whenever there are no longer sellers or buyers that can make offers in the market (Chandra-Putra et al. 2014).

For the purpose of running four scenarios (four quadrants) with 50 repetitions each, the model starts with a "baseline" set of parameters as follows:

1. Land value: US$6,785 per parcel
2. Property tax rate: 2.4% (Whitehouse Station, New Jersey), 4.04% (Salem, New Jersey), 3.877% (Linden, New Jersey), 4.189% (New Brunswick, New Jersey)
3. Mortgage interest: 8.6%
4. Number of workers that enter the world at every time step: 6
5. Number of workers that leave the world at every time step: 5
6. Number of resource-rich sites: 30
7. Maximum number of firms: 100

The simulation considers several data sources to support the first three assumptions. Time-series land value data are available at the state level (New Jersey), and the initial nominal land value for all four municipalities in the year of 1980 is US$6,785, which increases to US$66,171 in 2012 (Lincoln Institute of Land Policy 2014). The simulation normalizes these values based on the distance from each municipality to the regional economic core, New York City, with results successfully calibrated as shown in table 3. Property tax rate varies at the municipality level. Whitehouse Station, New Jersey, has the lowest average property tax rate for 1980–2012 year periods at 2.4% and Linden, New Jersey at 3.9%. Salem, New Jersey and New Brunswick, New Jersey have an average of 4.0% and 4.2% of property tax rates, respectively, for the same periods (New Jersey State Department of the Treasury 2014). The 30-year mortgage interest rate for all four municipalities has an average of 8.6% from 1980 to 2012 (Freddie Mac 2014).

How it Works

Calculations follow a sequence. One time tick represents a year. Firms (shown as gray-colored factory facilities in figures 2, 3, and 4) are created and destroyed. Workers (shown as persons) move in and move out. When a firm comes into the world, it samples 100 locations and chooses the one with the highest utility value (utility function for firm). In the beginning of each time step, a number of new workers enter into the world. When workers enter the world, they sample 100 locations and choose the one with the highest utility value (utility function for workers). Each worker has a 10-year length of stay. The amount of pollution at the pixel where the worker resides decreases the worker's length of stay. The model runs start with the first firm locating its facility, followed by workers locating themselves based on the workers' utility function. The first firm considers all locations to have the same numbers of workers, which is 0 workers.

Dominant location criteria for firms shown in figure 2a–c include availability of natural resources, presence of a pool of workers, and availability of shared high-valued waste. The key location criteria for workers include commuting cost, land-rent prices, and nonpolluted areas (see figure 3a–c). For calibration and validation, we run the model for 400 time ticks (approximating the period of Western settlement of North America) and then compare to recent decades' observed values.

Model Run Descriptions

The model is calibrated using local values for input data and validated using output values for average annual rents and commute times, and settlement patterns in four New Jersey cases, as described by the four quadrants in table 1. The first case is Whitehouse Station, New Jersey. Merck & Co., Inc., one of the largest pharmaceutical firms in the world, relocated its headquarters to Whitehouse Station, New Jersey in the early 1990s (Raver 1991). The Merck headquarters facility is considered to be environmentally friendly, and, being a corporate headquarters, many, if not all, employees earn high salaries. However, it does not draw its employees to live nearby based on local aerial images and zoning maps. It is also located far from traditional economic centers (reflected in the single factory present in figure 4a). There is a very high reliance on automobile transport. Given that workers commute from nonlocal housing units, a job-housing balance is not easy to achieve. The observed median commuting time for Whitehouse Station exceeds 30 minutes in 2012 based on U.S. Census data, which is in accord with our model. The model illustrates the people's commuting time to work by dividing their travel distance to work by the speed associated with their mode of transportation. Every town, reflected in each modeling scenario, has a different estimated average commuting time (see figure 4a).

The second case is the Salem, New Jersey. The Salem Glass Works is located in the center of this small city. The company has had a local presence since 1863, and most recently it decided to expand with a 50,000-square-foot facility completed in April 2002. The company plays a key role in the city's economy. This is a relatively low-polluting facility that pays low wages; hence, many employees minimize commuting costs by living in inexpensive housing nearby. The median commuting time to work is 20 minutes, 10 minutes lower than for Whitehouse Station, New Jersey. The close proximity of the local population to the Salem Glass Works facilities makes them vulnerable in case of any health or safety risk. In Salem, local residents have not experienced harm from living near the factory; however, the fertilizer plant in West, Texas, proved to be a less-benign neighbor. The model, shown in figure 4b, describes these phenomena, where people choose to locate their houses clustered around the facility, making them vulnerable to risks resulting from the firm's operation.

The third case is Linden, New Jersey, a purely economic agglomeration lacking housing within walking distance. The proximity to a shipping waterway and densely populated New York City made it an attractive industrial location during the early decades of the twentieth century. In 1907, John D. Rockefeller, the petroleum magnate, purchased hundreds of acres of land in Linden and Elizabeth, New Jersey, and then established Bayway Refinery. As the oil refinery grew and expanded, the city also developed industries such as shipping, auto assembly, and pharmaceuticals. The twentieth century saw the arrival of General Motors and Mercer in Linden's evolution, and the Bayway Refinery became one of the largest refineries on the East Coast. The manufacturing sector had the largest

Table 3 Model validation against observed data

	Commuting time (minutes)			*Median gross rent (USD)*		
Case	*Modeled*	*Observed*	*MAPE (%)*	*Modeled*	*Observed*	*MAPE (%)*
Whitehouse Station, NJ	28	30	2	$811	$980	6
Salem, NJ	19	20	2	$590	$798	9
Linden, NJ	18	19	7	$863	$1,126	2
New Brunswick, NJ	21	23	4	$980	$1,320	6

Source: Census (1980, 1990, 2000) and 5-year American Community Survey (2009, 2010, 2011, 2012), both of which are led by the U.S. Census Bureau.
Note: MAPE is presented for four cases.
NJ = New Jersey; USD = U.S. dollars; MAPE = mean absolute percent error.

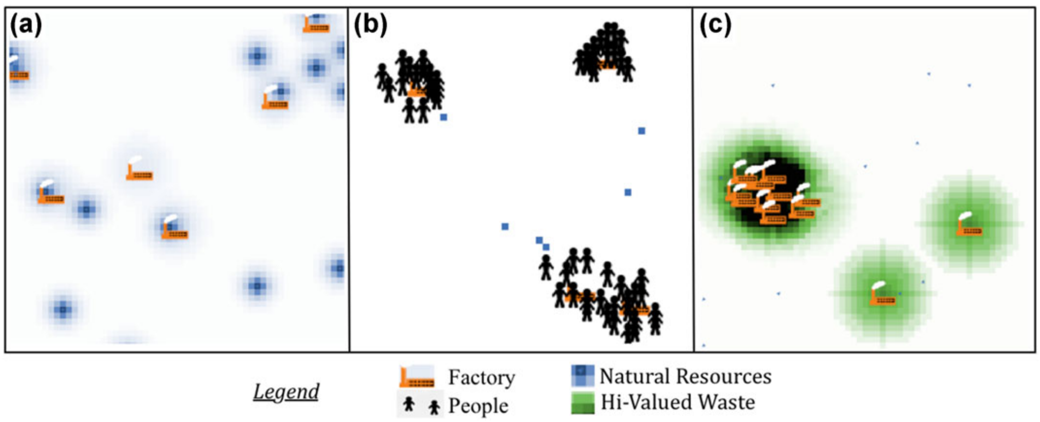

Figure 2 Factors affecting firm location: (a) natural resources; (b) labor pool; (c) high-valued waste.

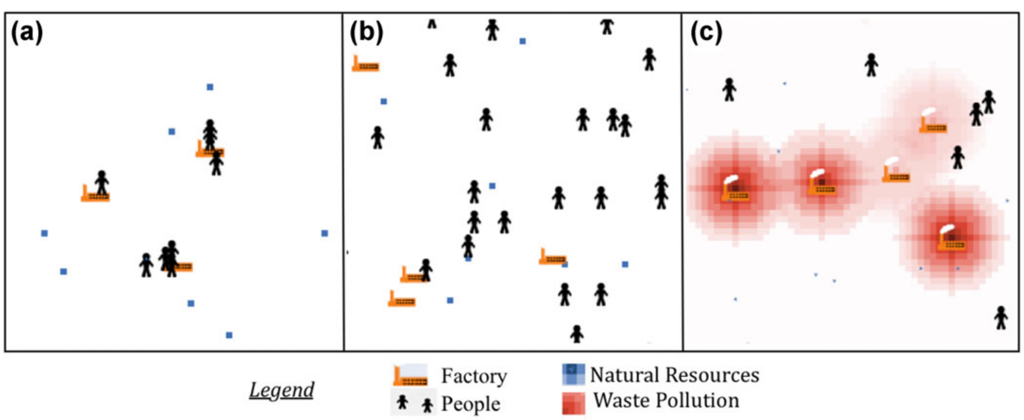

Figure 3 Factors affecting worker housing location: (a) commuting cost; (b) rent cost; (c) pollution.

proportion of the municipality's paid employees in the 2007 Economic Census, and manufacturing has shaped Linden's economy and created an economic agglomeration, as illustrated in its plant-intensive urban landscape. Though impressive in forming an industrial cluster, more than 80% of Linden's workers have commuted by car during the latest 30 years, according to U.S. Census data. The city's industrial plants can generate acute hazards or toxic emissions, and local workers know this. The model, as shown in figure 4c, reflects what occurs in Linden.

The last case is New Brunswick, New Jersey. New Brunswick was a colonial-era trans-shipment point that became an industrial city when Johnson & Johnson and other manufacturing companies located factories there in the last quarter of the nineteenth century. This less-car-dependent industrial city became a well-balanced city with short commuting times and a large percentage of walking commuters. The city has become an economic agglomeration that includes manufacturing and service industries while continuing to build housing units. This relatively well-balanced city has managed the environmental risks from industrial firms by encouraging cleaner production processes so that residents are willing to live locally. Figure 4d shows a model run with parameters set for New Brunswick. The figure shows how people choose their housing locations at the edge of a buffer zone based on commuting time and pollution level.

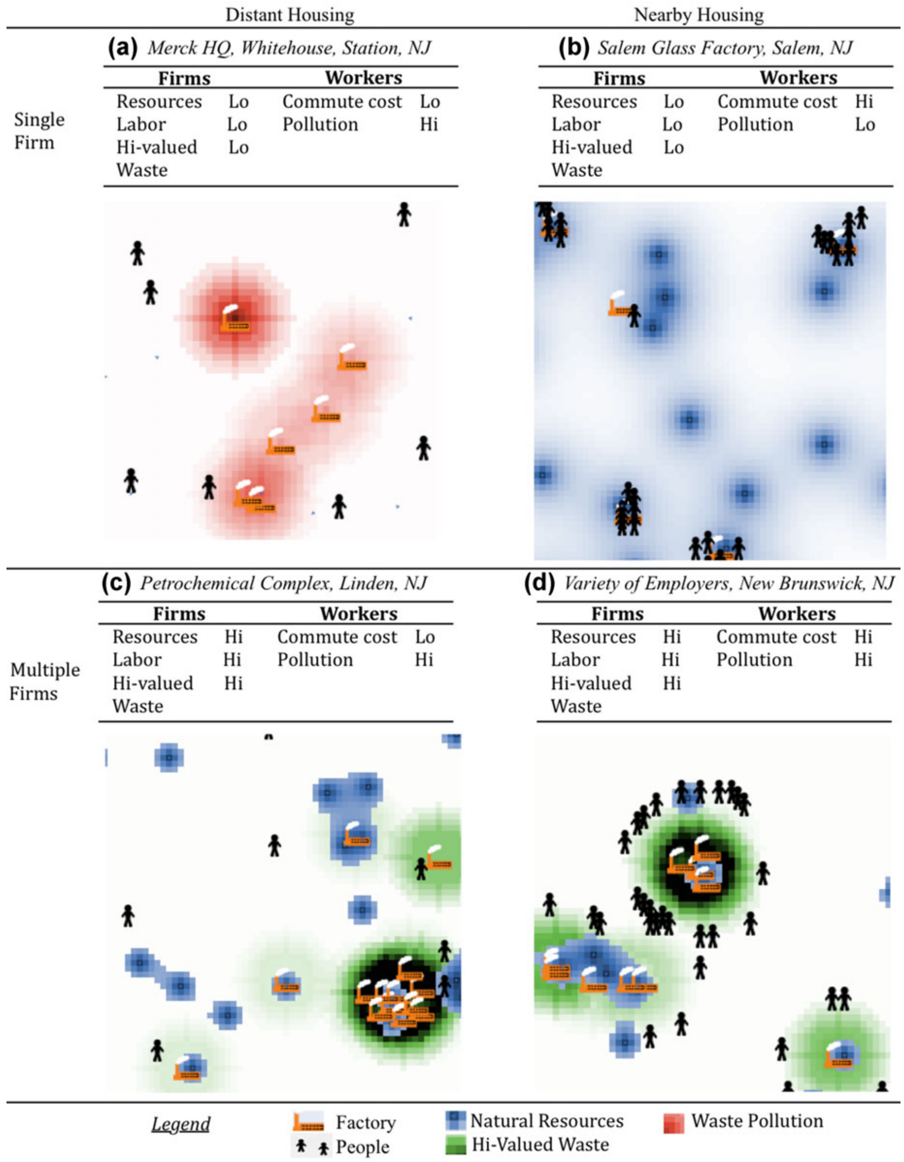

Figure 4 Summary of key inputs and graphical results for four scenarios: (a) Merck HQ, Whitehouse Station, NJ; (b) Salem Glass factory, Salem, NJ; (c) Petrochemical Complex, Linden, NJ; and (d) variety of employers, New Brunswick, NJ. HQ = headquarters; NJ = New Jersey.

Three additional cases (in the supporting information on the Journal's website) are mixes of the four cases just discussed. The first supplementary case looks at impacts of resource-sharing opportunities on industrial sites in quadrant 1. Parameter changes are intercepted during the simulation in order to perform this task. The experiment provides promising results; with resource sharing implemented, the model locates firms in close proximity to one another. This characterizes industrial cities in quadrant 3 where resource sharing and economic agglomeration emerge. The second supplementary case examines how better knowledge of environmental risks affects housing location choices. The experiment shows that once the environmental risks are apparent, people are no longer choosing to live nearby to their workplaces from where pollutants are coproduced. The people choose to locate their housing at a distance from their workplaces. This simulates how industrial cities in quadrant 2 transform into ones with characteristics of cities in quadrant 1. The last additional case study investigates factors that create well-balanced cities (i.e., cities that fall into quadrant 4). Several simulation runs cause cities in quadrants 1 and 3 to transform into cities like ones in quadrant 4.

Model Validation on Commuting Time, Median Gross Rent, and Job-Housing Ratio

In order to validate the model, we compare three components (travel time to work, median gross rent, and jobs-housing ratio). We use a multiplier value to scale the simulation outcomes as part of our validation process. The results follow the modeling logic for "travel time to work," such that the case of Whitehouse Station, New Jersey has a greater travel time to work than the cases of Linden, New Jersey, Salem, New Jersey, and New Brunswick, New Jersey (see table 3). Whereas there is not much variance in travel time to work over time, the model still shows consistency. The mean absolute percentage error (MAPE) measure between the observed data of four cities and the model shows good accuracy, with differences of 6% to 7% between predicted and observed commuting times for each city. The model representing Whitehouse Station, New Jersey, provides the best accuracy at 6% MAPE, compared to other modeled cities at 7%. In terms of "median gross rent," the model reflects the actual data for the year 2012. However, there are differences in the price changes over time between the model and the observed values, such that the MAPE values for median gross rent for the four cities vary from 1% to 9% (see table 3).

In terms of "jobs-housing ratio," the model runs on a single firm (e.g., Whitehouse, New Jersey, and Salem, New Jersey) have a higher ratio than model runs on multiple firms (e.g., Linden, New Jersey, and New Brunswick, New Jersey). This is mainly because more people are coming as more job opportunities are provided. Recall that this is a simplified economic model that assumes an export driven regional economy, and so it focuses only on the export-related jobs. Validation data for jobs-housing ratio are not available. Hence, we rely on this test of simple face validity. Another finding is that the shorter the distance between jobs and housing, the greater the jobs-housing ratio.

Discussion

The simulations support the claims that (1) environmental factors belong in industrial location theory and (2) housing belongs in IS theory.

The four jobs-housing scenarios are summarized in figure 4. They show that an isolated enterprise with commuters will emerge when the enterprise poses serious and evident environmental risks, or when the enterprise does not want competitors poaching its labor pool, and when relative commuting costs are small. A company town will emerge when agglomeration economies have little value for the firm, or when relative commuting costs are very high, and when environmental risks are low or poorly understood. An economic agglomeration will emerge when agglomeration economies have great value for specific firms, environmental risks can be managed well by shared infrastructure, opportunities for sharing waste streams might be present, and when relative commuting costs become very small. A balanced city, such as New Brunswick, New Jersey, will emerge when agglomeration economies have great value for the firm, environmental risks can be managed well by shared infrastructure, opportunities for sharing waste streams are present, relative commuting costs are high, and agglomerated amenities have value for residents.

In the case of Linden, the presence of high concentrations of industrial pollutants (including nitrogen dioxide and sulfur dioxide [SO_2]) in the 1980s and 1990s (US EPA 2014) is consistent with the fact that residents chose to live further from their workplaces and have longer commute times during that period. Even if we zoom into the city by virtual Earth maps, such as Bing Maps today, industrial and residential areas remain widely separated. From this perspective, zoning ordinances become essential to protect the health of local communities. In recent years, environmental recovery projects, such as the ConocoPhillips Global Refinery Settlement at Linden, New Jersey, and other U.S. sites have been initiated to rebuild livable communities and have achieved some success in controlling pollution (U.S. District Court for the Southern District of Texas 2005).

Engineered solutions can be effective in quickly ameliorating environmental problems, but they may need continuous materials and energy inputs, which spawn opportunities for promoting eco-efficiency and IS. One relatively successful example of an economic agglomeration that solved environmental issues and built a well-balanced city is China's Suzhou Industrial Park, which has evolved into an ecological urban area that integrates the industrial, residential, and commercial sectors. Through years of trial and error in building IS, environmental quality has been improved in Suzhou Industrial Park, where the levels of chemical oxygen demand and SO_2 emissions are one eighteenth and one fortieth of China's national average (Suzhou Industrial Park 2009).

Chertow (2000) suggests three evolutionary approaches for realizing IS, and we can examine their feasibility as follows. The first approach is to exploit simple material or energy exchange ("green twinning" or "by-product synergy"). By persuading businesses to invest and incorporate similar industrial participants to those found in Kalundborg or Suzhou, an economic agglomeration such as Linden could duplicate existing ISs. A second approach is to make full use of "pre-existing organizational relationships and networks" through material, energy, or information flows to build early IS. Linden has already established two cogeneration plants for energy cascading and established close linkages between several industrial firms. Environmental infrastructure-sharing projects are easier to accomplish in comparison with waste exchange (Heeres et al. 2004). From interactions among firms, other symbiotic ideas may emerge. A third approach is "the anchor tenant model," where large anchor tenants generate a significant portion of materials and energy as inputs to other colocated firms. At Linden city, anchor tenants are refineries and petroleum complexes and there are potentials for building IS.

The four categories of companies can be summarized as follows:

1. *Isolated enterprise with commuters* emerges when the enterprise poses serious and evident environmental risks or eschews agglomeration, and when commuting costs are small.
2. *Company town* emerges when agglomeration economies have little value for the firm, or when commuting costs are very high, and when environmental risks are low or poorly understood.

3. *Economic agglomeration* emerges when agglomeration economies have great value for the firm, environmental risks can be managed well by shared infrastructure, opportunities for sharing waste streams are present, and when commuting costs become very small.
4. *Well balanced city* emerges when agglomeration economies have great value for the firm, environmental risks can be managed well by shared infrastructure, opportunities for sharing waste streams are present, commuting costs are high, and agglomerated amenities have value for residents.

Conclusions

This model explores several potential evolutionary pathways that emerge from the interactions among firms and workers, as well as between these agents and their environment. It captures key factors determining whether industrial enterprises evolve into livable, well-balanced cities. Shared labor pools, opportunities to share environmental infrastructure, and the potential to create urban amenities all attract firms and workers into urban agglomerations. Absent information about the environmental characteristics of enterprises, households can make risky location choices. Land-use regulations based on a separation-of-uses doctrine can prevent such problems, but at the cost of reducing the feasibility of a walkable commute. Perhaps the most disturbing finding is that there appear to be numerous pathways leading to sprawling settlement patterns, and few that deliver well-balanced cities, once environmental considerations are added to the locational calculus.

The model has a potential for further development by adding more baseline parameters in order to reflect reality more precisely. It could also be extended to include other ways in which housing should be part of IS, such as housing as a user of energy and water and as a producer of waste. Further development may also utilize spatial econometrics methods that sit closer to data than agent-based models do, and by incorporating geographic information system elements into the models.

References

Alonso, W. 1964. *Location and land use*. Cambridge, MA, USA: Harvard University Press.

Axtell, R. L., C. J. Andrews, and M. J. Small. 2001. Agent-based modeling and industrial ecology. *Journal of Industrial Ecology* 5(4): 10–13.

Baas, L. W. and F. A. Boons. 2004. An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems. *Journal of Cleaner Production* 12(8–10): 1073–1085.

Baas, L. 2011. Planning and uncovering industrial symbiosis: Comparing the Rotterdam and Östergötland regions. *Business Strategy and the Environment* 20(7): 428–440.

Batten, D. 2009. Fostering industrial symbiosis with agent-based simulation and participatory modeling. *Journal of Industrial Ecology* 13(2): 197–213.

Batty, M. 1970. An activity allocation model for the Nottinghamshire-Derbyshire subregion. *Regional Studies* 4: 307–332.

Batty, M. and P. Longley. 1989. Urban growth and form: Scaling, fractal geometry, and diffusion-limited aggregation. *Environmental and Planning A* 21(11): 1447–1472.

Bendavid-Val, A. 1991. *Regional and local economic analysis for practitioners*, 4th ed. (pp. 77–85). Westport, CT, USA: Praeger.

Cervero, R. 1996. Jobs-housing balance revisited: trends and impacts in the San Francisco Bay Area. *Journal of the American Planning Association* 62(4): 492–511.

Chandra-Putra, H., H. Zhang, and C. J. Andrews. 2014. Modeling real estate market responses to coastal flooding. *Journal of Artificial Societies and Social Simulation* Forthcoming.

Chertow, M. R. 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment* 25(1): 313–337.

Chertow, M. R., W. S. Ashton, and J. C. Espinosa. 2008. Industrial symbiosis in Puerto Rico: environmentally related agglomeration economies. *Regional Studies* 42(10): 1299–1322.

Chertow, M. R. 2007. Uncovering industrial symbiosis. *Journal of Industrial Ecology* 11(1): 11–30.

Chertow, M. R. and J. Ehrenfeld. 2012. Organizing self-organizing systems. *Journal of Industrial Ecology* 16(1): 13–27.

Christaller, W. 1933. *Central places in Southern Germany*. Englewood Cliffs, NJ, USA: Prentice Hall.

Clarke, K., S. Hoppen, and L. Gaydos. 1997. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B* 24(2): 247–361.

Cole, M. A. and R. J. R. Elliott. 2005. FDI and the capital intensity of "dirty" sectors: A missing piece of the pollution haven puzzle. *Review of Development Economics* 9(4): 530–548.

Costa, I. and P. Ferrao. 2010. A case study of industrial symbiosis development using a middle-out approach. *Journal of Cleaner Production* 18(10–11): 984–992.

Desrochers, P. 2004. Industrial symbiosis: The case for market coordination. *Journal of Cleaner Production* 12(8–10): 1099–1110.

Ehrenfeld, J. R. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Ewing, R. 1996. *Best development practices: Doing the right thing and making money at the same time*. Chicago, IL, USA: Planners.

European Commissioner for the Environment. 2014. Chemical accidents (Seveso I, II and III)—Prevention, preparedness and response. http://ec.europa.eu/environment/seveso/. Accessed June 2014.

Fernandez, M. and J. Schwartz. 2013. Plant explosion tears at the heart of a Texas town. *The New York Times*, 18 April. www.nytimes.com/2013/04/19/us/huge-blast-at-texas-fertilizer-plant.html?pagewanted=all&_r=0. Accessed June 2014.

Forrester, J. 1969. *Urban dynamics*. Cambridge, MA, USA: MIT Press.

Freddie Mac. 2014. 30-year fixed-rate mortgage since 1971. www.freddiemac.com/pmms/pmms30.htm. Accessed June 2014.

Giuliano, G. 1991. Is jobs-housing balance a transportation issue? *Transportation Research Record* 1305: 305–312.

Heeres, R. R., W. J. V. Vermeulen, and F. B. de Walle. 2004. Eco-industrial park initiatives in the USA and the Netherlands: First lessons. *Journal of Cleaner Production* 12(8–10): 985–995.

Hotelling, H. 1929. Stability in competition. *Economic Journal* 39(1): 41–57.

Isard, W. 1956. *Location and space-economy*. New York: Wiley.

Kim, M. H. 2009. Eco-industrial development in the U.S. spatial form, contextual factors, and institutional fabrics of greener plants and offices. Doctoral dissertation in Planning and Public Policy, Rutgers University, New Brunswick, NJ, USA.

Landis, J. D. 1995. Imaging land use futures: Applying the California urban future model. *Journal of the American Planning Association* 61(4): 438–457.

Lee, D. 1973. Requiem for large-scale models. *Journal of the American Institute of Planners* 39(3): 163–178.

Lincoln Institute of Land Policy. 2014. Land and property values in the U.S. www.lincolninst.edu/subcenters/land-values/land-prices-by-state.asp. Accessed June 2014.

Lösch, A. 1943. *The economics of location*. New Haven, CT, USA: Yale University Press.

Lowry, I. S. 1964. *A model of metropolis*. Santa Monica, CA, USA: Rand Corporation.

Marshall, A. 1890. *Principles of economics*. London: Macmillan.

Mathews, J. and H. Tan. 2011. Progress toward a circular economy in China: The drivers (and inhibitors) of eco-industrial initiative. *Journal of Industrial Ecology* 15(3): 435–457.

Moses, L. 1958. Location and the theory of production. *Quarterly Journal of Economics* 72(2): 259–272.

New Jersey State Department of the Treasury. 2014. General tax rates by county and municipality. www.state.nj.us/treasury/taxation/lpt/taxrate.shtml. Accessed June 2014.

Otter, H. S., A. van der Veen, and H. de Vriend 2001. ABLOoM: Location behaviour, spatial patterns, and agent-based modelling. *Journal of Artificial Societies and Social Simulation* http://jasss.soc.surrey.ac.uk/4/4/2.html. Accessed 17 December 2014.

Paquin, R. L. and J. Howard-Grenville. 2012. The evolution of facilitated industrial symbiosis. *Journal of Industrial Ecology* 16(1): 83–93.

Portugali, J. 2000. *Self-organization and the city*. Berlin: Springer.

Raver, A. 1991. Cuttings; Corporate cottage, deep in a forest. *The New York Times*, 22 December. www.nytimes.com/1991/12/22/news/cuttings-corporate-cottage-deep-in-a-forest.html. Accessed May 2014.

Sasaki, Y. and P. Box. 2003. Agent-based verification of von Thünen's location theory. *Journal of Artificial Societies and Social Simulation* 6(2): 172–189.

Smith, D. M. 1971. *Industrial location: An economic geographical analysis*. New York: Wiley.

Suzhou Industrial Park. 2009. International concepts & local practices. www.sipac.gov.cn/english/zhuanti/jg60n/gjlnbtsj/. Accessed June 2014.

Tisue, S. and U. Wilensky. 2004. Netlogo: A simple environment for modeling complexity. In International Conference on Complex Systems, 16–21 May, Boston, MA, USA.

United States District Court for the Southern District of Texas. 2005. Consent decree in United States of America, State of Illinois, State of Louisiana, State of New Jersey, Commonwealth of Pennsylvania, Northwest Clean Air Agency versus ConocoPhillips Company, Civil action no. H-05-0258. www2.epa.gov/enforcement/consent-decree-conocophillips-global-refinery. Accessed 20 August 2014.

US EPA (U.S. Environmental Protection Agency). 2014. *U.S. air data*. www.epa.gov/airquality/airdata. Accessed 28 June 2014.

Van Berkel, R. F. 2009. Quantitative assessment of urban symbiosis and industrial symbiosis in Kawasaki, Japan. *Environmental Science & Technology* 43(5): 1271–1281.

von Thünen, J. 1966/1826. *Isolated state; An English edition of Der isolierte Staat*. Oxford, UK; New York: Pergamon.

Waddell, P. 2002. UrbanSim: Modeling urban development for land use, transportation, and environmental planning. *Journal of the American Planning Association* 68(3): 297–314.

Weber, A. 1929. *Alfred Weber's theory of the location of industries*, translated by C. J. Friedreich. Chicago, IL, USA: The University of Chicago Press.

White, R. and G. Engelen. 1993. Cellular automata and fractal urban form: A cellular modelling approach. *Environment and Planning* A, 25: 1175–1199.

Wilensky, U. 1999. NetLogo software. http://ccl.northwestern.edu/netlogo/ Accessed March 2014.

Wilson, A. 1970. *Entropy in urban and regional modeling*. London: Pion.

Wilson, A. 1976. Catastrophe theory and urban modelling: An application to model choice. *Environment and Planning* A 8: 351–356.

Wilson, A.G. 1981. *Catastrophe theory and bifurcation*. Berkeley, CA, USA: University of California Press.

Zhou, J., Y. Wang, and L. Schweitzer. 2012. Jobs/housing balance and employer-based travel demand management program returns to scale: Evidence from Los Angeles. *Transport Policy* 20: 22–35.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information includes the descriptions and figures containing the results for the three additional cases mentioned in the section *Model Run Descriptions* in the main article.