TOWARD A COMMON OBJECT MODEL FOR INTEGRATED TRANSPORTATION AND LAND USE MODELS

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ABSTRACT

Evaluating the effects of a change to one aspect of the modern urban environment requires knowledge about other parts and how they are interconnected. Thus, integrated simulations of many parts of the entire urban ecosystem are needed to create and evaluate the effects of policies. Many existing models target a single urban system - land use models, transportation models, water system models, etc. - however coupling them to create interconnected systems often requires great effort and resources. In this work we propose a common object model for integrated transportation and land use models (ITLUMs) using the High Level Architecture Standard (IEEE 1516) (IEEE 2010). This object model is the first step in a longer term effort to develop new simulation models that can be readily integrated through common data abstractions. Finally, the proposed object model is designed to be extendable to capture the elements from other models of the urban environment.

Keywords: federation object model, integrated transportation and land use models, urban environment

1 INTRODUCTION

Creating coupled simulations from independently developed models is a challenging task, even if the models have common conceptual aspects. Problems such as closed source codes, different languages of implementation, different ways of handling and expressing data, and different modeling paradigms all require developer time and resources to solve, and the final coupled models will often be brittle, requiring further efforts to extend, with vulnerabilities to new developments in each component model. Most efforts to date to create integrated transportation and land use simulations use ad hoc techniques that are specific to the particular simulation models that are being integrated.

On the other hand, there has been a substantial amount of effort to creating standard methodologies, approaches, and software to couple simulation models in general, with the High Level Architecture (HLA) for

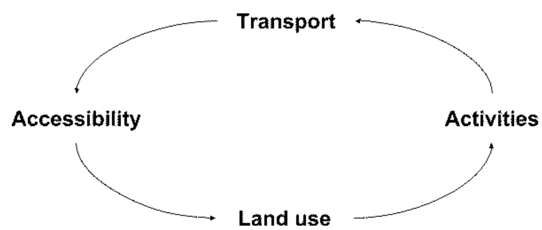

Figure 1: The 'land-use transport feedback cycle' (from Wegener and Fürst, 2004)

Modeling and Simulation, IEEE Standard 1516 perhaps the most well-known approach. Existing work has attempted to utilize HLA to couple land use and transportation models. For example, in the system described in (Jain, Fujimoto, Crittenden, Liu, Kim, and Lu 2015, Jain, Robinson, Dilkina, and Fujimoto 2016) models are specified in SysML and software tools automatically generate code stubs that are then used to connect the simulation models through HLA Runtime Infrastructure (RTI) software. The framework also manages the sequencing of execution of the integrated model.

In coupled simulations, each individual model must represent a similar slice of "reality" if meaningful conclusions are to be drawn from the results of the simulation. Consider a simple example - simulating the impact of ride-share systems and changes in transit on urban development in San Francisco, California. Each simulator has its own *conceptual model*, representing an aspect of the city that it aims to reproduce. In order to couple two models, there must be some agreement concerning overlapping aspects of the conceptual models. Individuals and businesses make location decisions in part based on transportation options and costs, and both will be represented in the land use and transportation models in some fashion. Even with HLA tools, there is a non-trivial amount of work that must be done to create coupled models. For example, developers will still have to work to define a common conceptual model that should be followed in all model implementations, ensure that all newly created models comply with that standard, and update the conceptual model as new domains are considered. In this work we aim to formalize what should be contained in this overlap, in the space of ITLUMs, by creating a common object model, or a FOM in HLA terminology, through studying the design and operation of several existing ITLUMs. By formalizing this conceptual space, future ITLUMs can be designed from the ground up using this object model, and existing ITLUMs can be modified to use the "language" defined by the FOM, in order to more easily integrate with other models. We have released our proposed FOM, described in Section 3, with the purpose of reducing the initial effort needed to create new ITLUM[1].

2 INTEGRATED TRANSPORTATION AND LAND USE MODELS

Integrated transportation land and use models (ITLUMs) - also referred to as Land-use-transportation interaction (LUTI) models - are crucial to modeling urban dynamics. The feedback loop between people's travel choices and urban development, highlighted in Figure 1 (Wegener and Fürst 2004), requires models that capture both sides of the circle. To begin our study we describe three existing ITLUMs created from independently developed models: UrbanSim and MATSim (Section 2.1), SILO and MSTM (Section 2.2), and the MARS model (Section 2.3), as well as other commonly used land use models (Section 2.4).

[1] Available at https://github.com/calebrob6/itlum-fom.

2.1 UrbanSim and MATSim

UrbanSim is a land use model that was first designed and implemented in the early 2000s to integrate with transportation models - a critical part of modeling the known interactions between land use development and accessibility (Hansen 1959) - and to allow for testing of different policy scenarios (Waddell 2000, Waddell 2002). This model falls into the class of accessibility-based location models (Wegener 2014) which predict the "opportunity for spatial interactions at potential locations" rather than actual spatial interactions. UrbanSim is modular by design, and consists of three broad sets of models that are run sequentially to describe the evolution of an area: employment, household, and real estate models. UrbanSim has gone through three different implementations, and been applied to simulate development in many cases including, but not limited to: Eugene-Springfield, Oregon, Seattle, Washington, Detroit, Michigan, and San-Francisco, California. In the second iteration of UrbanSim's implementation, developers and researchers of MATSim ("Multi-Agent Transport Simulation"), a popular transportation simulator (Balmer, Meister, Rieser, Nagel, and Axhausen 2008), created a plugin named MATSim4UrbanSim to couple the two models (Nicolai and Nagel 2010, Nicolai 2012, Nicolai 2013). MATSim is an useful tool that can derive accessibility measures between different locations through the simulation of the pathing choices of large numbers of agents. Nicolai et al. apply this model in Brussels, Belgium, the Puget Sound Region in Washington, and Zurich, Switzerland. Our first focus is on this coupling, specifically, the data that needs to be exchanged between the two models.

UrbanSim and MATSim are loosely coupled by passing data tables as comma separated files between them. This is a form of shared coupling (Berry, Buckley, and Teck 1997), where common data is stored in a shared location and UrbanSim's OPUS GUI is used to coordinate the execution of both models. Here, each model will run independently: after execution UrbanSim will write out relevant data tables to files for MATSim to read, then execute the MATSim simulation. In turn, MATSim will write out relevant files after running, then execute the next iteration of the UrbanSim simulation. The files exchanged between the two include the persons table (the home and work parcels for each person in the simulated population), job table (parcel location for each job in the simulation), and parcel table (the spatial location for each parcel, or building, in the simulation, and what "zone" the parcel is in). MATSim uses this data to generate an "agent" for each person in the UrbanSim population which populates a micro traffic simulation, and finally generates an origin-destination impedance matrix between UrbanSim zones and per zone accessibility values. MATSim will write out this accessibility data to file, which is then read by UrbanSim, and the process repeats (Nicolai 2012).

These four data tables, the persons, jobs, parcels, and accessibility tables, are the only pieces of data that are shared between UrbanSim and MATSim, however they represent a large fraction of the possible pieces of information that will be important to both *classes* of models. To implement the feedback loop between transportation choices, and land use choices, shown in Figure 1, there must at least be a representation of both "accessibility" and "activities" that is shared between the two models. The "accessibility" information passed to UrbanSim by MATSim contains both zone level information (logsum values), and zone-to-zone information (impedance values). These two types of information can be used to encode other relevant values, e.g. zone to zone travel times, zone "walkability", or zone transportation equity. Other potential "accessibility" data types that are not used between UrbanSim and MATSim include path based accessibility values, e.g. road link based congested speed. On the other side of the figure, the "activities" category represented in Figure 1 can hold a much wider range of data, as any piece of data that reflects different possible outcomes of the land use model could influence traffic patterns. The coupling between UrbanSim and MATSim uses the home and work locations of the UrbanSim population in order to derive trips on the road network in the MATSim simulation, however could use other household level information: number of vehicles, income, number of inhabitants, etc. Considering this, the representation of "activities" generated by the land use model must at least be able to represent detailed household level information.

2.2 SILO and MSTM

The Simple Integrated Land Use Orchestrator (SILO) model is a recently developed microscopic model of land-use that was designed to be integrated with travel demand models (Dawkins and Moeckel 2016). First, a synthetic population of agents are generated to match the population distribution in an area. The model will then simulate different events on an individual level with the synthetic population in order to determine how land use changes over time: buying and selling cars, household relocation, aging, marriage, birth, death, jobs hiring, jobs firing, housing construction, housing renovations, etc. Similar to UrbanSim, SILO requires a travel demand model to determine the accessibility of each location, which will influence how attractive a building there is to buyers. One advantage of SILO over UrbanSim and PECAS, noted in (Dawkins and Moeckel 2016), is that SILO is "built to function with less rigorous data collection and estimation requirements than traditional large-scale land-use models".

SILO has been integrated with the Maryland Statewide Transportation Model (MSTM) in several applications (Shahumyan and Moeckel 2015, Dawkins and Moeckel 2016, Shahumyan and Moeckel 2017)[2]. MSTM is a five-step travel demand model, developed by the state of Maryland, that includes trip generation, destination choice, mode choice, time-of-day choice, and network assignment steps (as opposed to traditional four step models that do not include the time-of-day choice step). After a simulation step, SILO will write information about the population, employment and automobile availability to file, which is subsequently read by MSTM as input data. Similarly, MSTM will write out pertinent information to file after a simulation step, including auto travel time, transit travel time, and auto-operating costs, which is read by SILO. This integration is part of a broader coupling with three other models: the mobile emissions model (MEM), building energy consumption and emissions model (BEM), and Chesapeake Bay land change model (CBLCM). The coupling and execution of all models is facilitated by the ArcGIS Model Builder interface with custom Python scripts. Further details concerning the model coupling step can be found in (Shahumyan and Moeckel 2015, Shahumyan and Moeckel 2017).

On a technical level, SILO and MSTM are coupled in the same way that UrbanSim and MATSim are coupled, in a shared coupling model that uses file I/O for communication. The difference between these two sets of coupled models is the greater level of detail present in the data exchanged between SILO and MSTM. The additional pieces of data that are present in the SILO/MSTM model (and *not* in the UrbanSim/MATSim model) are: zone-to-zone auto travel time, zone level auto-operating costs, and household level auto availability.

2.3 MARS Model

The Metropolitan Activity Relocation Simulator (MARS) is a popular ITLUM that has been applied to assist strategic decision making in many cities in both Europe and Asia (Pfaffenbichler and Shepherd 2002, Pfaffenbichler 2003, Shepherd and Pfaffenbichler 2006, Pfaffenbichler, Emberger, and Shepherd 2008). The current iteration of the MARS model is implemented in the Vensim programming environment and consists of transport, housing development, household location choice, workplace development, workplace location choice, and fuel and emission sub-models (Pfaffenbichler, Emberger, and Shepherd 2008). The different models operate as series of feedback cycles, e.g. numbers of commute trips increase as accessibility by car increases, which increases parking search time, which decreases accessibility by car, which finally balances the number of commute trips. One of the highlights of the MARS model is the ease by which it allows for different policy scenarios to be tested. The current implementation of the model comes with "a predefined set of transport and land use policy instruments" (Pfaffenbichler, Emberger, and Shepherd 2008). These policy

[2] SILO has also been coupled with MATSim in an ITLUM that is conceptually similar to the UrbanSim and MATSim coupling (Moeckel and Nagel 2016)

instruments involve substituting different models that exhibit different behaviors, and changes of model coefficients to allow for scenarios such as pedestrianisation, road capacity changes, and parking charges to be easily tested.

The interaction between the transportation and land use models again happens through accessibility data, and data on the spatial distribution of home and work locations. More specifically, after a given simulation iteration, accessibility values for all zones in the study area are calculated by the transportation module and passed as input to the location choice and development models. The location choice and development models run and determine the locations and quantities of households and jobs (also on a zone level) which serve as input to the next iteration of the transportation model. Instead of the agent based travel modeling seen in the previous two model couplings, MARS uses gravity based models to calculate intra-zone flows. The method by which the different pieces of data are passed between the models in the actual Vensim implementation is not reported, however, as Vensim is a closed source system, file I/O is the most likely option for further model integration.

2.4 Other Land Use Models

In the previous sections we have given three different ITLUM implementations from joining independently developed models. In this section we expand on two other popular choices for land use modeling.

WhatIf? (Klosterman 2001) is a zone based land use model that balances supply and demand for different land use types over all the zones in a study area in order to simulate development into the future. More specifically, in every iteration of the model, WhatIf? first determines land use suitability, projects land use demands, and allocates projected demand. This model does not take into account transportation based information directly, and instead relies on pre-determined control totals that correspond to different policy situations. As such, if travel demand information is taken into account when calculating the control totals, e.g. transition probabilities between different land use types for future years, this model could be incorporated into an ITLUM. An online implementation of WhatIf?, named Online WhatIf?, was developed as part of Australia's Urban Intelligence Network (Pettit, Klosterman, Delaney, Whitehead, Kujala, Bromage, and Nino-Ruiz 2015). This version of WhatIf? has been used in several applications in Australia, and allows for easy incorporation with other online datasets from a central repository.

The CLUE model is a cellular automata based land use model is another popular model that has had success in many applications (Veldkamp and Fresco 1996, Verburg and Overmars 2009, Verburg, van Berkel, van Doorn, van Eupen, and van den Heiligenberg 2010). The CLUE model is made up of a demand module and a spatial change module, where the demand module prescribes the amount of change of different land use types in an area, and the spatial change module allocates those changes to the physical layout of land use types. The operation of the demand module is flexible and can range from "simple extrapolations to complex economic models" (Verburg 2010). The spatial change module operates on a raster grid of land use types and starts from an observed configuration of land uses in an area, then projects the land use change into the future in discrete time steps. If the demand module takes into account changing traffic patterns, then this model could be integrated just as the other models in this study have been. Here the feedback loop would be that land use changes affect traffic patterns, which in turn affect how land use evolves over time, further influencing transportation.

3 PROPOSED COMMON OBJECT MODEL FOR URBAN ENVIRONMENTS

The development of a common object model, and specifically, a Federation Object Model (FOM) in HLA involves defining common abstractions and data representation that are used by *all* models in a federated simulation. The first step in creating a FOM for urban environments is determining the types of data that

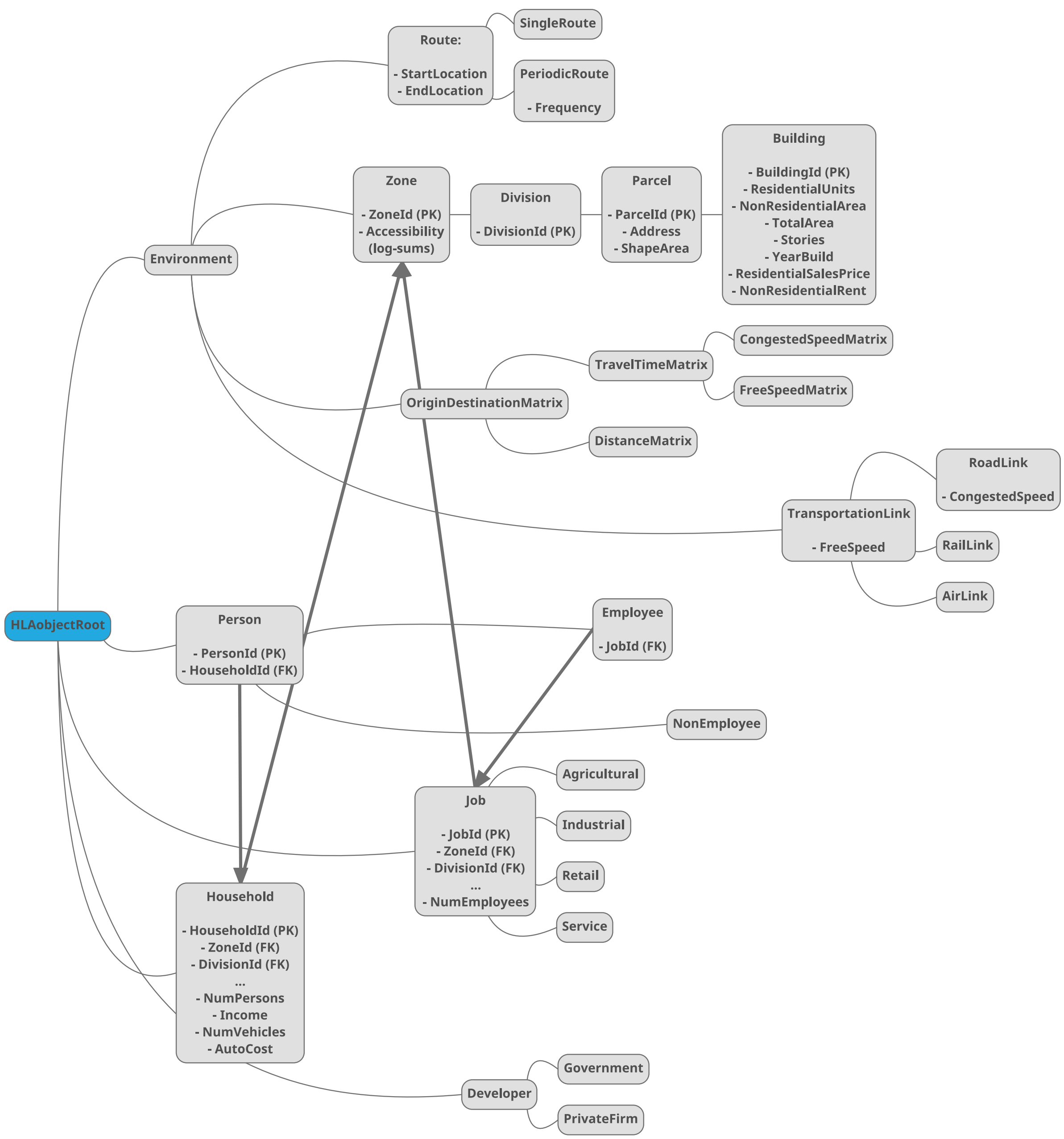

Figure 2: Object class and attribute structure of the proposed FOM.

need to be communicated between the land use and transportation models, hence allowing for federated ITLUMs to be created. It is important to start with these two models as many other models will depend on the data generated in the ITLUM feedback loop (Waddell and Ulfarsson 2004, Shahumyan and Moeckel 2015).

HLA driven model coupling has many benefits including: greater model interoperability, distributed execution of models, and the separation of model execution from model implementation. Indeed, HLA based coupling of independently developed models has resulted in successful applications in defense applications. The Real-Time Platform Level Reference Federation Object Model (RPRFOM) is a widely used common object model for defense simulations (SISO 2015). HLA was studied as one of several architectures used by the US Department of Defense in the 'Live, Virtual, Constructive, Architecture Roadmap' with the purpose of creating a multi-architecture model (Allen, Lutz, and Richbourg 2010). The creation of a common data model (the 'Joint Composable Object Model'), similar to our efforts in this work, was recognized as a key component for progress in the creation of multi-architecture simulations. HLA based modeling of coupled systems has been used in a variety of other applications, including critical infrastructure system simulation (Grogan and de Weck 2015). The components of a FOM include (copied from "IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) - Object Model Template (OMT) Specification" (IEEE 2010)):

1. Object model identification table: To associate important identifying information with the HLA object model
2. Object class structure table: To record the namespace of all federate or federation object classes and to describe their class-subclass relationships
3. Interaction class structure table: To record the namespace of all federate or federation interaction classes and to describe their class-subclass relationships
4. Attribute table: To specify features of object attributes in a federate or federation
5. Parameter table: To specify features of interaction parameters in a federate or federation
6. Dimension table: To specify dimensions for filtering instance attributes and interactions
7. Time representation table: To specify the representation of time values
8. User-supplied tag table: To specify the representation of tags used in HLA services
9. Synchronization table: To specify representation and datatypes used in HLA synchronization services
10. Transportation type table: To describe the transportation mechanisms used
11. Update rate table: To specify update rate information
12. Switches table: To specify initial settings for parameters used by the RTI
13. Datatype tables: To specify details of data representation in the object model
14. Notes table: To expand explanations of any OMT table item
15. Interface specification services usage table: To specify the HLA services used by a federate or in a federation
16. FOM/SOM lexicon: To define all of the objects, attributes, interactions, and parameters used in the HLA object model

The purpose of these definitions is to completely define the data structures used across simulators in a federated simulation. We will focus on the "Object class structure table" and "Attribute table" of our proposed FOM in this section. In Figure 2 we show the Object class structure of our proposed FOM as a tree. The root node of the tree is `HLAobjectRoot`, representing the most general class of object in our hierarchy, with five top level children: `Environment`, `Person`, `Job`, `Developer`, and `Household`. The general design principle that we follow is that the `Environment` class should represent objects grounded in the physical world, and the other classes should represent abstract actors that can operate on the `Environment`.

Specifically, the subclasses of the `Environment` class represent objects that deal with actual locations or objects in the world, and therefore provide a spatial "grounding" for the other classes. These subclasses include actual physical locations (as zones, divisions, parcels), physical objects (as roads or buildings) distances between physical locations, or paths between physical locations. The remaining four top level classes all describe different potential actors in the physical world and have been broken down into subclasses to allow for more nuanced representations in detailed ITLUM models. For example, the `Person` class has two child classes `Employee` and `NonEmployee`, which is an important distinction for some travel models, i.e. when generating home based work trips versus other types of trips.

We also show the "Attribute table" in Figure 2, where the attributes for each object are listed under the class name. The first important point is that most of the actor classes have foreign key (FK) attributes that allow them to be linked one or more instances of the `Environment` classes. These links are shown as bolded arrows between classes on the diagram. Specifically, every class in the FOM contains a primary key (PK)[3], and most classes contain a foreign key (FK) that allows them to be linked to other relevant classes. This mechanism makes the FOM definition very flexible; for example, throughout the execution of any ITLUM, `Person` objects can "move" by updating their `HouseholdId (FK)` to link to a different instance of a `Household` object, similarly, `Job` and `Households` can move, and new instances of all different objects can be added and referenced in future simulation iterations. In addition to the object linking mechanism, each class contains relevant attributes that might need to be shared between models. For example, `Household` has attributes indicating the number of people living in the household, the income of the household, and the number of vehicles owned by the household.

The purpose of the FOM is to represent all the possible objects that might need to be exchanged between models during the execution of an ITLUM. While we have been thorough in our description of the FOM, we note that it is not required that all of the classes be used in any given model coupling. In Section 4 we show the subsets of classes that each ITLUM pair, described in Section 2, would use, and how the subset would be used.

4 FOM ADAPTATION

The purpose of our proposed FOM is to factor out the conceptual data model needed for the creation of ITLUMs. This serves to reduce the overhead cost of coupling existing models, and provides a standard with which new ITLUMs/accessory models can be implemented in order to take advantage of the benefits provided by HLA. The advantages of this approach over manual coupling of land use, transportation and other models, are twofold. First, the manual creation of ITLUMs will require the creation of some sort of conceptual data model - i.e. the land use model will need to send data to the transportation model and vice versa. Our proposed FOM is well defined and, as we show in this section, is flexible enough to represent the coupling between the models discussed in Section 2. Secondly, an ad hoc creation of an ITLUM will make it difficult for further models to be integrated. With an HLA based coupling using our proposed FOM, the data descriptions are well defined, and communication between models is handled by the RTI, so further models can be integrated into the federation with relatively little overhead.

4.1 UrbanSim and MATSim

Recall that the UrbanSim/MATSim coupling involved reading and writing data tables on disk. The UrbanSim model writes out its persons, jobs and parcels tables which are then read by MATSim for the purpose of synthesizing home based work routes. Our FOM can capture this functionality exactly with the `Person`, `Job`, and `Parcel` classes. Each person in the UrbanSim simulation can be represented by the

[3]In Figure 2 some of the primary keys have been omitted for space.

Person class which can be linked to appropriate instances of Job and Household classes. Each Job and Household instance will be further linked to Parcel class instances which will give them physical locations in the simulation. MATSim can be made to use these representations, then generate its output - accessibility tables - in terms of the 'Accessibility' attribute in the Parcel objects and origin destination impedances recorded in an OriginDestinationMatrix object.

4.2 SILO and MSTM

The SILO and MSTM coupling is similar to the UrbanSim and MATSim coupling in that both pairs of models communicate through reading and writing files to disk. SILO will write out population, employment and automobile availability data to disk, while MSTM will write travel time, transit travel time, and auto-operating cost data. All of these pieces of data can be represented in our proposed FOM in a similar manner to the previous section. First, the population of SILO can be represented as Person objects linked with their corresponding Household and Job objects. Second, each Household object should use the 'NumVehicles' attribute to represent automobile availability. MSTM will represent both travel and transit travel time as TravelTimeMatrix objects, and use the 'AutoCost' attribute of Household objects to represent the auto-operating cost data. We note that as in the coupling described in (Shahumyan and Moeckel 2015, Shahumyan and Moeckel 2017), there are other models that can use data represented in the FOM, and that our FOM is purposefully designed to be extensible. We have kept the top level classes as broad as possible to allow space for further classes and sub-classes to be defined as new types of models are considered. Our efforts to create a FOM for ITLUMs is just a first step in creating a broader modeling framework of urban environments.

4.3 MARS Model

The MARS model consists of a group of sub-models that are executed sequentially and pass data between themselves during execution. The data that is passed between the transportation and land use sub-models includes zone accessibility data and the spatial distribution of household and jobs. These data types, again, similar to the other couplings, fit exactly in with the proposed FOM. The difference between this model coupling and the coupling seen in the previous two pairs of models is that MARS operates entirely on the zone level. Now, instead of links from Household and Job objects to Parcel or Building objects, the links will be Zone or Division objects[4]. All of the spatial objects are children of the main Environment object and exist in the FOM to represent areas at different levels of spatial resolution. Indeed, the only difference in the *representation* of the physical environment between the three pairs of models that we are examining is the level of detail at which the models operate on. Because the MARS model does not perform traffic assignment, there is no need for the internal conceptual model to represent roads, nevertheless, the output of the transportation model will be represented as an OriginDestinationMatrix object and changes in the 'Accessibility' attribute of zones in the same manner as the more complicated models.

5 CONCLUSION

The modeling of urban environments is an important endeavor, and as more data is collected due to efforts such as Smart City (Cocchia 2014), models can become more detailed. As models become more detailed, the overhead of creating a consistent conceptual framework for linking them together will become larger, therefore slowing progress. In this work we propose a Federation Object Model (FOM) for Integrated Transportation and Land Use Models (ITLUMs) by studying the coupling of three existing ITLUMs. Our

[4]Note that the Person object is not used in this coupling.

objective is to factor out the common conceptual work that needs to be performed when creating ITLUMs and provide a standard FOM that future modeling efforts can use to build and integrate suitable models with. We look at UrbanSim and MATSim, SILO and MSTM, and the MARS model as examples of widely used ITLUMs, and show how our proposed FOM provides a rich enough representation to be used as a replacement for the ways that the models are originally coupled in.

Future work in this research direction includes further updates to our proposed FOM. We would like to eventually design a FOM that is broad enough to cover more aspects of urban environments, which will require more studies like this one to analyze how different models work and are coupled. Possible extensions here involve water demand and distribution models, electricity demand models, air and water pollution models, and economic development models. Other future work involves creating coupled ITLUMs that are made to be HLA compliant, using this FOM, from the ground-up. This will afford many benefits including distributed execution of models, model interoperability between different research groups, and model re-use. Finally, any coupled models created using our FOM can be used to test more general modeling and simulation endeavors, such as speeding up distributed integrated simulation execution times.

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