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Pathways to the Circular City: Scenario Planning and Agent-Based Modeling to Explore Developer Decision-Making and City Policies

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Abstract

This article presents a novel use case of the deployment of agent-based modeling (ABM) to explore developers' decision-making along a spectrum of reuse in the built environment. This research project used ABM to model multiple pathways to realizing circularity at the community scale through the reuse of existing buildings and adoption of deconstruction as alternatives to demolition in Ithaca, New York. This exploratory analysis demonstrates (1) the use of ABM in scenario planning, (2) the use of ABM to assess how preservation and building material reuse options affect city-wide greenhouse gas emissions in the form of embodied carbon, (3) and the potential to use the model results in policy analysis. The results of the analysis emphasize trade-offs in local government policies. A Business As Usual scenario produces the most CO_2 emissions and the highest total dollars invested and total square footage developed. This is in contrast to the other three scenarios. A Maximize Preservation scenario achieves the lowest total embodied carbon emissions through retention of existing buildings while maintaining the second highest total investment in urban development. The Deconstruction Incentive and Mandatory Material Reuse scenarios, which involve incentivizing building material reuse, lead to strong ROI signals for developers, reducing the search for suitable properties for new construction as deconstruction becomes a viable avenue for generating returns. ABM-generated scenarios exhibit differences in the performance of developers according to their type and scale. This research produced a readily available ABM and graphical interface that could be used by researchers and local government agencies exploring pathways to achieving circular cities through policies that can affect urban development processes and embodied carbon emissions.

Keywords: scenario planning; agent-based modeling; circular economy; circularity; circular city

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1. Introduction

The concepts of circular cities and circular economy offer new ways of framing and exploring policy pathways for urban futures. The MacArthur Foundation defines the circular economy as "a system where materials never become waste" and in which "materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting" [1]. Williams defines the circular city as one that "reduces

waste and promotes the best use of resources," including in the adaptive reuse of buildings [2]. Frameworks, policies, and actions to achieve circularity in the built environment offer important means of striving toward sustainability and working to achieve climate mitigation goals [3]. Policies, including but not limited to, the preservation of buildings, the deconstruction of buildings, and the reuse of building materials, contribute to circularity in the built environment [4,5]. Pathways toward a circular economy through enacting policies at the local level is an important and growing area of research [6,7], as are analytical and scenario-based approaches to developing and assessing circular policies [8,9].

Scenario planning methods and tools can aid communities in exploring processes and policies related to circular cities, carbon neutrality, and climate mitigation. Agent-based modeling (ABM) is one scenario planning method recognized as having the potential to provide insights into the complexities of climate change and adaptation [10]. ABM can be useful in analyzing scenarios where diverse, interacting agents, such as individuals, firms, or government agencies, are modeled to understand their collective behavior and the resulting outcomes.

Scholarship has demonstrated the expansive capabilities of ABMs by showcasing how knowledge from various disciplines, such as politics, sociology, and economics, can also be included in the models [11]. By integrating elements from various fields, ABM can aid in the assessment of climate policies. These models offer an interdisciplinary tool for simulating complex systems. This integration has the potential for ABMs to incorporate the place-based knowledge vital for overcoming the challenges cities face in climate mitigation [12]. In this project, a multidisciplinary team of researchers set out to develop and test a replicable ABM-based tool for exploring circular city futures. The research team sought to answer the questions: How could scenario planning using ABM inform efforts to work toward a circular economy and account for the range of choices developers and property owners can make with regard to building preservation, adaptive reuse, and building material reuse? The team was inspired to look at these questions, given local interest in adopting a range of policies to advance building material reuse and preservation as means of working toward circularity and carbon neutrality [13]. The next two sections entail a review of literature relevant to this question and to the methods employed in this research.

1.1. Combining Agent-Based Modeling and Scenario Planning

Agent-based modeling and scenario planning represent analytical and participatory toolsets employed for modeling future changes to complex systems, such as urban environments. ABMs simulate interactions among autonomous actors within a system, replicating the actions and interactions of autonomous agents to assess their effects on the system as a whole. These simulations enable the exploration of system-level properties and non-linear dynamics [14]. Scenario planning is used to envision, in a structured manner, possible futures of a system in order to identify robust and flexible strategies for future [15]. ABMs are useful for bridging micro-level behaviors with macro-level phenomena, allowing researchers to investigate system-wide emergent patterns and phase transitions [16]. A key strength of these models is their flexibility and the ability to utilize diverse decision-making frameworks [17]. In urban studies, ABMs have been used to model traffic congestion, housing markets, land-use changes, developer decision-making [18], and urban infrastructure [19]. Important drawbacks of ABMs include methodological rigor, model specificity, and real-world applicability, which have been addressed by scholarship focusing on novel data sources and advanced validation [20].

Scenario planning is a structured method of preparing for plausible future states by analyzing trends, uncertainties, and possible disruptions [21]. Scholarship has recognized three major types of scenarios with distinct purposes: predictive, explorative, and norma-

tive. Predictive scenarios include forecasts and what-if analysis, distinct from explorative scenarios, which focus on modeling possible futures and comparing outcomes. Both are distinct from normative scenarios, which aim to guide a current preferred state toward a desired future [15]. An approach relevant to this study is Exploratory Scenario Planning (EXP), which is used in urban and regional planning to generate a wide range of plausible futures that accommodate uncertainty and produce corollaries of resilience [22,23].

Both ABM and scenario planning can be combined to provide a dynamic simulation environment that generates and explores future scenarios. This hybrid approach emphasizes the explorative overlap that both methods employ. Using ABM, the scenarios generated in an EXP approach can be examined and compared. One use of this hybrid approach is to study how agents respond to different scenarios, exploring the potential behaviors and interactions of the agents [24]. Learning mechanisms and social interactions can be incorporated into ABMs, enabling the pre-defined scenarios encountered by agents in the model [20]. The inclusion of learning, social interactions, and pre-defined scenarios can provide useful results to policymakers interested in evaluating the impacts of different policy interventions [25]. These scenario-based ABMs could aid the exploration of adaptive urban strategies, while providing insight into how local social systems operate under specific constraints, such as climate mitigation. While hybrid scenario-based ABMs hold promise, they will still suffer from the key challenges of both methods [26].

1.2. Circular Economy, Climate Mitigation, and the Built Environment

The intellectual framing of this project is climate mitigation through decarbonization of the built environment using Circular Economy (CE) principles. While CE is a complex term with a multi-layered history, the core of the concept has come to be defined by its contrast to a traditional economy that practices resource extraction and industrial production with a limited focus on maximizing the reuse of materials. CE emphasizes closed material loops that promote resource efficiency and sustainability with application across geographic and temporal scales of an economy [27]. A CE approach is important for the building and construction sector as it pertains to the reduction in waste and decreasing overall greenhouse gas (GHG) emissions by lowering embodied carbon emissions associated with construction [28]. Reducing GHG is important for climate mitigation in the built environment, as the building and construction sector is responsible for nearly a third of GHG emissions [29]. Scholarship has recognized the value of a CE framework in reducing GHG emissions and overall waste streams in the built environment. The reuse of materials, such as wood, concrete, glass, can reduce the carbon footprint of buildings versus sourcing new materials. Regarding development and construction specifically, CE prioritizes waste minimization strategies through strategies such as deconstruction, building material reuse, and design for disassembly [30].

ABM is one of several advanced simulation methods that can be used in research to achieve circular cities. Digital twins have been used to analyze 3D models of existing urban fabric for greenhouse gas emissions inventories [31] and used with Life Cycle Analysis (LCA) tools like the CareTool and Tally for Revit to assess scenarios at the building scale [32]. ABMs are distinct from the use of digital twins, as they are a technique to simulate behavior, rather than to simulate the built environment. Machine learning, artificial intelligence, deep learning, and big data analytics have been used for estimation of construction and demolition debris and to understand complex waste management systems [33]. Machine learning and ABM can be complementary techniques that move beyond classic environmental accounting like LCA that are typical linear models to models that simulate more complex and nonlinear systems [34].

As described below, the ABM in this study draws from a conceptual Building Reuse to Waste Hierarchy (Figure 1). This hierarchy articulates preferred strategies along a spectrum of reuse related to circularity. Most preferred strategies include preservation, maintenance and refurbishment, which maintain building material in situ with minimal expenditure of embodied carbon. Adaptive reuse, infill development around buildings, and whole building relocation are also preferred methods of extending the lifespan of buildings and minimizing embodied carbon associated with the first stages in a building's life cycle. Deconstruction at the end of a building's lifespan enables the ability to reclaim building materials and is preferable to demolition and landfilling of materials.

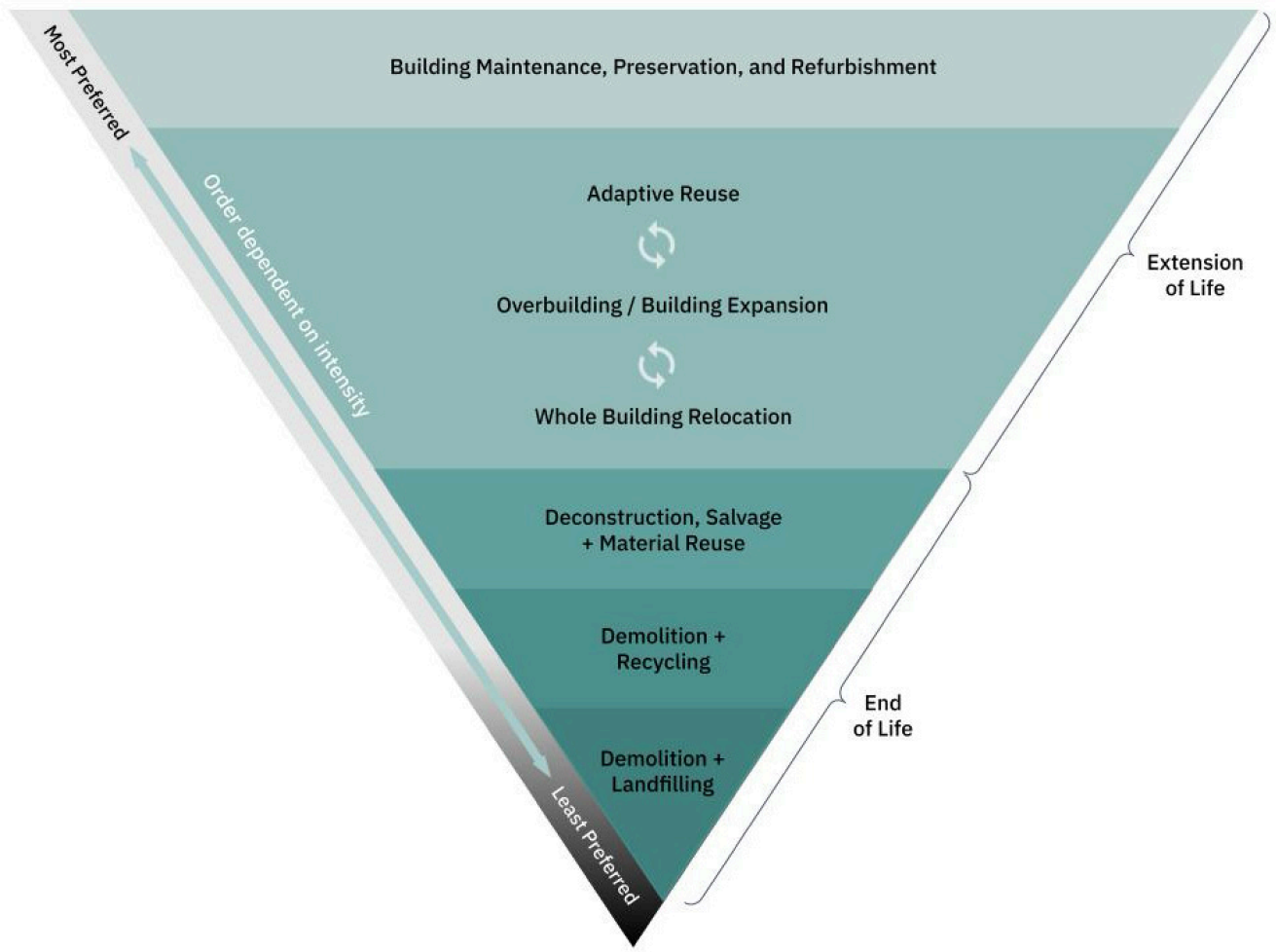


Figure 1. The Building Reuse to Waste Hierarchy underpins the choices that were incorporated into the agent-based model. The model was developed by researchers in the Just Places Lab.

The next section provides an overview of the methods used to develop an agent-based scenario planning tool. Next, the outcomes of initial runs of the ABM are detailed. A discussion of how ABM can become a tool for cities to develop policies to achieve more circular urban futures follows.

2. Materials and Methods

This multi-year study employed a methodology that integrated qualitative data gathered in focus groups, interviews, and surveys to inform the development of an ABM to understand developer behavior and urban parcel dynamics in Ithaca, New York. For researchers interested in replicating the qualitative, spatial, and quantitative methods in this and related studies, the report *Preservation within a Full Spectrum of Reuse: Scenario Planning*

Technologies to Plan Circular Futures contains live links to available survey questions and examples [32]. That report is intended to guide users through the use of ABM, as well as other technologies such as the production of digital twins and life-cycle analyses at the building and parcel scale that are beyond the scope of this article. Additionally, key details of the model, including the major features and values, and which python file these are located in, are presented in Table A1 of the Appendix A.

This research project was undertaken in the context of local government efforts to address carbon emissions. The City of Ithaca has committed to an ambitious climate mitigation agenda. In 2019, the City of Ithaca Common Council adopted the Ithaca Green New Deal (IGND), committing to community-wide carbon neutrality by 2030 with a focus on rectifying historical inequities and promoting social justice [35]. The initiative aimed to position Ithaca as a leader in climate mitigation. The IGND aims for carbon neutrality, renewable electricity for government operations by 2030, and a 50% emissions reduction in city vehicles by the same year. Ithaca provided a rich context for developing a replicable scenario planning tool that could be fully developed for deployment in other contexts.

The research team composed of researchers in architecture, regional science, and city and regional planning first utilized the results of a focus group and interviews. The focus group consisted of a structured discussion with building and planning officials in two adjacent municipalities, the City of Ithaca and the Town of Ithaca. The interviews were conducted with developers and architects to understand their perspectives and receptiveness toward preserving and adapting existing buildings and incorporating deconstruction as an alternative to demolition in their projects. In addition, this research drew from an analysis of building and demolition patterns and both qualitative and quantitative studies of incidents of demolition [36]. Insights from these other studies were folded into a survey of local developers to capture developer decision-making processes and preferences, providing key insights that informed the model architecture and scenario development process.

2.1. Developer Survey

The survey was designed to understand developer decision-making and had three main objectives. The first objective was to enrich the ABM with realistic developer behavior concerning reinvestment in property throughout the city. A second objective of the survey was to uncover key insights about how the built environment in Ithaca has been developed, including the nature, timing, and funding of projects. This also included questions concerning whether or not buildings were preserved, demolished, or deconstructed. The final objective was to inform a series of inputs that would form the basis of future scenarios. These inputs included how incentives or streamlined permitting processes could influence the use of certain types of development.

Based on initial research, the survey was focused on developers actively involved in property development. This included developers operating across different geographic scales. Selected development firms operated from the sub-local to the national levels, from two to several dozen employees. Firms were considered that had a range of types of properties, different numbers of properties, different capital requirements, and different underlying business objectives. Excluded from the survey were small-scale refurbishment projects run solely by homeowners. The structure of the survey was divided into four sections: (i) understanding development practices, (ii) decision-making factors, (iii) site suitability for reuse or new development, and (iv) alternatives to demolition.

Section one of the survey included questions about the types of projects initiated in the past ten years, such as single-family residential, multi-family residential, mixed-use, and adaptive reuse of buildings. This section also asked questions involving the frequency of incentive utilization, investment approaches, geographic spread of projects, and devel-

oper priorities. Section two of the survey asked respondents to rank factors influencing their decision-making. Section three of the survey sought to understand the criteria developers held for selecting properties. Assessed criteria included building construction type, age of building, soil conditions, utility availability, zoning regulations, expected future development, and proximity to key city areas. Section four surveyed developers on their perceptions regarding deconstruction, adaptive reuse, and reclamation of materials. This section focused on understanding the likelihood of a developer's willingness to engage in deconstruction, adaptive reuse, and use of reclaimed materials if the following were included: incentives, grants, positive publicity, streamlined permitting, and net-zero branding opportunities.

Twenty two firms were contacted through emails to participate in the survey and follow up reminders via email and phone calls. Eight developers proved willing to fully complete the survey. This represents a 36% response rate. The low number of responses introduces the potential for error. The small number of respondents was likely due to a reluctance on the part of developers to participate, as their decision-making is typically proprietary and often highly guarded. Reluctance to participate may have affected the results of the survey, introducing the potential for nonresponse or response bias. Additionally, the research team observed that the survey was very long, which may have affected completion rates.

Results from the survey were collated and analyzed for insights that could be used to inform the agent-based model. Figure 2 shows how developers rated the values of profitability, sustainability, community perception, and social equity, from least to most important. The results clearly show profitability as being the most important to a major of respondents. Figure 3 provides responses to the series of survey questions "How likely would you be to use reclaimed materials" with a series of possible policies or factors that complete the question. As shown in Figure 3, 100% of respondents indicated that they would be very receptive to using reclaimed materials if it saved money. Zero respondents indicated that they already use reclaimed materials and none of them responded "Not at all" to the question.

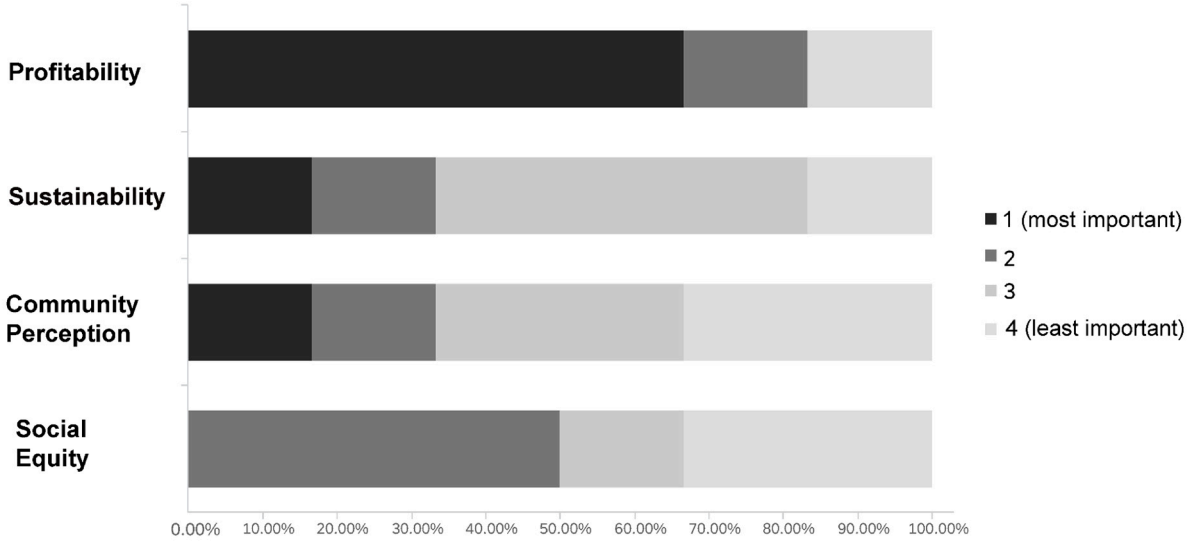


Figure 2. Responses to developer survey question: In considering your mission as a developer, how important are the following values when you invest in a property? Rated from 1 (most important) to 4 (least important) in decision-making.

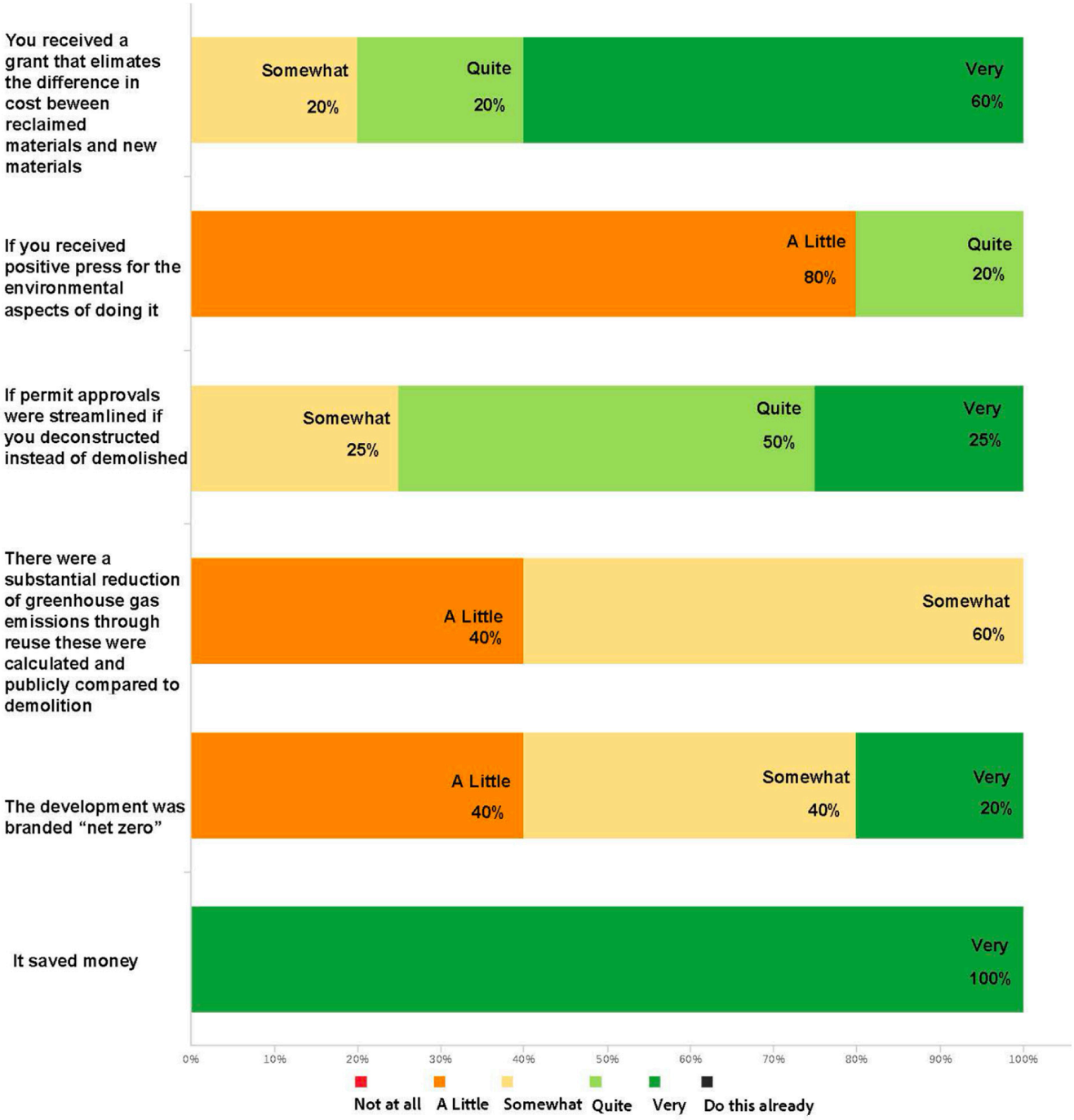


Figure 3. Responses to Developer Survey Question: How likely would you be to use reclaimed materials if. . .?

As noted earlier, the small number of survey responses can impact the reliability, representativeness, and validity of the simulation results. However, many of the survey responses appeared to be similar to insights gained from prior interviews and could be triangulated or validated in comparison with qualitative interview results. The study area is a small town with a very limited number of developers that undertake development projects. If the ABM is similarly replicated in a larger city, a larger set of survey responses is recommended or an alternative path to determining and testing developers' practices. Additionally, a higher response rate is likely to be achieved in a simplified survey. Alternative methods could be used to seed or to test the validity of the model include validation against historical observations and sensitivity analysis.

2.2. Agent-Based Model Design

The methodology for developing the ABM is organized into three sections: model architecture, production workflow, and model assessment framework. The model architecture consists of agents, the environment, and agent-environment interactions. In this model, the agents are developers who move through a two-dimensional map of Ithaca. Developers are categorized by size, capital availability, and construction timelines based on survey data. Each developer evaluates parcels for suitability using a rating system based on various criteria. Once a suitable parcel is identified, the developer moves to that parcel to begin development.

The model's environment is hierarchical, comprising city parcels. Individual parcels have unique identifiers, geometries based on real city data, and coordinates in a reference system. Some parcels are designated as historic properties or districts. The city parcel class manages the addition and removal of parcels and developers, governing dynamic interactions within the simulation while tracking metrics such as the improvement-to-land ratio. The city model class manages the overall simulation, coordinating parcels, developers, and visibility layers as the model progresses through time steps. This class loads GeoJSON parcel files along with CSV files containing data on zoning, building construction costs, and carbon calculation costs, tracking metrics such as the number of developed versus undeveloped parcels, development types, total square footage of new construction, and carbon emissions.

The model was developed in Python 3.8, using the mesa-geo library. After the modeling and software framework had been established and tested, OpenAI's ChatGPT 5 (re-leased 7 August 2025) was used for assistance with Python code development, including support for structuring, developing, re-structuring, and troubleshooting aspects of the code base. All outputs from this process were then reviewed and edited by the authors to ensure validity. The mesa-geo library was chosen for its ability to handle spatial data and model complex urban interactions. Its flexibility and scalability made it ideal for simulating Ithaca's urban development dynamics. Agent-environment interactions occur when agents assess parcels based on a suitability rating. This rating aggregates several weighted factors—i.e., proximity to key locations, improvement-to-land ratio, and development potential—into a final normalized score. Agents generally prefer parcels that meet specific criteria, such as proximity to bus stops, and parcels with zoning that matches their intended development. These interactions were informed by insights from the survey and interviews.

Phase one of the production workflow was the preprocessing of survey results. Survey results were collected, and insights were extracted for use in the model. These insights were incorporated into the agents and scenarios of the model. Data from the survey was primarily used to model developer behavior and preferences in urban development, along with the key factors influencing parcel assessment. In phase two, variables affecting developer behavior and property reuse potential were identified and translated into code. From here, scenarios were developed and implemented that would simulate policy changes, financial incentives, and stakeholder interactions. Finally, phase three involved running multiple iterations of the model to produce refinements.

The ABM is structured on several key assumptions. The core components include agents, interactions, assessments, and visualization (Figure 4). The primary agents, representing developers, are categorized by capital constraints, construction timelines, and market share. They are responsible for evaluating and transforming parcels based on various assessment criteria. The environment, represented by parcels, encompasses the geospatial attributes that define each parcel's reuse potential. Interaction involves the processes of assessment and the actions taken by developers, which include evaluating

the suitability of parcels and implementing a range of reuse strategies to optimize the development outcomes.

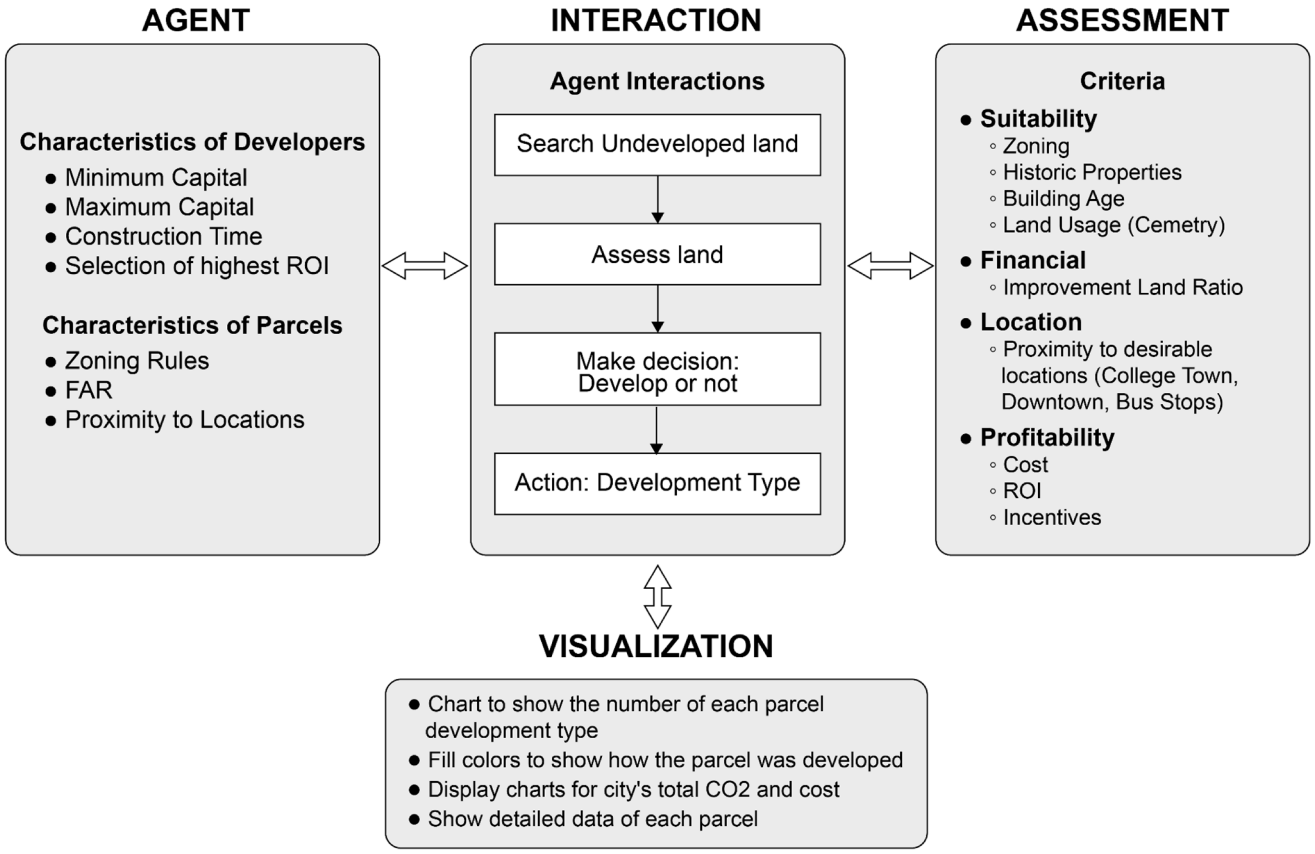


Figure 4. Model architecture.

Real estate developers are the agents in the model who reconstitute the built environment of the city. Developers were classified into seven general types. This typology was developed from an analysis of local directory information for developers who operate in the region and from a review of existing literature. The typology was developed independently from the survey of developers and then the typology was compared to survey responses for further refinement. Developer classifications relate to the size of the project a developer will pursue (i.e., by construction time), the starting capital range available to spend, and how many of a given type are operating within the city (Table 1). For any simulation run and specified number of developers, the model will instantiate the total number of developers as close to the percentages listed in Table 1. To make for a more realistic representation, developers were constituted as firms, where each firm is able to deploy a fixed number of maximum concurrent developments based on its capital allocation capabilities.

At the start of the simulation, the iteration loop runs for a set number of steps, with each step representing three months. In each iteration, developer agents select a random parcel and make decisions to develop or not, and the type of development given predefined criteria guiding their choices (Figure 5). These criteria include the improvement-to-land ratio (ILR), development suitability, proximity to desirable locations, and profitability, all evaluated through a mix of spatial and financial analysis. Agents prioritize parcels with lower ILRs, higher floor-to-area ratios (FAR), and those closer to key urban areas. Additionally, factors such as zoning regulations, available capital, and the potential for material reuse influence whether a parcel is preserved or redeveloped.

Table 1. Table of Developer Types/Assumptions.

Developer Type	Minimum Capital ($)	Maximum Capital ($)	Construction Time (Years)	Percentage Total Developers	Max. Concurrent Developments
Large-Scale	10,000,000	50,000,000	5	21.05%	4
Regional	3,000,000	10,000,000	3	15.79%	3
Local Mid-Market	1,000,000	3,000,000	3	15.79%	3
Small-Cap	250,000	1,000,000	3	21.05%	4
Specialty	50,000	250,000	1	15.79%	3
Micro-Infill	25,000	50,000	1	5.26%	1
Owner-Builder	10,000	25,000	1	5.26%	1

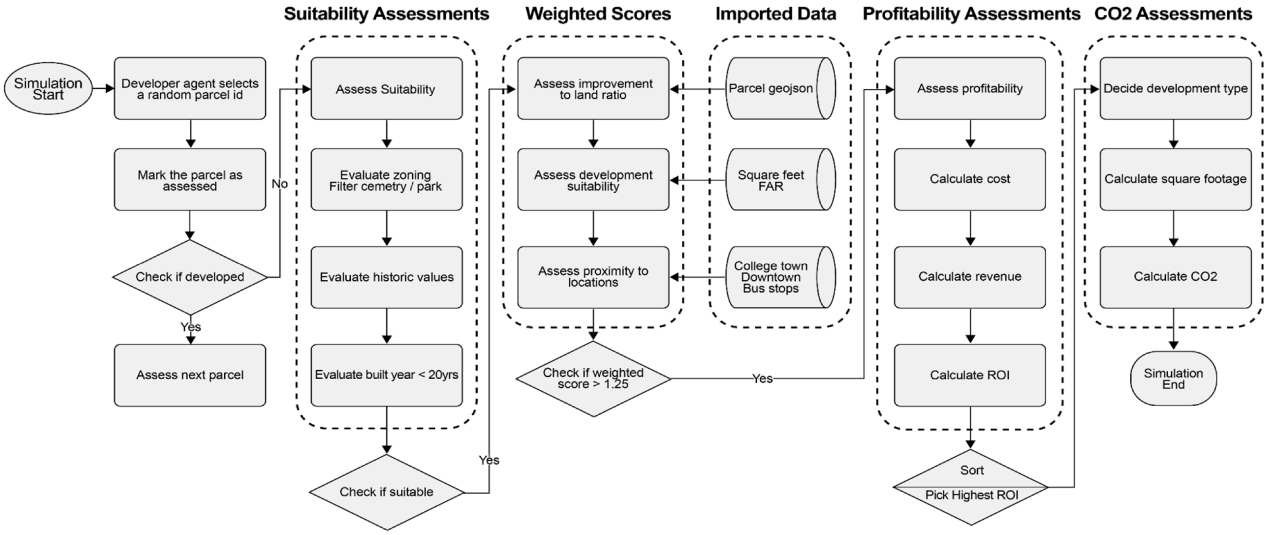


Figure 5. Developer Agent Decision Flowchart.

As the simulation progresses, agents adjust their actions dynamically in response to evolving constraints and opportunities. This dynamic adjustment occurs through a simple ε-greedy action-value mechanism where agents explore to locate optimal development projects influenced by the scenario constraints. ε-greedy action-value is a simple reinforcement-learning rule where, at each step, an agent chooses a random action with probability ε (ε = 0.33) and otherwise picks the action with the highest learned value, using estimated ROI as a tie-breaker. Action values, the Q-values, are updated from observed payoffs via a temporal-difference rule, so projects that yield higher rewards become more likely over time. In the model, developers individually initialize with fixed learning parameters and a Q-table, which contains the learned actions. Developers search for projects randomly and within development utilize the ε-greedy algorithm to determine optimal development types. Optimal development is a function of ROI above the developer threshold and costs less than the developer's capital. Given the agent can have multiple optimal development types per parcel, the developer either randomly selects a development action for a fixed probability or selects a development action that has the highest learned Q-value. The Q-table is updated per developer, which affects the next development choice of the developer. Importantly, developers are not learning future actions or estimating future rewards, nor are they reaching a convergence condition.

Additionally, the model includes a proxy market mechanism, by way of changing salvage price. Salvage price enters as a per-area credit for recovered materials that lowers effective project cost and raises return-on-investment (ROI) on deconstruction and material-

reuse options. As the salvage price increases, ε-greedy developers are more likely to choose reuse-heavy projects over virgin new builds.

Developers operate in an environment where different city policy configurations can exist. These configurations, termed scenarios, were developed based along the spectrum of reuse (Figure 1). The scenarios are defined as follows:

- Business as Usual: Current development practices and regulations remain unchanged, serving as the baseline against which other scenarios can be compared. Developers follow Ithaca's existing building codes and development regulations, with no additional incentives or mandates to engage in preservation or deconstruction of buildings or reuse of building materials.
- Incentives for Deconstruction + Reused Materials in New Construction: Financial incentives are provided to developers who choose to utilize reused materials, such as through deconstructing existing buildings. Tax credits, grants, subsidies, or low-interest loans are offered for saving—in the case of deconstruction—or using a certain percentage of reused materials. The awareness and availability of reusing materials have increased due to government campaigns.
- Mandatory Use of Reused Materials in New Construction: Regulations require developers to incorporate a minimum percentage of reused construction materials in their projects. Building codes are revised to mandate the use of reused materials, such as 20% by volume, with penalties imposed for non-compliance. Enhanced enforcement mechanisms and regular inspections ensure developers conform to new building codes. Based on conversations with researchers, reused material amounts are aspirational. It is still relevant to model given a scenario-based approach and the long-term horizon presented in this paper.
- Maximize Preservation of Existing Buildings: This scenario involves leveraging both incentives and regulations to achieve a 90% rate of building reuse. By offering financial incentives such as tax breaks, grants, and low-interest loans, along with implementing mandatory reuse ordinances and zoning adjustments, the aim is to prioritize the preservation of existing buildings.

The qualitative descriptions above were translated into six key parameters for use across the scenarios of the model: building reuse percentage, preservation incentive, material reuse incentive, material reuse percentage, minimum material reuse mandate, and city reuse enforcement strength (Table 2). Enforcement strength, in the context of the model, means that the city is enforcing minimum material reuse on new developments, and should not be confused with zoning rule enforcements, which are hard-coded into the model.

Table 2. Scenario Parameters.

Scenario	Building Reuse (%)	Preservation Incentive ($/ft^2)	Material Reuse Incentive ($/ft^2)	Material Reuse (%)	Min. Reuse Mandate (>%)	Material Reuse Enforcement Strength (0–1)
Business as Usual	10%	0	0	1%	0%	0.0
Incentives for Deconstruction + Reused Materials in New Construction	10%	0	40	25%	0%	0.4
Mandatory Use of Reused Materials in New Construction	10%	0	10	50%	20%	0.9
Maximize Preservation of Existing Buildings	90%	60	0	0	0%	0.0

In general, these parameters influence developer feasibility calculations when assessing whether or not to develop a parcel. Feasibility is determined through a mechanism

that considers cost versus capital availability and predicted return ROI versus the agent's threshold. The building reuse percentage shifts the cost-revenue mix from new building to refurbishment of existing floor area by the specified amount. For the preservation incentive, expected revenue is increased by a subsidy per square footage for the amount of a retained (i.e., preserved) structure, while the material reuse incentive adds to annual revenue for the reused portion of new construction. The material reuse percentage fixes the total amount of new construction that incorporates reused materials, connecting the salvage pricing market to developer decision-making. In the case of the minimum material reuse, a floor for total material reuse in new development is set, effectively penalizing ROI calculations in favor of not using virgin materials. Finally, enforcement strength impacts the learning process of developers by increasing material reuse mandate penalty, reducing total ROI and pushing development away from virgin material use.

The model outputs, given any selected scenario, included both a map of Ithaca and the parcel development changes made by the agents, graphs detailing per-run metrics across different dimensions, and summary print statements aggregating model metrics provided at the end of each simulation run. The metrics provided can be generalized in the following four categories: results of construction activities by type, developer-as-firm metrics, total embodied system CO_2 emissions generated, and the percentage of reuse or deconstruction activities.

3. Results

The ABM model was set to run for 45 quarters, or approximately ten years: from January 2025 to April 2036. The number of developers (i.e., firms), was set to 20 out of a total of 100, which included the per-developer maximum concurrent development counts. The learning rate—or how quickly developers update their preferences—was set to 0.2 out of a total of 1.0. The developer exploration rate, which approximates how often firms will try a non-optimal development project, was set to 0.33 out of a total of 1.0. With these settings, the four scenarios were each run 50 times. Each run used a different randomly generated seed, and the seed associated with each run was recorded to manage randomness, and collected minimum, maximum, and mean results for 19 outputs. Mean values are reported in Table 3, while the full values are available by request. Following this, we compared the results across each scenario.

Table 3. Key performance metrics used to evaluate each development scenario. These metrics are grouped by type.

Model Reporting	Scenario: Business as Usual	Scenario: Deconstruction Incentive	Scenario: Mandatory Material Reuse	Scenario: Maximize Preservation
Environmental indicator				
Embodied CO_2 (t)	28,433.49	18,738.19	19,540.59	17,012.34
Urban Development Activity and Investment indicators				
Total Investment ($)	11,387,626.92	7,062,035.38	6,872,301.14	7,141,988.56
Total Developed Footage (ft^2)	6,186,242.03	4,113,133.45	4,260,093.11	4,124,826.46
Total Parcels Assessed (*n*)	270	205	215	271
Building Material Reuse Indicator				
Avg Salvage Price ($/$ft^2$)	19.94	19.96	19.90	20.02
Total No New Construction Parcels (*n*)	128	94	97	213

Table 3. *Cont.*

Model Reporting	Scenario: Business as Usual	Scenario: Deconstruction Incentive	Scenario: Mandatory Material Reuse	Scenario: Maximize Preservation
Types of Urban Development				
Total Refurbishment + Addition (reused materials) Parcels (*n*)	13	15	29	11
Total Refurbishment + Addition (virgin materials) Parcels (*n*)	11	8	8	11
Total Deconstruction + Rebuild (reused materials) Parcels (*n*)	8	69	61	10
Total Demolition + Rebuild (virgin materials) Parcels (*n*)	95	8	9	10
Total Vacant Lot: New Build (reused materials) Parcels (*n*)	2	7	7	10
Total Vacant Lot: New Build (virgin materials) Parcels (*n*)	9	1	1	2
Developer Activity by Type of Developer				
Developer: Large-Scale	57	8	41	58
Developer: Regional	46	36	38	46
Developer: Local Mid-Market	35	27	28	34
Developer: Small-Cap	46	36	38	46
Developer: Specialty	62	47	49	63
Developer: Micro-Infill	10	9	8	10
Developer: Owner-Builder	10	9	9	11

3.1. Scenario Comparison

The final model state, per a single run of each scenario, at the end of 45 quarters, is shown in Figure 6. Each of the four images shows development change per parcel in the city, with plots colored one of the seven types of construction, which represent five categories: no change, refurbishment, deconstruction, demolition, or construction on a vacant lot. As can be seen, all four scenarios had a large percentage of parcels with no new construction. This is an expected result, as developers across the scenarios find that anywhere from 45% to 78% of parcels they examine are either not worth developing or cannot be developed for a variety of reasons. Reasons for not developing can include ROI considerations or an inability to pursue redevelopment given constraints associated with historic designations. Importantly, the geographic distribution of development activity is shifted toward downtown Ithaca and the surrounding business improvement district (BID). This results from explicit modeling choices, such as including higher developer ROI located near downtown (and the nearby Collegetown neighborhood) and the prevalence of bus stops.

Looking at Figure 6, the top left scenario, Business As Usual, shows significant demolition activity with virgin material usage in new construction, while Deconstruction Incentive and Mandatory Material Reuse prefer deconstruction, and Maximize Preservation limits all construction types, producing mostly no new construction. Deconstruction is functionally similar to demolition, but instead involves the systematic dismantling of buildings, requiring more time and injecting into developer ROI considerations an increase in value from the salvage of on-site material. The economic value could come from one or more of the following sources: tax incentives from the donation of materials, direct resale of materials to other users or contractors, reuse of materials in new projects in lieu of purchasing new materials or realizing value from local or state government incentives.

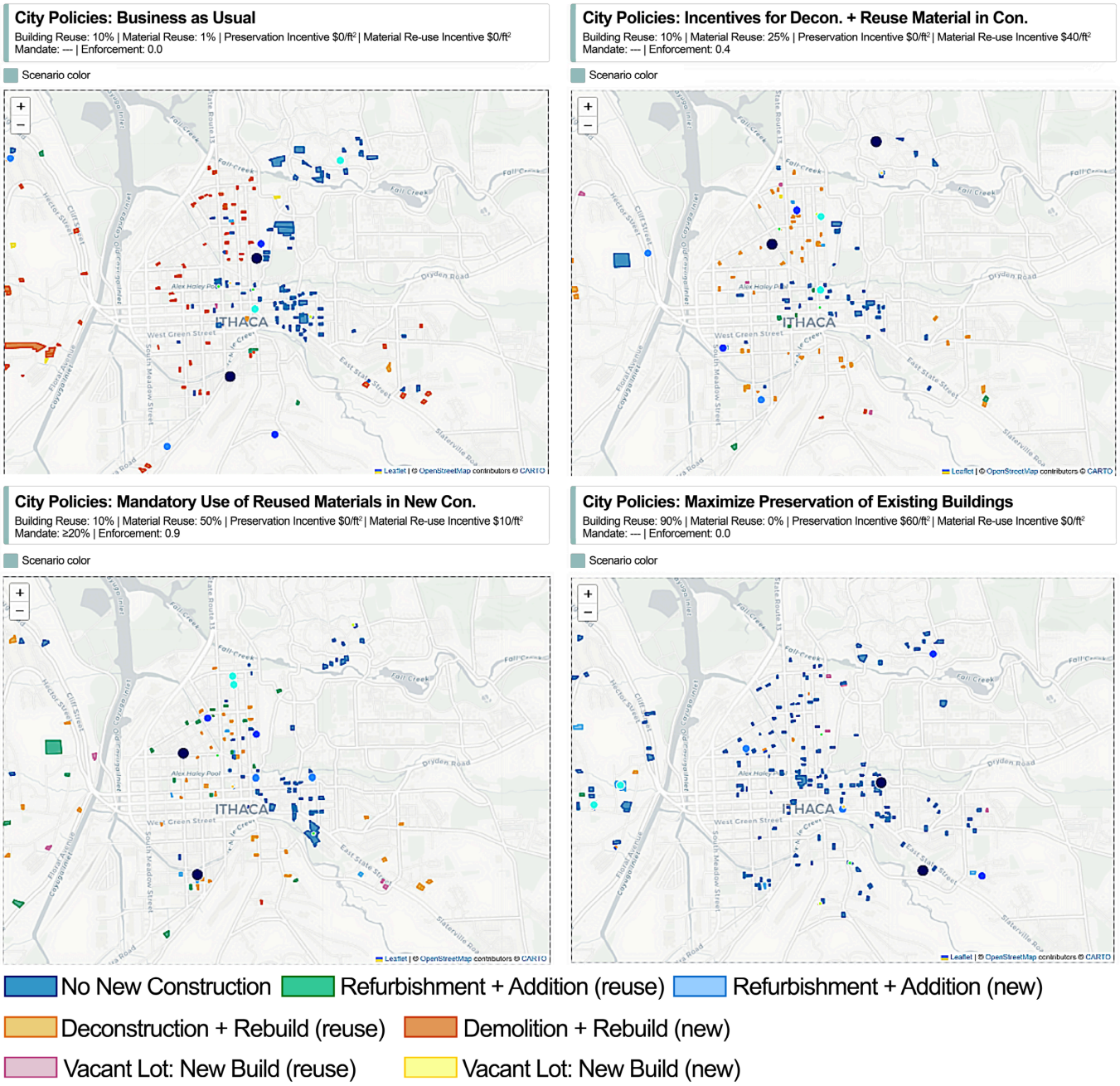


Figure 6. Scenario Comparison: Model Run (clockwise from top left to bottom right: Business As Usual, Maximize Building Reuse, Maximize Recovery of Building Material, and Maximize Preservation and Reuse).

Deconstruction became viable when material reuse incentives and mandates increased above the Business As Usual scenario baseline. This tradeoff between demolition and deconstruction is a key feature of this project and comes from core assumptions derived from the pyramid of reuse (Figure 1). Scenarios with high deconstruction counts have lower activity for all other development types, yet still have high total developed parcels. In contrast to the other three scenarios, Maximize Preservation restricts total parcel development and reaches the second greatest amount of investment activity, which is driven by incentives, mandates, and enforcement.

The results of each scenario run are shown in Table 3. This table summarizes the key performance metrics used to evaluate each development scenario, including embodied CO_2 emissions, total investment cost, total developed building area, and the number of

parcels assessed. Embodied CO_2 here captures up-front emissions from materials, transport, and construction—and deconstruction—only. This excludes operational energy use and end-of-life emissions. Embodied carbon is important because its impacts are front-loaded and therefore crucial for near-term carbon estimation. It also tracks factors such as average subsidy and salvage price per square foot, alongside detailed parcel-level outcomes describing whether sites were left undeveloped, refurbished, deconstructed, rebuilt, or developed on vacant lots, and whether reused or virgin materials were employed. Additionally, total development per our seven developer types is included in our summary results.

Of the four scenarios, Business As Usual produces the most CO_2 emissions and total development while having the highest total dollars invested and total square footage developed. This is in contrast to the other three scenarios, which all have considerably lower development, embodied carbon, investment, and square footage developed. Importantly, scenarios Deconstruction Incentive, Mandatory Material Reuse, and Maximize Preservation all have similar values when it comes to embodied carbon, investment dollars, and developed square footage. Noteworthy in the results is that Maximize Preservation has the highest number of parcels with no new construction and limited development across any of the other development options yet achieves the lowest total embodied carbon (17,012.34 tons) while maintaining the second highest total investment ($7,141,988.56). Both Deconstruction Incentive and Mandatory Material Reuse achieve similar results across many scenario outputs, including embodied carbon (18,738.13 tons and 19,540.59 tons, respectively), total investment ($7,062,035.38 and $6,872,301.14), total developed square footage (4,113,133.45 sq. ft. and 4,260,093.11 sq. ft.), no new construction, and deconstruction. Interestingly, Deconstruction Incentive and Mandatory Material Reuse diverge in the distribution of development per developer type, with significantly more projects completed by large-scale developers in the Mandatory Material Reuse scenario. Forty-one projects were completed by large-scale developers in the Mandatory Material Reuse scenario versus eight projects by large-scale developers in the Deconstruction Incentive scenario). More testing and verification of these results is recommended.

3.2. Analysis

In general, the four scenarios show that policy levers have a significant impact on what gets built, how much construction happens, and the total number of projects developers are willing to consider. The results indicate that incentives and mandates both play important roles in shaping developer decision-making when it comes to the reuse of buildings and materials. In an environment with limited policy intervention, represented by the Business As Usual scenario one, developers pursue many projects, reject many opportunities, and follow a standard form of economic logic: demolish and use virgin materials to make a new structure.

Across the four models, a distinction can be made between total developer assessment activity versus total urban development intensity, where total developer assessment activity is the assessment of parcels and intensity is the transformation, or development, of parcels. Two scenarios, Business As Usual and Maximize Preservation, have high developer assessment activity, while the other two scenarios, Deconstruction Incentive and Mandatory Material Reuse have moderate development activity. However, of the four scenarios, Maximize Preservation has low development intensity, with mostly no new construction on parcels despite the significant developer assessment activity. This marks the first result of our paper: that a Maximize Preservation scenario can lead to the lowest embodied carbon requirements, but this comes with moderate investment dollars, while producing limited parcel-level changes in the built environment. From the city's perspective, embodied carbon is minimized while not significantly constraining developer investment activity,

especially relative to the total investment dollars recorded in the Deconstruction Incentive and Mandatory Material Reuse scenarios. From a developer's perspective, while few projects actually pass ROI hurdles for parcel-level development, there are still considerable opportunities to invest in the market given the preservation incentive for square footage development.

The two scenarios, Deconstruction Incentive and Mandatory Material Reuse, each have the lowest developer assessment activity across our four scenarios. These two scenarios show the overall lowest number of parcels with no new construction, a focus on deconstruction as development activity, and produce comparable amounts of investment dollars and developed footage. In both of these scenarios, we can see the second result of our study: that incentivizing material reuse leads to strong ROI signals for developers, reducing the search for suitable properties as deconstruction becomes a viable avenue for generating returns. Importantly, the overall moderate development activity and high urban development intensity lead to moderate embodied carbon emissions, though still much lower than the Business As Usual scenario. Either of these two scenarios, either Deconstruction Incentive or Mandatory Material Reuse, could offer a balance for both the city and developers, addressing carbon emissions concerns, while leading developers to find development that meets their ROI needs and that stimulates significant market-wide activity. The policies of either of these scenarios could be relevant for a city looking to maximize the interests of the following: emissions reductions, developer ROI, household transformation that results in new buildings, and support for a local budding material reuse market.

In our model, the city is unconstrained by how much it can subsidize deconstruction, most evident in the Mandatory Material Reuse scenario. This provides a cautionary tale. In the Mandatory Material Reuse scenario, large-scale developers learn that there is significant financial incentive to deconstruct buildings and use the cost savings to expand investment and development, while developers at other scales may be constrained in responding to mandates. The dominance of larger-scale developers in some scenarios may represent a threat to smaller-scale developers. This was a concern raised by local small-scale developers in interviews and survey results. These small-scale developers described themselves as more sensitive to local context and community needs, but also having less capital and more sensitivity to new requirements.

Developer differences play an important role in the outcomes. At a fundamental level, total available capital per project influences those projects that, after ROI calculations are considered, are deemed feasible. Crucially, though, as can be seen in the Deconstruction Incentive scenario, the largest developers (i.e., large-scale) are unable to develop many projects, and are likely being outcompeted by mid-sized developers because the material reuse incentive per square footage offsets the high-capital advantage of any larger developer. From this, we note another result of our study: that scenario policy configurations can have a differential impact on developer types, producing environments that favor—or disfavor—certain classes of developers.

The results of this exploratory model should be used with caution. As noted earlier, key assumptions in the model were derived from a combination of interviews and a survey with a limited number of responses. This can introduce errors in the model. Additionally, the perspectives and behavior of developers in a small college town in New York may differ from those in other cities or regions. The primary contribution of this research project was to develop and test ABM techniques for scenario planning. As noted above, the results and models developed in this research project are available for replication. It is recommended analysts, officials, and planners select scenario planning techniques that are most appropriate to the time, resources, and concerns of their community. The research

team found the ABM modeling process to be time-intensive and required the use of simulation tools that may not be realistic unless without a robust partnership between university researchers and local officials.

4. Discussion

The results of the ABM scenario simulations are one aspect in a larger project aimed at realizing circularity at the city-scale, using material and building reuse. While the output from the scenarios provides important insights, the goal of this project is to operationalize those insights in collaboration with local community stakeholders. Having an accessible user interface design offers an inclusive and interactive platform that can be expanded to engage a broader range of stakeholders.

As an additional component of the project, a visual interface was designed for iterative engagement with local stakeholders. Although it is rarely emphasized in the ABM literature, this feature is important. First, the visual interface can aid in communicating the model variables and results to users. Second, the interface aims to be a focal point for discussion, both about observed changes and desired changes in the city. Third, it functions as an educational and advocacy tool, with the potential to influence actors such as city officials. As shown in Figure 7, the interface offers users the chance to explore the four policy configuration scenarios, to understand how developer behavior changes, and to learn how the spectrum of reuse influences carbon emission outcomes in Ithaca. Users have access to a map, a drop-down for selecting policy configuration scenarios, a range of feature selectors, various results charts (e.g., construction types, CO_2 emissions, dollars invested, etc.), and the spectrum of reuse pyramid (Figure 1) for use as educational support. Changes could include implementing advanced visualization techniques, such as 3D mapping and interactive charts, which could offer richer insights into the spatial effect of various reuse options. It is also crucial to note that setting up, testing, and maintaining the graphical interface has complexities and can be demanding. These tasks would require technologically proficient university researchers or city officials to replicate, operate and maintain it. Beyond this, they would need to have a commitment to interactive, open public use of the graphical interface. This interface has been made freely available on GitHub (see the Data Availability Statement below) for replication in other studies and communities.

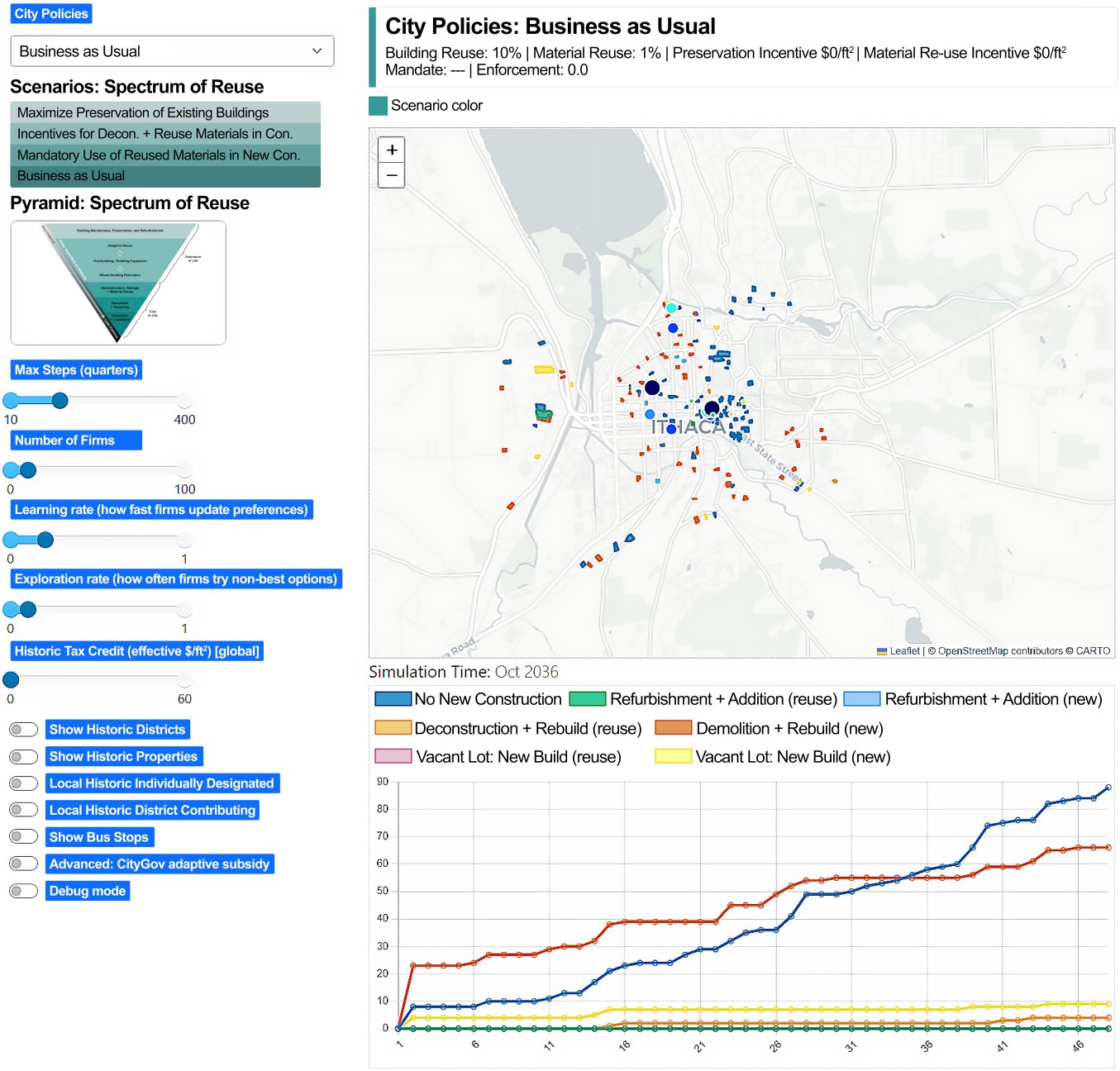


Figure 7. User Interface.

5. Conclusions

This research developed an ABM model that simulates developer behavior along a spectrum of reuse, offering an exploratory scenario-planning tool for examining various urban development scenarios that can be used to implement circularity in the built environment. The model incorporated survey data on developer behavior. Results across the four reuse scenarios show different future states of Ithaca under different policy configurations. Depending on how city leaders—supported by community stakeholders—choose to support or encourage material reuse and building reuse, different development patterns emerge that impact investment and embodied carbon throughout the city.

Importantly, this research has limitations. Despite the triangulation of survey data with a focus group, prior interviews, and an analysis of building and demolition permits, and the creation of a developer typology based on locally available directory information, the incorporation of insights from a small number of survey responses increases the chance that

assumptions in the model are incorrect. The small sample size of the developer survey restricts the ability to draw statistically significant conclusions about developer behaviors and preferences. Increasing the sample size would yield more reliable data, offering a deeper understanding of the factors influencing development decisions. Given this limitation, results should be treated with caution and understood to be exploratory in nature.

Further calibration and validation should be performed before application for policy analysis. The model also requires more precise and region-specific cost assessments to improve the accuracy of the economic analyses. Future researchers can utilize RSMeans data to improve the model. Improving CO_2 reduction calculations for different development types is also essential, as a more detailed examination of carbon impacts will enhance the model's relevance to sustainability goals. Novel methods to quantify the benefits of deconstruction and reuse practices in terms of the amount of CO_2 reduced are also needed. In addition, visualizing job opportunities and resilience calculations within the modeling framework is essential for municipalities to gain a more holistic understanding of urban development impacts.

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Institutional Review Board Statement: This research was reviewed and approved for an exemption by Cornell University Institutional Review Board for Human Participant Research staff. The project as described does not meet the definition of "human subjects research" as defined by the Department of Health and Human Services Code of Federal Regulations 45 CFR 46, for the following reasons: Research focuses on methods/policies/procedures related to various aspects of development, building and building material reuse and is not designed to contribute to generalizable knowledge about human participants who will contribute to the study. This project is not subject to review and oversight by Cornell's Human Research Protection Program, and IRB approval is not required for the project activities to commence.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The agent-based model code is publicly available on GitHub (https://github.com/RealtimeUrbanismLab/ithacaDeveloperABM, accessed on 8 June 2026). GitHub does not assign version numbers to the platform itself; reproducibility is ensured by referencing the specific commit used to generate the results reported here: commit 174898a414ee984b1fe0b3fc22ed00c54b963e7b on branch v2. Available online: https://github.com/RealtimeUrbanismLab/ithacaDeveloperABM/commit/174898a414ee984b1fe0b3fc22ed00c54b963e7b (accessed on 8 June 2026).

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Abbreviations

The following abbreviations are used in this manuscript:

ABM	Agent-based Model
CE	Circular Economy
CO_2	Carbon Dioxide
CSV	Comma-Separated Values
LCA	Life Cycle Analysis
FAR	Floor Area Ratio
GHG	Greenhouse Gases
ROI	Return on Investment

Appendix A

The key details of the model, including the major features and values, and which python file these are located in, are presented below in Table A1.

Table A1. Key Features of the Model.

Feature	Descriptor	Code
Spatial Domain	Map on 42.4433, −76.499	server_multiple.py
Simulation Calendar	Quarter-year ticks (0.25 yr per step)	agents.py
Start Year	2025	model.py
Agent Types	Parcel, Developer, and optional CityGov	model.py
Number of Firms (Developers)	1 to 100, slider set to 10	server.py
Developer Size	Capital ranges and base construction time (yrs): from \$50 M to \$10 k; time from 5 years to 1 year	dictionaries.py
Maximum Concurrent Development Per Firm	Contingent on capital size: from 4 to 1	agents.py
Learning Rule	Per-developer ε-greedy over Q(state, action); Q-update with step size α	agents.py
Minimum Build Duration	0.5 years (floor applied to projects)	model.py
Per Building Type Duration Adjustments (year/project)	Pres, NoNew: 0.00; Pres, Reuse: 0.01; Pres, New: 0.02; Demo, Reuse: 0.03; Demo, New: 0.02; Empty, Reuse: 0.01; Empty, New: 0.005	dictionaries.py
Deconstruction Parameters	labor_mult 1.5; duration_mult 2.5; salvage_mean 0.45; salvage_sd 0.10	dictionaries.py
Parcel Assessment Weights	improvement-to-land 3.0; suitability 2.0; proximity 1.0	dictionaries.py
Environment Thresholds	ROI threshold 0.70; parcel assess threshold 0.15; salvage price 20.0	model.py
Historic Preservation Rule	Force preservation for locally designated historic parcels	agents.py
Construction Cost and Rent (by building type)	New: Residential cost 2.0001, rent 2.6, time/ft^2 0.3; Office 1.9707, 1.9, 0.3; Retail 1.6198, 1.7, 0.3. Reno: Residential 1.0005, 0.5, 0.2; Office 0.9521, 1.0, 0.2; Retail 0.9024, 0.8, 0.2. Reuse: Residential 1.5000, 0.8, 0.1; Office 1.0000, 1.5, 0.1; Retail 0.8000, 1.3, 0.1. Demolition cost index 0.05.	construction_cost.csv
Embodied Carbon	New build uses high per-ft^2 factor; renovation uses lower factor; preservation-only = 0; material reuse subtracts a credit proportional to reuse share.	carbon_emissions.csv; model.py
Carbon Emission Factors	CO_2 factor (index): New 100; Material Reuse 20; Preservation 5. (All Time_per_ft = 0 in source table.)	carbon_emissions.csv
Zoning Constraints Summary	25 districts/4 uses {Office, Retail: 12; Residential: 10; Office: 2; Factory: 1}. Max stories: 2–14; Max height: 30–140 ft; Lot coverage: 20–100%. Minimums present in business/CBD zones: min height 25 ft (n = 11), min stories 2 (n = 12).	zoning_rule.csv

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