

An Extensible, Modular Architecture for Simulating Urban Development, Transportation, and Environmental Impacts

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Abstract

UrbanSim simulates the development of urban areas, including land use, transportation, and environmental impacts, over periods of twenty or more years. Its purpose is to aid urban planners, residents, and elected officials in evaluating the long-term results of alternate plans, particularly as they relate to such issues as housing, business and economic development, sprawl, open space, traffic congestion, and resource consumption. From a software perspective, it is a large, complex, system, with heavy demands for excellent space efficiency and support for software evolution. It consists of a collection of models that represent different urban actors and processes, an object store that holds the state of the simulated urban environment, a model coordinator that schedules models to run and notifies them when data of interest has changed, and a translation and aggregation layer that performs a range of data conversions to mediate between the object store and the models. The paper concludes with a discussion of the lessons learned regarding software architecture to support rapid evolution within the field of urban simulation.

1 Introduction

Patterns of land use and available transportation systems play a critical role in determining the economic vitality, livability, and sustainability of urban areas. Transportation interacts strongly with land use. For example, automobile-oriented development may induce demand for more roads and parking (which in turn induces more automobile-oriented development), while compact urban environments may induce more walking and demand for transit. Both land use and transportation have significant environmental effects, in particular on emissions, resource consumption, and conversion of rural to suburban or urban land.

Good technical support can play an important role in fostering informed civic deliberation and debate on these issues. To aid urban planners, residents, and elected officials in evaluating alternate scenarios—packages of policies and investments—we want to simulate the effects of these scenarios on patterns of urban growth and redevelopment, of transportation usage, and resource consumption, over periods of twenty or more years.

Early attempts at comprehensive urban simulations in the 1960s and early 1970s were largely unsuccessful (Lee, 1973, 1994). Much has changed since then, both on the supply side (including dramatically improved hardware, theoretical and methodological advances such as discrete choice modeling (McFadden, 1973, 2000), and the emergence of a commercial GIS market), and on the demand side (including public concern over sprawl, legal challenges to transportation plans made without considering their land use implications (Garret and Wachs, 1996), and regulatory requirements such as the Clean Air Act Amendments of 1990). As a result, there has been somewhat of a renaissance in interest in urban simulation modeling over the past decade.

However, in terms of planning agency practice, land use planning is still often poorly integrated with transportation planning, despite their strong interactions. While transportation models have been in routine use by metropolitan planning organizations for decades, the state of common practice in land use modeling, and in integrated land use and transportation modeling, is much less advanced than that for transportation modeling alone. For example, the Travel Model Improvement Project sponsored by the U.S. Department of Transportation and the Environmental Protection Agency has focused a substantial investment on TRANSIMS, a new traffic microsimulation model (Nagel et al., 1999), but almost no federal investment has occurred on land use modeling to integrate with these new travel models.

The UrbanSim system has been designed and implemented in response to these needs. It is a system for simulating the development of urban areas, including land use, transportation, and environmental impacts, over periods of twenty or more years (Waddell, 2000; Waddell et al., 2000, 2001). From a software perspective, it is a large, complex application, with heavy demands for excellent space efficiency and support for software evolution. The system is fully operational and freely available via our web site at www.urbansim.org. It consists of around 130,000 lines of Java code for the core UrbanSim system; including the visualization, data preparation, and calibration tools, the total is approximately 200,000 lines, plus another 100,000 lines of automatically generated code. It has been applied to Eugene-Springfield, Oregon; Salt Lake City, Utah; and Honolulu, Hawaii, working with the planning

organizations in those metropolitan regions. Application to other regions is underway. We have also done a historical validation of the system, starting UrbanSim with 1980 data for Eugene-Springfield, running it through 1994, and comparing the results with what actually transpired (Waddell, 2000). Correlations between results of the 15 year simulation and observed data were generally above 0.8 at the level of the grid cell, and were higher for spatial aggregations such as traffic analysis zones.

2 Related Work

There is a huge body of work on urban transportation modeling, land use modeling, and integrated land use/transportation modeling. Reviews and assessments of existing systems are given in references Dowling et al. (2000); Environmental Protection Agency (2000); Miller et al. (1999); Parsons Brinckerhoff Quade and Douglas (1998); Southworth (1995), among others. Considerable progress has recently been made in land use modeling in both experimental and deployed systems. However, except for UrbanSim, all the operational models in use by planning agencies rely on a cross-sectional, aggregate, equilibrium approach. Such models include DRAM/EMPAL (Putman, 1983), TRANUS (de la Barra, 1995), MEPLAN (Echenique et al., 1990), METROSIM (Anas, 1994), and 5-LUT (Martinez, 1992). The cross-sectional, equilibrium framework implies that there are no relevant temporal dynamics to the processes of urban change; rather, one can model urban development as a static process that represents an economic or a transportation optimization problem. In other words, these models could be run for the year 2050 without needing to model the dynamics of evolution between the current time and the year 2050. Clearly, this is a severe simplification, and makes problematic the potential integration of these models with models of dynamic environmental processes, or even of the dynamic evolution of human behavior with respect to the built environment. The approach taken in UrbanSim more closely compares to the dynamic disequilibrium HUDS model (Kain and Apgar, 1985) and the DORTMUND microsimulation model (Wegener, 1983; Wegener and Spiekermann, 1996), but differs from these in having substantially greater spatial detail and incorporating the nonresidential dimensions of urban development.

Another substantial body of related work concerns Integrated Assessment Models (IAMs), which model the interactions between human and ecological systems in an integrated way. A major motivation for models of this kind is the assessment of global environmental change (Alberti, 1999; Dowlatabadi, 1995; Parson and Fisher-Vanden, 1995; Rotmans et al., 1995; Weyant et al., 1996). While the first generation of operational IAMs has emerged in the mid-eighties, their roots can be traced back to earlier modeling work in the late sixties and early seventies (Forrester, 1971; Isard, 1969; Meadows et al., 1982; Odum, 1983). Not surprisingly, all of these global-scale models are quite aggregate, predicting environmental disturbances from broad measures of economic growth and urbanization. The UrbanSim approach, by contrast, uses substantial spatial detail, and a clearer behavioral approach grounded in discrete-choice theory.

In addition to global models, spatially-explicit regional integrated models are now emerging,

such as the Patuxent Landscape Model (Voinov et al., 1999). The Patuxent Landscape Model contains an economic land use conversion model that uses a statistical process to determine probabilities that grid cells will be allocated to forest, agricultural, or urban usage. The resulting conversion probabilities are used to predict land use patterns which determine the land cover values used as an input to the PLM's hydrology component. Communication between the land conversion and hydrology models is implicit through changed data values in grid cells. Several of the factors used in its land use conversion component are similar to ones used in UrbanSim (e.g., access to infrastructure, historical tax assessor data), but UrbanSim explicitly models agents and their actions rather than using statistical or finite-element processes.

Finally, another area of related work concerns agent-based modeling, artificial life, and cellular automata. In agent-based modeling in its pure form, individual agents and their actions are simulated, with each agent having local knowledge; global behavior then emerges from these agent-level interactions. Agent-based modeling has been used for a wide range of applications, including economic, sociological, biological, and physical simulations. Two that are closely related to UrbanSim are Sugarscape (Epstein and Axtell, 1996; Brookings Institution, 2000), a simulation of a small, artificial society, and Aspen, a microanalytic simulation of the entire U.S. economy (Pryor et al., 1996; Sandia National Laboratories, 2000). These approaches attempt to produce plausible macro-level behavior as emergent properties of micro-level behavior. This approach has not yet evolved to the point of operational use in applied planning settings, but represents a significant area of ongoing research.

Cellular automata have been used for simulating urban development (Batty, 1998, 1999; Clarke et al., 1997), as well as for other applications such as simulating change in land cover, freeway traffic, or the spread of wildfires. In its classic form, a cellular automaton consists of a regular array of cells, each of which has a finite number of states. Each state change must be local, depending only on the states of neighboring cells. Urban processes, such as sprawl or urban decay, can emerge from simple local rules. However, these restrictions do not always mesh well with our goal of supporting deliberation about public policy. For example, rather than viewing the conversion of rural areas to urban ones as an analog of a biological process in which the suburb grows and occupies increasingly wider areas, in UrbanSim we view this process as the result of interactions among the Land Developer Model (which simulates developers actively seeking out development opportunities throughout the region in response to market conditions, zoning regulations, taxes and incentives, and the like), the location choice models (which simulate residents or businesses seeking housing and commercial space), and the Land Price Model. More recently, researchers have experimented with extensions of the cellular automata formalism that incorporate extensions such as more agent-like behavior or non-local search (Batty and Jiang, 1999; O'Sullivan and Torrens, 2000).

The UrbanSim approach assimilates aspects of these recent developments in highly disaggregate agent-based and cellular automata models, while retaining the flexibility to use macro-scale model components when appropriate. This assimilative approach requires that the software architecture support multiple modeling approaches, and not be optimized or restricted to only one. Models may be designed to operate at different temporal and spatial scales, requiring unusual flexibility from the software architecture.

One implication of this for the software architecture is the need for a flexible mechanism for assimilating model components and coordinating their behaviors. To meet this need, we use *implicit invocation*, a software engineering technique in which different system components communicate indirectly, rather than directly using procedure calls. In our realization of implicit invocation, models communicate by registering interest in objects and fields held in the Object Store, and by being notified when such an object or field has been changed by another model; but not by invoking each other explicitly. This allows models to be developed more independently of each other. (See Section 4.1 for details.) Additional advantages and other applications of implicit invocation are described in references Garland and Shaw (1993); Sullivan and Notkin (1992); Sullivan et al. (1996). Implicit invocation is essentially an event mechanism; related concepts include active variables in LOOPS (Stefik et al., 1986), active databases such as AP5 (Cohen, 1989), and the Smalltalk-80 Model-View-Controller (Krasner and Pope, 1988) and Field integration mechanisms (Reiss, 1994). A discipline of defining and using event-based programming mechanisms is evolving (Barrett et al., 1996; Carzaniga et al., 1998; Garland and Notkin, 1991).

The UrbanSim simulation approach, in summary, differs along several lines from prior urban simulation models. It is far more disaggregate than any operational model implemented to date. It uses a dynamic, path-dependent approach that does not impose simplifying assumptions of general equilibrium. It is designed for operational use to examine the effects of land use, transportation, and the environmental plans and policies. And it adopts an assimilative approach that draws from multiple streams of ongoing research in urban simulation, including multi-agent, cellular automata, and macro-scale models. The software architecture described in this paper provides a modular and extensible simulation environment that facilitates developing and integrating urban models with varying temporal and spatial scales.

3 Overview of the UrbanSim Architecture

To simulate an urban region, UrbanSim employs a collection of interacting *models*, representing different actors and processes in the urban environment, such as residents, businesses, land developers, and transportation networks. Each model encodes the behavior of agents in the simulation, as well as the objects they operate upon, such as land parcels and buildings. Objects correlate directly with easily-identifiable objects in the real world, making it easier to reason about their properties and behaviors. Agents can be shared across models, as can the objects they operate upon. Much more than other urban modeling systems, the UrbanSim model is very disaggregate and has high data requirements. These requirements enable modeling of processes to be done at a fine level, which allows use of detailed spatial data in a manner not possible with more aggregate systems. At the same time, this makes the design and implementation of the system more difficult from a software perspective. Figure 1 illustrates the software architecture of the UrbanSim system.

In addition to the models, the other principal components of UrbanSim are a *model coordinator* that schedules models to run and notifies them when data of interest have changed, an *object store* that holds the shared representations of agents and other entities in the

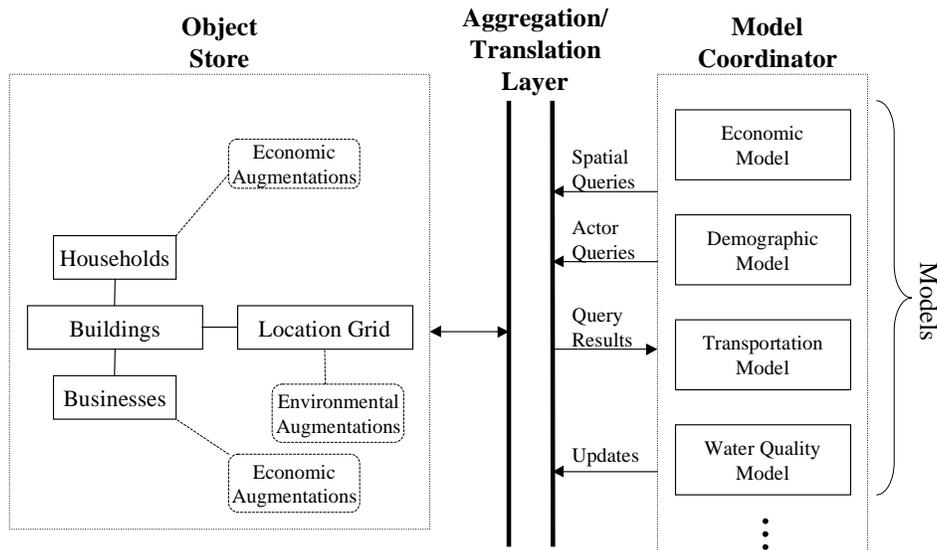


Fig. 1. UrbanSim architecture

simulated world, and a *translation and aggregation layer* that performs a range of data conversions to mediate between the Object Store and the models. The models do not communicate directly with each other; rather, they communicate via shared data held in the Object Store, mediated by the translation and aggregation layer. This extensible, modular architecture supports system evolution, in particular replacing a model with a revised one, and creating and integrating new models. It allows models to define and share common sets of objects that they all operate upon, via the Object Store (regardless of the original source of the data), and also allows them to monitor changes to data fields, providing a convenient method for models to synchronize their actions.

A primary goal of this architecture is to move as much of the software complexity out of the individual models and into the supporting infrastructure as possible. This supporting infrastructure need be written just once, and can have the attention of an expert programmer. The models, on the other hand, are both numerous and frequently changing due to rapidly evolving theory, methods and modeling needs. Often, specifying them is difficult, requiring considerable domain-specific expertise, specialized data, and testing; the more one can relieve the model designers of programming burdens the better, so that they can concentrate on issues arising from the domain.

3.1 Models

The initial software implementation of UrbanSim (Waddell, 1998) was a collection of tightly-integrated component models, including a developer, economic and demographic transition components, a land use component, and an external transportation model. The functionality of each model was intermingled with the functionality of the others, creating a large, complex system that did not lend itself to specialization, refinement, or enhancement. In creating a new framework for the UrbanSim model we sought to meet the following requirements:

- agent-level microsimulation of choice behavior
- a grid-based structure to represent spatial information, to facilitate detailed spatial queries and simulation
- easy replacement of one model by a new version, to support system evolution
- easy integration of new models
- support for different temporal and spatial scales
- support for visualization of the model output and its processes, for explanations and debugging

The new architecture has met these requirements. It has also proven relatively robust and stable, and has supported extensive model evolution, the introduction of several additional model components and integration with an external, concurrently-running visualization environment (Pinnel et al., 2000).

Models represent different actors or processes in the urban environment. In addition to encapsulating the behavior of the actor or process, each model is also responsible for defining the set of object types it operates on, and the fields of those objects with which it is concerned. A model can specify that it wishes to share fields also declared by other models, thus providing one technique for data-level coupling and integration of models via the Object Store. A model can also declare new object types that encapsulate domain-specific data not previously declared (e.g., a water quality model might declare a nutrient load value). A model may specify a set of object types and fields it wishes to monitor for updates, creations, or deletions. Each model is also responsible for indicating how frequently it wishes to be executed; there are no external constraints on how frequently or regularly a model need run.

The design of the models is informed by research in urban economics, sociology, civil engineering, and other disciplines. A discussion of the theoretical basis for the various models is given in references (Waddell et al., 2000; Waddell, 2000). A detailed specification of the models is given in reference (Waddell et al., 2001). The present paper and (Waddell et al., 2001) are complementary: the present paper concentrates on the supporting software architecture, while the latter concentrates on the model specifications.

3.1.1 Currently Implemented Models

A list of the models in the current version of UrbanSim is given below, and shown graphically in Figure 2. Each model runs once per simulation year, unless otherwise noted. All of these models consist of a collection of domain-specific case-based rules or decision rules that are encoded in Java code. The models operate on a database consisting of individual households, jobs, and grid cells of 150 by 150 meters containing real estate and land. Most of the models simulate the choices of households, businesses and developers using discrete choice models (multinomial logit) and Monte Carlo simulation.

Demographic Transition Model The Demographic Transition Model is responsible for modeling births and deaths in the simulated population of households.

Household Mobility Model The Household Mobility Model simulates the choices of households deciding whether to move from their current residential location.

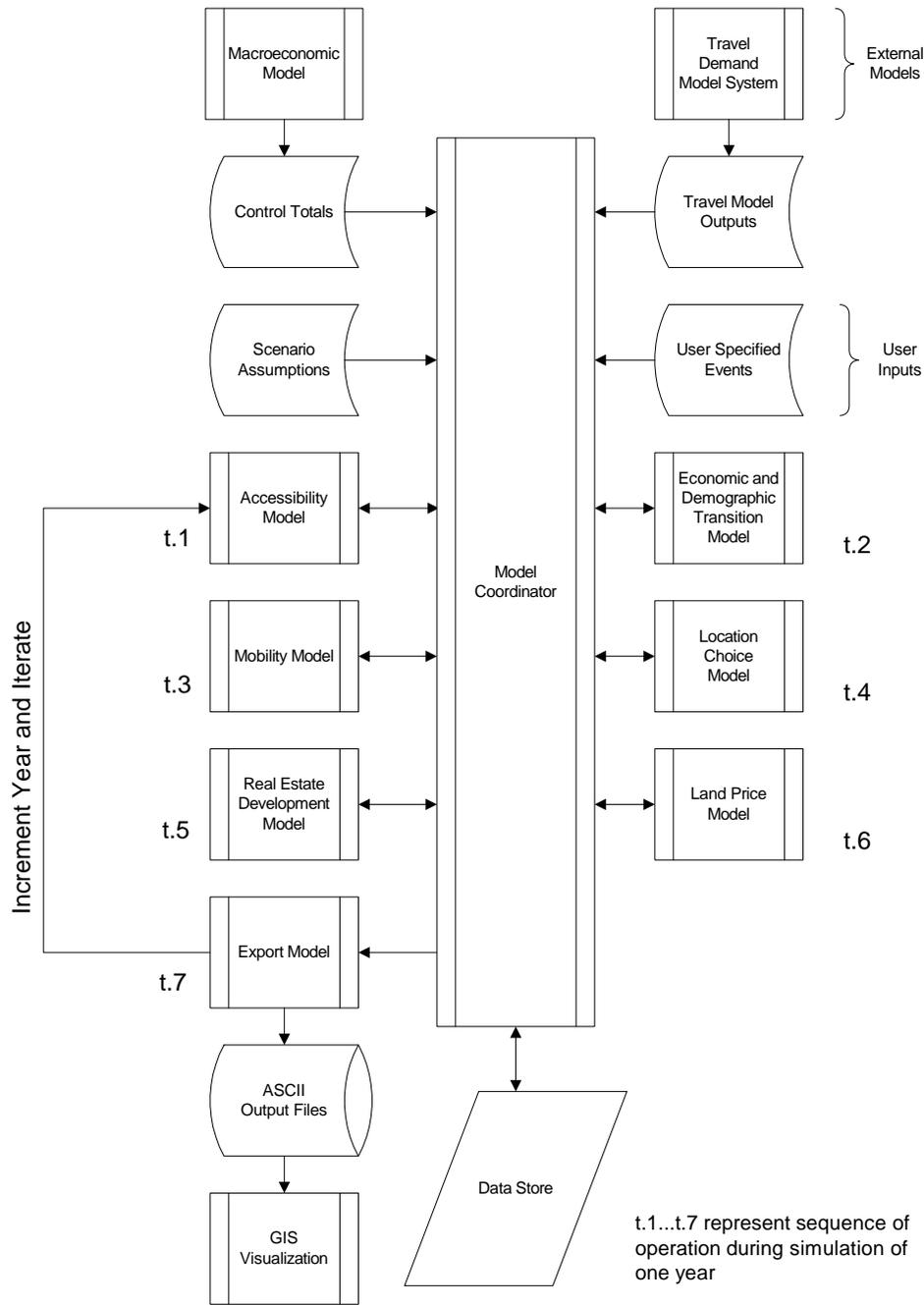


Fig. 2. UrbanSim model components (source: (Waddell et al., 2001))

Household Location Choice Model The Household Location Choice Model is responsible for determining a location for each household that has no current location.

Economic Transition Model The Economic Transition Model is responsible for modeling job creation and loss.

Employment Mobility Model The Employment Mobility Model determines which jobs will move from their current locations during a particular year.

Employment Location Choice Model The Employment Location Choice Model is responsible for determining a location for each job that has no location.

Accessibility Model The Accessibility Model encapsulates the interface to a (possibly external) travel model. It is responsible for maintaining accessibility values for objects within each traffic analysis zone.

Land Developer Model The Land Developer Model simulates the action of a developer making decisions about where and what kind of construction to undertake (if any), including both new development and redevelopment of existing structures.

Land Price Model The Land Price Model simulates the evolution of land prices at each grid cell as the characteristics of locations change over time.

3.1.2 Temporal Scale Issues and Simplifications

UrbanSim provides a much more disaggregate and detailed simulation than other urban land use models. Even so, to keep the computation manageable, the model makes many simplifying assumptions. For example, the Demographic Transition Model, like most of the models, runs once per simulated year. Each simulated year, it adjusts the total population values and distributions, but in reality people are born and die, and move into and out of the region, every day. Similarly, the Land Price Model simulates the operation of the real estate market at a temporally aggregate level, adjusting prices once per year rather than continuously. The software architecture has been designed to accommodate events based on any time scale specified by a model, to allow the integration of models with different time steps. (See (Waddell et al., 2000; Waddell, 2000) for additional discussion of the theoretical basis for these design decisions and their consequences.)

3.1.3 Defining a Model

The description of a model consists of a Model Definition File, and separately, a Java class definition for the model. The Model Definition File includes the model’s name, and the set of objects and object fields it reads and writes, along with flags indicating if the fields are to be shared with other models (i.e., sharing a field with an already-created model). Shared variables are specified explicitly in the model definition rather than implicitly through duplicated names in order to ensure that any duplicate use of an object field is deliberate. This avoids a potential problem where commonly-used names may be used in independent models but with different semantics, and sharing the variables in that case would cause erroneous results. For example, one model might refer to “population” as a count of persons, and another as a count of households, in which case trying to share the field would produce inconsistencies. Information from all the relevant model definitions is combined to produce the definitions of the objects in the Object Store (Section 3.3.2).

The remainder of the model’s functionality is specified by a Java class, which must be a subclass of the abstract class **Model**. The following are the key methods defined by **Model**, and which are overridden in concrete subclasses.

init Perform any model-specific initialization, including notifying the Model Coordinator which objects and fields it wishes to monitor for changes.

run Perform the work of running the model at the current simulated time.

nextScheduledRunTime Return a **float** indicating the next simulated time that the model

wishes to be run.

onCreate Perform any needed bookkeeping if an object of interest has been created. This method is invoked if one of the objects in which this model has registered interest has been added to the Object Store.

onChange An object type or field that this model monitors has been changed—react accordingly.

onRemove Perform any needed bookkeeping if an object of interest has been removed from the Object Store.

If the degree of interaction between a new model and existing models can be expressed at the data level and there is a well-defined order between them (e.g., one model’s outputs are always used as inputs by another model), then no additional information is required. For example, the output of the Demographic Transition Model (i.e., newly-created households that reside in limbo) is an input to the Household Location Choice Model, and this interaction is wholly defined at the data level (i.e., the existence of new households in limbo). If models need to be more tightly coupled, or operate on differing temporal scales, the data notification interface can be used. For example, a continuous-time model can be set to monitor changes to data fields it uses as inputs, and compute an updated set of outputs only when its inputs have changed. The Translation/Aggregation Layer can help with models that operate on different spatial scales, for example by aggregating from the parcel or grid-cell level to the zonal level. The key methods used in providing this functionality are the `onCreate`, `onChange`, and `onRemove` methods of `Model` (as defined above), and the `postQuery` and `postUpdate` methods of the Model Coordinator (Section 3.4), which pass information through the Translation/Aggregation Layer and on to the Object Store.

In addition to providing a mechanism for coupling several models using implicit invocation, another application of the model notification mechanism is to support the caching of frequently-accessed data within a model, rather than repeatedly accessing it from the Object Store. This can be helpful if a model needs to perform costly processing on a large amount of data, as it can compute the results once and recompute only what is needed as parts of the underlying data are changed. Data modification messages serve as notification that the model’s cache is no longer valid, and supply the specific data element(s) which have changed. For example, the Land Price Model maintains regional and zonal-level vacancy rates. These more aggregate vacancy rates change slowly over time, so the Land Price Model computes them once, and modifies them as needed as households and employees move about the region, rather than recomputing the aggregate vacancy rates every time the model runs. As the vast majority of employees and households remain where they are at each simulation step, this approach substantially reduces the overall number and size of queries to the Object Store.

3.2 Model Coordinator

The Model Coordinator is responsible for managing the collection of models present in a simulation. It is responsible for determining the execution order of models, resolving any data dependencies one model may have on another, and notifying a model when another model has changed data it is monitoring.

Some key methods defined by the Model Coordinator class are:

runSimulation Run the simulation once the event queue has been populated.

executeEvent Execute a single event (provided as an argument to this method).

getOrdering Determine a total ordering among a collection of events (provided as an argument to this method).

3.2.1 *The Event Queue*

The Model Coordinator maintains an event queue containing timestamped events. These events include requests by a model to execute at a future time, development events scheduled to occur at a future time, database updates that were created by exogenous events that did not occur instantaneously, and policy events that indicate planned changes in regional or local policy. Running the simulation consists of gathering the set of events that are to occur at the current timestep, determining a total order for those events that preserves any data or ordering dependencies they may have, and then executing them in that order.

The event queue is thus the traditional data structure used in discrete event simulations, except for the additional consideration of breaking ties among events scheduled to occur at the same time. Any number of models or simulation events may be scheduled to execute at the same instantaneous timestep. However, the Model Coordinator may *not* then execute these events in an arbitrary order—there may be dependencies among them. For example, if the Household Mobility Model and the Household Location Choice Model are both scheduled to execute at time t , the Household Mobility Model must be run first, determining a set of households that decide to move, and then the Household Location Choice Model must be run to find available housing units for them. In other words, the choice to move from a current dwelling and the choice to look for a new dwelling are not independent; this dependency is reflected by the constraints on the order in which the models are run.

Since models are not restricted to running at regular intervals, in general it is not possible to determine execution orders until run-time. This introduces an enormous amount of complexity not found in most other urban modeling systems, which typically have a fixed ordering of execution. When more than one event is to occur at a given timestep, it is necessary to determine a total order of the events that preserves any order dependencies that may exist between them. Dependencies are of two types, data-level dependencies, and model-level dependencies between model execution events.

A data dependency exists between two models when one model writes to a field that another model reads from. In such cases, it is essential that the reading model reads the correct version of the data, and the writing model overwrites data only when it is safe to do so from another model's perspective. In the absence of other ordering dependencies, we assume that all reads to a field occur before any writes to it, and that writes can occur in any order. This reflects the typical access pattern of models, which generally read from many objects and write to a small number of fields of a small number of objects. (The fields written to generally have a very small overlap with reads from other models.)

A model-level dependency is an ordering dependency explicitly introduced by a model's

author, in the form of a set of partial orderings between two or more models. This provides a mechanism to order models based on their semantics rather than their syntax (data reads/writes). For example, the Land Developer Model and the Land Price Model could be executed in either order, based on their inputs and outputs, but we schedule the latter to execute after the former so that adjustments in land price due to this year’s demographic and economic changes do not affect development. This is based on the simplification of market dynamics that we adopt: that development decisions are made once per year, looking at the state of the region in the prior year to decide what should be built in the current year.

To determine a valid total order for a collection of events, a directed acyclic graph is constructed. Events are represented as nodes in the graph, and directed edges are created between events that access the same data fields of objects or that have model-level dependencies, with the direction of the edge indicating that the source node (event) must occur before the destination. When determining the possible dependencies between two model execution events, we must compute the transitive closure of all models and all fields that may potentially be read from or written to on the basis of the notification mechanisms. To ensure correctness, the full chain of potential reads and writes must be considered. Model-level dependencies override data-level dependencies in the case of conflicts. A topological sort is used to generate a valid total ordering of the events to be executed.

3.2.2 Development, Employment, and Policy Events

UrbanSim supports events that create, modify, or delete buildings; create, move, or delete businesses or households; or change the urban growth boundary or re-zone land. Many of these events are generated by models. (For example, the developer model generates building development events.) However, events can also be read from an external file, allowing the modeler to introduce development projects and policy changes into the event pipeline that are exogenous to the models. For example, a scenario author may wish to simulate the effects of a major business leaving the region, a shopping center being constructed, or a modification to the urban growth boundary that occurs at a particular time in the simulated future.

3.3 Object Store

The representations of agents in the world (such as households and businesses), and the objects they operate upon (such as buildings and land parcels), are held in the Object Store. The Object Store serves as an in-memory database that can be queried or updated, and that supports filtering on entity attributes.

The basic interface to the Object Store is through its `postQuery` and `postUpdate` methods. A model constructs a `Query` object by filling in the object type and set of fields to query for (e.g., the age and size category fields for households), and adds any `Filter` objects to the `Query` as desired (e.g., a filter that returns only households with a given number of workers). The `postQuery` invocation returns a `QueryResult` object, which contains a copy of all relevant data from the Object Store, including internal object IDs for all values returned. Updates work in a symmetric fashion, with a model constructing a `Update` object whose form is similar to

`QueryResult` with the addition of the update type (create, modify, remove).

From a software engineering point of view, the Object Store also serves to encapsulate representation decisions about the entities in the simulation. From outside the Object Store, these act as traditional instances in an object-oriented language. However, they are represented more efficiently within the Object Store. Further, rather than defining these objects by writing a class definition, we use information in the Model Definition Files to give a description of just the portion of each object relevant to the corresponding model. These partial descriptions are then integrated by the system during the code generation phase to produce the eventual object definition.

3.3.1 Object Overhead Issues

Modeling Eugene-Springfield (a relatively small metropolitan region) requires some 350,000 objects to be represented in the Object Store. If these were represented as ordinary Java objects in our current Java implementation (Sun Java 2.0), there would be an additional overhead of approximately 20 bytes per object, for a total of seven megabytes. A larger region such as Salt Lake City requires some 1.5 million objects. Given the typical access patterns for the fields of objects (Section 3.3.3), performance is much improved if all the objects can be held in main memory, and so reducing space overhead is important.

Therefore, we represent objects efficiently within the Object Store, using parallel arrays holding the fields of each object type. For example, each `Household` object includes a integer field to hold its location, and a byte field to hold its income category. Rather than storing 300,000 explicit `Household` objects in the Object Store (with the attendant object overhead), we hold the information in a series of arrays, including an integer array `Location` with 300,000 elements, a 300,000 element byte array for income categories, and so forth.

Since these fields almost always hold primitive Java types such as **floats** or **ints**, rather than reference types, storing the fields directly in large arrays eliminates most of the space overhead. It also eliminates wasted space in each object due to word alignment padding, as would arise for byte fields. The encapsulation provided by the Object Store means that this non-standard representation is not visible outside it.

Other data structures have been implemented in a lightweight fashion, such as dynamic arrays, hash sets, and hash tables, to allow for storage of primitive types (**ints**, **floats**, etc.) in a fashion that eliminates the Java object-level overhead present from using Java's built-in data structures such as the `ArrayList` and `HashMap`.

3.3.2 Construction of Object Class Definitions

Objects in the Object Store consist of the union of all fields defined by models for each object type and by the set of default object definitions (which are shared by most models). Queries can return copies of any of the fields of objects, and updates can modify fields or create or remove instances of objects. The Object Store's functionality has been tailored to the needs of UrbanSim-style models, including the ability to perform spatial queries on geo-referenced data (a task poorly performed by traditional databases).

The complete definition of each object type, and the Java code used to access and query it, is generated automatically from these partial object descriptions. For example, the **Zone** object type represents a traffic analysis zone. Partial definitions of **Zone** are given by both the default object definitions and the Developer Model. These definitions are combined, and used to generate the final version of the **Zone** object. Query/Update access methods, and routines that enable objects to be saved or loaded from disk, are generated automatically as well.

3.3.3 Swapping

The contents of the Object Store may be too large for the available main memory. To handle this, we provide a simple swapping mechanism that allows an array holding the contents of a field for an object type, e.g. the **Location** field from the **Household** type (Section 3.3.1), to be written out to disk if need be. This mechanism reflects the typical access patterns of models, which generally access every object of a given type, but only a small number of fields of each such object. (The more typical unit of swapping is the object—but given this access pattern, swapping on a per-object basis would be less desirable, since we would swap in entire objects, even most of the fields would not be immediately needed.) However, it is still preferable if possible to keep all data in main memory, since all of it is touched during each simulated year. Thus far, we have not used a commercial database as a back end, due to a desire to not tie the Open Source UrbanSim code to a proprietary system. However, we plan to offer access to commercial databases as an option (but not a requirement) in a future version.

3.4 Translation and Aggregation Layer

The Translation and Aggregation Layer (T/AL) is responsible for converting between different levels of spatial and/or temporal aggregation from queries or updates and the objects in the Object Store. For example, models can query for zonal population totals. The Translation/Aggregation Layer computes and maintains these totals independent of the information in the Object Store, which consists of population information at the grid cell level.

At present, the T/AL is implemented using a set of methods in the Model Coordinator, rather than as a separate component, and serves only to cache query results for data aggregated at the zonal level. The two key methods that implement the T/AL, both in **ModelCoordinator**, are **postQuery** and **postUpdate**, to post a query or an update to the Object Store respectively. However, as the system evolves and we integrate models from increasingly diverse domains, we expect the T/AL to become increasingly important as we need to share data at widely different levels of spatial or temporal aggregation. At that time we may re-implement it as a separate component in its own right.

3.5 *Data Import and Export*

On the input side, UrbanSim requires a substantial amount of data to simulate an urban area, including census, employment, parcel, zoning, and transportation network data. We have written a suite of custom data preparation tools that can convert data to the formats we require, merge datasets, detect inconsistencies, and in some cases fill in missing data or correct errors in base year input data using heuristics. This input data is generally made available to UrbanSim in the form of delimited ASCII text files.

On the output side, UrbanSim's output module is responsible for gathering, aggregating, and exporting data from the Object Store to a set of external ASCII text files containing requested extracts or summaries from the Object Store. Currently, the export model writes output files containing households and jobs by type, housing units, non-residential square footage, and land and improvement values, summarized by grid cell and by Traffic Analysis Zone. These files are then passed on to other systems (including GIS software, statistical software, spreadsheets, and the external travel model) for subsequent analysis and graphical display. To simplify the software engineering aspects of data export, we have defined the output module as a model, analogous to the Demographic Transition Model, the Household Mobility Model, and so forth (Section 3.1). This allows the Export Model to be scheduled to run at defined times, querying the Object Store to take a snapshot of the state of the simulation. Conceptually, however, it is not a model like the Demographic Transition Model or others, since it does not represent an agent in the simulated world, and only performs reads of the Object Store, not writes.

Finally, in addition to input and output files, the system can write a snapshot of the current state of the Object Store to an external file, allowing the system to be restarted quickly from a given point in the simulation.

4 **Experience and Lessons Learned**

Perhaps the most important software lesson learned from this work has been the value of moving as much of the complex functionality out of the individual models and into the supporting infrastructure as possible; most of the specific lessons discussed below are ways of achieving this goal.

4.1 *Implicit Invocation*

Models do not communicate directly with each other, but rather communicate by registering interest in objects and fields held in the Object Store, and by being notified when such an object or field has been changed by another model. The architecture thus uses a form of implicit invocation (Garland and Shaw, 1993; Sullivan and Notkin, 1992; Sullivan et al., 1996), in which components interact by generating and responding to events, rather than by explicitly invoking each other's methods. As in other systems, implicit invocation has proven

to be a powerful technique for addressing component interaction complexity in UrbanSim. Two advantages of using implicit invocation have been:

- the ability to decouple models, since each model registers interest in objects and fields, makes changes to the Object Store, and responds to changes independently of the other models. This has made it significantly easier to experiment with new models and to evolve existing ones.
- ensuring a consistent interface for model interactions, since all interactions occur via the Object Store.

While our implicit invocation mechanism has worked well for the current style of models, we expect that it would break down if we moved to a much finer-grained simulation, for example, one in which households could move, developers could begin constructing new buildings, and so forth, at any time, rather than on a yearly basis. The anticipated problems arise from the current mechanism being relatively coarse-grained: in the current architecture, a model cannot specify that it wishes to monitor a field in a particular object, only that it wishes to monitor a field in all objects of a given type. Any additional filtering or selection must occur within the callback code that is executed within the model as a result of the notification. This has been quite acceptable in the current system, but could introduce excessive numbers of unnecessary notifications in a more fine-grained approach, leading to unacceptably slow execution speeds.

A related difficulty is that the complexity of the callback code increases as more models use it to monitor and update related fields. For example, adding a new model that affects the existing functionality embedded in notification methods requires that the callback code in the new model take into account all of the existing functionality and not override or invalidate any of its actions.

4.2 *Explicit versus Implicit Execution Ordering*

We originally intended to handle most of the specification of model execution ordering using implicit data-level dependencies (Section 3.2.1). However, experience showed that the simple data-level ordering dependency rules (all reads to a field before any writes to it) failed to capture many important semantic constraints on model execution ordering. Thus in practice, the bulk of ordering dependencies are specified explicitly by model creators.

We also allow user-supplied model-level ordering dependencies to override data-level ones. For example, the Export Model only reads from the Object Store and never writes to it. The implicit data-level dependencies would require that it run before other models. However, we use an explicit ordering constraint to require that it be run *after* all the other models, so that it exports the information after the simulation has completed for the current simulated instant of time. However, if there are ordering dependency conflicts at the same level (i.e., at the model-level, or at the data-level in the absence of any overriding model-level dependencies), an error will be signaled.

The current design has worked well in practice, but is not entirely satisfying, and may begin

to cause problems if the number of models increases dramatically. At that point we expect we will need to re-examine the issue, and perhaps find more sophisticated ways to determine implicit ordering constraints that reduce the need for explicit orderings.

4.3 Object Storage and Representation

Java's overhead for object representation (specifically, the class tag and the overhead of word alignment padding) has made the overhead of using standard Java objects in the Object Store prohibitive. Instead, we use a nonstandard object representation, namely parallel arrays holding the fields of each object type. However, this is not visible outside of the Object Store's encapsulation boundary. This solution is not new to UrbanSim: it is akin to the use of marshalling in Smalltalk, CORBA, Java, etc. It is also more loosely related to the concept of flyweight objects (Calder and Linton, 1990; Gamma et al., 1995), although unlike flyweight objects, objects in the UrbanSim Object Store do not have extrinsic state that depends on their context.

The approach has had enormous benefits in the context of UrbanSim. Memory requirements have decreased by a factor of seven or more as compared with the original object-based implementation, making the simulation of large areas such as Salt Lake City, Utah feasible on modest desktop systems. It has also facilitated the addition of disk-based swapping to the Object Store to handle cases in which the simulation's storage requirements still exceed the available memory.

4.4 Automatic Generation of Code from Declarative Specifications

We have made considerable use in UrbanSim of the technique of generating Java code automatically from declarative specifications. One example is the generation of object class definitions for objects in the Object Store, along with query and update methods (Section 3.3.2). The automatic generation of Java code that defines objects and their interface with the Object Store removes much programming burden from experimenters who introduce a new model or replace an existing one, as they do not have to write code that defines or manipulates object types. (This is particularly important since we use a non-standard representation of objects within the Object Store.) It also ensures that a consistent interface exists between the Object Store and every object that is contained within it.

We have also used automatic generation of Java code to define specialized, lightweight data structures optimized to store primitive Java types (**ints**, **floats**, etc.) with a minimum of memory overhead. These include lightweight dynamic arrays (**SimpleDynamicArray**), lightweight hash tables and sets (**HashTableIntInt**, **HashSetInt**, **HashSetFloat**, etc.), and some additional wrapper objects.

The issue addressed by these lightweight data structures is that in the standard Java library there is just one class definition for e.g. **HashSet**, whose element type is **Object**. Therefore, to store **ints** in a standard hash set, each **int** must be wrapped using the **Integer** class, leading

to a considerable overhead in both space and time. Our automatically-generated `HashSetInt` class eliminates this overhead. If sufficiently powerful generic types were incorporated in future versions of Java, the need for these specialized lightweight data structures would be eliminated (or more precisely, they would be generated by the Java system itself rather than by us). Note that to be useful for our purposes, such a design must provide heterogeneous, not homogeneous, translation of generic types—homogeneous translation does not handle the space overhead problem. (In heterogeneous translation, the compiler produces different versions of the code for each instantiated type; in homogeneous translation, just one version. For Java, homogeneous translation requires wrapping each primitive type, which adds a tremendous space penalty. Both varieties of translation are available in the Pizza extension to Java (Odersky and Wadler, 1997); GJ (Bracha et al., 1998) and NextGen (Cartwright and Steele Jr., 1998) provide only homogeneous translation.)

4.5 Choice of Programming Language

UrbanSim is implemented in the Java programming language. Java has provided a solid environment for implementing a system of this kind, particular strengths being automatic storage management, static typing, a rich class library, and portability. While its execution speed is not comparable to C++, current compiler technology (e.g., Just-In-Time compilation) has provided reasonable performance. Perhaps the biggest problem for us has been the overhead of object representation, which has required unorthodox object representations within the Object Store (Section 3.3).

Java provides many advantages over other programming languages that were considered. These advantages include:

- Object-oriented language, where we can use inheritance and subclassing to increase reusability of language-level objects and code we write;
- Automatic storage management, which helps improve software reliability by eliminating memory allocation and storage errors that can be difficult to find and fix in other environments;
- A rich collection of data structures and libraries, which improves productivity when writing code;
- Portability, so that we can run the UrbanSim model on a variety of platforms without needing to modify the source code;
- Performance, which is reasonably good due to the use of Just-In-Time (JIT) compilers, and is substantially better than interpreted languages.

We considered using one of the dedicated modeling languages or environments which are available, such as Stella, Swarm (Luna and Stefannson, 2000; Swarm Development Group, 2000), StarLogo (StarLogo Group, 2001), or the MIMOSE framework (Möhring, 1996). However, none of these met our requirements for portability, generality, and efficiency. We thus chose to implement a framework from scratch, enabling us to customize and optimize it for the specific domain and types of models we work with.

4.6 *An Open Source Software Approach*

The UrbanSim software is licensed under the GNU General Public License (GPL) from the Free Software Foundation. This license is well-known among software developers, and is used for such systems as the linux operating system and the emacs text editor. It is not so commonly used for software for urban modeling, but has some significant benefits. The license allows anyone who has the software to further distribute it, to change it, or to use parts of it in new programs. Further, it requires that any distribution of the system or of derivative works continue to be licensed under the GPL. The distribution must include the source code as well as the compiled object code, or make the source code easily available. (Please see the GPL itself (Free Software Foundation, 1991) for the precise terms of the license.)

The benefits of licensing UrbanSim under the GNU General Public License are that other researchers and practitioners can freely apply the software, as well as build on it and distribute those results as well. In contrast, a proprietary license would typically require the payment of fees, and might well not include the source code. Using the GPL license also has quite different implications from placing the source code in the public domain: if this were done, the version in the public domain would be freely available, but someone else could produce a derivative work (perhaps involving changes to a relatively small percentage of the system), and then place this derivative work under a restrictive, proprietary license.

The original implementation work on the software architecture described in this paper was done by a single programmer (the first author). Subsequently, however, portions of the infrastructure and many of the models have been modified or created by others. We use the Concurrent Versions System (CVS) (Cederqvist, 2000) as a means of coordinating and integrating programming work performed by the different programmers who work on this project. CVS maintains a central repository with the definitive copy of the source code. A programmer checks out a copy of the system, which can be freely modified on that programmer's personal disk directory. When the new version is ready, the programmer can then check it in to the repository. CVS keeps track of the different versions of the system, and watches for conflicting check-ins by different programmers, notifying them so that the differences can be resolved.

CVS is often used for Open Source development projects, since it is admirably suited to coordinating the work of programmers at geographically distributed locations. Another feature of CVS is that the developers can allow anyone read-only access to the repository, so that others can track the latest versions of the software. We have not yet used these features, but plan to in the near future as a way of coordinating work with a Metropolitan Planning Organization that will be applying UrbanSim to that region.

5 Conclusion

UrbanSim is both a vehicle for research on modeling urban systems and a practical system that has been used in planning work in several U.S. cities. The software uses a modular architecture that allows models to be written as independently as possible, and that provides for a clean separation between the models and the data on which they operate. This has supported extensive experimentation with alternate modeling techniques, and also supported implementing a system that is much more disaggregate and responsive to policy considerations than others of its kind. The primary software lesson learned from this work has been the value of moving as much of the complex functionality out of the individual models and into the supporting infrastructure as possible; specific techniques for achieving this include implicit invocation, efficient object representation in an encapsulated object store, and extensive use of automatic generation of code from declarative specifications.

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