SHULGI: A GEOSPATIAL TOOL FOR MODELING HUMAN MOVEMENT AND INTERACTION

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ABSTRACT

Theories and models of movement are central to understanding a wide range of social phenomena that crosscut numerous disciplines. Despite its importance, walking is one form of movement for which models are badly underdeveloped within tools such as transportation geographic information systems (GIS-T) that modern planners and researchers use. Analysts and researchers are in need of tools that can integrate the complexities of nonmechanized modes of transportation and are also capable of easily producing appropriate models that can be studied in the service of making critical decisions and obtaining useful insights within different social-theoretical perspectives. This paper introduces the developing agent-based modeling tool called SHULGI. This tool enables multiple sociological and socio-physical processes to be incorporated in order to assess different factors that can impact transportation decision making and events. Particular attention is given to SHULGI's modeling capabilities for addressing pedestrian movements within an urban context. Models discussed in this paper include metabolic and human decision models that will enable different types of agents to develop satisficing or optimizing route selections. These selections can impact overall traffic and movement within the transportation networks addressed. Simulation functionality and outputs provide a preliminary demonstration of SHULGI's capabilities.

Keywords: Pedestrian Movement, Agent-Based, GIS-T, Repast Simphony, Archaeology

INTRODUCTION

Theories and models of movement are central to understanding a wide range of phenomena that crosscut numerous disciplines. Models of how people move and interact are complicated by the fact that people are thinking agents. We perceive the world and the actions of people around us and chose to alter our own movements and activities accordingly. This context is experienced by nearly everyone, every day, and it is something that scholars working within the broad interdisciplinary boundaries of location theory have strived to understand for centuries (von Thünen 1826; Weber 1909; Christaller 1933). A critical question in location theory is how does transportation and movement through space affect activities and the use of space at

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particular places? This seemingly simple question belies a complex dialectic between transportation and land use that plays an important role in defining human-human and human-environment interactions.

This paper introduces an object-based geosimulation environment for modeling transportation, called SHULGI, which seeks to address this critical question in location theory. SHULGI uses the newly released Repast Simphony (Repast S) modeling toolkit as its foundational technology (North et al. 2005). With a modular object-based framework, SHULGI is designed as an easy to use, flexible simulation tool that can model multiple modes of transportation at multiple temporal and spatial scales. This paper will begin to demonstrate SHULGI's capabilities in modeling pedestrian traffic within an urban context. Despite its importance, models for addressing walking in existing spatial modeling tools, such as transportation geographic information systems (GIS-T), are largely underdeveloped. SHULGI incorporates a methodology for modeling pedestrian movement as developed by Branting (2004), which has demonstrable applicability in both the present and the past.

SOCIAL THEORY AND MOVEMENT

While movement creates opportunities for nearly boundless sets of choices and actions, it is at the same time self-limiting. Choices individuals make concerning what to do at a given point in time, along with the routes chosen to get to the required location to engage in that activity, will variously constrain what individuals can do in wider or shorter spans around the time of that activity. The realization of the importance of choices and movement within the finite framework of time has been used for decades to powerful effect within time-geography as a way to parse social and individual actions and interactions (Hägerstrand 1970; Pred 1986; Kwan 1999). The concept of the path taken by the individual through time and space is central to time-geography conceptualizations, accurately reflecting the importance of linear movement within this equation. Traffic patterns, as the aggregates of individuals' movement, can be seen through this lens of time-geography as constraining and, at the same time, as very revealing of the choices people make, including the activities they engage in individually and corporately.

In a complementary theoretical vein, location theory has long stressed the importance of movement and transportation in parsing choice, particularly in terms of land-use planning. Land-use and transportation form a symbiotic relationship in this regard, a point stressed by Blunden (1971). By the time of von Thünen around 1800, transportation was seen as a key factor in optimizing land-use allocation (von Thünen 1826). This was subsequently carried over into explicitly urban situations through work undertaken by Alonso (1964). Transportation and land-use played a key role in the calculus of industrial production and consumption put forth by theorists such as Weber (1909) and Isard (1956) and research addressing the transport of goods and services (Christaller 1933; Lösch 1954). The importance of transportation and movement seen in each branch of these basic schools of location theory continues to this day, with transportation and land-use playing key roles in human-to-human and human-to-environmental interactions (Rapoport 1977; Rapoport 1990; Johnston and de la Barra 2000; Stough 2004).

MODELING MOVEMENT

GIS-T Approach to Transportation and Pedestrian Traffic

A methodology addressing both the paths and patterns of traffic along with their symbiotic relationship to land-use offers enormous possibilities for exploring not only the form of the built environment, but also the social and individual thoughts and actions involved in its creation and alterations. GIS-T provides particularly good tools and methods to address both of these areas and indeed is being used by city and regional planners around the world. GIS-T is a domain within GIScience that only emerged during the 1990s, linking together established transportation models and methods with the display and organizational abilities of GIS (Thill 2000; Goodchild 2000). It provides network-based modeling and analysis tools that are particularly effective in forecasting and exploring traffic patterns both at various levels of aggregation as well as individual movement.

For situations where traffic is constrained, either through the framework of the built environment or through repeated practice (Helbing et al. 1997), GIS-T proves particularly effective. This applicability includes the case of pedestrian traffic, which might be considered much more variable than that of mechanized modes of transport (e.g., cars or trains) that require significant infrastructural investments (Branting 2004). There are a number of advantages to modeling pedestrian transportation using network-based approaches like those found in GIS-T (Branting 2004). Yet, surprisingly, this functionality is an almost unexplored area within the domain, with most GIS-T work focused specifically on modern mechanized transport. One of the key reasons why this is surprising is because walking is the most common mode of movement and transportation in the present as well as the past (Amato 2004; Solnit 2000; Branting 2004). For preindustrial cities, such as the ancient city at Kerkenes Dağ that is the focus of the case study below, modeling traditional modes of transportation like walking is crucial for understanding transportation. But even in present-day case studies, pedestrian transportation is a critical part of any transportation system and one that is growing in importance in light of issues with congestion and energy policies.

While the pedestrian GIS-T methodology developed by Branting (2004) has performed remarkably well, there is room for improvement. Three key difficulties with the methodology in its current implementation were identified. First, there are limitations in the flexibility of the method. Dynamic activity in time and space has always presented problems for GIS (Peuquet 2001). This was compounded by difficulties in implementing more complex scenarios, particularly those involving interactions between people in time and space. Second, the methodology became cumbersome as the range of simultaneous factors applied to a given scenario was expanded. This difficulty was manifested less in terms of computational processing speed but had more to do with the specification of the combinatory interactions between the factors. Third, the pedestrian GIS-T methodology was difficult and expensive to utilize. Several commercially available software packages, including ESRI's ArcGIS and Caliper's Transcad, were used to power both the modeling and the enormous amount of data formatting and preparatory work necessary between the various stages. Significant investments were needed in terms of both time and money to apply the methodology.

Agent-Based Modeling and Transportation Modeling

Agent-based modeling (ABM) provides a way beyond these difficulties with the pedestrian GIS-T methodology. Numerous cases have applied ABMs to transportation issues (Rickert and Nagel 2001; Batty 2001; Lake 2001), particularly because ABMs provide clear benefits to understanding human choice and decision making in movements within grids or networks. SHULGI has been designed to take full advantage of this flexibility and to allow for future extensions within a modular framework. In addition, SHULGI has been designed to make the modeling of complex transportation easier than in the GIS-T methodology by facilitating data integration, analysis, and model creation and use within this framework.

Among the benefits of SHULGI, the system allows users to load different forms of spatial and nonspatial data, either through a user's graphical user interface (GUI) or eXtensible markup language (XML) file reference, to instantiating simulation agents or other objects. Users can select from among the built–in least cost pathway algorithms, which currently include the A* and Dijkstra algorithms (Hart et al. 1968; Dijkstra 1959), or load those created by the user through XML references. In SHULGI, the A* and Dijkstra algorithms have been slightly modified so that they can factor multiple edge weights. Specific models that can be chosen in SHULGI include those that address pedestrian movements. These models address metabolic expenditures, velocities, and route decision making. The metabolism models that have been integrated include the Pandolf and McDonald models (Pandolf et al. 1977; McDonald 1961). These models take into account energy requirements over a given terrain. The velocities for these models are derived from studies of human walking (Sun et al. 1996; Kawamura et al. 1991). Time costs for the activity can also be determined from separate models such as Imhof (1968). Route decision models, which enable agents to decide where to go at a given time step, will be discussed shortly. In addition to using currently integrated models, users can create their own models, and then reference these within an XML structure to add the models within SHULGI's model library that provides the full array of model choices to analysts.

In SHULGI, models are not integrated directly with agent or entity objects; this aspect of its design is beneficial in that it allows various theoretical perspectives to be integrated using the same agent or entity[1] types. In summary, users can select a range of models addressing a specific behavior, with processes relevant for applied theoretical perspectives strictly implemented within models. Users can use SHULGI and Repast S tools that allow the construction of additional models and objects (North et al. 2005; Parker et al. 2006). In addition, SHULGI can be run within a computer cluster; the current implementation uses Terracotta software (Terracotta 2007). Current simulation models can be executed by using process-oriented discrete events, enabling contextual data to be passed to objects applying processes at relevant simulation time scales.

Object types that can be instantiated with spatial (e.g., shapefile) and nonspatial (e.g., CSV file) data include those listed in Table 1. After the appropriate simulation data have been loaded, users can map the data to an object type (e.g., TransportAgent) applied in the simulation. Data loaded and mapped include velocity values or default initial locations. Mapping the specific object parameters and data is accomplished through XML references or a GUI that

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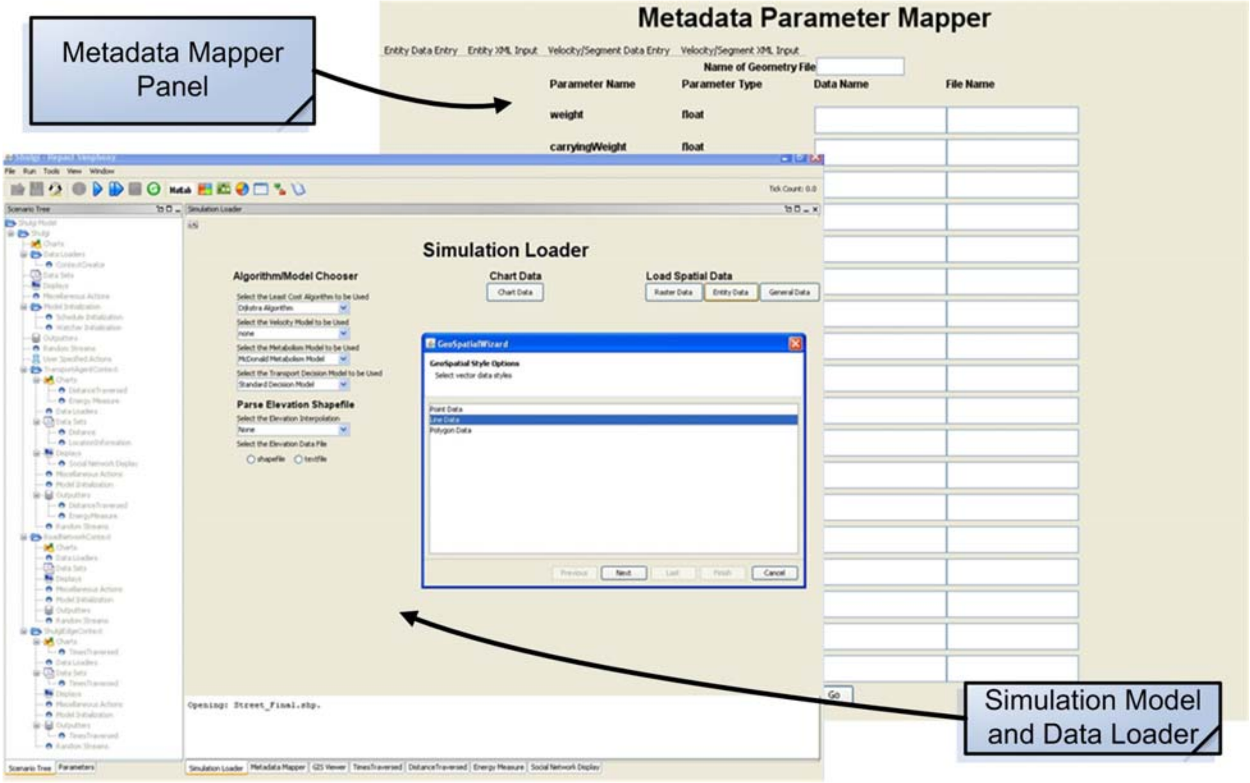
[1] Entity objects are software objects that have behaviors or processes associated with them. Entity objects can be agents; however, entities can also be noncognitive physical or environmental objects such as trees or river systems.

applies users' input. Regardless of the technique, users reference the locations (e.g., column titles, file locations) of the data values and the object variables that link to the data. Once the data mapping is complete, the simulation can be executed. Alternatively, simulation scenarios can be executed via batch runs, which can link to multiple computer nodes or a single computer. Batch mode is used for both verification and validation (V&V) as well as for producing a large number of results. Input data for batch simulations are all loaded via XML files using custom and Repast S batch mode capabilities. In batch mode, all mapping of object parameters with input data is performed automatically using XML files after the mode is launched. Figure 1 shows SHULGI's current interface used for data, model, and analytical tool integration as well as data mapping to simulation objects.

Table 1 Object types integrated in SHULGI

Object	Description
TransportAgent	Any type of moving agent
ShulgiEdge	Modified network edge
Structure	Compounds or fixed structures
Network	A Repast S network object
DestinationNode	A node a TransportAgent desires to reach
RoadNetworkNode	A node a TransportAgent can traverse



Select the Least Cost Algorithm to be Used: Dijkstra Algorithm

Select the Velocity Model to be Used: none

Select the Metabolism Model to be Used: McDonald Metabolism Model

Select the Transport Decision Model to be Used: Standard Decision Model

Select the Elevation Interpolation: None

Select the Elevation Data File: ○ shapefile ○ textfile

GeoSpatial Style Options

Select vector data styles

Point Data

Line Data

Polygon Data

Opening: Street_Final.shp.

FIGURE 1 SHULGI's interface that loads models and data as well as allows mapping of data to objects

Kerkenes Dağ Case Study

The primary area to which SHULGI has been applied to date is that of pedestrian movements and route decision making. Current example scenarios derive from data obtained from the archaeological site of Kerkenes Dağ, an ancient city in Turkey dating to the 6th century B.C. (Summers et al. 2005; Summers et al. 2007). This example is one of the same datasets used in the development of the GIS-T methodology, allowing a direct comparison between the two approaches. As with the GIS-T methods, the type of agent is disaggregated from a generic human being into different genders and age groups based on the differing walking characteristics of each (Branting 2004). Six different types of agents have been used so far: young men (aged 10–34), young women (aged 10–34), middle-aged men (aged 35–55), middle-aged women (aged 35–55), older men (aged 56–75), and older women (aged 56–75). The movement space that agents operate within SHULGI can be either a grid or network. In the examples executed, SHULGI has been applied using road networks. Road network edges (i.e., ShulgiEdge object) can store multiple weight values or calculate a given weight as needed in runtime. The Standard Decision Model (SDM) is a SHULGI test model used by agents to decide where to move based on agent goals. Calculated metabolic expenditures using the Pandolf or McDonald models, with inputs for slope and speed based on localized internal and external factors, determines how costly an edge is for the given type of agent in the Kerkenes Dağ examples. In other words, the more energy required to cross a given route segment, the more costly that entire route becomes to an agent. In this first example, agents simply determine where to go by finding the nearest DestinationNode (DN) that was not previously visited by an agent. The agent then determines the shortest path route using a least cost algorithm. A DN represents an ultimate destination that agents want to reach and that are associated with the center of compounds or walled urban blocks. Agents, therefore, attempt to visit each DN only once or until the simulation ends. In contrast, a RoadNetworkNode (RNN) is a type of DN that forms the ShulgiEdge nodes, but an RNN can be traversed continuously in the SDM. The following Java code in Figure 2 illustrates the decision step used by agents to find the path to the nearest DN.

```
public void decideTargetLocation(){
      target = null;
      shortestPath = new ArrayList<ShulgiEdge>();
      RoadNetworkNode lastStep = null;

      //sort DestinationNodes, fined nearest node
      PriorityQueue<DestinationNode> destinationQueue =
              priorityQueue(ta.getX(), ta.getY(), ta.getZ(),
              destinationNodes.size());
      destinationQueue.addAll(destinationNodes);
      boolean got = false;
       while((!got || lastStep == null)&& !destinationQueue.isEmpty()){
             //potential node
              target = (RoadNetworkNode) destinationQueue.poll();
             if (!visited.contains(target))  //see if visited node before
                   got = true;
             else
                   continue;

             lastStep = getLastStep(); // edge prior to DestinationNode
       }
      removeEdges(); //removes other destination nodes
      if (lastStep != null)
             findShortestPath(source, lastStep); //gets shortest path
      addEdges(); //add all removed DestinationNodes
      if (shortestPath.size() != 0)  //connect to final edge
         shortestPath.add((ShulgiEdge) network.getEdge(lastStep, target));

 }
```

FIGURE 2 Decision step used by agents to find the path to the nearest DN

Currently, output produced by SHULGI can be viewed or analyzed in different formats and within different tools. This function includes a GIS viewer that used GeoTools 2.3 (GeoTools 2007) to output spatial changes and movements of agents. Chart tools and network layout displays can be used to visualize some of the results. Aggregate and agent outputs produced are also provided as comma delimited data, which can then be analyzed with Repast S or other tools.

Results

Results from SHULGI help demonstrate the modeling tools' capabilities discussed previously. Scenarios have focused on energy expenditure by agents as they traverse the street network of Kerkenes Dag. Figure 3 shows the street network layout of the city with compounds, urban blocks, city wall, streets, and young male agents. In this image, GeoTools is used to visualize agents as they move across the network based on the SDM. One of the key interests for the initial modeling trials is to determine which roads are the most primary used by agents in order to reach most destinations. Among other output results that can be displayed, the GeoTools viewer in SHULGI can show the number of instances that roads are used or the overall traffic volume. Other GIS output results can be selected by the user within a wizard editor coupled in SHULGI. Disaggregated and aggregated output, such as energy expended by agents, can be shown within graphs. Figure 4 indicates the mean energy expenditure of young men as they move along routes selected during simulation time steps. This graph is produced using Repast S plug-in tools for data output and display. In addition to mean energy expenditure, simulations record mean and maximum distance traveled as agents move along various routes (Figure 5); in this case, output is shown using Repast S chart tools. Figure 5's results provide an indication as to whether or not young men need to travel significantly further in a given time instance to reach more distant nodes from their original locations. Other visual displays include network layouts; however, this display has not been used extensively in the current SHULGI scenarios. At this stage of SHULGI's development, our efforts are focused on conducting V+V on the current models that have been integrated as well as on performing further tool enhancements to enable more detailed analyses of modeling results.

These results are preliminary for the agent categories to which the scenarios have been applied, but outputs produced do show the benefits of applying an approach that can couple metabolic and other relevant cost and decision models within an overall ABM approach. By using models for social and physical processes affecting route costs, results can be used to assess optimal or satisfactory route selections for agents as influenced by multiple factors.

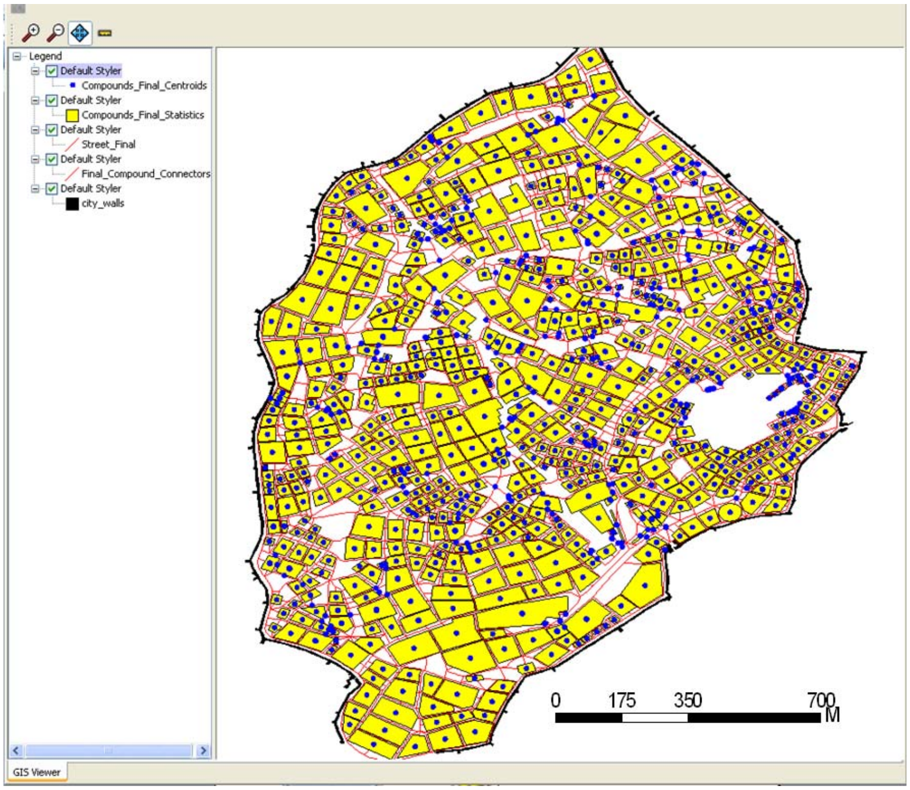


FIGURE 3 The street network (in red), compounds (in yellow), city wall, and young male agents (blue dots) during the simulation as they move and reach compounds

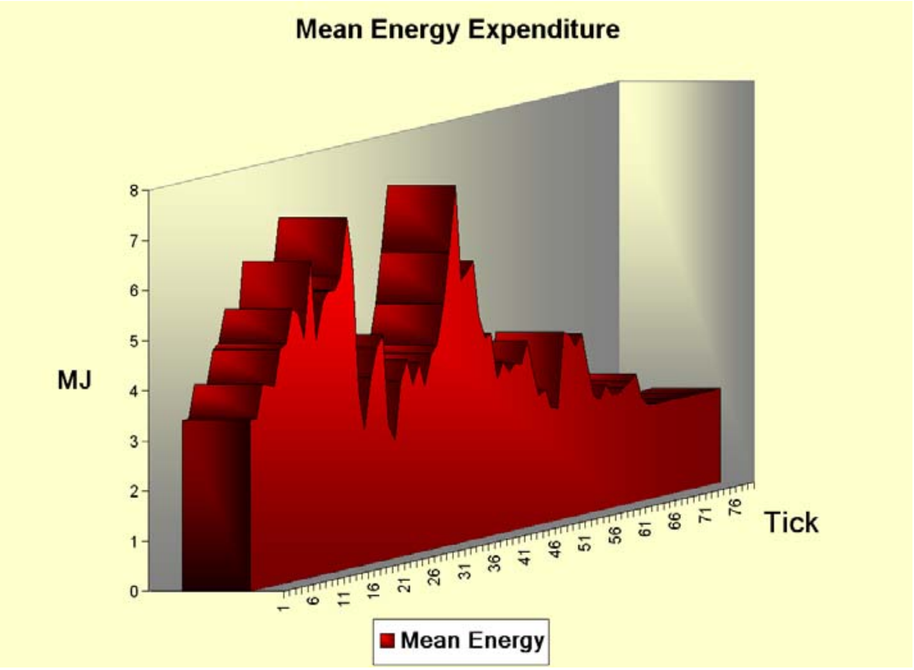


FIGURE 4 Mean energy expenditure (MJ/time step) for all young male agents

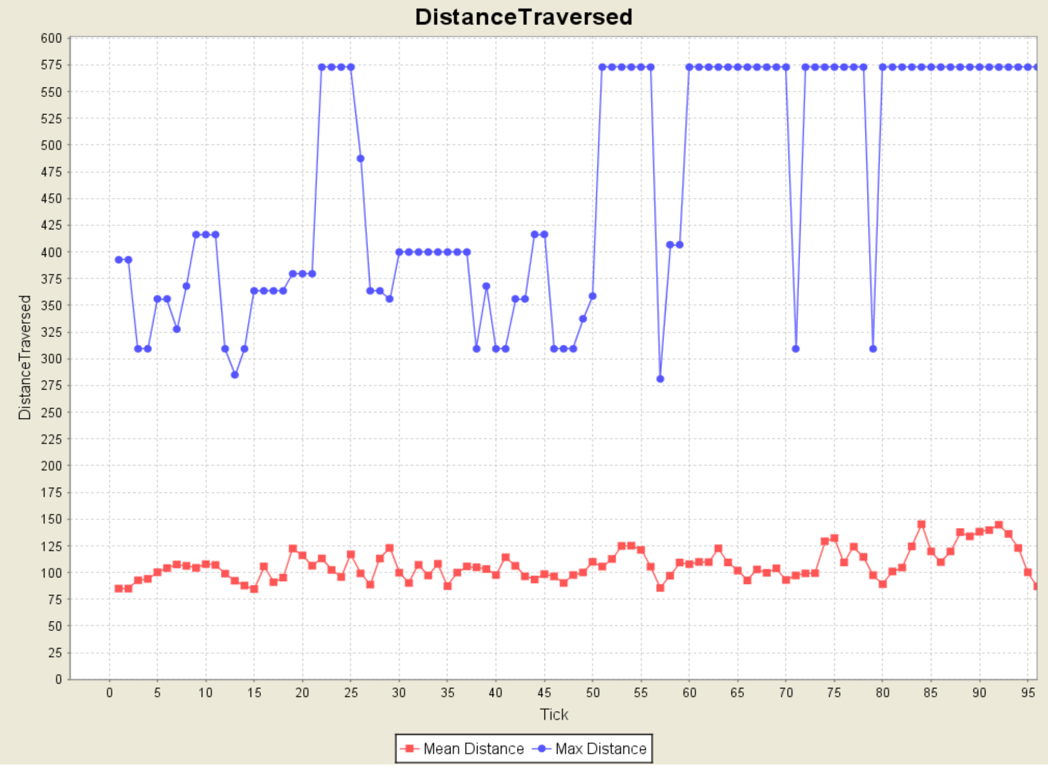


FIGURE 5 Mean (red) and maximum distance traveled (blue) during simulation time steps; distance measurements are in meters

DISCUSSION

Although SHULGI's full range of planned modeling capabilities have not been implemented, its tools have proven able to reproduce results developed within GIS-T applications and provide significant enhancements. By using an ABM approach, the modeling of pedestrian or other forms of movement can be far more flexible to theoretical applications and integration of alternative models and behaviors as compared to other geospatial approaches. Proper ABM design enables alternative models at varied temporal scales to be applied to different scenarios, allowing researchers to assess how individuals in a given transport structure may change or adapt their movements. The ability of SHULGI to simplify the integration of data and models for pedestrian movements addresses deficiencies in tools used by urban planners and geographers.

We anticipate that as SHULGI develops further, enhanced capabilities will be enabled. For instance, although SHULGI has been executed on multiprocessor clusters, our effort seeks to make the inclusion of multiple nodes a relatively simple process for the user by using appropriate GUI-based tools within SHULGI's main interface. We intend to apply and enhance SHULGI's capabilities to address other domains, including the modeling of pedestrian traffic in modern urban centers, as the tool further develops. The development of SHULGI as a freely available tool will insure its affordability for scholars and researchers interested in applying this ABM technology to their own transportation and land-use research.

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REFERENCES

Alonso, W., 1964, *Location and Land Use: Toward a General Theory of Land Rent*, Cambridge: Harvard University Press.

Amato, J.A., 2004, *On foot: a history of walking,* New York: New York University Press.

Batty, M., 2001, "Agent-based Pedestrian Modeling," *Environment and Planning B: Planning and Design B* **28**:321–326.

Blunden, W.R., 1971, *The Land-Use/Transport System: Analysis and Synthesis*, Oxford: Pergamon Press.

Branting, S., 2004, *Iron Age Pedestrians at Kerkenes Dağ: An Archaeological GIS-T Approach to Movement and Transportation*, Ph.D. Thesis, State University of New York at Buffalo.

Christaller, W., 1933, *Die zentralen Orte in Süddeutschland*, Jena, Germany: Gustave Fischer.

Dijkstra, E.W., 1959, “A Note on Two Problems in Connexion with Graphs,” *Nmerische Mathematik* 1:269–271.

GeoTools, 2007; available at http://geotools.codehaus.org.

Goodchild, M.F., 2000, “GIS and Transportation: Status and Challenges,” *Geoinformatica* **4**(2):127–139.

Hägerstrand, T., 1970, “What about People in Regional Science?,” *Papers of the Regional Science Association* **24**:7–21.

Hart, P., N.J. Nilsson, and R. Bertram, 1968, “A Formal Basis for the Heuristic Determination of the Minimum Cost Paths,” *IEEE Transaction on Systems Science and Cybernetics SSC* **4**(2):100–107.

Helbing, D., J. Keltsch, and P. Molnár, 1997, “Modelling the Evolution of Human Trail Systems,” *Nature* **388**(6637):47–50.

Imhof, E., 1968, *Gelande und Karte*, Zürich, Switzerland: Eugen Rentsch-Verlag.

Isard, W., 1956, *Location and Space-Economy: A General Theory Relating to Industrial Location, Market Areas, Land Use, Trade, and Urban Structure*, Cambridge, MA: M.I.T. Press.

Johnston, R.A., and T. de la Barra, 2000, “Comprehensive Regional Modeling for Long-Range Planning: Linking Integrated Urban Models and Geographic Information Systems,” *Transportation Research Part A* **34**:125–136.

Kawamura, K., A. Tokuhiro, and H. Tahechi, 1991, “Gait Analysis of Slope Walking: A Study on Step Length, Stride Width, Time Factors and Deviation in the Centre of Pressure,” *Acta Medica Okayama* **45**:179–184.

Kwan, M-P, 1999, “Gender and Individual Access to Urban Opportunities: A Study using Space-Time Measures,” *The Professional Geographer* **51**:210–227.

Lake, M., 2001, “The Use of Pedestrian Modeling in Archaeology, with an Example from the Study of Cultural Learning,” *Environment and Planning B: Planning and Design B* **28**:385–403.

Lösch, A., 1954, *The economics of location*, New Haven: Yale University Press.

McDonald, I., 1961, “Statistical Studies of Recorded Energy Expenditure of Man: Expenditures on Walking Related to Weight, Sex, Age, Height, Speed, and Gradient,” *Nutrition Abstracts and Reviews* **31**(3):739–762.

North, M.J., T.R. Howe, N.T. Collier, and J.R. Vos, 2005, "The Repast Simphony Development Environment," in *Proceedings of the Agent 2006 Conference on Social Agents: Results and Prospects*, pp. 69–79, Chicago, IL, October 13–15.

Pandolf, K.B., B. Givoni, and R.F. Goldman, 1977, "Predicting Energy Expenditure with Loads While Standing or Walking Very Slowly," *Journal of Applied Physiology* **43**:577–581.

Parker, M.T., M.J. North, N.T. Collier, T.R. Howe, and J.R. Vos, 2006, "Agent-Based Meta-Models," in *Proceedings of the Agent 2005 Conference on Generative Social Processes, Models, and Mechanisms*, pp. 159–166, Chicago, IL, September 21–23.

Peuquet, D.J., 2001, "Making Space for Time: Issues in Space-Time Data Representation," *GeoInformatica* **5**(1):11–32.

Pred, A., 1986, *Place, Practice and Structure: Social and Spatial Transformation of Southern Sweden,* Cambridge: Polity Press.

Rapoport, A., 1977, *Human Aspects of Urban Form: Towards a Man-Environment Approach to Urban Form and Design,* Oxford: Pergamon Press.

Rapoport, A., 1990, "Systems of Activities and Systems of Settings," in *Domestic architecture and the use of space: An interdisciplinary cross-cultural study*, S. Kent (ed.), pp. 9–20, Cambridge: Cambridge University Press.

Rickert, M., and K. Nagel, 2001, "Dynamic Traffic Assignment on Parallel Computers in TRANSIMS," *Future Generation Computer Systems* **17**(5):637–648.

Solnit, R., 2000, *Wanderlust: A History of Walking,* New York: Penguin.

Stough, R.R., 2004, "Institutions, Land Use and Transportation," in *Handbook of Transport Geography and Spatial Systems,* D.A. Hensher, K.J. Button, K.E. Haynes, and P.R. Stopher (eds.), pp. 27–42. Amsterdam: Elsevier.

Summers, G., F. Summers, and S. Branting, 2005, "Kerkenes News 7, 2004"*, Kerkenes Haberler 7*, Ankara, Turkey: METU Press; available at http://www.kerkenes.metu.edu.tr/kerk2.

Summers, G., F. Summers, and S. Branting, 2007, "Kerkenes News 9, 2006," *Kerkenes Haberler 9*, Ankara, Turkey: METU Press; available at http://www.kerkenes.metu.edu.tr/kerk2.

Sun, J., M. Walters, N. Svensson, and D. Lloyd, 1996, "The Influence of Surface Slope on Human Gait Characteristics: A Study of Urban Pedestrians Walking on an Inclined Surface," *Ergonomics* **39**(4):677–692.

Terracotta, 2007, available at http://www.terracotta.org.

Thill, J-C, 2000, "Geographic Information Systems for Transportation in Perspective," *Transportation Research Part C* **8**:3–12.

von Thünen, J.H, 1826, *Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie*, Jena, Germany: Fischer Verlag.

Weber, A, 1909, *Über den Standort der Industrie: Reine Theorie des Standorts*, Tübingen, Germany: Mohr.