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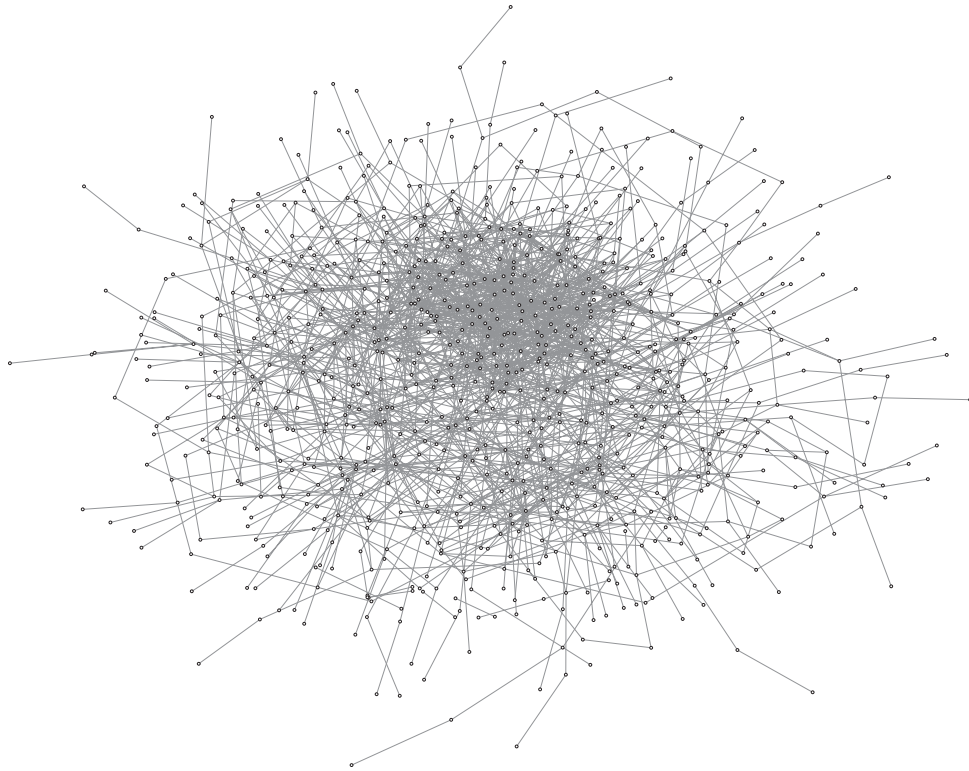
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Model for Coupling Multi-Agent Social Interactions and Traffic Simulation

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Title of paper

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Abstract

While transportation researchers have long recognized that travellers' decisions are interdependent, actor interdependencies are rarely incorporated in our field. Good reasons for this are that the common statistical tools requiring the assumption of independent decision makers have worked well for many applications. Meanwhile, real maps of social, work, and business interactions have not been made at the scope required for transportation studies. As discretionary travel constitutes an increasing proportion of traffic, and policy makers seek ways to reduce low-occupancy vehicle travel, understanding these interdependencies will be more important for modeling and policy impacts. Agent simulation is available in lieu of comprehensive empirical studies to construct the interdependencies between travellers and activity-travel choices. This paper introduces a general spatial social interaction model, based on the Multi-Agent Transportation Simulation Toolbox (MatSim-T, Rieser et al 2007), to serve as a laboratory for scenario- and hypothesis testing. The model has two features that suit it to general study of social networks and activity spaces: modular structure and the speed to simulate large numbers of agents in the travel simulation. The basic tools of transportation science: utility maximization, activity plans, and generalized travel cost, are used to construct social networks for a geographically distributed population of agents. This network is then used in a further step to modify travel demand (location, activity, and/or timing). This paper summarizes the model, presents some preliminary results, illustrating some of the issues of investigating complex socio-spatial dynamics, and sketches an experimental plan for hypothesis testing. Patterns seen in real social networks can be reproduced with reasonable behavioral assumptions. The paper concludes with thoughts on the computational challenge of scaling the models to large samples of agents, and the integration of the socializing dynamic with a large-scale microsimulation.

Keywords

behavior microsimulation – social networks – activity-based planning – travel behavior

1. Introduction

Travel utilities (and decisions) are almost always modelled as individually independent across decision makers: a function of the traveller's own characteristics and the attributes of modes, routes, and destinations. The fact that people plan trips and activities jointly, depending on the trips and activities of other people, has been ignored with few exceptions (Kurani and Kitamura 1996). This compromise has been reached consciously and with good reason, including convenient econometric model estimation tools (e.g. Ben Akiva and Lehrman 1985) and the lack of datasets detailing decision-maker interactions (Manski 2000).

Representing behavior as entirely independent succeeds as long as it considers regulary occurring, relatively inelastic equilibrium behavior, like work (non-discretionary) trips, where the boundary conditions of the problem dominate the solution. Travel preferences in this case can be assumed to be explained by the sociodemographic characteristics of the traveller and by generalized travel costs; any deeper processes of orchestrating the trip take either a long-term character exogenous to the model (Hensher 2002), i.e. choice of home/work location, or they play an insignificant role due to the relatively limited flexibility of the traveller. More flexible (discretionary) behaviors are explained by adding variables like taste heterogeneity and cohort or habitual behavior effects, either as random coefficients or based on panel datasets or assumed distributions. While such extensions improve the statistical specification and the conceptual validity of the models somewhat, they neglect accounting for traveller/decision maker interactions. This rules them out for studying important processes of real behavior, and may limit their usefulness in prediction, as well. That is, the model output without interactions may be plausible, but it may be for the wrong reason (Shy 2001).

Endogenizing interactions amounts to explicitly accounting for who influences whom, when and how much. This new dimension may help resolve spatio-temporal behaviors that would otherwise be subsumed by sociodemographic explanations. But there is a major drawback to methods using social interactions, because it becomes necessary to know the specific social connections (social network), as well as the direction and strength of influence on an individual's decision making that is communicated by this network: the so-called *reflection problem* (Manski 1993; Bramoullé et al. 2007). This metaphor refers to the difficulty an observer has in determining whether a person moves his image in a mirror or vice versa: without knowing the relationship between the two people in view, i.e. which one is a reflection, the observer cannot separate cause and effect. It applies to the sociological problem of determining to what extent the correlated decisions between an individual and a group is a result of a process of choosing peers with the same attitudes, versus a process by which members of a group influence one another to conform to some group norm. In order to

correctly represent how the society functions, one needs precise knowledge about, or hypotheses of, social topologies and the dynamic processes at work in the system.

Both communication and person-to-person encounters are crucial for the maintenance of social networks and the social capital that they enable (Larsen et al. 2006). A reciprocal interaction between travel/communication and social networks is therefore a logical starting postulate: social networks generate communication/travel, but communication/travel opportunities enable the spatial spread of the social networks. But these are rarely observed (Manski 2000).

1.1 Goals

This work accepts that observations of social interactions in the transportation context are sparse, and employs a micro-simulation to achieve basic understanding of a realistic range of interactions between travellers that could potentially be influencing activity-travel choices. The leading research question is how to generate and characterize social connections (networks) and activity spaces concurrently such that they are consistent with both social theory and travel behavior theory. The micro-simulation is a modular object-oriented structure using the Java-based MATSim Toolbox (summarized recently in Rieser et al. 2007) and it enables the researcher to conduct and document experiments by combining desired algorithms and/or datasets for the three main elements of study: socializing, geography, and travel behavior, and to adjust the strength of their coupling. Using multi-agent simulations to model inter-actor relationships that lead to macro-scale system properties is a combination of deductive and inductive methods, sometimes called “generative science” (Sawyer 2004). Agent modeling allows researchers to control and experiment with microscopic behavior and observe the emergent macroscopic system (Banks 1993; Axtell 2000). There are virtually no limits to the assumptions a researcher can make in the social network module, though the success of algorithms will depend on computing limitations (and the justification for the assumptions).

This paper describes the implementation of the social network module within the MATSim-T micro-simulation framework. A summary of social networks and the geography of social travel is followed by a description of other work on social networks in transportation. Then the MATSim-T social network module is described. Sample results illustrate some of the possible configurations of the module. Future work will include scaling studies and application to a large synthetic population on a realistic road network. The social network statistics and the activity space dimensions will be compared with what is known from the data to elucidate relationships to use in future work in surveying or policy analysis.

2. What is known about travel and social networks

2.1 Real social networks

2.1.1 Definition of terms

A social network (graph) is a mathematical expression referring to a set of nodes (vertices), representing people, and links (edges) representing well-defined relationships between the people. The links can be valued and directed (arcs) to represent relationship strengths, and these values can change in time. The 2-person subset of a social network consisting of a node-link-node subgraph is called a "dyad". The subject being studied is called an "ego" and those he is linked to, "alters". This paper uses "friend" loosely to mean "alter". Network statistics help discern paths of information flow and give some indication of their efficiency, resilience, and resistance to disruptions. The measures are counting procedures focused on certain constellations of links and nodes: clustering (essentially a normalized count of triangles), shortest path length (minimum number of links connecting two nodes), and degree (number of links entering or exiting a node) will be referred to here because they are commonly observed in real social networks.

The evidence from samples of real social networks indicates that they are neither well-represented by models in which relationships are equally likely between all individuals, independent of physical distance (Erdős/Renyi network), nor by models of lattices, in which every person's link pattern is identical (e.g. knowing all spatial neighbors). Instead, real social networks fall somewhere in between these two well-studied theoretical structures, presenting a so-called "small world" structure with properties of both types of networks, in which a few individuals belong to local social clusters, but also to other distant clusters, thus providing shortcuts through society (Watts 1999; Newman et al. 2002). Small world network statistics are characterized by a higher clustering coefficient than an Erdős/Renyi graph, and a comparably small average shortest path length ($\log(\text{number of nodes})$).

In addition to small world properties, observed social networks exhibit a degree distribution between exponential and scale-free (Dorogovtsev and Mendes 2003). The frequency of observations of high degree nodes is higher than in a Poisson-distributed degree of an Erdős/Renyi or Watts/Strogatz graph, meaning that there is a tendency for certain individuals to attract social connections at much higher rates than other individuals. People preferentially associate with certain other people, for whatever reason (Barabasi et al. 1999), and the degree of neighbors is correlated (unlike in an Erdős/Renyi graph).

Social networks used in/emerging from transportation studies should exhibit these realistic characteristics, or else network phenomena will not have the proper heterogeneity or spread quickly enough. In short, many social networks may be considered "realistic", but Erdős/Renyi networks are not. Furthermore, how the clustering, geodesic distances, degree, and other characteristics of social networks relate to geography and travel behavior must still be understood.

2.2 Datasets of social travel

There are few datasets available to study the geography of social interactions. Data is needed in the microsimulation for initializing social networks, for descriptions of travel-related interactions, and for comparison with measures of ego networks and activity behavior with simulation output: degree distributions and clustering coefficients, the frequency and location of face-to-face meetings, the activity types associated with these meetings, the number of participants, their relationship, the planning process, and so on.

(Axhausen and Frei 2007) summarize a wide range of studies about the geographical distribution of social contacts. Universally, face-to-face contact frequency falls with an inverse function of distance. However, microscopic rules are more difficult to extract. Datasets focusing on the social influences on travel behavior (Carrasco and Miller 2006; Silvis et al. 2006; Axhausen and Frei 2007; Mok et al. 2007) are characterized by detailed questions about behavior posed to small numbers of travellers. They are useful for indications but not for statistical modeling or to provide strong support for hypotheses. In epidemiology, Christakis and Fowler (2007) constructed a geocoded dynamic social network of spatial interactions of 5124 people over 35 years and analyzed the role of network statistics in the spread of obesity. A geographical analysis is pending. Rothenberg, et al. (2005) analyze the distances between sex partners in an HIV study, though the graphs of sexual partners cannot be extrapolated well to entire populations due to the seldom occurrence of closed triangles.

2.3 Application of social networks in transportation

2.3.1 Econometric studies

Statistical analyses of social network effects published in the transportation literature follow the theory of Manski (1993) and derivations of Durlauf and Cohen-Cole (2004). (Dugundji and Gulyas 2003; Páez and Scott 2004; Dugundji and Walker 2005) generated social networks on the basis of a number of factors (common zip code, common residential or work zone, common workplace, sociodemographic categories) and used them to estimate

econometric discrete choice models estimated on revealed preference data. The studies show that the endogenous normative opinion of a peer group in certain social networks can have significant explanatory power for mode choice and trip generation. However, neither microscopic behavior nor individual interactions could be taken into account in these models.

2.3.2 Microsimulations

Microsimulations of social networks in the transportation literature include work from Arentze and Timmermans (2006), Hackney and Axhausen (2006), and Marchal and Nagel (2006). Arentze and Timmermans (2006) present a fully developed concept for social interactions and activity patterns based on the ego-centric (personal) network, including abstractions of homophily (McPherson et al. 2001), social need, and satisfaction. Their utility functions maximize the value of ego networks within the total discretionary time budget of the agent. Tests were limited to small numbers of agents, so there are no summary statistics of the social networks, and it is noted that the complex results of even this small sample are difficult to summarize and understand.

In Hackney and Axhausen (2006), social networks evolve with activity spaces by weighing travel cost against participating in social activities in the utility function, while agents exchange information with their affiliates about where other socializing opportunities exist, exploring space to maximize the utility of socializing. It is a rudimentary activity travel model with homogenous agents and no explicit valuation of a social network, intended as a template for realistic models with estimable utility functions. Despite its simple logic, the geographic provenience of the agents adds substantial complexity to existing network generation algorithms. Statistical analysis of the networks indicates exponential degree distributions and probabilities of affiliation proportional to an inverse function of distance between alters' home addresses. This model's algorithms are not scalable to models larger than several thousand agents because of high demands on computer memory.

Marchal and Nagel (2006) have modeled the spread of information about secondary location choice (shopping) along the affiliation network of co-located coworkers to accelerate the learning curve of agents. The work served above all to illustrate the feasibility of the approach in a large-scale microsimulation, but does not have an extensible API or easily exchanged "world" scenarios, and is a fixed Erdős/Renyi graph topology (except for geographical effects).

3. Social Networks Module

3.1 API

This work build on previous travel behavior simulations by adding flexibility. The social network module is approached as an application programming interface (API) extending the MATSim-Toolbox (Multi-Agent Transportation Simulation Toolbox, see (Rieser et al. 2007)) to let the researcher construct social experiments using Java. MATSim offers the great advantage of a mature I/O, rich database, modularity and object-oriented structure, error handling, memory management, and parallel-processed dynamic traffic assignment.

The first modification is to attach an EgoNetwork object to the Knowledge (Mental Map) of each agent. The EgoNetwork is simply a list of friends and a list of the links to the friends. Here, a "friend" is a very imprecise name for adjacency in a matrix of agents. A global SocialNetwork is introduced, including all agents and consisting of a list of pointers to the EgoNetworks. The researcher can access links and people using either piece of information. The SocialNetwork class defines whether links are directed or undirected, and contains methods to initiate, strengthen, and remove links, a saturation function to simulate the cognitive limitations that prevent humans from maintaining too many friends, as well as setup algorithms to initialize the social network. A set of interaction classes are provided to let the agents meet each other in space or to communicate nonspatially (exchange Knowledge without explicit travel). A class is also available to enable the modification of plans based on new Knowledge (a step called RePlanning in MATSim-T) and a plan scoring function. Finally, the package includes a statistics module using the JUNG network statistics package (O'Madadhain et al. 2005) that outputs social, geographic, and travel statistics for each agent, each edge, and for the graph as a whole, for each iteration step. Certain distributions are calculated during the run and other detailed inquiries are left for postprocessing.

3.2 Suggested Application Framework

A social network emerges through a lifetime of activities, and this API could theoretically be used with MATSim to simulate long periods of interactions and large geographies of activities. However, the value of such "whole world" models is overwhelmed by conceptual challenges, lack of data, and computational hurdles, and is not the main goal of this effort. Feasible simulation deals with activities taking place during the shorter periods specified in the MATSim input activity plans, thus a snapshot of social relations in time. Though iterative calculations will be presented to reconcile social networks with geography and transportation behavior, they do not represent dynamics or even microeconomic processes, but rather

marginal probability distributions, much in the way that social network generation algorithms in the physics literature have done.

The kinds of hypotheses testable in this framework pertain to the effect of geography and/or travel patterns, and vice versa. Social networks can be used in three kinds of experiments: first, the researcher can choose a fixed set of agent plans and allow agents who meet face to face to establish relationships with one another, perhaps augmented by other non-spatial social processes. This generates a geographically embedded social network which can be studied to evaluate the plausibility of the geographic and social mechanisms or algorithms leading to social links. Second, a social network can be generated using any number of algorithms and the plans can be altered to maximize utility, again with the goal of evaluating the plausibility of the assumptions and to compare the resulting activity plans with those that do not use interdependent agents. Third, the social network and the plans can be coupled and altered together according to the researcher's hypotheses about the interdependence of activities and social connections. This does not represent an evolution of social networks in time, but a relaxation of the system.

4. Sample application

To illustrate the use of the API, a sample program is described to simulate the simultaneous generation of geographic social networks and plan modification. Its steps are first outlined and then discussed in more detail below. The program consists of five basic steps (*base configuration and assumptions in italics*):

- 1) Read in initial plans, agents, world, road network, facilities map: *1008 agents, 5 activity types, ≤ 4 out-of-home activities per plan, see Figure 1*
- 2) Initialize social connections: *Erdős/Renyi graph of degree 3, undirected links, saturation effects*
- 3) Permit spatial (face to face) encounters according to the agents' plans: *co-location only, no time windows*
- 4) Modify social connections: *links are strengthened by encounters; weak links are removed*
- 5) Permit the exchange of other information on the social network, not requiring face-to-face encounters: *exchange of information about one facility and one other person possible per social link per iteration*
- 6) Modify plan: *allow changing the location of certain activity types*
- 7) Write the output statistics

These steps are to be repeated until an equilibrium is reached (i.e. the average degree and/or clustering coefficient is constant, Kosinets 2007 personal communication). The iteration procedure reconciles the initial social connections with respect to the activity plan of the agent and the geographic characteristics of the "world". The order of the steps and the algorithms involved can be changed according to the experimenter's needs.

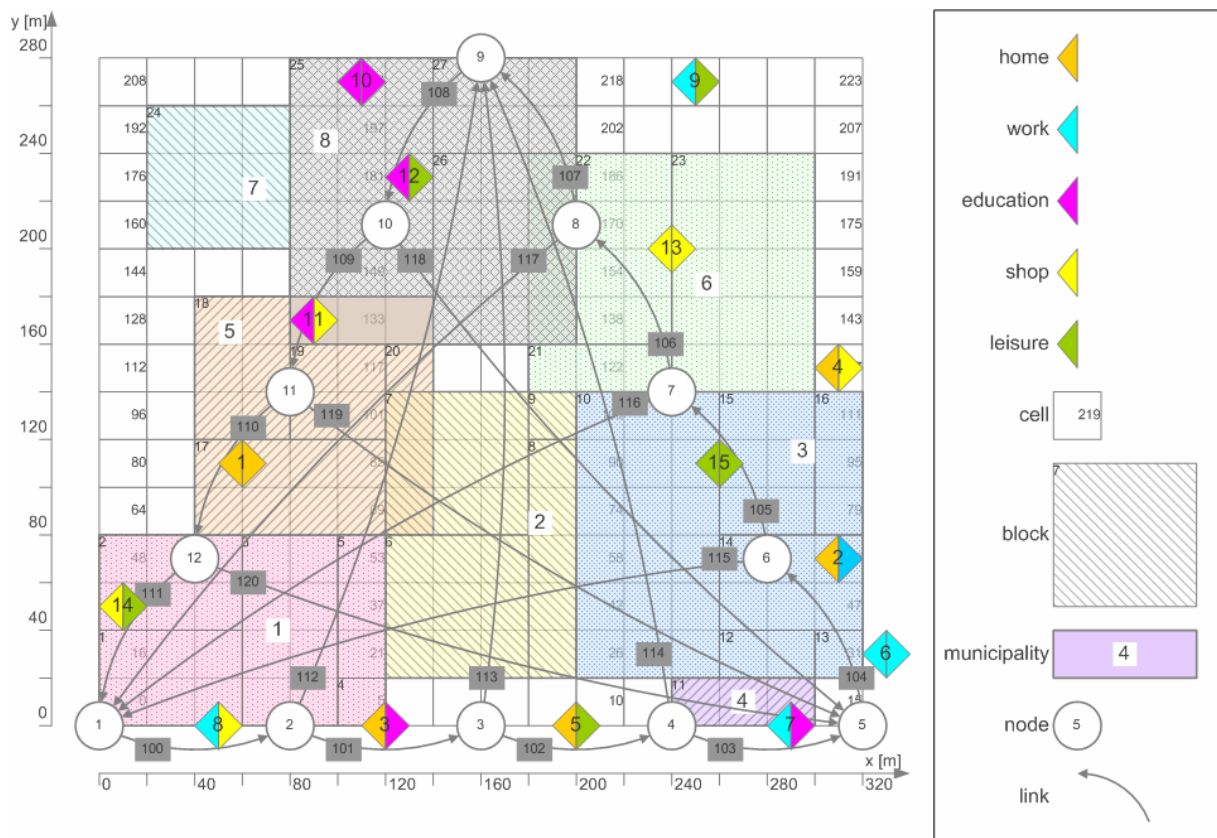
4.1 Initialization

The initial social connections may take any topology the researcher desires to generate. This initial network might conceivably be based on household relationships, extra-household family, work colleagues, geography, or other index of affinity. Note that the selection of characteristics for a Person in MATSim is small (*sex, age, has_drivers_license, has_car_avail, is_employed*). Using social network generation algorithms on detailed sociodemographic information would require working directly with the Census data instead of

the MATSim synthetic population (an additional Person class and Household layer are in development).

The test scenario uses the TriangleTest world packaged with MATSim-T (Figure 1). 1008 agents are initialized with day plans of up to 4 randomly-sequenced activities each, beginning and ending at the agent's home location. The 5 activity types are: home, work, education, shop, leisure. The agents are assigned randomly to a home location, and the locations of their activities are also random. This world contains a rather low number of facilities, which is not ideal for generating geographic social networks. But it is useful because it contains all the geographic layers (road network, jurisdictions, lattice grid) necessary to run tests and analyses.

Figure 1 The geographic world of TriangleTest



Source: (Balmer 2007)

4.2 Spatial encounters (face-to-face)

The spatial encounters are based on the activities of the agents. Agents may meet only when they visit the same facility. A time window may be easily added because activities have start and end times. Miller (2005), for example, contributes a new comprehensive view on time window constraints on behavior.

Social contacts are strengthened in this example if befriended agents re-encounter each other. If not, they may befriend one another, with a saturation effect. Agents befriend one another at a location at a random rate, depending on the activity type, with decreasing probability depending on how many friends they have. With undirected links, there is automatic mutual agreement to befriend.

4.3 Modification of the social network

Social links that have not been renewed by face-to-face contact may be removed randomly after a certain time threshold, with removal probability scaling with link age or degree of an agent-node (as in (Jin et al. 2001)). This might be replaced, for example, by a function which incorporates the type of relationship and sociodemographics of the agents (Burt 2000).

4.4 Non-spatial information exchange and unobserved social behavior

Passing information along the social network nonspatially is a class written to account for the fact that not all social activities can be observed in a single day (or week) plan, and the fact that not all social contact requires face-to-face travel. In this method, agents exchange information from their Knowledge about geography and from their EgoNetworks about each other. It is assumed that the introduction of friends to each other occurs when information about other agents is transmitted: i.e. A telling B about C amounts to A introducing B and C. This closing of triads is an important phenomenon in social networks that leads to correlated degrees, clustering, small worlds, and exponential degree distributions (Jin et al. 2001; Dorogovtsev and Mendes 2003). Seen another way, nonspatial friend introductions is a way to control the correlations between clustering and space, versus if friend introductions took place only spatially. The non-spatial social interaction is a substitute for explicitly modelling all face-to-face meetings that would be needed to generate complete EgoNetworks. Again, one can imagine making the exchange of information depend on a criterion, such as agents exchanging information that they personally find valuable, or that they believe their friend would find valuable (Altenhoff 2003).

4.5 Plan modification and scoring

A special "strategy" module has been written to use the social network by randomly modifying the location of activities within the plan with locations from the agent's knowledge. The standard strategy modules in the MATSim package can also still be used, but these existing routines do not take advantage of the social network. This knowledge-based replanning algorithm replaces the location of an activity with a certain activity-specific probability. For instance, it is very unlikely that a person changes home location, slightly likely that he changes work or school location, but highly likely that he changes leisure or shopping locations. Whether these changes to the person's activities result in changes to his social network depends on the other settings in the model. The plan selector used for illustration in this example chooses the plan with the shortest total length (Euclidean distance for fast calculation). It does not use the dynamic assignment module of MATSim, in order to save time. To evaluate the effects of the social networks on route choice and traffic flows, it would be necessary to assign this demand to the network and to evaluate the socializing component of utility in the activities. Many other replanning strategies could be used by the agents besides secondary location choice, for instance, attempting to negotiate with alters to time their activities together at the same places, or to coordinate similar routes (simulate carpooling).

4.6 Specification of the Utility Function

The dynamic assignment uses the standard Toolbox utility function for individual plan scoring, which does not take into account the presence of other agents at an activity. For studies investigating the influence of social networks on the spatial or temporal distribution of activities, a new utility function would be needed.

The utility specification for capturing the value of interactions is a difficult problem to solve. While it is necessary to include some parameterization of these concepts in the utility to simulate certain social processes, this poses a danger of double counting. Part of this is due to the "reflection problem": being with coworkers has value because they help one work, which has value only because coworkers make work possible. In addition, the way in which the agents interact implicitly captures part of the value of the social network: this includes information passed about destinations, routes, schedules, traffic conditions, or other agents. A utility function accounting for the remaining value of relationships must exclude these implicit valuations which are realized in the iterative information exchange and plan modification steps.

Furthermore, the form of socializing utility is activity-dependent. Many activities rely on a certain number of people being present; for some activities it matters a great deal who exactly these people are (identified alters, i.e. playing sports or going to the correct workplace with the correct coworkers), and for others only their number or some other mean field indicator may be important (unidentified alters, i.e. spectating in a stadium at a sports event or going to a bar). And finally, the interplay of identified and unidentified alters is subject to discussion: does one go to a bar full of strangers with a group of friends when one would not go alone?

4.7 Output

The statistics package outputs indicators of social, geographic, and travel behavior. Additionally, all movements on the road network in MATSim are output each iteration of the dynamic assignment, so that traces of movements in space can be analyzed. The modified activity plans are large files and are written out at intervals. Routines exist in the Toolbox to calculate activity spaces and to plot movements in GoogleEarth, which could be used for analysis and presentation, respectively.

The variables and format to be output has not been. Degree histograms are output in text format and the entire social network is output each iteration in a format readable in the Pajek network analysis software package (Batagelj and Mrvar 2003). The files of agent, edge, and graph statistics enable concurrent socio-spatial analyses using post-processing code written in R. Runs exceeding 10,000 agents will not be able to output agent- and edge-based statistics because the data volume will exceed the capabilities of post-processing software and hardware, so more on-the-fly analyses will be built in.

5. Results

Twenty verification runs illustrate the effect of assumptions in the program outlined in Section 4. The parameters and the algorithms chosen for the illustrative experiments are summarized in Table 1 and defined in the appendix (Table 4). Setting up each run is a matter of turning on and off algorithms by changing keywords in the input configuration file. All cases begin with a random initialization and run for 100 iterations.

Table 1 Configurations of the verification runs

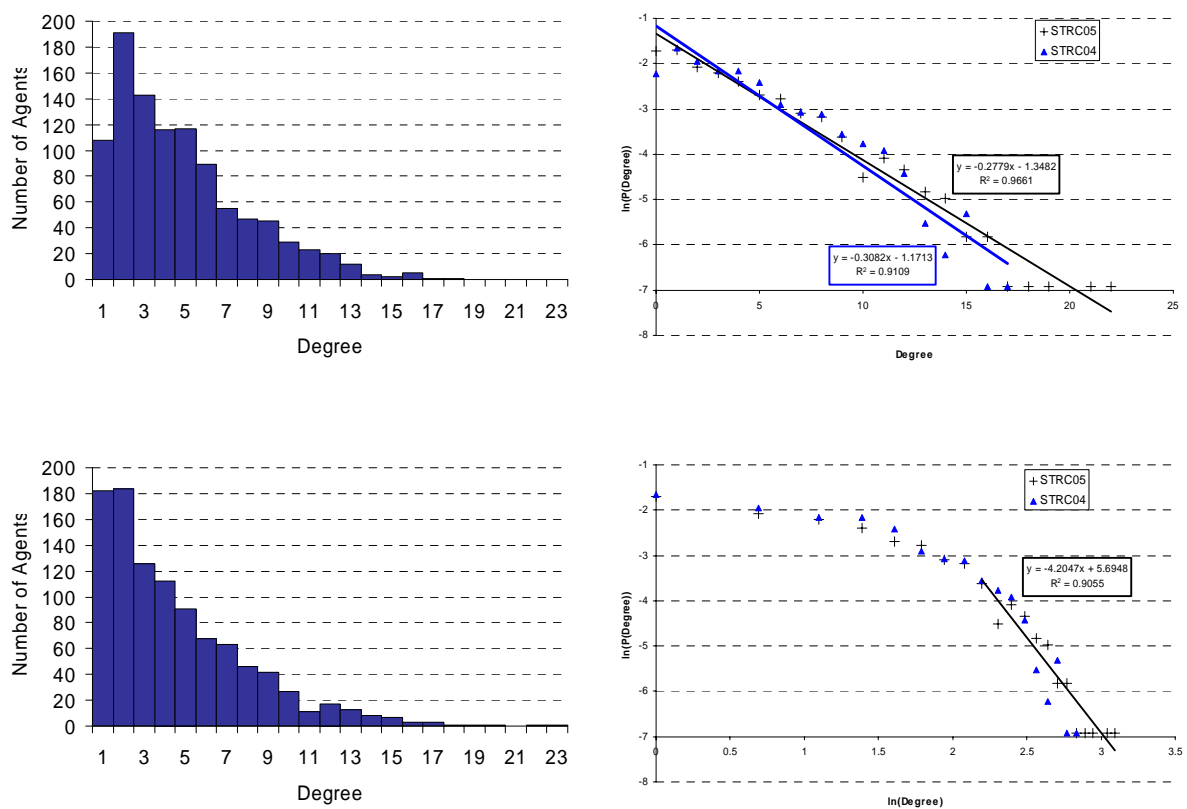
	Growing Social Network		Equilibrium Social Network		
	Saturation	No Saturation	Removal	Constant	Removal + Sat
Replan	14,15	3,4,10,11	18	19	20
No Replan	6,12,13	1,2,5	7,8,9,16		17

These runs are a sample of the application and not a detailed behavioral study. There can be no reference case consisting of a standard MATSim run (without social network exchanges) because there is no secondary location choice replanning strategy without social networks. If one were to be programmed without social networks, the choice sets of the agents, consisting of initial knowledge, would be determinant in the final outcome. A consistent comparison with the exchanges on the social network is not possible.

The set of “growing” social networks lacks link removal and serve to quantify the effects of parameters and algorithms on the growth rate of the networks in order to estimate settings for negative feedbacks that will allow for equilibrium. Programs 7, 8, 9, 16, and 17 are cases of spatially embedded social network equilibria without activity replanning. These assume that the input activity plans are socially optimal and that the social networks are embedded in these activities. Run 18 adjusts the equilibrium social network and the plan simultaneously. Run 19 assumes that a given social network is fully described, and that the plans need to be reconciled with this network.

Preliminary analysis of Run 16 with equilibrium social network versus Run 18 with Replanning of secondary locations shows consistency along some dimensions, but wide divergence in others, highlighting the necessity of probing the output in multiple dimensions. The degree distribution, for example, is indistinguishable between the two runs (Figure 2).

Figure 2 Analysis of degree distribution for two simulated networks



The histograms on the left show the degree distribution of the 100th iteration for the two runs. The locations of activities were adjusted using knowledge from the social network in the lower run (Run 18) but not in the upper run (Run 16), i.e. in this run, agents met and befriended each other continuously at the same locations. The plot on the upper right shows a log-linear plot comparing the distribution to exponential. The plot on the lower right is a log-log comparison with a scale-free distribution (the linear fit is for Run 18). Both runs yield exponential degree distributions but the run with replanning has a slightly thicker tail. The effect is too slight and the network is too small to show a statistically significant difference.

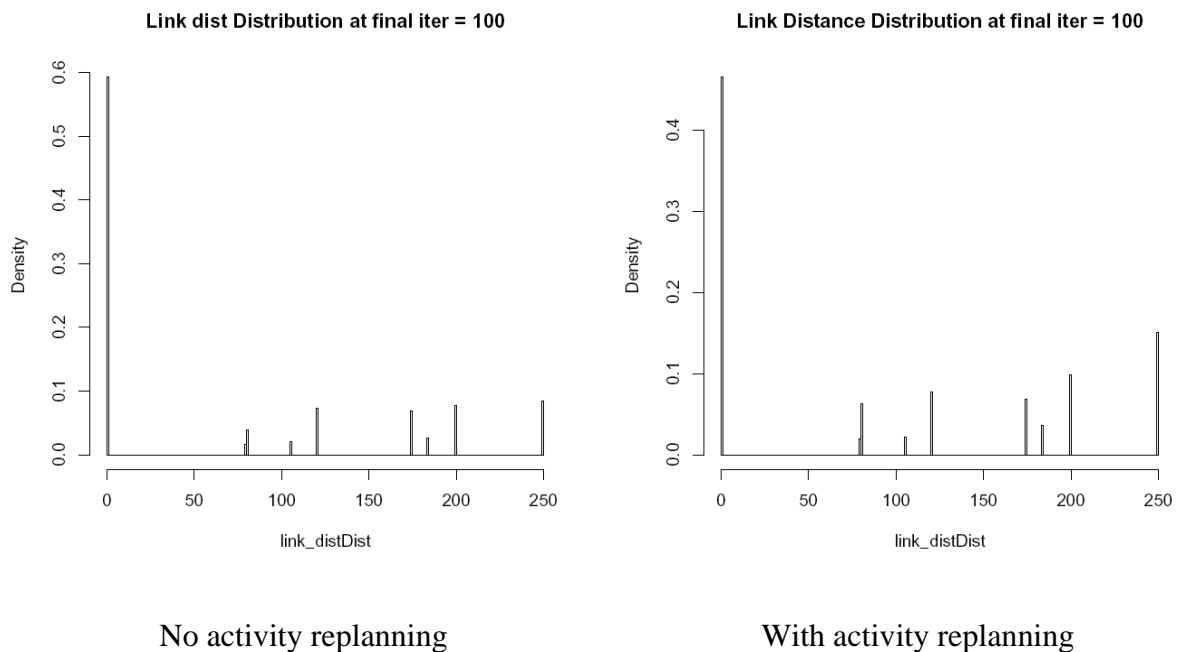
However, large differences in other indicators of the social network are obvious in the comparison of Table 2. While both social networks are distinctly different from randomly connected networks, the run without replanning is much more clustered than with replanning.

Table 2 Selected statistics of the emergent social networks (N=1008)

Run configuration	Diameter	Number of components	Average clustering ratio relative to Erdős/Renyi	Average Degree
Run 16 no replanning	14	125	2.13	3.77
Run 18 location replanning	12	195	1.31	3.57
Erdős/Renyi	$\sim 12 \pm 1$	$\sim 48 \pm 3$	1.00	3.6-3.7

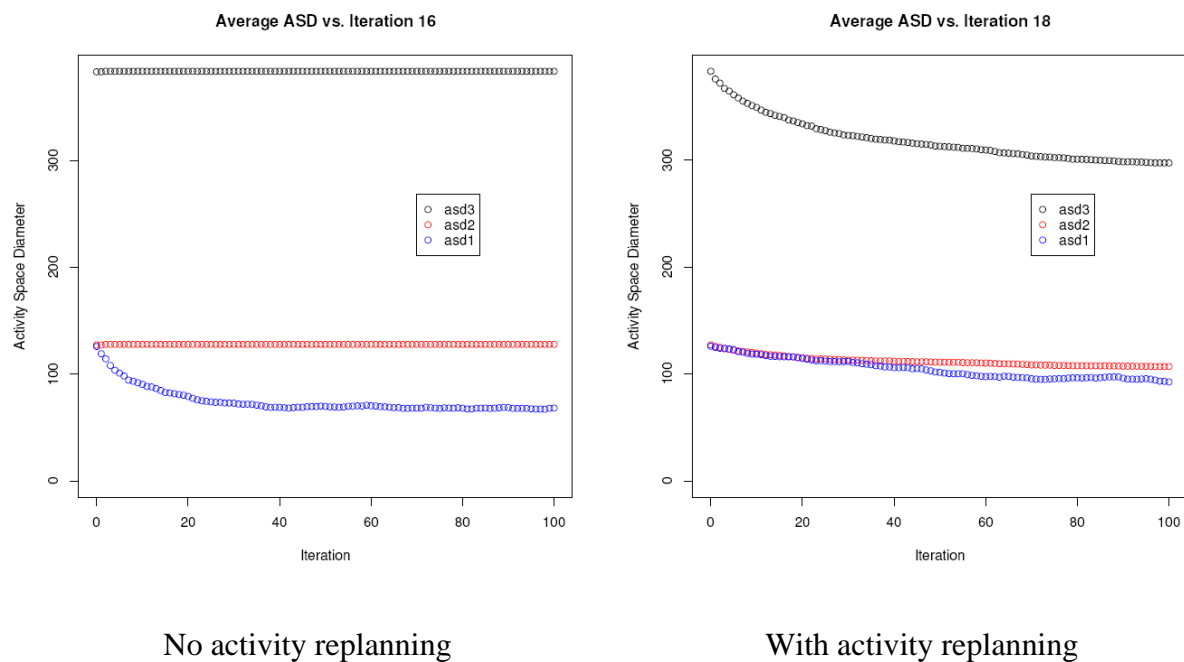
The spatial resolution of the test case is not sufficient to illustrate geographical changes. The expected relationship of inverse distance and friendship likelihood is not observed in either model (Figure 3). In fact, when activities are replanned, the number of far-away friends increases.

Figure 3 Link probability versus distance between homes of agents



The increased average distance to friends with replanning, relative to no replanning, is illustrated again in Figure 4. In the figure, asd3 is the average over all agents of the total length of their plan, asd2 is the average distance from the agent's home to all of its activities, and asd1 is the average distance from the agent's home to the homes of all of its friends. While this is an interesting finding, namely, that optimal relocation of secondary activities to minimize travel time increases the average radius to friends' home locations, it is not certain whether this is an artifact of the test "world" geography or of the algorithms. Certainly the very few number of residential and other locations relative to the number of agents represents a special social situation and not the higher-resolution applications for which this modelling is intended.

Figure 4 Indicators of activity space size versus iteration



Asd3 = average activity chain length; asd2 = average distance to agent's activities; asd1 = average distance to agent's friends

A utility function with explicit valuations of social networks was not implemented due to considerations outlined earlier. Likewise, a negotiation or game theoretic interaction between the agents for scheduling or location choice has also not been implemented. As such, certain important feedback loops have not yet been activated

5.1 Calculations of Run Time and Memory

The calculation for the test run 16 without replanning requires 14 seconds on a 1.8GHz processor with 500MB available RAM. Running the replanning every social network iteration takes 12 minutes. Nearly all the speed is recovered (and route detail lost) by replacing the dynamic assignment with Euclidean distance for producing initial plans (Run 18). The computational burden of the social network interactions scales roughly with degree times the number of agents N , i.e. a function of N^2 . Increasing the size of the social network for this population of 1008 agents (25 acquaintances) nears 500MB of memory. An increase of the number of agents to the Zurich region (100x) with many more activity locations will not be feasible and will require a strategy for reducing the information retained in RAM (Knowledge, activity Plans). Batch calculations are not yet configured but will be necessary, since agent experimentation is a fundamentally probabilistic endeavor in which every run is a sample of the system.

6. Future/Continuing work

A scenario with more spatial variation is needed to test the geographic distributions. The scenario of Zurich is prepared and the runs can be made soon. Testing will follow an experimental plan such that the model can be verified before any attempt is made at comparison with real distributions. Dynamic contributions to scaling (universal) effects versus situation-specific effects must be identified and quantified in order to simplify the models. The plan takes the broad form of Table3.

Table3 Framework for the experimental plan for micro-simulation of geographic social networks

Social Network	Social dynamics	Utility function	Activity plan
Fixed	Geographic information exchange	Standard	Fixed
Changing	Introducing friends	With socializing factor	Replanning: utility maximization
	Removing social links		Replanning: game theoretic
	Saturation effects		
	Directed links		
	Weighted links		

Verification and identification of relevant parameters and model effects are the first priority. Run time and analysis of output, followed by exchangeable output file formats (a DTD standard for XML) will follow before research turns to simplified representation of social networks (for scaling up the population) and more interesting types of interactions and perhaps even agent games for runs on smaller populations.

7. References

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8. Appendix

Table 4 Summary of the sample runs

No.	z	F2F	P	FOF	Sat	Removal Rule	Info	P_a	P_r	Summary of Test Setup
1	3	0.05	1	0	0	0	0	1,1,1,1,1	0,0,0,0,0	Base case: Erdős/Renyi initial graph; meet and befriend face to face with equal probability at all activities; no introductions; no information sharing; no adjusting plans
2								0.1,1,0.01,1,0.01		Probability of befriending varies across activity types
3							0.05		0,0,1,0,1	Sharing information with friends, replanning shop and leisure
4	0						0.05		0,0,1,0,1	No face to face meeting; sharing information with friends, replanning shop and leisure
5	0		0.01							No face to face meeting; FOF introductions
6					-0.5					Strong saturation
7						rand, 0, 0.05				Random link removal after 0 iterations at $p = 0.05$ per link each iteration
8						age, 0, 0.005				Random link removal after 0 iterations at $p = 0.005$ * link age (in iterations) per link each iteration
9						deg, 0, 0.005				Random link removal after 0 iterations at $p = 0.005$ * node degree per link each iteration
10	0		0.01				0.05		0,0,1,0,1	No face to face meeting; FOF introductions; sharing information with friends; replanning shop and leisure
11	0		0.01				0.05	0.1,1,0.01,1,0.01	0,0,1,0,1	No face to face meeting; FOF introductions; sharing information with friends; probability of befriending varies across activity types; replanning shop and leisure
12				0.05	-0.5					FOF introductions and strong saturation
13				0.05	-0.25					FOF introductions and weak saturation
14				0.05	-0.25		0.05		0,0,1,0,1	FOF introductions; weak saturation; sharing information with friends; replanning shop and leisure
15				0.05	-0.25		0.05	0.1,1,0.01,1,0.01	0,0,1,0,1	FOF introductions; weak saturation; sharing information with friends; probability of befriending varies across activity types; replanning shop and

Table 4 Summary of the sample runs

No.	z	F2F	P	FOF	Sat	Removal Rule	Info	P _a	P _r	Summary of Test Setup
16				0.01		deg, 0, 0.005				leisure FOF introductions; random link removal after 0 iterations at p = 0.005 * node degree per link each iteration
17				0.01	-0.25	deg, 0, 0.005				FOF introductions; weak saturation; random link removal after 0 iterations at p = 0.005 * node degree per link each iteration
18				0.01		deg, 0, 0.005	0.05	0.1,1,0.01,1,0.01	0,0,1,0,1	FOF introductions; Random link removal after 0 iterations at p = 0.005 * node degree per link each iteration; sharing information with friends; probability of befriending varies across activity types; replanning shop and leisure
19	0						0.05		0,0,1,0,1	Constant social net; sharing information with friends; replanning shop and leisure
20				0.01	-0.25	deg, 0, 0.005	0.05		0,0,1,0,1	Run 18 with saturation

- z = average degree of initial Erdős/Renyi graph;
- F2F = proportion of agents meeting face to face this iteration (1 meeting per agent per facility visited);
- P = probability of 2 agents befriending upon meeting;
- FOF = proportion of agents introducing 2 friends this iteration (1 set of friends introduced per agent per turn);
- Sat = exponent of saturation rate of friendships ($P_{Sat} = \exp^{Sat * degree}$);
- Removal= probability of removing a link is either random, age*remove, or degree*remove. Parameters = minimum link age at which to apply rule, remove;
- Info = proportion of agents exchanging location information this iteration (1 piece of information per link);
- P_a = Activity = modifier on probability of befriending, according to activity type ("home","work","shop","education","leisure");
- P_r = Replace = probability of replacing facility with knowledge ("home","work","shop","education","leisure").

Total probability of adding a social link = $P * P_{Sat} * P_a$

