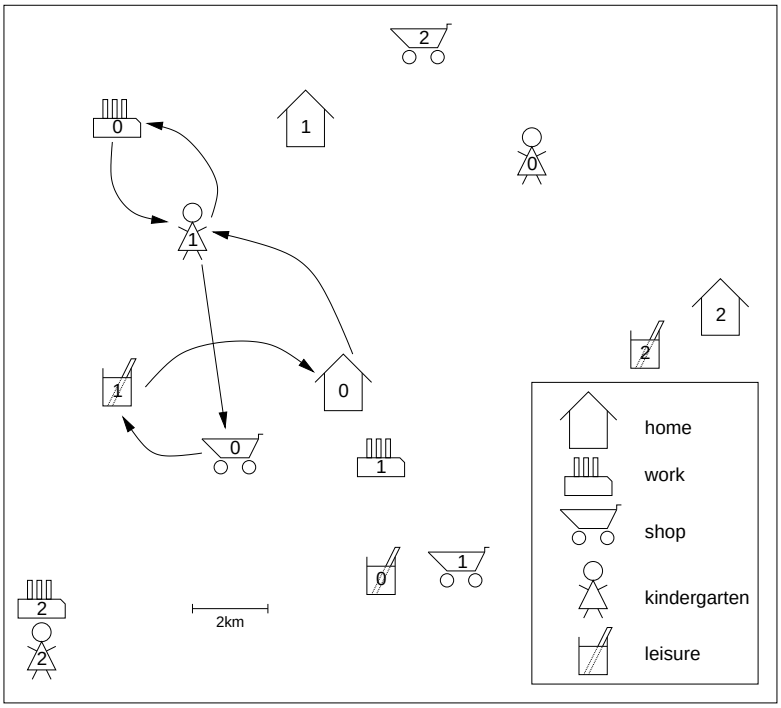

Generating Complete All-Day Activity Plans with Genetic Algorithms

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Abstract

The four step process generates demand via trip generation and trip distribution. It is well known that this method has disadvantages because it decouples trip distribution (and later steps) from demographic information, and it is difficult to make it time-dependent. An alternative is activity-based demand generation, which contructs complete all-day activity plans for each member of a population, and derives transportation demand from the fact that consecutive activities at different locations need to be connected by travel. Besides many other advantages, activity-based demand generation also fits well into the paradigm of multi-agent simulation, where each traveler is kept as an individual throughout the whole modeling process.

Despite these advantages, there are unfortunately rather few operational activity generation models, which can be used to actually drive simulations. Being operational includes the capability to actually generate fully specified plans (including patterns, locations, and times), to be able to generate such plans for population sizes of several millions, and to display sensitivity to congestion.

In this paper, we present a new approach to the problem, which uses genetic algorithms (GA). Our GA keeps, for each member of the population, several instances of possible all-day activity plans in memory. Those plans are modified by mutation and crossover, while "bad" instances are eventually discarded.

Any GA needs a fitness function to evaluate the performance of each instance. For all-day activity plans, it makes sense to use a utility function to obtain such a fitness. In consequence, a significant part of the paper is spent discussing such a utility function. In addition, the paper shows the performance of the algorithm to a few selected problems, including very busy and rather non-busy days.

Keywords

Activity generation; Utility functions; Genetic Algorithms; Location choice; Multi-agent traffic simulation

1. Introduction

It is a recent trend in transportation research to use the problem of activity planning in order to generate demand for transportation. Transportation demand is naturally derived from performing activities at different locations. The larger context of this work is the push towards an integrated multi-agent simulation model for transportation planning. Multi-agent simulations can be employed on many levels, from housing choice down to driving behavior. Our own initial goal is to replace the four-step process by a multi-agent simulation. This implies the following modules and methods:

- The process starts by generating a **synthetic population** from census data. A synthetic population is a Monte-Carlo realization of the information provided by the census data.
- Next, synthetic **activity plans** are generated for each member of the population. This is the topic of this paper.
- Once the activity plans are known, each individual plans the travel that connects activities at different locations, including **mode choice** and **route choice**.
- Up to here, the computations of the agents are essentially independent (apart from possible small-scale coordination problems such as household coordination or ride sharing). In contrast, in the **traffic (micro-)simulation**, all agents' plans are simultaneously executed and the results of interaction are computed. One important interaction result is congestion.
- As is well known, the causal relation between the modules goes into both directions. For example, if many agents chose activities at many different and far apart locations, then this will cause congestion. This congestion will cause them to select activities which necessitate less travel. The typical way to solve this problem is to use **iterations** between the modules. This can be either interpreted as relaxation or as human learning.

In the context of such a simulation system, all plans need to be specified in an unambiguous way so that the micro-simulation can execute them. In addition, since we are interested in large scale scenarios with up to 10 mio agents, the computation of the plans should not need more than a small number of seconds per agent.

Finally, multi-agent simulations for scenarios of that size use parallel computing for computational speed. It is difficult to implement within-day replanning in such a parallel system without giving up parallel performance. For that reason, most if not all large scale multi-agent transportation simulations at this point need the complete all-day activity plan *pre*-planned before the simulated day starts.

2. Problem description

The problem of activity planning is the task to generate a complete activity plan for an agent from a set of possible activities. In this context, a complete activity plan is an activity plan that stores which activities are to be executed and in which order, it assigns a location to each activity and also an execution time and a duration.

Activity planning divides into three subproblems:

- The first subproblem is to select activities to be executed and to decide in which order they should be executed. We refer to this subproblem as *activity pattern generation*.

- The second subproblem is to find the places where the activities are going to be executed. We call this *location selection*. The location selection has to fulfill a number of constraints in order to be meaningful. For instance children should be fetched from school at the same place where they were dropped off before.
- The third subproblem is to decide when the activities have to be executed and for how long. We call this *time allocation*. Once again, time allocation is subject to several restrictions as well. The most simple one of this is that the execution times should be ordered in correspondence with the activity pattern.

In reality, all of us do activity planning every day with sufficient speed and satisfactory results. Nevertheless this problem is quite difficult to solve automatically on the computer. The main problem with activity planing is the huge amount of possible plans for a given set of activities. Even if one is just concentrating on *activity pattern generation* for a list of ten activities, there are almost 10 million possible solutions. It is clear that we get even more problems if we want to include *location selection* and *time allocation*.

To make the problem even worse, it would be desirable to extend the length of the activity plan to a week or even a month because day plans are not independent in general as some activities do not have to be executed every day. For instance you do not have to go shopping every day, but you normally cannot omit shopping for a longer period. Since the space for possible solutions scales exponentially with the length of the desired activity plan, generating complete week plans is a problem that is several orders of magnitude more complex than generating day plans.

3. Related work

There are many models tackling the same problem. One can maybe differentiate the following directions:

- A possible way to solve this problem is to use a nested multinomial logit model. One such system is described by Bowman (1998). The decision is decomposed into many hierarchical levels, such as: the choice between different activity patterns, the choice between different locations, the choice between different starting times for the patterns, etc. This method demands that approximations of the lower level results are available at the upper levels: For example, in order to decide between different activity patterns, it is necessary to have a performance estimate for each pattern, which can only be obtained if the algorithm has some idea about the locations and times that will be chosen for each pattern. In practice, this is achieved via the so-called logsum terms, which backpropagate the lower level solutions to the higher levels. That is, the algorithm starts at the leaves of the decision tree. There, it computes, for each given activity pattern and location choice, utilities for each possible time choice. It then calculates the expected utility from this, and passes this on to the location choice level. The location choice level then calculates, for each given pattern, the expected utility for each location choice and passes the resulting expected utility for each pattern one level up, etc. Once the algorithm is at the highest level, it selects between the patterns according to the utilities. Once the pattern is selected, for this given pattern it selects between the locations. Once the locations are selected, it decides on the time-of-day when the pattern is started.

  Discrete choice models have a similar conceptual approach as our model in that they make choices based on utilities. The two main differences are that, at least conceptually, discrete choice models enumerate *all* possible alternatives, and that they do not chose the option with the best utility but they chose between options with probabilities which are related to utilities. The first aspect means that a huge number of options needs to be considered; the second (behaviorally justified) aspect

means that efficient search methods such as branch-and-bound cannot be used because even "bad" branches of the search tree have a probability that they will be selected.

- An arguably related approach is STARCHILD and successors. Instead of making a probabilistic choice between different options, it finds the optimal solution. Because of this simplification, methods from mathematical programming can be applied (e.g. Recker, 1995).
- Both approaches mentioned so far always look at the complete schedule. As an alternative, a traveler may build the schedule as he/she goes. An extreme version of this is PCATS (e.g. Kitamura, 1996), which conditions decisions on the past history, but does not look into the future. The advantage is much more manageable computational complexity; the disadvantage is that the algorithm does not pick up scheduling constraints which lie in the future.
- The work by Doherty and coworkers (e.g. Doherty and Axhausen, 1998) implies that real-world activity scheduling is a combination of the above aspects, i.e. that some decisions are made a long time in advance while others are rather spontaneous. An implementation of this approach is ALBATROSS (e.g. Arentze *et al.*, 2000).

Also, there are other micro-simulation models of human behavior, such as URBANSIM (Waddell *et al.*, 2003) or ILUTE (Salvini and Miller, 2003), which at this point concentrate on even higher level aspects, such as residential choice.

4. Idea: Genetic Algorithms

Trying to solve the problem by enumerating all possibilities—a complete search—is infeasible. This is especially true if one has only very limited computer time for program execution, as is the case with large scale multi-agent implementations. Furthermore, for our problem it is not absolutely necessary to find the global optimal solution. In fact, in many cases what people use as their plan is far from being optimal. It would be sufficient to find a "good" solution.

The idea for this paper is to use a Genetic Algorithm (GA) to find good all-day activity plans. GAs have been used for many problems with huge search spaces. GAs maintain a population of solution instances during the search process, and search progress is made by mutation, crossover, and selection, as explained below. In our case, the members of the population are represented by possible day plans for a single given traveler. The quality of such a day plan is rated by a fitness function which uses informations and restrictions known about the activities, and estimates how well the day plan meets them.

A random population of such day plans is created at the beginning of the algorithm and their quality rated as described above. All the generatad day plans represent a possible day plan for the same traveller. New individuals are created by crossover between two good day plans and mutating the offspring. When new, better day plans are found, then the worst plans are removed keeping allways a population of constant size. This procedure is repeated a number oftimes. At the end, the best day plan is used as solution of the problem.

Note that the work "population" is used with two different meanings in this text: First, there is a population of travelers that populates the multi-agent traffic simulation. But second, there is also a population of solution instances within the GA. In the remainder of the text, in general the second meaning will be used.

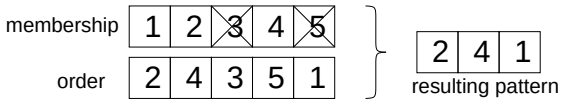


Figure 1: One possible encoding of the activity pattern “241”

5. Implementation

As mentioned above, crossover, mutation and selection are vital components of each GA. Before these operators can be defined, it is necessary to come up with a way of representing a solution instance in the computer. This way of representation is referred to as **encoding**. Encoding is of prime importance for the definition of crossover and mutation and it has a large influence on the potential performance of a GA. That’s why one should always spend some time in figuring out a good encoding for one’s problem before starting the definition of the other operators.

For our problem of activity planning, we used a combination of binary encoding, permutation encoding and value encoding in the following way:

- Each activity can be either included in the day plan or excluded from it. The informations about inclusion of activities is stored in an array of bits, where each bit holds this information for one activity. If a bit is set to one the corresponding activity is included in the day plan, if it is set to zero the corresponding activity is excluded from the plan.
- A second array stores the order of the activities. It holds always a full set of activities, regardless of which activities are actually member of the day plan and which not. When evaluating the day plan, the positions with disabled activities are ignored. See figure 1.
- Our day plans also include the informations about the location selection. In our model we assume that there exists a facility that is assigned to each activity. This facility can be thought of as a type of building or place that is needed in order to perform the activity. For instance, for the activity “go shopping” we would need the facility “shop”. We do also assume that each facility exists at multiple locations as for example there are multiple shops in a city where shopping can be done. The concept of facilities makes it possible to have locations of activities that depend on each other. For instance, this is needed to take care of the fact that one has to fetch his children at the same school as one has drooped them off before. The day plan has to store the selected location for each facility. This information is held in a third array.
- The allocated time to the activities is stored in a fourth array which stores floating point numbers; in addition, there is an entry which contains the starting time of the day plan. Activity starting times of the allocated time slots are a result of adding up the allocated times of the previous activities of the day plan.

The parents for a new individual are selected at random out of the current population. That is, better day plans do *not* have a higher probability than worse day plans to reproduce themselves. We did not want to prefer better day plans in parent selection because we did not want to risk a too early degeneration of the population. However, the introduction of a different parent selection scheme, for example rank selection, could yield a faster convergence. Recall from section 4 that offspring is only kept when it is better than the currently worst member of the population, and in that case, the worst member is removed.

The implementation of the **crossover operator** is built of three parts:

- First, the array which stores the membership information is processed using uniform crossover. That is each flag is copied randomly from one of the parents.
- Second, we crossover the arrays that store the order information in the following way: Before we start, we decide randomly which parent should precede in case of a collision. This information is needed during the rest of order crossover. We create a temporary array to store the order information of the newly created offspring. This array is three times larger then necessary in order to provide enough space for insertions of elements. For each activity, we now randomly select a parent and put the activity at the same position in the offspring as it was in the selected parent. If the target position is already taken—this means that another activity was copied earlier to this position—the new activity is inserted before or after the already present activity, dependent on the precedence information from the first step. As a postprocessing step we remove the holes in the temporary array by copying it to the final array.
- Third, for each activity the time allocation is copied randomly from one of the two parents.

We believe that our implementation of the crossover operator has several advantages compared to single point crossover. Single point crossover is a very popular implementation of crossover. The offspring is created from the parents by taking their representations, choosing a random crossover point and copying the first part up to this point from the first parent and the second part beginning at this point from the second parent.

However, for sequencing problems such as ours, this approach does not work since there is a large chance that in the offspring, some activities will be performed twice while some others will have completely vanished. A solution, coming from GA encoding for the Traveling Salesman Problem, is to take the first part verbatim from the first parent, and then to fill up the remaining spots with the remaining activities in the sequence they are in the second parent, skipping activities which are already present in order to avoid duplicate activities in the offspring.

That encoding has however the disadvantage that it only looks at the sequence and not at all at time-of-day. In contrast, in our implementation, activities have a tendency to stay at their position within the day plan. In addition, our crossover operator shuffles the activities more than a single point crossover would, and our tests showed that this yields a more stable—although slower—convergence. This is desirable, because our experience with GAs shows a considerable tendency to keep stuck in local optima when using single point crossover.

The **mutation operator** is split into four parts: First, for each activity, the membership information is flipped with a probability p_{mut}. Second, the order of the activities is permuted. With a probability p_{mut} two activities, both chosen at random, are exchanged. This is done n times where n is the total number of activities. Using the same idea as in the crossover operator, the activities are exchanged ignoring the membership information. Third, the time allocation of each activity is changed by multiplying it with a factor $f = e^X$, where X is drawn uniformly from the interval $[-p_{mut}/2, p_{mut}/2]$. Fourth, a new start time of the activity plan is calculated by adding a random time uniformly drawn from $[-p_{mut} \cdot 12h, p_{mut} \cdot 12h]$.

6. Utility function

As already mentioned earlier, our GA needs to rate the quality of the day plans in the population. For that purpose one has to define a *fitness function* which somehow defines what a “good” day plan is. We

use a fitness function that is the sum of the utilities of all activities that are performed.

$$F = \sum_{i=1}^{n} utility(type_i, start_i, dur_i, lastloc_i, loc_i) \tag{1}$$

Here, $type_i$ is the type of the activity, $start_i$ is the starting time of the activity, dur_i is the amount of time allocated to the activity, $lastloc_i$ is the location of the last activity and loc_i is the location of the current activity. In the following part, we will discuss all aspects of our utility function in detail.

In our model, the utility of an activity depends on the following parameters:

- The allocated time to the activity
- The time of day when the time slot for the activity starts
- The location where the activity takes place
- The location where the last activity took place.

The total utility of an activity i is the sum of five terms, each of which is modeling a certain aspect of the utility function.

$$U_{total,i} = U_{travel,i} + U_{dur,i} + U_{wait,i} + U_{late.ar,i} + U_{early.dp,i} \tag{2}$$

Here, $U_{travel,i}$ denotes the disutility of traveling from the last location to the next one, $U_{duration,i}$ denotes the utility of executing the activity for a certain duration, $U_{wait,i}$ denotes the disutility of waiting (for instance waiting for a shop to open) and $U_{late.ar,i}$ and $U_{early.dp,i}$ denote penalties for coming too late or leaving too early respectively.

The utility (= fitness) of the complete day plan is then given by the sum of all utility contributions of all fitnesses:

$$U_{total} = \sum_i U_{total,i} \; . \tag{3}$$

Note that this has the consequence that when removing an activity, the travel terms at *both* ends are modified. That is, if an activity is far out of the way, then dropping that activity will reduce overall travel considerably, while dropping an activity that is on the way will have a negligible effect on travel times.

In the following, the different terms and their parameters will be discussed in detail. All terms except $U_{duration}$ are linear in the time needed for that activity. Despite the detailed discussion, it should be kept in mind that the technology of using a GA is entirely independent from the specific utility function. If a different utilty (or general scoring) function is desired, it is very simple to replace it.

6.1 Duration

For the utility of activity duration it seems to be widely believed that the marginal utility of duration should be decreasing with longer durations. We also think that the marginal utility of duration should be nonnegative.

At first glance, this may seem to be not very intuitive because with nonnegative marginal utility of duration for a single activity there is nothing that limits its execution time. However, considering more than one activity and a limited time budget, it can be seen that the available time will be distributed in order to achieve a higher overall utility. In the absence of other restrictions such as travel times or opening times,

the optimal time allocation for a given activity pattern is reached if all activities have the same marginal utility of duration.

We decided to use a logarithmic function as utility of duration:

$$U_{dur}(t_{dur}) = \beta_{dur} \cdot t_{opt} \cdot \ln(\frac{t_{dur}}{t_0}) \; . \tag{4}$$

Here, t_{dur} is the duration of the activity as it is actually performed, and t_0 is the duration at which the utility starts to be positive. This can be interpreted as minimal duration.

β_{dur} is the marginal utility of duration of the activity at its optimal duration t_{opt}, as can be seen by taking the partial derivative:

$$\frac{\partial U}{\partial t_{dur}}(t_{dur}) = \frac{\beta_{dur} \cdot t_{opt}}{t_{dur}} \; . \tag{5}$$

Setting $t_{dur} = t_{opt}$ yields indeed β_{dur} for the marginal utility.

For unrestricted activities, one would assume that $\partial U / \partial t_{dur}(t_{dur})$ is the same for all activities that are actually performed—otherwise the agent would just reallocate durations in the direction of improvements. This allows to give order-of-magnitude values for many of the free parameters in the utility function.

For example, the marginal utility of duration around the operating point should be similar to the utility of time β_t of the person that we try to model. If one assumes that activity durations are usually close to the optimal duration given by t_{opt}, then this means that the parameter β_{dur} can be set to $\beta_{dur} = \beta_t$. We will use $\beta_t = \beta_{dur} =$€ 20/h.

The marginal utility is independent of the minimal duration t_0. This means that for day plans that are not too tight the optimal solution is almost independent of the t_0's. (If dayplans are tight, the durations of some activities may drop below t_0, in which case this statement is no longer correct.) As a consequence, we can use the parameters t_0 to ensure that the utilities of all activities at their operating point have certain value. Based on the utility of sleeping 8 hours with a t_0 of 2 hours, we decided that the utility of all activities at thier operating points should be $200€/p$, where p is a priority value. This yields the following equation for the parameter t_0:

$$t_0 = t_{opt} \cdot e^{-200/(t_{opt} \cdot p \cdot \beta_t)}, = t_{opt} \cdot e^{-10\mathrm{h}/(t_{opt} \cdot p)}, \tag{6}$$

A result of this is that even activities with a high priority can still be dropped if they are very inconvenient. As we will see later, this has sometimes inconvenient results, such as picking up a child from kindergarten but never dropping it off. On the other hand, it is certainly true that schedules can become so tight that even high priority items are dropped, for example by asking someone else to help out. For that reason, making high priority activities completely obligatory is not plausible.

6.2 Generalized travel costs

Traveling has a disutility that is linear in time, i.e.

$$U_{travel}(t_{travel}) = -\beta_{travel} \cdot t_{travel} \; .$$

The disutility of traveling should be larger than disutility of waiting. Otherwise, agents would prefer to stay on congested roads for a long time instead of arriving too early at their destination. We set $\beta_{travel} = 2\beta_{wait}$.

6.3 Waiting

Following the Vickrey model of departure time choice (e.g. Arnott *et al.*, 1993), both waiting and arriving late are penalized lineary. For waiting:

$$U_{wait}(t_{wait}) = -\beta_{wait} \cdot t_{wait} \ .$$

Here, β_{wait} is the marginal disutility of waiting. β_{wait} should be rather small; we will set it to $\beta_t/3$.

6.4 Penalty for late arrival

For late arrival, this becomes

$$U_{late.ar}(t_{start}) = \begin{cases} -\beta_{late.ar}(t_{start} - t_{latest.ar}) & \text{if } t_{start} > t_{latest.ar} \\ 0 & \text{else.} \end{cases}$$

Here, t_{start} is the starting time of the activity, $t_{latest.ar}$ is the latest possible starting time for the activity and $\beta_{late.ar}$ is a parameter that quantifies the disutility of coming late. $\beta_{late.ar}$ should be roughly as high as the utility of time β_t. We use $\beta_{late.ar} = 18$€/h.

6.5 Penalty for leaving too early

We also have to introduce some penalty when an activity is ended too early. We choose to make this linear in how much one leaves too early:

$$U_{early.dp}(t_{end}) = \begin{cases} -\beta_{early.dp}(t_{earliest.dp} - t_{end}) & \text{if } t_{end} < t_{earliest.dp} \\ 0 & \text{else.} \end{cases}$$

Here, t_{end} is the ending time of the activity, $t_{earliest.dp}$ is the earliest possible ending time for the activity and $\beta_{early.dp}$ is a parameter that quantifies the disutility of leaving too early. For the parameter $\beta_{early.dp}$ we used a value of 6€/h.

6.6 Opening times and similar constraints

Many activities can only be carried out during certain times of the day. For instance shopping can only be done when the stores are open. The question is what utility we want to assign to activities which violate these constraints.

One possibility would be to assign a very low utility to those activities, e.g. minus infinity. This policy would be very efficient in avoiding invalid day plans. But it would not make very much sense, for the following reason: Assume that you have to compare two time allocations for the activity "shop". In the first scenario you go shopping at 7:59am and shop for two hours. In the second scenario you go shopping at 8:00am and shop also for two hours. The shop opens at 8am. The first time allocation is invalid because you try to shop while the shop is closed. So the utility of the first scenario would be very low. The second scenario, however, has a very high utility. With this policy, the minimal change of one minute in time allocation would produce a huge change in utility which is certainly not realistic. In reality, we would have waited one minute in front of the shop. That means that one should set parameters such that both utilities are almost the same.

Based on these reflections, we come up with the following constraint handling policy:

- At the beginning of the allocated time slot, we assume that the agent travels from the location of the last activity to the location of the new activity. The time spent for traveling yield a disutility according to the section about travel costs.
- From the moment of arrival at the activity location until the end of the time slot, as much time as possible is spent actually performing the activity.
- If for some reason, for instance because of opening hours, it is not possible to use all this time for performing the activity the remaining time is spent waiting. Waiting yields a negative utility according to the section above.
- Since we use a logarithmic function for the utility of duration, it is possible that this utility becomes negative. If this is the case, and if it is more efficient to spent the whole time waiting, the activity is not executed at all. It may sound weird to travel to an activity that is not executed. However, it is important to note that we need to calculate meaningful utilities for no matter which day plans the GA generates, because this is the material the GA works with. Since traveling to an activity location without executing the activity does not make sense, the GA will eventually find a better solution, such as either completely dropping the activity, or allocating sufficient time for it.

6.7 Time of day dependence of utility

The utility of many activities depend on the time of day on which they are executed. For example, many sports activities can even be carried out only at daylight. The most complete model to take care of time of day dependence would be to integrate a weighted marginal utility of each activity over its whole duration. The weighting would then be responsible for the time of day dependence.

Due to the complexity of this approach, and because there seems to be a lack of information on how to model it in detail, we decided not to use any model for time of day dependence. We simply assume that there is no dependence. This means that "leisure at 4am" will result in the same utility as "leisure at 8pm".

Despite the bizarre example, we believe that—for most real world examples of day plans—we do not sacrifice very much realism in our results. There are many constraints that a day plan has to fulfill, leaving only very little room for absurd day plans.

Note that for instance the "beginning of work" is already anchored because of the late penalty, and shopping can only be done during opening times. We may have to also anchor sleep since that is preferably done when it is dark.

6.8 Summary of parameters

The following is a listing of all parameters of our utility function and the values that we used.

Marginal utility of any activity:	$\beta_t = 20$ €/h.
Marginal disutility of travel time:	$\beta_{travel} = 12$ €/h.
Marginal disutility of waiting:	$\beta_{wait} = 6$ €/h.
Marginal disutility of coming late:	$\beta_{late.ar} = 18$ €/h.
Marginal disutility of leaving too early:	$\beta_{early.dp} = 6$ €/h.

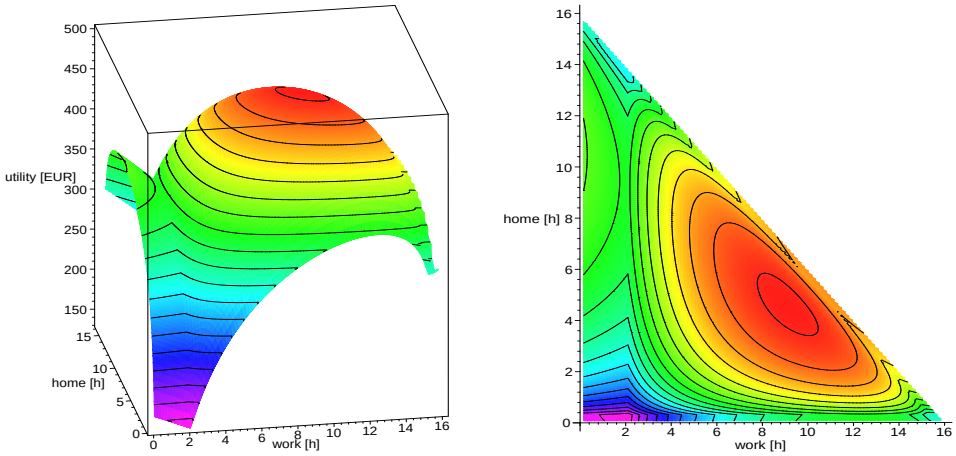


Figure 2: Utility of activity pattern *home-work-leisure-home*
t_{opt} of work, leisure and home set to 8, 2 and 4 hours respectively
Total time budget of 16 hours, i.e. time surplus

6.9 Plots of utility landscape

In order to show some properties of the utility landscape, we exemplarily analyze plots of some activity patterns. Because of the limited number of displayable dimensions, our choice is restricted to very short activity patterns with a maximum of four activities.

Now, if we would use full length day plans with such a limited number of activities, the resulting day plans would be rather slack, and as a result of that, many of the typical problems with activity planning would simply not arise.

Our way out of this problem is to use shorter time budgets for our example activity plans. In consequence, the plans that we are going to talk about here are no longer complete day plans but rather partial plans. However, since the calculation of the utility values is completely additive, having a look at partial plans does make sense.

As a further simplification, we assume during our investigations that all activities can be carried out at the same location. By applying this simplification, we do not have to define a lot of location related parameters. However, the problems that can be observed in this simplified context have the same complexity as with traveling enabled. This is due to the fact that our travel times are independent of time of day and because they are linear in the geometric distance of the locations.

We first show the typical utility landscape of an activity chain with four activities *home*, *work*, *leisure* and *home*. The desired duration for *work*, *leisure* and *home* had been set to 8, 2 and 4 hours respectively. There were no additional constraints that had to be fulfilled except that the total length of the plan was fixed to 16 hours; i.e. there is a time surplus.

The utility function of the two parameters *duration of work* and *duration of leisure* has one clean global optimum. It should be easy to find the global optimum of this activity pattern even with standard optimization techniques. At the borders of the domain, there exist small regions where the utility increases again. This is due to the definition of the utility function which has a cutoff at very short durations. For example, when the duration of work becomes less than two hours, it becomes better to not work at all, in which case the additional leisure time makes a positive contribution.

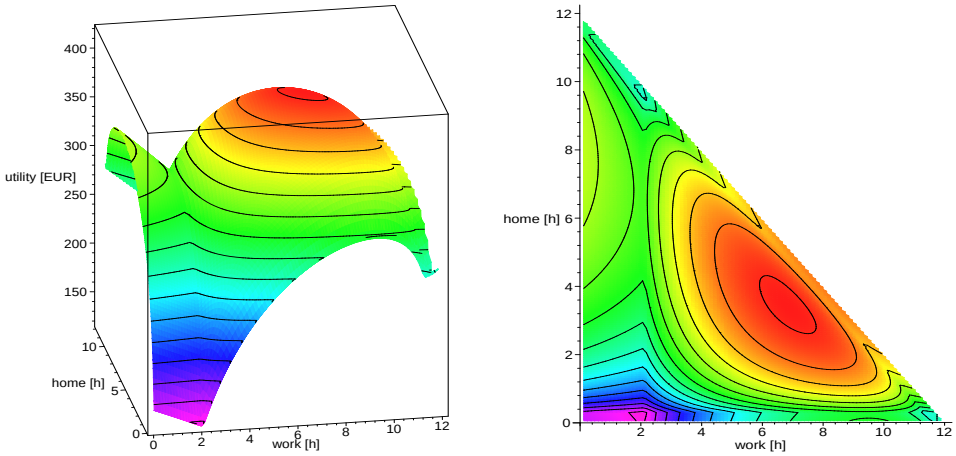


Figure 3: Utility of activity pattern *home-work-leisure-home*
t_{opt} of work, leisure and home set to 8, 2 and 4 hours respectively
Total time budget of 12 hours, i.e. it is a tight plan

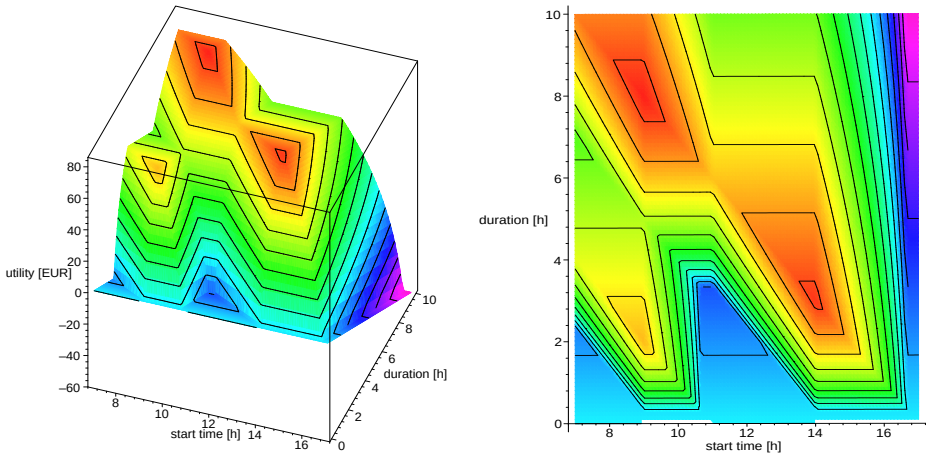


Figure 4: Utility of activity *shop*. Shop open 9–11, 14–17. Note, in contrast to the other plots of the utility landscape, in this plot there is no constraint on the total length of the partial plan.

Note in figure 2 that the optimum is not at the three "optimal" durations t_{opt} but at slightly longer durations. This is due to the fact that the desired plan length of 16 hours is longer than the sum of the "optimal" durations which is 14 hours.

In order to show the effect of the time budget on the time allocation, we show another plot of the same activity pattern but this time with a desired plan length of 12 hours. See figure 3.

Note that the optimum is shifted towards shorter times and the utility of the optimum is roughly 100€ lower.

The utility landscape of activities with opening hours is much more complex. As an example we show the utility of shopping in a store that is open during the morning from 9 until 11 and in the afternoon from 14 until 17. Without opening hours the landscape would be very smooth and completely independent of time of day. *With* the opening hours some interesting new properties can be observed.

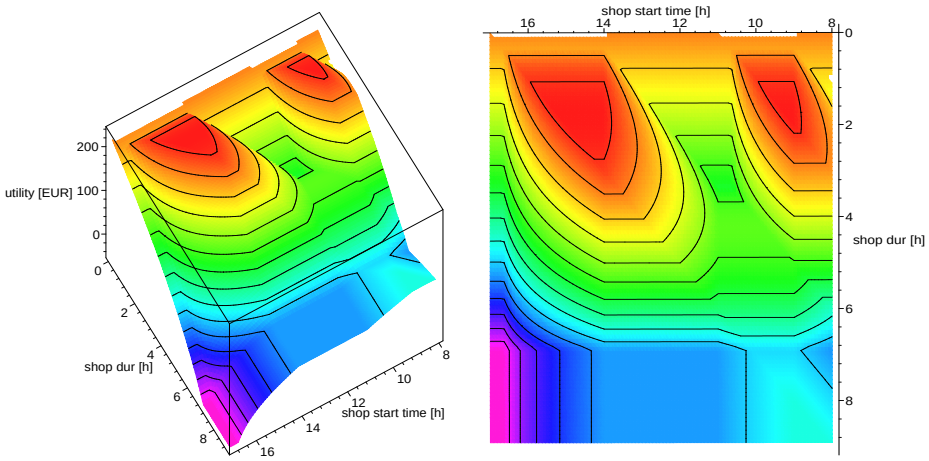


Figure 5: Utility of activity pattern *work-shop-work*. The shop is open 9–11 and 14–17. Note, for the calculation of the utility of work only the total working duration is regarded. That is, the sum of working duration before shopping and after shopping is first calculated and then the utility for work is calcualted.

In figure 4 we see that now there exist three local optima. The global optimum corresponds to showing up in the shop at 9 in the morning and staying there until 17 in the evening. The lunch break is spent waiting. The two local optima in the morning and the afternoon are much more meaningful. The early local optimum corresponds to coming at 9am when the shop opens and leaving the shop at 11am when it closes. The late local optimum corresponds to coming at 14 when the shop opens and leaving at 17 when it closes. The reason why the global optimum looks this way lies in the fact that our marginal utility is always nonnegative. The effect of that is that shopping more automatically yields more utility. However, it is important to note that the additional utility is rather small, if shopping has already been performed for a long time.

The structure of the fitness landscape becomes even more complex when we consider an activity *chain* that includes a complex activity with opening hours. Figure 5 shows the utility of the activity pattern *work-shop-work*. The desired durations for the activities were set to eight hours for the total working duration and two hours for the shopping activity. The overall plan was set to start at 8 and last until 17; i.e. the plan is tight.

The utility for this activity pattern shows two equivalent global optima. They correspond to go shopping in the morning for almost two hours and to go shopping in the afternoon. The optimum in the afternoon is wider, because the shop is open for three hours in the afternoon.

7. Tests and results

In this section, we want to show the general ability of our model to generate complete day plans. For that purpose, we designed a simple city. In our city there exist a number of different facilities including apartments, working places, shops, kindergartens and recreational areas. For each of these facilities, there exist three different locations between which an agent can choose. The different locations of the facilities are summarized in a map. See figure 6.

For our tests we assume that travel times are simply proportional to the geometric distance between two locations and that the travel speed is constantly 10km/h.

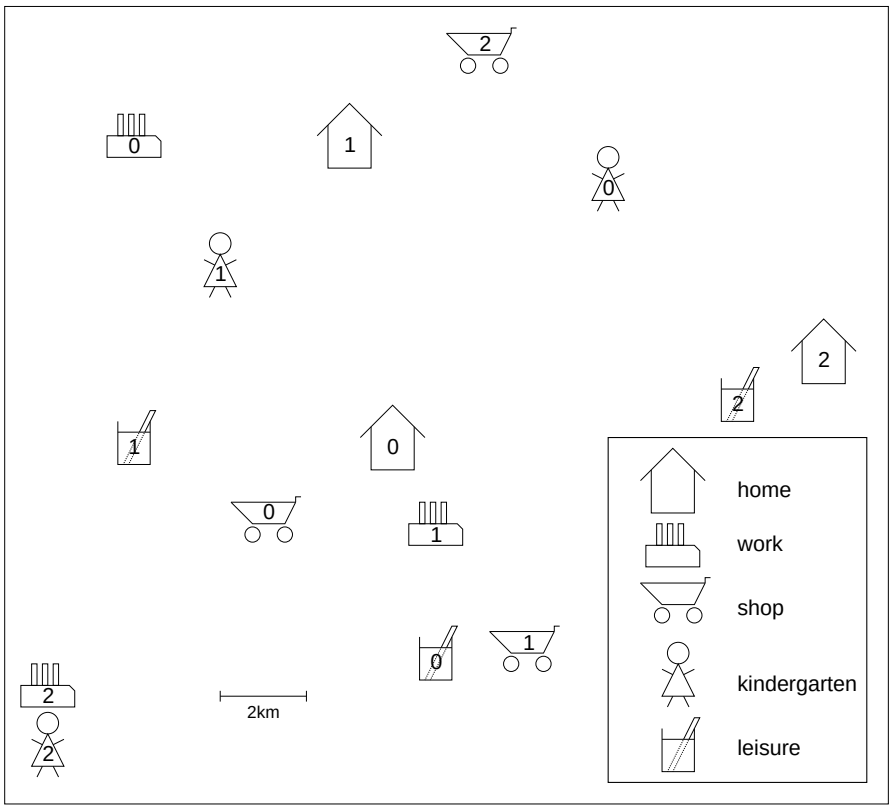


Figure 6: Map of facilities

We want to test our algorithm for different kinds of agents with different lists of activities that they would like to accomplish. For this purpose, we defined three different scenarios. Each scenario is defined by a set of activities that are available. The scenario “full10” is the one with the largest set and consist of ten activities which are listed in figure 7. The other two scenarios use a subset of these activities.

All facilities needed by the activities except for the facility “home” are not open during the whole day. The opening times used for our investigations are summarized in figure 8.

The three scenarios are defined as follows:

- As mentioned above, the “full10” scenario defines a scenario with set of ten activities. This scenario consists of the activities “sleep”, “breakfast”, “lunch”, “dinner”, “early work”, “late work”, “bring children to kindergarten”, “fetch children from kindergarten”, “shop”, and “leisure”. The purpose of this scenario is to show the performance of our algorithm if there are very many activities to perform.
- In the “houseman” scenario, the agent has only eight of the ten activities of the “full10” scenario to choose from, leaving out both work activities. That is, the remaining activities are: “sleep”, “breakfast”, “lunch”, “dinner”, “bring children to kindergarten”, “fetch children from kindergarten”, “shop” and “leisure”. Since in this scenario the agent does not have a work location, we changed the facility for eating lunch from “work” to “home”. This scenario simulates a rather dense day plan of a non working person.

Name	priority	t_{opt} [1]	$t_{latest.ar}$ [2]	$t_{earliest.dp}$ [3]	$t_{short.dur}$ [3]	Facility
sleep	1	8.0	25.0	29.0	6.0	home
early work	1	4.0	9.0	11.0	3.5	work
late work	1	4.0	14.0	15.0	3.5	work
breakfast	3	0.5	10.0		0.25	home
lunch	2	1.25	14.0	12.0	0.75	work/home[4]
dinner	2	2.0	21.0	18.0	0.75	home
bring to kindergarten	1	0.25	9.0	8.5	0.25	kindergarten
fetch from kindergarten	1	0.25	16.0	15.5	0.25	kindergarten
shopping	3	2.0			0.5	shop
leisure	3	2.0			1.0	leisure

[1] Note that t_0 is derived from the priority and t_{opt}. See section 6.1 and equation (6).
[2] Latest starting time. If the activity starts later a penalty is applied. See section 6.4
[3] Both, $t_{earliest.dp}$ and $t_{short.dur}$ address the problem of not executing an activity enough long. If the activity is ended before $t_{earliest.dp}$ a penalty applies. The same penalty applies if the duration of the activity is shorter than $t_{short.dur}$. See section 6.5
[4] Depending on the scenario, the facility of the activity "lunch" was either work or home. See description of the scenarios.

Figure 7: Activities of our test case

Facility Name	Opening Times
Home	00:00-24:00
Work	06:00-20:00
Kindergarten	8:30-9:00 15:30-16:00
Shop	09:00-19:00
Leisure	14:00-24:00

Figure 8: Opening times of the facilities. An activity can only be carried out when the required facility is open. Note facility "Kindergarten" has two opening times. The first one defines when children can be dropped off and the second when they can be picked up.

- In the "pensioner" scenario, the set of activities consists only of 5 activities; these are "sleep", "lunch", "dinner", "shopping" and "leisure". As in the "houseman" scenario, the facility for having lunch was changed to "home". With this scenario we want to show how our model deals with day plans with a large freedom in time allocation.

We do two separate investigations for each scenario. In the first investigation we run the algorithm for a long time in order to rate the quality of the best solution that the algorithm possibly produces. In the second investigation we want to rate if the algorithm is capable of finding usable day plans within a limited time, therefore we run the program for a short time. This second question is especially important if we want to generate day plans a large number of agents.

For the quality investigation we run the algorithm for 10,000,000 generations with a GA-population size of 300. The execution takes between 140 and 230 seconds on a 2.4GHz Pentium 4 Laptop. For the usability and speed investigation we change the parameters in order to achieve a higher convergence speed taking into account that we sacrifice some stability for that reason. The GA-population size is reduced to 50 and the number of generations is limited to 200,000. Here, the execution takes between 3 and 5 seconds.

The quality test for the "full10" scenario was run with 5 different initializations. At the end of each

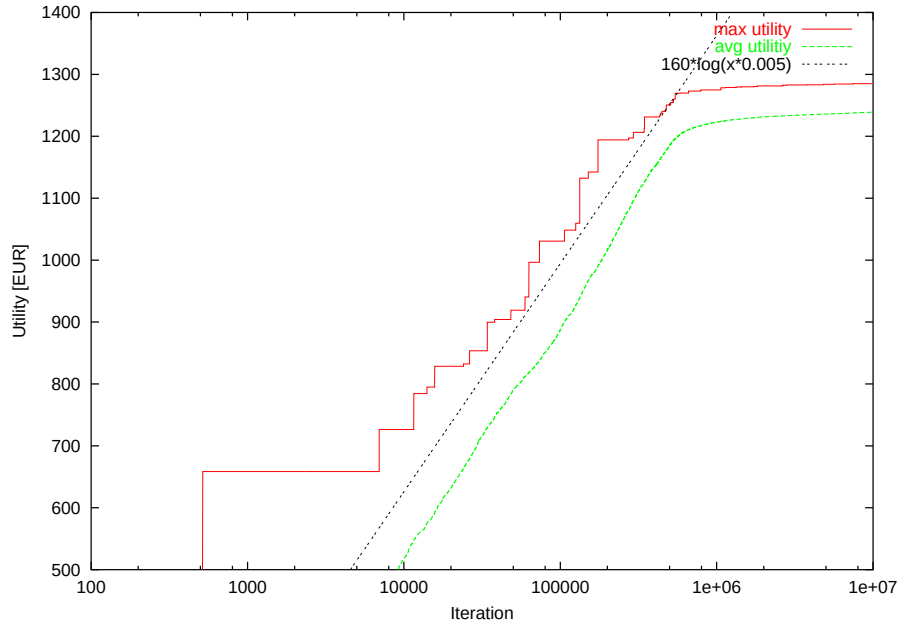


Figure 9: Convergence graph for "full10" scenario. The test was run for 10 mio iterations in order to get the best possible quality of the resulting day plan. The graph shows the maximal and average utility of the population of a typical long run.

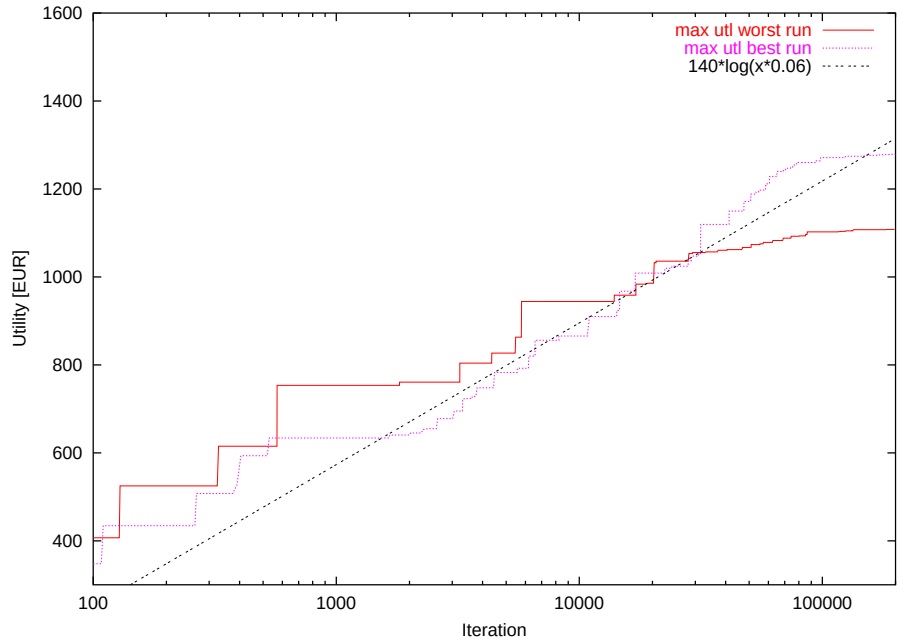
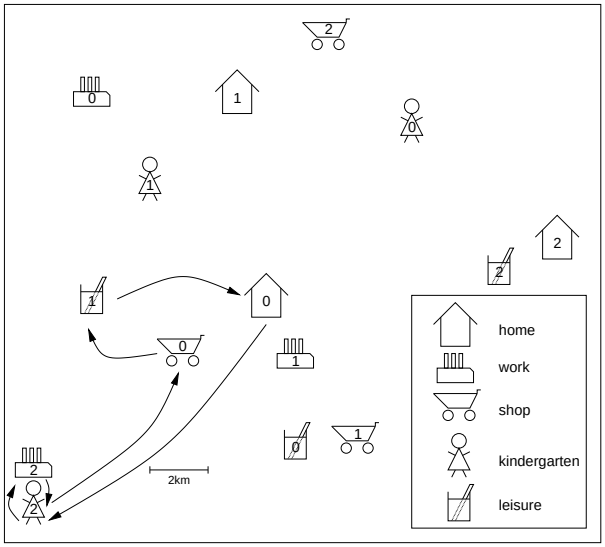


Figure 10: Convergence graph for "full10" scenario. The tests were run for only 200,000 iterations to test the performance of the algorithm if there is only limited time for finding a good day plan. The graph shows the maximum utility of the population for the best and the worst short run.



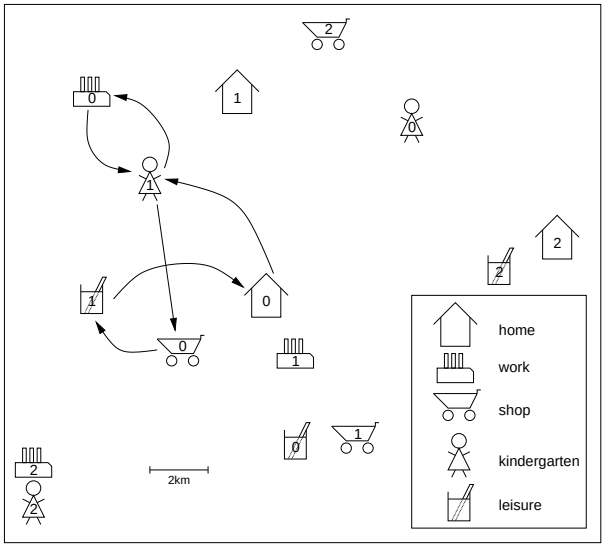
Activity Name	Travel Time	Execution Time	Location
Breakfast		06:56–07:26	home 0
Bring children[1]	07:26–08:30	08:30–08:40	kiga[3] 2
Early work	08:40–08:46	08:46–11:52	work 2
Lunch		11:52–12:40	work 2
Late work		12:40–15:40	work 2
Fetch children[2]	15:40–15:46	15:46–16:00	kiga[3] 2
Shop	16:01–16:43	16:43–18:26	shop 0
Leisure	18:26–18:48	18:48–20:27	leisure 1
Dinner	20:27–21:03	21:03–23:02	home 0
Sleep		23:02–06:56	home 0

[1] Bring children to the kindergarten.
[2] Fetch children from the kindergarten.
[3] Kindergarten

Figure 11: Best day plan for the “full10” scenario after 10 mio iterations. The total utility is 1284.93€. The map graphically summarizes the day plan.

run, the day plan with the highest utility value was always identical in terms of generated pattern and location selection. Only the time allocations differed, but the differences were within very few minutes. In figure 9 we show a typical convergence graph for the quality tests. The best day plan found for the “full10” scenario in the quality test is shown in figure 11. Note that the children are not dropped off at home before continuing with the day plan; especially “leisure” is performed together with the children. This can be observed in almost all generated day plans. The reason for this shortcoming is the absence of a constraint that would force the agents to drop children off before starting with the next activity. The way we have modeled the utility function it is clearly preferable to take the children along because this minimizes traveling distance.

In the five short runs for investigation of speed and usability for the scenario “full10” three times a solution was found that is identical to the one shown in figure 11 in terms of generated pattern and selected locations. Only the time allocations were not as sophisticated. The total utility varied between 1277.54 and 1278.84€. In the two remaining runs, two different solutions were found. The solution shown in figure 12 differs only in terms of location selection and time allocation while the solution



Activity Name	Travel Time	Execution Time	Location
Breakfast		07:27–07:56	home 0
Bring children	07:56–08:30	08:30–08:42	**kiga 1**
Early work	08:42–09:03	09:03–11:54	**work 0**
Lunch		11:54–12:49	**work 0**
Late work		11:54–12:49	**work 0**
Fetch children	15:18–15:39	15:39–15:57	**kiga 1**
Shop	15:57–16:33	16:33–18:13	shop 0
Leisure	18:13–18:35	18:35–20:26	leisure 1
Dinner	20:26–21:02	21:02–23:30	home 0
Sleep		23:30–07:27	home 0

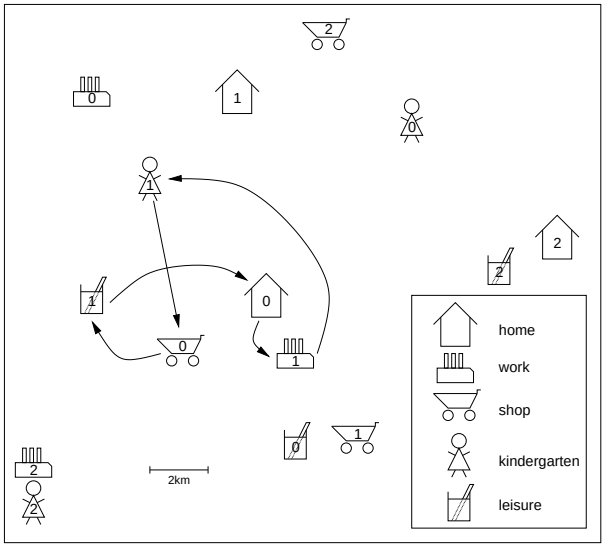
Figure 12: first alternative day plan for the “full10” scenario after 200,000 iterations. The total utility is 1276.46€.

shown in figure 13 differs also in the generated pattern. Note that in this day plan the activity “bring children to kindergarten” is left out. In figure 10 we compare the convergence of the best and the worst short run.

In all runs for the “pensioner” scenario (five long runs and five short runs) the same day plan was found with respect to the generated activity pattern and the selected locations. The time allocations to the different activities was also very similar. The similarity of the day plans can also be seen when looking at the total utility which was always between 638.483 and 638.514€—a very narrow interval. The only difference between the plans was their starting time which varied in the range from 10:33am to 11:45am. This is due to the lack of constraints for the activities. That is, it does not matter at which time inside the range the day plan starts. In figure 14 we show the best day plan found. It starts at 11:45am.

It seems that our algorithm has no problems to find a good solution for the “pensioner” scenario. In order to test this assumption we show the convergence graph of one of the usability runs in figure 15. One can see that the algorithm converges already very early. In fact, a solution identical to the one shown in figure 14 in terms of generated pattern and selected locations is already found after 30,000 generations—which is only 15% of total number of generations.

In all five long runs for the “houseman” scenario and in four of the five short runs the same day plan



Activity Name	Travel Time	Execution Time	Location
Breakfast		06:14–06:46	home 0
Early work	06:46–06:59	06:59–10:56	work 1
Lunch		10:56–11:59	work 1
Late work		11:59–15:04	work 1
Fetch children	15:04–15:51	15:51–16:00	kiga 1
Shop	16:00–16:37	16:37–18:26	shop 0
Leisure	18:26–18:47	18:47–20:27	leisure 1
Dinner	20:27–21:03	21:03–23:06	home 0
Sleep		23:06–06:14	home 0

Figure 13: Second alternative day plan for the “full10” scenario after 200,000 iterations. The total utility is 1107.89€. Note, the activity “bring children to kindergarten” is left out.

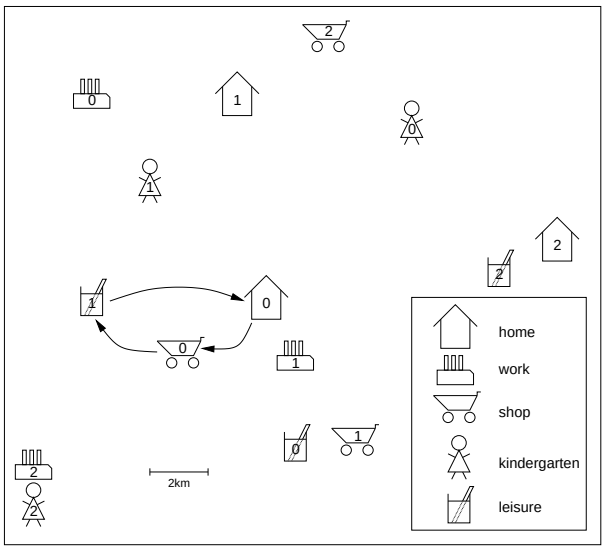
was found with respect to the generated activity pattern and the selected locations. The time allocations were also very similar, they all lay within ten minutes. The resulting utilities vary between 1040.51 and 1043.04€. We show the best day plan found in figure 16.

The day plan found in the remaining short run is topologically different from the other day plans. It leaves out the activity “leisure”. See figure 17.

The resulting day plans for all three scenarios are very convincing throughout. All aspects of activity planning—activity pattern generation, location selection and time allocation—are taken care of very well. The convergence of the genetic algorithm seems to be very stable, as for each scenario at the end of almost all test runs the same good solution is found. It seems, that our tests have not yet pushed our algorithm to its limits, it would be interesting to see how it performs on generating complete week plans.

8. Further work

One interesting aspect of activity planning is to generate activity plans for households instead of generating them for single agents. This problem is more complex than simply generating individual day plans



Activity Name	Travel Time	Execution Time	Location
Lunch		11:45–13:36	home 0
Shop	13:36–13:57	13:57–16:54	shop 0
Leisure	16:54–17:15	17:15–20:14	leisure 1
Dinner	20:14–20:50	20:50–23:47	home 0
Sleep		23:47–11:45	home 0

Figure 14: best day plan found for “pensioner” scenario. The total utility is 638.514€.

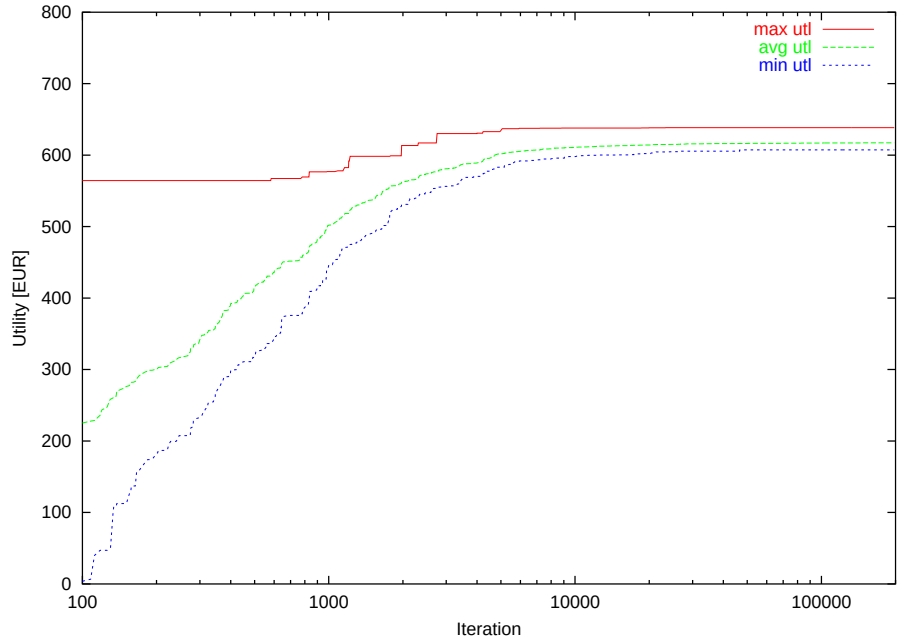
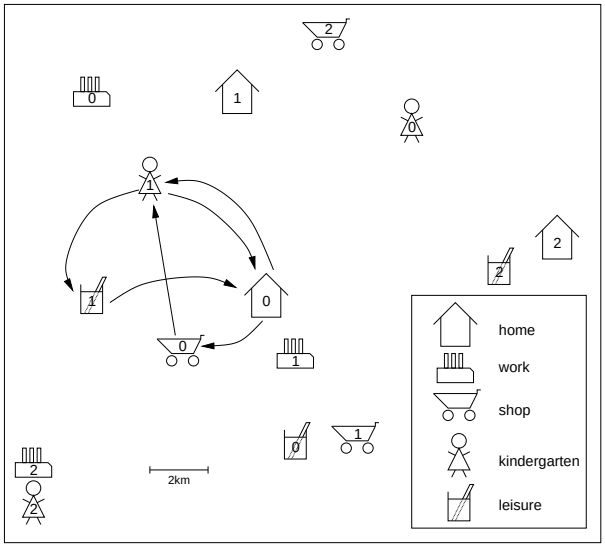


Figure 15: Convergence graph for “pensioner” scenario for a typical short run. In this test, the goal was to find a good day plan within limited time.



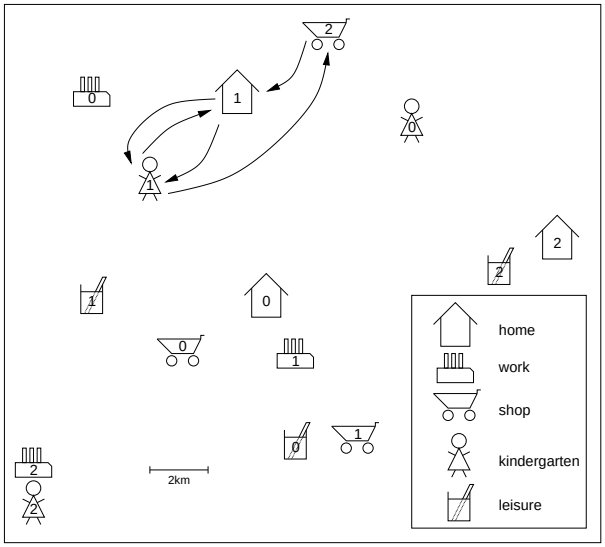
Activity Name	Travel Time	Execution Time	Location
Bring children	08:08–08:42	08:42–08:59	kiga 1
Breakfast	08:59–09:33	09:33–10:17	home 0
Lunch		10:17–12:02	home 0
Shop	12:02–12:23	12:23–14:58	shop 0
Fetch children	14:58–15:35	15:35–15:52	kiga 1
Leisure	15:52–16:19	16:19–18:51	leisure 1
Dinner	18:51–19:27	19:27–22:02	home 0
Sleep		22:02–08:08	home 0

Figure 16: best day plan found for the “houseman” scenario. The total utility is 1043.04€. Note that the agent fetches the children and performs activity “leisure” with them. The reason why it does not drop them off at home before is that there is no constraint forcing it to do so and the presented day plan minimizes travel time.

for each of the occupants of a household since the all-day activity plans of different occupants depend on each other. For instance, only one of the agents living in a household has to go shopping.

The present model that we use for estimation of travel times between different locations is not very realistic. We are planning to include travel times from a simulation in order to increase realism. With time dependent travel times we hope that phenomena like congestion avoidance within the day plans will emerge.

We would like to use the presented method to generate the individual day plans for the agents of traffic simulations with up to 10 mio agents. From that point of view it is clear that we have to make our algorithm much faster. One way to do that would be to use only a preselected set of activity patterns instead, i.e. limiting the search space, or to generate simultaneously the day plan for multiple similar agents.



Activity Name	Travel Time	Execution Time	Location
Breakfast		07:13–08:05	home 1
Bring children	08:05–08:30	08:30–09:00	kiga 1
Shop	09:06–09:52	09:52–12:36	shop 2
Lunch	12:36–12:58	12:58–15:03	home 1
Fetch children	15:03–15:28	15:30–15:58	kiga 1
Dinner	15:58–16:23	16:23–19:20	home 1
Sleep		22:02–08:08	home 1

Figure 17: second day plan found for the “houseman” scenario. The total utility is 1019.66€.

9. Summary

A genetic algorithm (GA) was presented that constructs all-day activity plans. It uses as input a set of possible activities, and a utility function to score activity schedules. The GA attempts to construct good solutions which maximize the utility function. It does that by maintaining a *population* of solution instances, which are mutated, and which, importantly, breed new solutions by crossover. Crossover means that two solution instances are selected, and part of the new solution comes from one parent, and the other part from the other parent.

The algorithm is then run on several examples. It is shown that the algorithm generates plausible solutions both for crowded and for relaxed activity sets, and that it can do so even when the computation time is restricted.

The most important aspect of this work is that arbitrary utility functions can be used. A GA does not guarantee optimal solutions, but it will nearly always generate plausible solutions. Given that humans do no better, this may be sufficient for most if not all travel forecasting purposes.

Acknowledgments

Kay Axhausen helped us along the way with numerous pointers to actually evaluate all-day utility functions. Nevertheless, the responsibility for our choices remains with us.

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