



A Report from the University of Vermont Transportation Research Center

# Integrated Transportation and Land Use Models: Systems Approaches and Applications for Modeling Transport Alternatives

TRC Report 12-001 | Boumans | January 2012



**“Integrated Transportation and Land Use Models: Systems Approaches and Applications for Modeling Transport Alternatives”**

**UVM Transportation Research Center**

**Subcontract ID#21604**

January 20, 2012

Prepared by:  
Roelof M. Boumans, PhD

AFORDable Futures LLC  
4685 Greenbush Rd  
Charlotte, VT 05445  
[www.afordablefutures.com](http://www.afordablefutures.com)

Transportation Research Center  
Farrell Hall  
210 Colchester Avenue  
Burlington, VT 05405

Phone: (802) 656-1312  
Website: [www.uvm.edu/transportationcenter](http://www.uvm.edu/transportationcenter)

## **Acknowledgements**

Dr. Roel Boumans would like to acknowledge the efforts of Eric Gaza, student at the GUND Institute for Ecological Economics for his work on this project.

## **Disclaimer**

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the UVM Transportation Research Center. This report does not constitute a standard, specification, or regulation.

## Table of Contents

<b>ACKNOWLEDGEMENTS.....</b>	<b>I</b>
<b>LIST OF FIGURES .....</b>	<b>III</b>
<b>1. INTRODUCTION .....</b>	<b>1</b>
<b>2. RESEARCH METHODOLOGY.....</b>	<b>3</b>
<b>2.1 MIMES DEVELOPMENT .....</b>	<b>3</b>
<b>2.2 MIMES DATA REQUIREMENTS.....</b>	<b>4</b>
<b>2.3 ANALYTICAL METHODOLOGY.....</b>	<b>5</b>
<b>3. RESULTS .....</b>	<b>6</b>
<b>4. IMPLEMENTATION/TECH TRANSFER.....</b>	<b>11</b>
<b>5. CONCLUSIONS.....</b>	<b>12</b>
<b>APPENDIX 1. TRANSPORTATION MODEL SIMILE CODE.....</b>	<b>14</b>
<b>REFERENCES.....</b>	<b>23</b>

## List of Figures

Figure 1-1. MIMES conceptual model diagram.....	3
Figure 3-1. Overview of the model diagram using the declarative language of Simile .....	7
Figure 3-2. Sample run of the traffic emergent patterns.....	10
Figure 3-3. Example of model output in following an individual traveler.....	10

## 1. Introduction

Ever since World War II, decision makers concerned with transportation and the transportation infrastructure have strived to transport and deliver goods and services to consumers in the most efficient manner possible for economic well-being. Only recently the goal of economic wellbeing has been amended with the aim to support the enhancement of *Quality of Life*<sup>1</sup> as illustrated in a statement by the Vermont Agency of Transportation:

The Vermont Agency of Transportation's vision is a safe, efficient and fully integrated transportation system that promotes Vermont's quality of life and economic wellbeing.<sup>2</sup>

Their vision to preserve, develop, and enhance an integrated Transportation system to support Vermont's quality of life and economic well-being, invites an in depth discussion on the connections between Quality of Life and economic wellbeing. The objective of such a discussion would be to provide meaningful input towards their mission which is stated as follows: "to work cooperatively and plan for and accommodate the need for movement of people and commerce in a safe, reliable, cost-effective, environmentally responsible, and equitable manner."<sup>3</sup>

The effort to work cooperatively and plan for transportation calls for a decision-support tool (DST) which can share diverse sources of information and test scenarios against agreed upon indicators of preference. Although there are legacy models (i.e. URBANSIM<sup>4</sup> and TransCAD<sup>5</sup>) which provide indicators on the efficiency of transporting people and commerce in a safe, reliable, and cost-effective manner; they fail to provide insight into issues of environmental responsibility and equity. There is thus a need to develop a DST to link these models to an analytical framework to assess these linkages.

Costanza et al<sup>6</sup> while at the Gund Institute for Ecological Economics (GIEE) worked on a series of efforts to develop indicators of Quality of Life apart from the more traditional economic ones. Boumans<sup>7</sup> and Mulder<sup>8</sup> applied concepts from Quality of Life them for use in modeling complex integrated systems to predict global and local dynamics of the Natural, Social, Human and Built capitals to provide insight into the dynamics of environmental quality (total services provided by the ecosystems) and social equity (quality of life among intentional communities).

We hypothesize that using a DST based on indicators of Quality of Life linked to the legacy models, trade-offs among the efficiency and costs of transportation, environmental quality, and social equity will be more readily apparent and easier to analyze for most transportation decision-makers.

To research our hypothesis, we proposed to carry out the following activities:

- Develop a decision-support tool which integrates Quality of Life indicators into the legacy models
- Develop scenarios for exploratory simulations
- Calibrating the models against QoL observations
- Organize workshops for transportation planning professionals (data gathering; co-joint analyses; treatments; access to different sets of indicators; cultural backgrounds) to disseminate the technology.

The project objective was to create an integrated regional modeling platform for analysis, planning, and design of sustainable transportation systems. The modeling platform was to optimize transportation issues to other needs for social, natural and build infrastructure. The modeling paradigms were to be systems oriented to allow for transportation issues to be placed in context with the other major issues with which they are interdependent, including land use, energy, economics, environment and quality of life. The model was to be of “intermediate complexity” to use the results of more detailed modeling projects for calibration and support.

The Work Plan for this project originally consisted of four interactive elements:

- **Regular stakeholder workshops** to verify model design and components, to review preliminary results, and to design and review scenarios.
- **Intensive model development activities** between workshops. This would include model coding, calibration, and testing, as well as development of user interfaces. Existing more complex models (i.e. URBANSIM) would be used for cross-calibration and testing.
- **Problem-based (atelier) courses** structured around the project and involving students from many departments on campus.
- **Web-based outreach.** A sophisticated, interactive web site will be developed that will serve to connect stakeholders during project development and to serve as the major portal for delivery of the Integrated Modeling Package after completion.

This final report summarizes the methodology of the modeling system used, development of the decision-support tool, presentation of results from the modeling, discussions on technology transfer, and a section outlining the overall conclusions of the project.



## 2. Research Methodology

### 2.1 MIMES Development

The modeling system we explored for this study was MIMES (Multiscale Integrated Models of Ecosystem Services), a framework developed by Boumans and Costanza<sup>9</sup> to address the magnitude, dynamics, and spatial patterns of ecosystem service values at multiple scales. MIMES explicitly addresses system dynamics of natural, human, built and social capital by integrating a suite of models coupled through an interaction matrix. The interaction matrix allows a MIMES case study to pass information among subject specific simulation models to derive the values of ecosystem services.

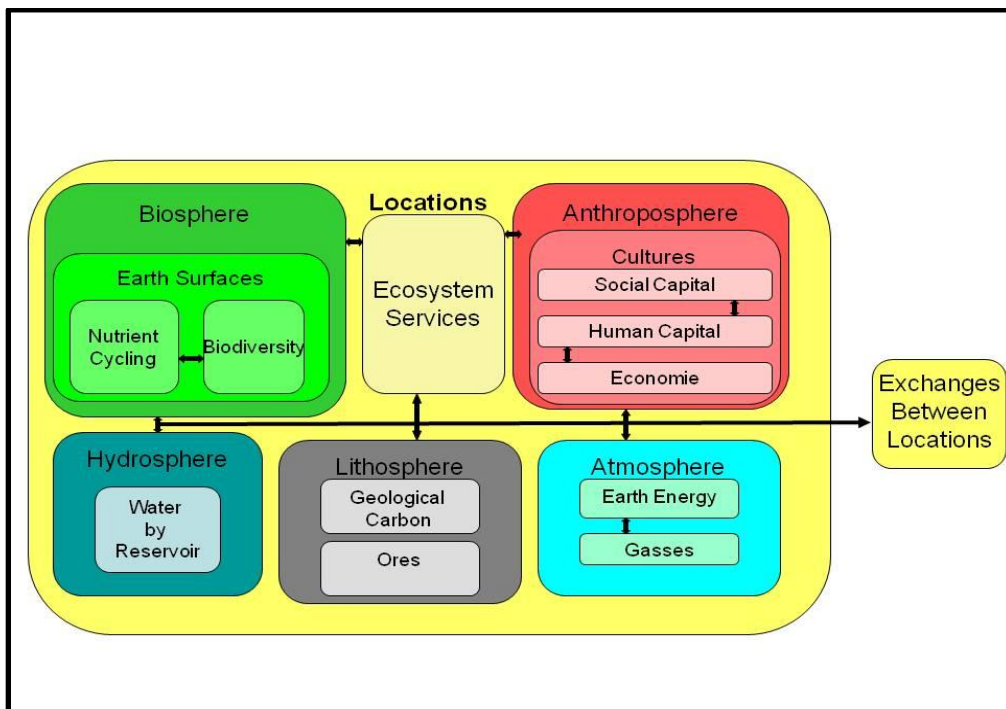


Figure 1-1. MIMES conceptual model diagram.

MIMES models consists of submodel compartments or “spheres” (e.g. biosphere, hydrosphere, lithosphere, atmosphere, anthroposphere) linked to an ecosystem service production compartment defined within a location (e.g. polygon). Locations are coupled through input-output linkages. Location-location linkages represent flows of materials, people, and services across space and time. Models so far implemented within the MIMES interaction matrix are inspired by pre-existing models recoded within the SIMILE declarative modeling software<sup>10</sup>

The interaction matrix was inspired by the Millennium Assessment Report<sup>11</sup>, UNEP’s GEO assessments<sup>12</sup>, and GLOBIO<sup>13</sup>). Hydrology simulations are based on the Patuxent Landscape Model (PLM)<sup>14</sup>, EcoSim<sup>15</sup>, WaterGAP<sup>16</sup> and SWAT<sup>17</sup>. The Atmosphere is a rather coarse and general formulation of the GCM - CLIMBER<sup>18</sup>). The Lithosphere is represented through data input on availability of soil and mineral resources. The Biosphere includes an agent-based model to simulate species diversity and animal movement between locations based on the work of Barber<sup>19</sup> and process-based land use dynamics as described in the GUMBO<sup>20</sup>. Land-use sub-models are inspired by BIOME-BGC<sup>21</sup> to simulate the changes

in stoichiometric distribution of elements in functional distinctive ecological components. The Anthroposphere recognizes a multitude of cultures within each location where each culture is represented by its human, social and built capital. The Anthroposphere borrows from GUMBO in simulating social and human capital dynamics while building upon International Futures'<sup>22</sup> approach to describe economic tradeoffs among different sectors and cultures in the local economy

The MIMES framework considers multiple ecosystem goods and services simultaneously and aims to explore their tradeoffs and responses to interacting, environmental and human drivers. As such, the MIMES facilitates understanding of spatial patterns of land use, the dynamics of ecosystem goods and services values, and the information available for estimating ecosystem services.

MIMES captures the biological and economic processes that give rise to these services, and creates scenarios that show how policy actions alter future service distribution and trade-offs. These trade-offs can be:

- (1) trade-offs among value systems;
- (2) trade-offs among ecosystem service production units; and
- (3) trade-offs among users of ecosystem services that have different and possibly conflicting needs for these services.

The focal application of the MIMES is to predict, comprehend, and support decisions which minimize ecosystem service trade-offs while sustaining ecosystem service values.

## 2.2 MIMES Data Requirements

Data requirements for MIMES must supply the following four database tables or matrices:

- **Make Tables**  
Data are gathered on spatial, temporal, and contextual attributes of ecosystem components (i.e. species, habitat, physical conditions and materials flux). Typically, these data enter the model through simulation models. That is, a holistic system that organizes and propagates data into the make table.
- **Use Tables**  
The use table consolidates the ecosystem service demand profiles of all the stakeholders, divided by economic sector. Since this information rarely exists in one place, the source data are derived from stakeholder input, bill of materials by sector, and as expert estimations. This step does not require enormous precision, but every cell must still be estimated.
- **Impact Tables**  
The impact table summarizes the physical impact on ecosystem service generation per unit production within sector. This accounts for “externalities” produced by the economic activities and their impacts on the ecosystems.
- **Decision Tables**  
Data that guides a scenario run enters into a decision table. The decision table looks at actions taken by each kind of decision maker relevant to each of the sectors. For example, the heads of a household make a decision to have a baby, at which point the sector “household population” increases, consequently placing a set of new pressures and demands on the ecosystem, with resulting effects. Often, modelers examine the outcomes of a single decision; here, we regard the entire matrix of decisions by all

decision makers as an important and dynamic layer in the model. Thus MIMES concentrates on dynamic scenarios, not just point sensitivity analyses.

Collectively, these four steps result in the telling of the story of a human-natural coupled system, and the generation and flow of ecosystem services that support the human enterprise in space and time.

## **2.3 Analytical Methodology**

### **System dynamics and modeling**

System dynamics – as developed by Forrester in the 1950's<sup>23</sup> - is an analytical method for understanding the dynamic behavior of complex systems. A system is an entity which maintains its existence through the interaction of its parts, where a systems model is a simplified representation of the system. Systems dynamics modeling is a deductive approach to knowledge that commences from a general conceptualization of hypotheses and proceeds to validate the results through expert verification and calibration against observations. Simulation modeling aids in developing a level of understanding of the interactions of the parts of a system, and of the system's properties/behavior as a whole.

System dynamics has been used by many researchers to help in decision-making with regards to natural systems, most notably by Odum <sup>24</sup>. Natural systems are typically composed of complex interactions with many unknown parameters which create significant challenges for robust statistical analyses. Validation through expert input and field observations are standard methods for ensuring the model output is realistic and accurate<sup>25</sup>. Modelers seek to optimize the model to keep the parameterization as simple as possible while maintaining the overall complexity of the system<sup>26</sup>.

### 3. Results

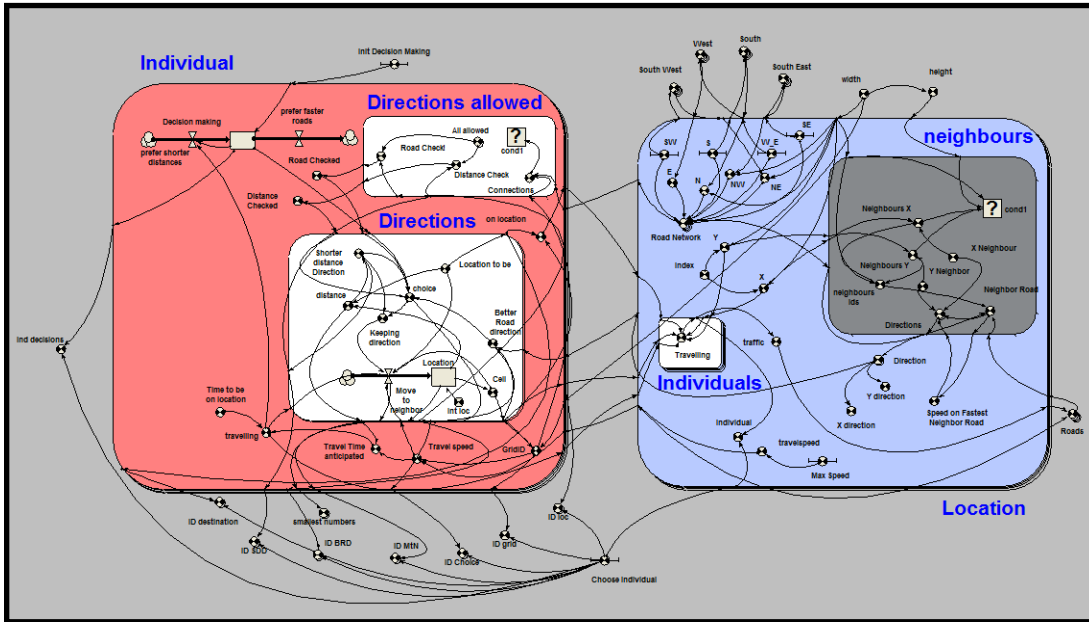
In 2007, Mulder, Troy, and Boumans<sup>27</sup> published a systems dynamics model describing the development and spatial arrangement of a metropolitan area as the emergent property due to a population density increase with different social groups matching their preferences for four types of resource profiles distributed across the landscape. The influx of people changed these distributions to lead to mismatches and internal migrations within the metropolitan area.

The resources were classified into four capitals - built, human, social, and natural - and were measured in census blocks for Baltimore, Maryland, USA. Capitals as units of production were generalizations of “Make” areas of human needs. For example, built capital creates shelter from the weather to address a human need for residency, social capital are the rules and norms we share to satisfy the human need for social cohesion, human capital is the existence of knowledge and technology necessary in the upkeep and development of built and social infrastructures, and natural capital is the producer of ecosystem services also known as the benefits from nature<sup>28</sup>.

Mulder et al (2007) showed how the match/mismatch of distribution in “Use” (resource needs) and “Make” (capital or resource production) influenced land values to cause demographic variation due to willingness to pay for, and access, the four types of capital, thus highlighting the important of preference variations across socio-economic groups. In other words, the highest land values emerged where capital distributions matched the preference distributions of resident wealthy social groups. When distributions in capital did not match that of the needs of the residents, it was suggested that these mismatches could be compensated for in sharing the capital resources in neighboring areas through trade facilitated by a connectivity matrix. Optimizing the match between household needs and the areas of production was assumed to have a cost -the connectivity cost matrix - proportional to the ease of navigating the connectivity matrix.

Under this grant we explored algorithms to estimate the transaction costs in transportation when individuals with multiple “Uses” have to negotiate among multiple “Make” locations. The analytical goal is to assess the ability of those who have to negotiate these connectivity cost matrices to achieve an acceptable match between needs and production reflected in a “Quality of Life” index as discussed in Chase et al.<sup>29</sup>.

The model separates the dynamics between the individuals travelling and the spaces travelled (Figure 3-1) while functionality is added to the model for interaction and exploration.



**Figure 3-1 Overview of the model diagram using the declarative language of Simile<sup>30</sup>.**

In the red field are attributes\* associated with individuals travelling, while the blue field contains attributes for the locations travelled. Attributes in the grey field are either connections between locations or variables designed to select model output in exploration of the dynamics. The present makes use of hypothetical data, with input variables designed to be populated with case study data.

The integrated transportation model is composed of two models – “INDIVIDUAL” and “LOCATION”. The agent-based model “INDIVIDUAL” - with attributes of individuals travelling - is replicated for all individuals that have the potential to use the connectivity matrixes (transportation mode specific roads). The number of individuals, for now, set to be 10,000, needs to be informed by the specifics of a case study, either through survey data or through the process of scenario development (the “what if” questions). Conflicts and synergies among modes of transportation occur when individuals are assigned the use of multiple matrixes with a choice at the beginning of a journey. The “LOCATION” model defines the spatial parameters of the simulations and tracks the movement of aggregations from “INDIVIDUALS” across the landscape.

\* Attributes are defined as properties associated with a model or submodel.

**Attributes for the “INDIVIDUAL” model**

- 1) A state variable called “Decision making” which describes the change in behavioral dynamics of an individual to opt for the faster road at the start of a journey and for the shortest distance path closer to destination. Without considering these behavioral shifts many of the simulated journeys never completed.
- 2) A submodel called “Directions allowed” specifying the travel mode specific connectivity matrix informed by the “LOCATION” submodel. The variable “All allowed” sets the (x,y) directions the individual is able to travel and needs to be informed by data on road networks specific to the individual’s travel mode of choice. The options under “All allowed” are ranked for the direction of shortest distance (“Distance Checked”) and for direction of the fastest roads.
- 3) A “Directions” sub model to indicate the directions the traveler is actually travelling. Attributes to the “Directions” submodel are the input variables on the location when the journey begins (“int loc” set to random (x,y) coordinates for the test runs) and the end location of the journey “Location to be” (also set by random (x,y) coordinates). When applied in case studies, the “int loc” coordinates are the end coordinates of the previous trip, while “Location to be” variable is to be informed through a set of conditions aimed in resolving resource mismatches and is the research domain in full scale implementations of the MIMES. In MIMES, locations are both, the areas of services production (e.g. natural areas to enjoy ecosystem services, schools and libraries to provide human capital, etc.) and the areas of service use. The distribution of the service production at location is defined as the resource “Make” profile. The individual’s cultural preferences at location for these services are the resource “Use” profiles. The “Location to be” variable for an individual at any point in time is the location of production of the service ranking most desirable in a constant need to eliminate mismatches in the “Make”-“Use” profiles. The “Quality of life” index (QoL) is defined as the reverse of an individual’s “Make”- “Use” mismatch, and can be aggregated to indicate QoL at a location or for a particular cultural group at location.

The ability for individuals to resolve “Make”-“Use” mismatches and achieve highest levels in QoL is determined by the time constraints in satisfying their needs (i.e. the “Use profile) versus the distance between areas of productivity, modified by the ease and speed of travel.

The variable “Choice” within the “Directions” submodel is where the individual decides the direction to take the faster or the shorter road. This choice is weighted through the “Decision making” state variable and is constant for as many time steps as the individual is at one location (“Keeping direction”). The number of time steps for an individual to travel a location is derived from “Travel speed” and the length of the road on location (set to 1 for the test runs and needs to be informed from road data layers when the model is implemented).

- 4) The flow variable “Move to neighbor” resets the variable “Location” to indicate the individual to be at a different set of (x, y) coordinates. The variable “Travel speed” is the speed of moving across the landscape available to the individual. “Travel speed” is informed by the number of individuals at a location) in the “LOCATIONS” sub-model, which represents the travel mode specific connectivity matrix<sup>†</sup>
- 5) The variable “Travel Time anticipated” considers the mode of transportation and distance to travel. “Travel Time anticipated” checked against the input variable “Time to be on location” sets the start of each journey.

### **Attributes for the “LOCATION” model**

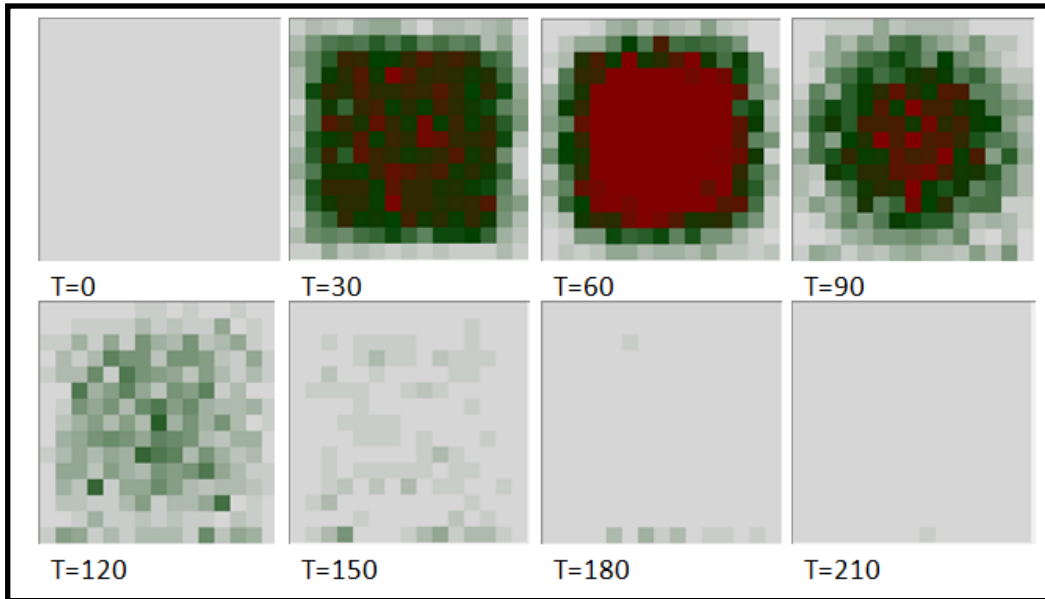
The model “LOCATIONS” mimics the “Location” submodel under the MIMES paradigm<sup>91</sup>. In MIMES, they are the areas of service production, while in this model, they are the locations where individuals are present. The individuals have travelled to these locations for particular services, or they use these locations to pass through in journeys to other locations. Attributes to the Location submodel are, the coordinates of neighboring locations (submodel “Neighbors”) in the eight cardinal/ordinal directions, the available road connection to those neighboring locations, the maximum speed that a mode in travelling is allowed, or is able to achieve, and the number of individuals present. An estimate on the density in traffic is achieved when all individuals at location are summed together under the variable “traffic”. The traffic estimate is used in modifying the traffic speed in neighboring cells and informs the individual/choice variable on the fastest road to travel.

### **The User Interface:**

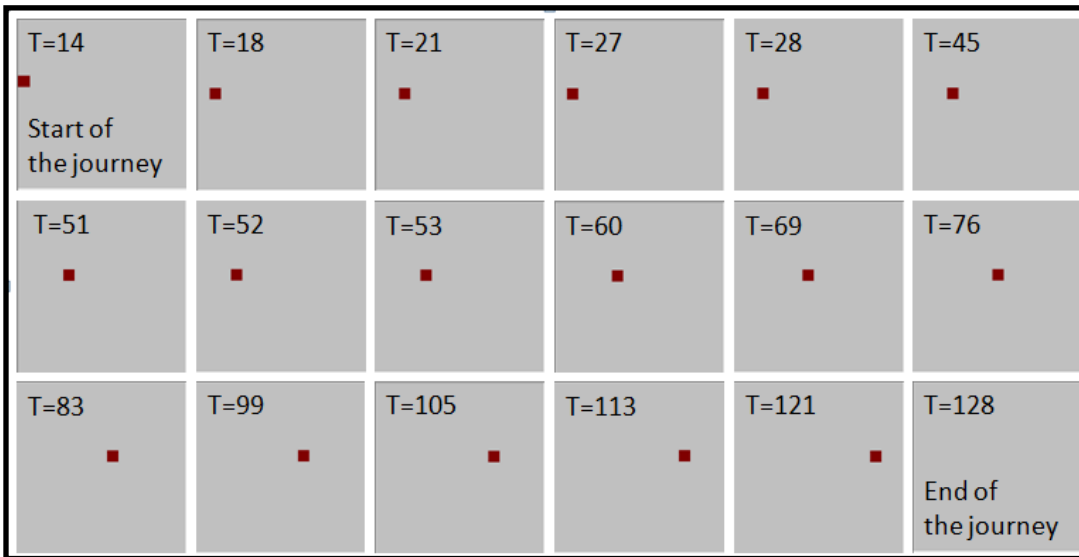
Functionality is built into the model to observe traffic dynamics as the emergent behavior resultant from the number of individuals involved, choices in mode of transportation, layout of the road network, the spread in areas of service production and the cultural defined need preferences for those services (Figures 3-2 & 3-3).

---

<sup>†</sup> Travel mode connectivity matrix is the explicit restrictions on which mode of transport (i.e. car, bike, foot) can utilize which roads.



**Figure 3-2. Sample run of the traffic emergent patterns. Model output simulating a 15 by 15 location matrix where 10,000 individuals starting at randomly chosen locations need to travel to randomly chosen destinations using the same mode of travel. Panels are timeframes of 2.5 hours. Time to be on location is randomly assigned to each of the individuals from 10 to 50 minutes after the start of the simulation. Travel times are severely delayed due to underestimates by travelers who are confronted with traffic jams in the center of the matrix.**



**Figure 3-3. Example of model output in following an individual traveler. Presented are frames in a dynamic output from the start at T =14 to the end of the journey T=128. . Large lapses between changes in location (e.g. T=28 and T=45) indicate periods the traveler is experiencing congested roads.**



## **4. Implementation/Tech Transfer**

MIMES Make, Use and Impact tables are mostly developed with stakeholders during its implementation into a decision support tool. Such decision support tools are presently under development for Human Uses within the Stellwagen Marine Reserve<sup>32</sup> and ecosystem services and public health modeling currently under development by the EPA<sup>33,34</sup>.

## 5. Conclusions

Presented are the developments for agent based modeling for application in spatial dynamic simulations. The objective in developing these spatial dynamic simulation capabilities is to serve the knowledge context in decision support tools. These agent based dynamics are intended to help plan urban areas in the design of transportation networks, and in making the choices for allocating service areas (economic and ecological services) when the objective is to optimize Quality of Life.

The project was successful in developing and demonstrating the agent based dynamics required in spatial dynamic simulations.

The project was not successful in demonstrating the algorithms under a case study while making use of existing data. Developing spatial dynamic simulations capabilities for case studies, requires the integration of Geographical Information Systems (GIS) with the computational capabilities for dynamic simulations, the numerical solving of integrated nonlinear systems of differential equations over time (systems dynamics. While Most GIS systems have the capabilities to solve for models based on linear regression equations<sup>‡</sup>), they do not feature the stock flow model paradigms of systems dynamics. Software packages designed for systems dynamics, such as Stella, Vensim, and SIMILE, however, do not feature spatial representations.

SIMILE, a systems dynamics program, offers systems dynamics capabilities across multi-dimensional arrays. We were able to demonstrate spatial dynamic modeling within SIMILE by assigning unique x and y coordinate dimensions in the parameterization of an array of unit models – see Fitz et al<sup>35</sup> - where all unit models together cover all locations in a landscape.

The tendency of GIS software is to use computational resources in maintaining high resolution data across space with low content resolution (i.e. large amount of pixels with few attributes assigned). Systems dynamics simulation models tend to use computational resources to achieve high content resolution (large amounts of attributes describing nonlinear integrated systems) and are not designed to cover high spatial resolutions. An application of a case study would have required:

1. Finding the optimum tradeoff between content and spatial resolutions in lieu of available computational power (not a focus in this study).
2. Increased computational power of SIMILE. This eventually happened after this project ended, when Simulistics, the makers of SIMILE, compiled a 64-bit version and subsequent acquisition of a 64-bit gaming desktop with over-clocked processors.
3. The capacity to run exported SIMILE models under software optimized for super computers and parallel processing. In December 2012, this option became available,

---

<sup>‡</sup> See: [http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=An\\_overview\\_of\\_ModelBuilder](http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=An_overview_of_ModelBuilder)

and it is now possible to run SIMILE export modules within the open source software language “R”.

Developing the capability for spatial dynamic models to merge the complexity of non-linear models with the resolutions of GIS will require the smart design of a database that needs to be able to store output files on each of the model variables, at each time step, at the resolutions preferred in GIS, for every time the model is executed under a different scenario. These large amounts of data will require development of a user interface for intelligent inquiries into the outcomes of the model scenario runs.

## Appendix 1. Transportation Model SIMILE Code

### Model Transportation

1. Variable Choose individual :
  - 1.1. Choose individual = Variable parameter
  - 1.2. Minimum = 1, Maximum = 10
2. Variable ID BRD :
  - 2.1. ID BRD = element([[Better\_Road\_direction]],Choose\_individual)
    - Where:
      - 2.1.1. [[Better\_Road\_direction]] = Value(s) of Individual/Directions/Better Road direction
      - 2.1.2. Choose\_individual = Value(s) of Choose individual
3. Variable ID Choice :
  - 3.1. ID Choice = element([[choice]],Choose\_individual)
    - Where:
      - 3.1.1. [[choice]] = Value(s) of Individual/Directions/choice
      - 3.1.2. Choose\_individual = Value(s) of Choose individual
4. Variable ID MtN :
  - 4.1. ID MtN = element([[Move\_to\_neighbor]],Choose\_individual)
    - Where:
      - 4.1.1. [[Move\_to\_neighbor]] = Value(s) of Individual/Directions/Move to neighbor
      - 4.1.2. Choose\_individual = Value(s) of Choose individual
5. Variable ID SDD :
  - 5.1. ID SDD = element([[Shorter\_distance\_Direction]],Choose\_individual)
    - Where:
      - 5.1.1. [[Shorter\_distance\_Direction]] = Value(s) of Individual/Directions/Shorter distance Direction
      - 5.1.2. Choose\_individual = Value(s) of Choose individual
6. Variable ID destination :
  - 6.1. ID destination = element([[Location\_to\_be]],Choose\_individual)
    - Where:
      - 6.1.1. [[Location\_to\_be]] = Value(s) of Individual/Directions/Location to be
      - 6.1.2. Choose\_individual = Value(s) of Choose individual
7. Variable ID grid :
  - 7.1. ID grid = element([[GridID]],Choose\_individual)
    - Where:
      - 7.1.1. [[GridID]] = Value(s) of Individual/GridID
      - 7.1.2. Choose\_individual = Value(s) of Choose individual
8. Variable ID loc :
  - 8.1. ID loc = element([[Cell]],Choose\_individual)
    - Where:
      - 8.1.1. [[Cell]] = Value(s) of Individual/Directions/Cell
      - 8.1.2. Choose\_individual = Value(s) of Choose individual

## 9. Variable Roads :

9.1. Roads =  $\text{[travelspeed]}/\max(1, \text{[traffic]})$

Where:

9.1.1.  $\text{[travelspeed]}$  = Value(s) of Location/travelspeed

9.1.2.  $\text{[traffic]}$  = Value(s) of Location/traffic

## 10. Variable South :

10.1. South =  $\text{[S]}$

Where:

10.1.1.  $\text{[S]}$  = Value(s) of Location/S

## 11. Variable South East :

11.1. South East =  $\text{[SE]}$

Where:

11.1.1.  $\text{[SE]}$  = Value(s) of Location/SE

## 12. Variable South West :

12.1. South West =  $\text{[SW]}$

Where:

12.1.1.  $\text{[SW]}$  = Value(s) of Location/SW

## 13. Variable West :

13.1. West =  $\text{[W\_E]}$

Where:

13.1.1.  $\text{[W\_E]}$  = Value(s) of Location/W\_E

## 14. Variable height :

14.1. height =  $225/\text{width}$

Where:

14.1.1. width = Value(s) of width

## 15. Variable ind decisions :

15.1. ind decisions =  $\text{element}(\text{[Decision\_making]}, \text{Choose\_individual})$

Where:

15.1.1.  $\text{[Decision\_making]}$  = Value(s) of Individual/Decision making

15.1.2.  $\text{Choose\_individual}$  = Value(s) of Choose individual

## 16. Variable init Decision Making :

16.1. init Decision Making = Variable parameter

16.2. Minimum = 0, Maximum = 1

## 17. Variable smallest numbers :

17.1. smallest numbers =  $\text{least}(\text{[[Location]])}$

Where:

17.1.1.  $\text{[[Location]]}$  = Value(s) of Individual/Directions/Location

## 18. Variable width :

18.1. width = 15

**Submodel Individual**

Submodel "Individual" is a fixed\_membership multi-instance submodel with dimensions [10000].

19. Compartment Decision making :
- 19.1. Initial value = init\_Decision\_Making  
Where:  
19.1.1. init\_Decision\_Making = Value(s) of ../init Decision Making
- 19.2. Rate of change = + prefer shorter distances - prefer faster roads
20. Flow prefer faster roads :
- 20.1. prefer faster roads = 0
21. Flow prefer shorter distances :
- 21.1. prefer shorter distances = if Decision\_making==1 then 0 else travelling\*rand\_var(0,0.001)  
Where:  
21.1.1. Decision\_making = Value(s) of Decision making  
21.1.2. travelling = Value(s) of travelling
22. Variable Distance Checked :
- 22.1. Distance Checked = if any({Distance\_Check})then 1 else 0  
Where:  
22.1.1. {Distance\_Check} = Value(s) of Directions allowed/Distance Check
23. Variable GridID :
- 23.1. GridID = element([Cell],1)+(element([Cell],2)-1)\*width  
Where:  
23.1.1. width = Value(s) of ../width  
23.1.2. [Cell] = Value(s) of Directions/Cell
24. Variable Road Checked :
- 24.1. Road Checked = if any({Road\_Check\_}) then 1 else 0  
Where:  
24.1.1. {Road\_Check\_} = Value(s) of Directions allowed/Road Check!
25. Variable Time to be on location :
- 25.1. Time to be on location = round(rand\_const(10,50))
26. Variable Travel Time anticipated :
- 26.1. Travel Time anticipated = sqrt(element([distance],1)^2+element([distance],2)^2)\*Travel\_speed  
Where:  
26.1.1. Travel\_speed = Value(s) of Travel speed  
26.1.2. [distance] = Value(s) of Directions/distance
27. Variable Travel speed :
- 27.1. Travel speed = element([travelspeed],GridID)  
Where:  
27.1.1. GridID = Value(s) of GridID  
27.1.2. [travelspeed] = Value(s) of ../Location/travelspeed
28. Variable on location :
- 28.1. on location = if sum(abs([Location\_to\_be]-[Cell])) ==0 then 1 else 0  
Where:  
28.1.1. [Location\_to\_be] = Value(s) of Directions/Location to be

28.1.2. [Cell] = Value(s) of Directions/Cell

29. Variable travelling :

29.1. travelling = if time()>Time\_to\_be\_on\_location-  
Travel\_Time\_anticipated then 1 else 0

Where:

29.1.1. Travel\_Time\_anticipated = Value(s) of Travel Time anticipated

29.1.2. Time\_to\_be\_on\_location = Value(s) of Time to be on location

**Submodel Individual/Directions :**

Submodel "Individual/Directions" is a fixed\_membership multi-instance submodel with dimensions [2].

30. Compartment Location :

30.1. Initial value = int\_loc

Where:

30.1.1. int\_loc = Value(s) of int loc

30.2. Rate of change = + Move To neighbor

31. Flow Move to neighbor :

31.1. Move to neighbor = if Cell==Location\_to\_be then 0 else  
travelling\*Travel\_speed\*Keeping\_direction

Where:

31.1.1. Location\_to\_be = Value(s) of Location to be

31.1.2. Keeping\_direction = Value(s) of Keeping direction

31.1.3. travelling = Value(s) of ../travelling

31.1.4. Travel\_speed = Value(s) of ../Travel speed

31.1.5. Cell = Value(s) of Cell

32. Variable Better Road direction :

32.1. Better Road direction =  
element(element([[Direction]],GridID),index(1))

Where:

32.1.1. GridID = Value(s) of ../GridID

32.1.2. [[Direction]] = Value(s) of ../Location/Direction

33. Variable Cell :

33.1. Cell = round(Location)

Where:

33.1.1. Location = Value(s) of Location

34. Variable Keeping direction :

34.1. Keeping direction = if choice == -last(choice) then  
Shorter\_distance\_Direction else choice

Where:

34.1.1. Shorter\_distance\_Direction = Value(s) of Shorter distance Direction

34.1.2. choice = Value(s) of choice

35. Variable Location to be :

35.1. Location to be =  
element([round(rand\_const(1,15)),round(rand\_const(1,15))],index(1))

36. Variable Shorter distance Direction :
- 36.1. Shorter distance Direction = (if distance==0 then 0 else distance/abs(distance))
- Where:
- 36.1.1. distance = Value(s) of distance
37. Variable choice :
- 37.1. choice = if rand\_var(0,1) >Decision\_making then (Distance\_Checked\*Shorter\_distance\_Direction) +((1-Distance\_Checked)\*Better\_Road\_direction\_0) else (Road\_Checked\*Better\_Road\_direction\_0)+((1-Road\_Checked)\*Shorter\_distance\_Direction)
- Where:
- 37.1.1. Road\_Checked = Value(s) of ../Road Checked
- 37.1.2. Decision\_making = Value(s) of ../Decision making
- 37.1.3. Distance\_Checked = Value(s) of ../Distance Checked
- 37.1.4. Shorter\_distance\_Direction = Value(s) of Shorter distance Direction
- 37.1.5. Better\_Road\_direction\_0 = Value(s) of Better Road direction
- 37.1.6. if rand\_var(0,1) >Decision\_making then (Distance\_Checked\*Shorter\_distance\_Direction) +((1-Distance\_Checked)\*Better\_Road\_direction\_0) else (Road\_Checked\*Better\_Road\_direction\_0)+((1-Road\_Checked)\*Shorter\_distance\_Direction)
38. Variable distance :
- 38.1. distance = Location\_to\_be-Location
- Where:
- 38.1.1. Location\_to\_be = Value(s) of Location to be
- 38.1.2. Location = Value(s) of Location
39. Variable int loc :
- 39.1. int loc = element([round(rand\_var(1,15)),round(rand\_var(1,15))],index(1))

**Submodel Individual/Directions allowed :**

Submodel "Individual/Directions allowed" is a conditional fixed membership submodel of dimensions [8].

40. Condition cond1 :
- 40.1. cond1 = Connections==1
- Where:
- 40.1.1. Connections = Value(s) of Connections
41. Variable All allowed :
- 41.1. All allowed = element([[ -1,-1],[0,-1],[1,-1],[-1,0],[1,0],[1,1],[0,1],[1,1]],index(1))
42. Variable Connections :
- 42.1. Connections = element(element([[Road\_Network]],GridID),index(1))
- Where:
- 42.1.1. [[Road\_Network]] = Value(s) of ../Location/Road Network
- 42.1.2. GridID = Value(s) of ../GridID



43. Variable Distance Check :

43.1. Distance Check =  
all([Shorter\_distance\_Direction]==[All\_allowed])

Where:

43.1.1. [All\_allowed] = Value(s) of All allowed

43.1.2. [Shorter\_distance\_Direction] = Value(s) of ../Directions/Shorter distance  
Direction

44. Variable Road Check! :

44.1. Road Check! = all([Better\_Road\_direction]==[All\_allowed])

Where:

44.1.1. [All\_allowed] = Value(s) of All allowed

44.1.2. [Better\_Road\_direction] = Value(s) of ../Directions/Better Road direction

### Submodel Location

Submodel "Location" is a fixed\_membership multi-instance submodel with dimensions [225].

45. Variable Direction :

45.1. Direction = sum({[Directions]})

Where:

45.1.1. {[Directions]} = Value(s) of neighbors/Directions

46. Variable E :

46.1. E = element([West],index(1)+1)

Where:

46.1.1. [West] = Value(s) of ../West

47. Variable Index :

47.1. Index = index(1)

48. Variable Max Speed :

48.1. Max Speed = Variable parameter

48.2. Minimum = 0, Maximum = 65

49. Variable N :

49.1. N = if (index(1)-width) <= 0 then 0 else element([South],index(1)-  
width)

Where:

49.1.1. [South] = Value(s) of ../South

49.1.2. width = Value(s) of ../width

50. Variable NE :

50.1. NE = if index(1)-width-1<1 then 0 else  
element([South\_West],index(1)-width-1)

Where:

50.1.1. [South\_West] = Value(s) of ../South West

50.1.2. width = Value(s) of ../width

51. Variable NW :

51.1. NW = if index(1)-width<=0 then 0 else  
element([South\_East],index(1)-width+1)

Where:

51.1.1. [South\_East] = Value(s) of ../South East

51.1.2. width = Value(s) of ../width

52. Variable Road Network :

52.1. Road Network = [NE,N,NW,W\_E,E,SE,S,SW]

Where:

52.1.1. SW = Value(s) of SW

52.1.2. S = Value(s) of S

52.1.3. SE = Value(s) of SE

52.1.4. E = Value(s) of E

52.1.5. NE = Value(s) of NE

52.1.6. N = Value(s) of N

52.1.7. NW = Value(s) of NW

52.1.8. W\_E = Value(s) of W\_E

53. Variable S :

53.1. S = Variable parameter

53.2. Minimum = 0, Maximum = 1

54. Variable SE :

54.1. SE = Variable parameter

54.2. Minimum = 0, Maximum = 1

55. Variable SW :

55.1. SW = Variable parameter

55.2. Minimum = 0, Maximum = 1

56. Variable Speed on Fastest Neighbor Road :

56.1. Speed on Fastest Neighbor Road = greatest({Neighbor\_Road})

Where:

56.1.1. {Neighbor\_Road} = Value(s) of neighbors/Neighbor Road

57. Variable W\_E :

57.1. W\_E = Variable parameter

57.2. Minimum = 0, Maximum = 1

58. Variable X :

58.1. X = int(fmod(Index-1,width))

Where:

58.1.1. Index = Value(s) of Index

58.1.2. width = Value(s) of ../width

59. Variable X direction :

59.1. X direction = element([Direction],1)

Where:

59.1.1. [Direction] = Value(s) of Direction

60. Variable Y :

60.1. Y = int((Index-1)/width)

Where:

60.1.1. Index = Value(s) of Index

60.1.2. width = Value(s) of ../width

61. Variable Y direction :

61.1. Y direction = element([Direction],2)

Where:

61.1.1. [Direction] = Value(s) of Direction

62. Variable individual :

62.1. individual = element([Travelling],Choose\_individual)

Where:

62.1.1. [Travelling] = Value(s) of Individuals/Travelling

62.1.2. Choose\_individual = Value(s) of ../Choose individual

63. Variable traffic :

63.1. traffic = sum([Travelling])

Where:

63.1.1. [Travelling] = Value(s) of Individuals/Travelling

64. Variable travelspeed :

64.1. travelspeed = Max\_Speed/(65)

Where:

64.1.1. Max\_Speed = Value(s) of Max Speed

**Submodel Location/neighbors :**

64.2. Submodel "Location/neighbors" is a conditional fixed membership submodel of dimensions [8].

65. Condition cond1 :

65.1. cond1 =

Neighbors\_X>=0,Neighbors\_X<width,Neighbors\_Y>=0,Neighbors\_Y<height

Where:

65.1.1. Neighbors\_Y = Value(s) of Neighbors Y

65.1.2. Neighbors\_X = Value(s) of Neighbors X

65.1.3. height = Value(s) of ../height

65.1.4. width = Value(s) of ../width

66. Variable Y Neighbor :

66.1. Y Neighbor = element([-1,-1,-1,0,0,1,1,1],index(1))

67. Variable Directions :

67.1. Directions = if

Speed\_on\_Fastest\_Neighbor\_Road==Neighbor\_Road then [X\_Neighbor,Y\_Neighbor]  
else [0,0]

Where:

67.1.1. Y\_Neighbor = Value(s) of Y Neighbor

67.1.2. X\_Neighbor = Value(s) of X Neighbor

67.1.3. Neighbor\_Road = Value(s) of Neighbor Road

67.1.4. Speed\_on\_Fastest\_Neighbor\_Road = Value(s) of ../Speed on Fastest Neighbor  
Road

68. Variable Neighbor Road :

68.1. Neighbor Road =  
element([Road\_Network],index(1))\*element([Roads],neighbors\_ids+rand\_cons  
t(0,0.01))

Where:

68.1.1. [Road\_Network] = Value(s) of ../Road Network

68.1.2. neighbors\_ids = Value(s) of neighbors ids

68.1.3. [Roads] = Value(s) of ../Roads

69. Variable Neighbors X :

69.1. Neighbors X =  $X + X\_Neighbor$

Where:

69.1.1. X\_Neighbor = Value(s) of X Neighbor

69.1.2. X = Value(s) of ../X

70. Variable Neighbors Y :

70.1. Neighbors Y =  $Y + Y\_Neighbor$

Where:

70.1.1. Y\_Neighbor = Value(s) of Y Neighbor

70.1.2. Y = Value(s) of ../Y

71. Variable X Neighbor :

71.1. X Neighbor =  $\text{element}([-1,0,1,-1,1,-1,0,1],\text{index}(1))$

72. Variable neighbors ids :

72.1. neighbors ids =  $\text{width} * \text{Neighbors\_Y} + \text{Neighbors\_X} + 1$

Where:

72.1.1. Neighbors\_Y = Value(s) of Neighbors Y

72.1.2. Neighbors\_X = Value(s) of Neighbors X

72.1.3. width = Value(s) of ../width

### Submodel Location/Individuals :

Submodel "Location/Individuals" is a fixed\_membership multi-instance submodel with dimensions [10000].

73. Variable Travelling :

73.1. Travelling =  $\text{if } \text{element}(\text{element}([\text{Cell}],\text{index}(1)),1) == X+1 \text{ and } \text{element}(\text{element}([\text{Cell}],\text{index}(1)),2) == Y+1 \text{ then } (1 - \text{element}([\text{on\_location}],\text{index}(1))) * \text{element}([\text{travelling}],\text{index}(1)) \text{ else } 0$

Where:

73.1.1. [[Cell]] = Value(s) of ../Individual/Directions/Cell

73.1.2. [on\_location] = Value(s) of ../Individual/on location

73.1.3. [travelling] = Value(s) of ../Individual/travelling

73.1.4. Y = Value(s) of ../Y

73.1.5. X = Value(s) of ../X

## References

- <sup>1</sup> Costanza, R. et al. "An Integrative Approach to Quality of Life Measurement, Research, and Policy". *SAPIENS* Vol.1 / n°1 (2008)
- <sup>2</sup> Resource Systems Group, Inc. et. al. "*Vermont Long Range Transportation Business Plan*". Vermont Agency of Transportation. (March 2009). front material.
- <sup>3</sup> Ibid.
- <sup>4</sup> Waddellm, P. et al. "The Open Platform for Urban Simulation OPUS and UrbanSim Version 4.3: User Guide and Reference Manual." The UrbanSim Project. University of California Berkeley and the University of Washington. (Jan. 23, 2011)
- <sup>5</sup> Flammia, G. and A. Rabinowicz. "Turning Transportation Planning Data Into Effective Web Sites." A White Paper. Caliper Corporation. Newton, MA. (2002).
- <sup>6</sup> Costanza, R. et al. "Quality of Life: An approach integrating opportunities, human needs, and subjective well-being." *Ecological Economics* 61 (2007) p. 273.
- <sup>7</sup> Boumans, R. et al. "Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model". *Ecological Economics* 41 (2002) p. 529-560.
- <sup>8</sup> Mulder, K. et al. "The contribution of built, human, social and natural capital to quality of life in intentional and unintentional communities." *Ecological Economics* 59 (2006) p. 13-23.
- <sup>9</sup> Boumans R. and Robert Costanza. "The multiscale integrated Earth Systems model (MIMES): the dynamics, modeling and valuation of ecosystem services." In: Van Beers, C.; Petry, D.; Pahl-Wostl, C. (eds.) *GWSP Issues in Global Water System Research No. 2: Global Assessments: Bridging Scales and Linking to Policy*. Report on the joint TIAS-GWSP workshop held at University of Maryland University College, Adelphi, USA, (10 & 11 May 2007) p. 104-107.
- <sup>10</sup> Muetzelfeldt, R., "Declarative modelling in ecological and environmental research." Position Paper EUR 20918, European Directorate-General for Research, European Commission, Brussels, Belgium (2004).
- <sup>11</sup> Millennium Ecosystem Assessment. "Ecosystems and Human Well-being: Synthesis". Island Press (2005).
- <sup>12</sup> UN Environment Program. "Global Environment Outlook GEO-4: Environment for Development." Progress Press, Ltd. Malta (2007).
- <sup>13</sup> Alkemade, R. et al. "GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss." *Ecosystems* 12 (2009) p. 374-390.
- <sup>14</sup> Voinov, A. et. al. "Patuxent landscape model: integrated ecological economic modeling of a watershed." *Environmental Modelling and Software* 14 (5) (1999) p. 473-491.

- <sup>15</sup> Kedra, K. and L. Winkelbauer. "Ecological and environmental monitoring and simulation system for management decision support in urban areas: ECOSIM Validation Plan." *Environmental Software & Services GmbH* (1997).
- <sup>16</sup> Alcamo, J. and T. Henrichs. "Critical regions: a model-based estimation of world water resources sensitive to global changes." *Aquatic Sciences* 64 (2002) p. 352-362.
- <sup>17</sup> Glassman, P.W. et al. "The soil and water assessment tool: historical development, applications, and future research directions." *Transactions of the American Society of Agricultural and Biological Engineers*. Vol 50 (4) (2007) p. 1211-1250.
- <sup>18</sup> Claussen, M. and A. Ganopolski. "The climate system model CLIMBER." In *Modelling climate change and its economic consequences – a review*. European Academy for the Study of Consequences of Scientific and Technological Advance. (1999) p. 40-54.
- <sup>19</sup> Barber M.C. "Bioaccumulation and Aquatic System Simulator (BASS) User's Manual." Beta Test Version 2.1. EPA Report No. 600/R-01/035. Ecosystems Research Division. U.S. Environmental Protection Agency. Athens, GA. (April 2001).
- <sup>20</sup> Boumans, R. et al. "Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model". *Ecological Economics* 41 (2002) p. 529-560.
- <sup>21</sup> Running, S.W. and Hunt, E.R. Jr. "Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models." In Ehleringer, J.R. and Field, C. B. (eds) *Scaling physiological processes: leaf to globe*. Academic Press, San Diego (1993) p. 141-158.
- <sup>22</sup> Hughes, B. B. 1999. "The International Futures (IFs) modeling project." *Simulation Gaming*. Vol 30 no. 3 (1999) p. 304-326.
- <sup>23</sup> Forrester, Jay (1971). "Counterintuitive behavior of social systems." *Technology Review*. Vol 73 No 3 (1971) p. 52-68.
- <sup>24</sup> Odum, H.T. *Environment, Power, and Society*. Wiley-Interscience New York, N.Y. (1971).
- <sup>25</sup> Jørgensen, Sven Erik & Bendoricchio, G. *Fundamentals of ecological modelling*. Gulf Professional Publishing. (2001) p.79.
- <sup>26</sup> Wainwright, J. and M. Mulligan. *Environmental Modelling: Finding Simplicity in Complexity*. John Wiley & Sons, Ltd. (2004).
- <sup>27</sup> Mulder, K. et al. "The role of built, human, social, and natural capital in determining land values, and the influence of demographics upon this relationship." *Spatial Economic Analysis*. Vol 2 Issue 2 (2007) p. 135-156.

- <sup>28</sup> Daily, G. “Nature's Services: Societal Dependence on Natural Ecosystems.” Washington, DC: Island Press (1997).
- <sup>29</sup> Chase, L. et al. “Participatory modeling as a tool for community development planning: tourism in the Northern Forest.” *Community Development*, Vol 41 No 3 (2010) p. 385-397.
- <sup>30</sup> Muetzelfeldt, R. and Massheder, J. “The Simile visual modelling environment.” *European Journal of Agronomy*. Vol 18 (2003) p. 345-358.
- <sup>31</sup> Kerchner C., et al. “The Value of the Kol River Salmon Refuge's Ecosystem Services”. Research conducted by UVM's Dept. of Community Development & Applied Economics and Gund Institute for Ecological Economics. Funded and prepared for the Wild Salmon Center (2008).
- <sup>32</sup> <http://www.seaplan.org/ocean-planning/tools-to-inform-decision-making/ecosystem-tradeoff-modeling/mimes/>
- <sup>33</sup> US Environmental Protection Agency. “Ecosystem Services Research Program (ESRP): Albemarle-Pamlico Watershed and Estuary Study (APWES) Research Plan. US EPA Office of Research and Development. EAP/600/R-10/180 (December 2010).
- <sup>34</sup> Victory, W. “Addressing Public Health Impacts from Climate Change using Systems Thinking Action Teams 2010 – 2011.” National Environmental Public Health Leadership Institute. 2010-2011 Fellow Project.
- <sup>35</sup> Fitz C., et al. “Development of a Generic transforming Ecological Model (GEM) for a range of scales and ecosystems.” *Ecological Modeling* Vol 88 (1996) p. 263-295.