Simulation and Optimization of Habitat Network Permeability

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Abstract: Landscape fragmentation is a major threat to a lot of wildlife species with a large spatial activity range. To ease the migration through the landscape, a lot of different measurements can be implemented. Though, due to limited resources, these should be placed where they are most effective.

The simulation framework SimapD presented in this paper is capable of assessing the network permeability and incorporates effects of anthropogenic obstacles, like roads, into the assessment. Through an individual-oriented simulation an overall permeability index for a habitat network is obtained. Based on this simulation approach, an algorithm is presented for optimizing such habitat networks concerning its permeability. It is intended to be applied to find optimal mitigation strategies. The complete procedure is illustrated by an example.

Keywords: landscape fragmentation, individual-oriented simulation

1   Introduction

Today's landscapes are affected by a lot of requirements of human beings, e.g. people's transportation, mobility, and spare time needs. To meet all these needs the landscape is permanently transformed by building of roads, channels, railroads, recreation areas, residential areas, etc. All these transformations lead to a significant fragmentation of the landscape, where more and more large scaled natural areas become fragmented into smaller parts. One of the major causes of landscape fragmentation is the dense road network (Forman and Sperling 2002; Oggier et. al. 2001).

This creeping process of landscape fragmentation is a significant threat to wildlife species which depend on spacious migrations, either daily, seasonal or during their lifetime (Baier et. al. 2006; Forman 2003). Depending on the species, the spatial scales for these migrations can range from a few hundred metres to some hundred kilometres of range. The large scale mi-

gration is especially important for gene exchange between different local populations and the establishment of new populations. The ability for local, i.e. small scale migrations is a vital trait of habitat quality which also determines the survival probability of a local population. In fragmented landscapes the migration is often impaired by linear obstacles either due to increased barriers (e.g. fenced areas) or loss of individuals while conquering the obstacle (e.g. road kills) (Forman and Sperling 2002).

Due to the threats on wildlife species there are political attempts to enforce a de-fragmentation of the landscape and to ease the migration of wildlife species again. Measurements include but are not limited to the construction of green bridges or underpasses (Trocmé 2006; Hlaváč 2005). Since there are generally only limited financial resources for the implementation of mitigation measures, information where they are most effective for the de-fragmentation of the landscape are crucial.

The goal of this work is to support the identification and mitigation of conflict hotspots due to human activity and wildlife requirements, especially with regards to wildlife migration. The main questions are: Where does a potential high risk of conflicts exists, how does these conflicts affect the permeability of the landscape for wildlife, and where are the most effective locations for mitigation measurements leading to a more permeable landscape structure? To answer these questions we propose our simulation based Java programming framework called SimapD, an abbreviation for "simulation of anthropogenic population disturbances".

In Section 2 some related approaches are discussed, while section 3 introduces the model language used to define the habitat network within SimapD. The individual-oriented simulation algorithm for assessing the network permeability is presented in section 4. Based on our simulation approach, an algorithm for the optimization of habitat networks will be applied, which is outlined in section 5. After that, some remarks on the quality of the optimization will be stated in section 6. Finally, a conclusion and outlook will be given.

2   Related Approaches

Of course, there are known applications and simulation approaches which also deal with landscape fragmentation problems. Meta-X [Grimm et. al. 2003] for example simulates meta-populations and evaluates their mean population viability. A meta-population constitutes several sub-populations living in so called patches which are connected by migration corridors. These corridors can be used by individuals to migrate between

populations, so that even previously extinct patches can be repopulated. Each corridor has a distance which can be interpreted as it's resistance for an individual's migration. For example, if there is a large road that crosses a wildlife trail the respective corridor has a large distance.

Meta-X' quite abstract notation of models does not directly match properties of the real landscape. The simulation results are obtained by a Markov-chain algorithm and are difficult to interpret regarding concrete landscape characteristics. The mean population viability used by Meta-X as the main metric is a good measure to compare different meta-population scenarios, but it fails when it comes to linking the results to traits of the meta-population network. The size of the habitat network is always determined by the size of the studied meta-population, due to the underlying Meta-X simulation model that requires each patch to be a suitable habitat for the species. Hence, only modeling relevant parts of a landscape with anthropogenic disturbances is difficult.

FRAGSTATS (McGarigal 2002) is a tool for computing several landscape metrics on raster maps. This includes metrics to determine the degree of landscape fragmentation, like the effective mesh size (Jaeger 2000). Most of these metrics are based on a statistical analysis of the landscape pattern. The dynamics of (artificial) obstacles in the landscape, e.g. the road traffic volume, are not considered. The metrics used by FRAGSTATS are especially useful for evaluating landscape changes over time. An identification of main conflict zones between wildlife and human activity is not possible in an intuitive manner, since population related attributes like wildlife migration corridors are not considered.

3   Habitat Network Model

Comparable to Meta-X, the habitat network in SimapD is described by an undirected graph where the edges represent possible migration corridors in the landscape, and the nodes link two or more corridors. The location of possible migration corridors can be obtained by GIS-Analysis for example (Strein et. al. 2006). A node may represent a habitat or patch of a population, but it is also allowed to simply use it as a juncture for multiple corridors. This definition applies to all regional scales, especially to small scales, where it is not sensible to assume that every node represents a suitable habitat for a species.

Specific properties of the species, like population size, or mortality and fertility rate are not explicitly modeled in SimapD for two reasons: First, these parameters are rarely known for most wildlife species and second,

these factors are supposed to play not an important role for measuring the network permeability. This is of course different for models which try to assess the development of the population size over time, like Meta-X. SimapD basically measures the permeability of a network. For this purpose, it uses an individual-oriented simulation approach where individuals are sent for a walk through the network. This replays what happens in reality when individuals utilize the landscape for migration.

To avoid the problem of assessing crossing or mortality events per time unit, SimapD models corridor attributes statically. Each corridor has two properties: a resistance rate which determines the probability that an individual will use the corridor for a transition, and a mortality rate which determines the probability that an individual gets killed when using the corridor for transition. By these two properties all migration related events generally caused by anthropogenic obstacles can be described: successful corridor transition, death during transition, and holding the individual off from crossing. Depending on the intensity of the anthropogenic disturbances these attributes can be adapted per corridor. SimapD also supports the use of sub-models, which may calculate the corridor attributes on base of disturbance specific parameters (Finke et. al. submitted).

4   Permeability evaluation

The permeability of a habitat network is evaluated by an individual-oriented simulation algorithm. During the simulation a large number of individuals are sent through the graph for a random walk (Figure 1).
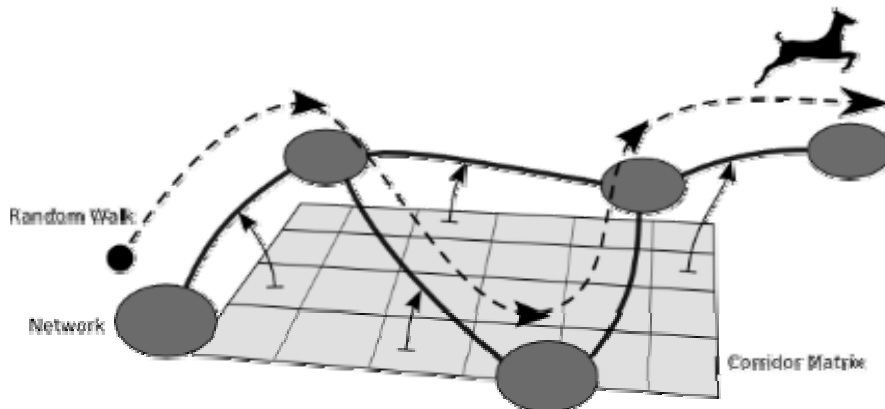

Figure 1: Composition of a SimapD model

Based on the resistance and mortality rates, provided in the corridor matrix, a Monte-Carlo simulation determines whether the individual gets killed during a corridor transition, reaches the distant patch, or is hold off by the resistance and therefore stays in the same patch. The random walk stops, if either the individual is killed or a maximum path length is reached, specified as a simulation parameter. To treat all nodes of the network in an equal manner, each node releases exactly one individual per simulation run.

A number of statistical parameters are collected during these walks, including the usage and killing rate of each corridor, the visiting rate for each node, etc. The simulation terminates, if the relative frequency distribution of the number of node visits becomes stable for an adequate number of runs, that is, if it does not change more than a small epsilon value between these runs. The SimapD user can control the required number of runs with a stable frequency distribution, and their maximum allowed variability by specifying the used epsilon value. Depending on these values, the simulation time may vary.

A measure for comparing different network configurations is deduced from the performance of each random walk and is denoted by the network permeability index λ_k. For each random walk p the path length s(p) and the number of different graph nodes visited v(p) are used to calculate the path index $\varphi(p)$ by: $\varphi(p) = s(p){*}v(p)$. Based on these values a relative frequency distribution of the path indices is calculated. If the network has a low permeability, this path index distribution is shifted to the lower end of the distribution range (low values). The better the permeability of the network is, the more the distribution moves to the right (higher values) and converges to a normal distribution (Finke in press). The distribution describes nicely the characteristic of the overall network permeability. The expected value of this distribution is used as an aggregated measure and denoted by λ_k. Here, k is the maximum path length which determines the possible range of values for $\varphi(p)$, and hence also for the expected value of the path index frequency distribution.

The measurement λ_k can be used for decision support on different mitigation scenarios. An example can be found in (Finke in press).

5   Optimizing habitat networks

To improve the permeability for a given habitat network, often different measurements can be applied. However, in the majority of cases there are only limited financial resources available, so the investments should be

placed where they are most effective. On this account the question for a given network is: Where should a fixed amount of financial resources be invested into the structure to gain best overall permeability increase? In case of SimapD such investments can be represented by a cost distribution that assigns a certain amount of effort (represented by its cost) to each corridor attribute for improving the corridor mortality respectively resistance rate.

5.1 Optimization algorithm

As proposed by Grüning and Sonnenschein (2005) an optimization algorithm based on tabu-search can be applied to obtain such a requested optimal cost distribution. The tabu-search algorithm (Michalewicz and Fogel 2000) requires a lot of iterations for achieving good results, which demands for a very fast evaluation of a specific solution, i.e. a specific cost distribution. To avoid time consuming simulation runs for each scenario to be processed, a meta-model (not to be confused with the Meta-X model) is used which calculates the output based on regression analysis instead of simulation. Grüning and Sonnenschein (2005) used a support vector machine (svm) algorithm for learning such a meta-model that maps the input cost distribution to the simulation output of a specific habitat network. Such a meta-model can be applied without simulation and thus leads to a significant performance gain. However, the quality of the optimization highly depends on the quality of the meta-model (see section 6).

For the optimization of the network, virtual cost units are distributed to the corridor attributes affecting them positively. The influence is expressed by a cost function c(x) that calculates the mortality or resistance rate when a given amount x of costs is applied (Grüning and Sonnenschein 2005):

$$c(x) = 1 - 2 * \left(\frac{1}{1 + e^{-x}} - \frac{1}{2} \right)$$

The inverse function $c^{-1}(r)$ determines the already invested costs from a certain mortality or resistance rate r. By concatenating these two functions, the improvement r' is calculated when additional costs x are assigned to a corridor attribute: $r' = c(c^{-1}(r) + x)$

The optimization goal is to maximize the network permeability index λ_k, where the maximum path length k is twice the network diameter. This requires a meta-model that maps the cost allocations applied to the corridor matrix to the λ_k values, yield by simulation.

The procedure for obtaining such a model is split into different steps according to Hsu et. al. (2006). First, an adequate number of training data is generated by the simulation model. This data set is used to train the svm

model. There are different flavors of svm kernels and learning algorithms (Smola and Schölkopf 1998). The kernel determines how the training data is moved into a higher dimensional space to find appropriate support vectors, which classify the data properly. By applying a Lagrange interpolation on the resulting support vectors, a function approximation can be obtained instead of a simple classification of the data. The "radial basis function"-kernel (rbf-Kernel) is suitable for such function approximations and is used in the following.

Most svm kernels have to be parameterized with proper values to gain best prediction results. These values are problem dependent and must be determined in advance according to the available training data. Hence, in a second step a grid search combined with cross validation is applied to the training data set to find best parameterization for the rbf-kernel (Hsu et. al. 2006). With the best performing kernel parameters the final meta-model can be trained in a third step and used for λ_k prediction.

5.2 Optimization Example

An example scenario for illustrating the approach sketched so far is depicted in Figure 2. This is an adapted version of the example scenario from Grüning and Sonnenschein (2005) who applied the optimization approach to a Meta-X model. The scenario represents a set of six patches, which are divided by a larger road into north and south compartments. For SimapD each corridor is described by a resistance rate r, which is correlated to the corridor length l from the original example. The mapping is done with the function $r(l) = 1 - e^{-l/a}$ where a is a scaling factor, set to a=45. The corridors affected by the road have additional mortality rates associated with them (see Table 1, unoptimized columns).
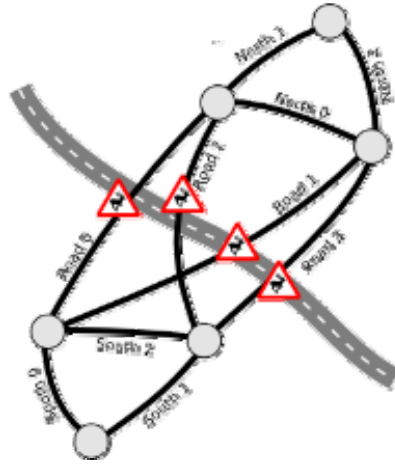
Figure 2: Layout of the example habitat network used for the optimization

For the actual optimization of the network a total amount of two cost units is assumed, allocatable in steps of 0.1 units. Initially, the costs are equally distributed over all corridors; i.e. each corridor gets 0.1 cost units to reduce the mortality as well as the resistance rate. For the results presented below, the tabu-search runs 10000 iterations with a tabu-list length of 150 entries. Other variations of these tabu-search parameters did not yield better results.

As a result, the optimization algorithm distributed the costs as noted in Table 1. The main amount of costs is allocated to the SOUTH 1 and ROAD 3 corridors to improve their resistance rate. Minor allocations are applied to the ROAD 2, ROAD 1 and NORTH 1 corridors. The distribution suggested by the optimization algorithm yields a network permeability index gain of 16% regarding the initial unoptimized version; that is from $\lambda_6 = 7.67$ to $\lambda_6 = 9.24$. This is nearly the same improvement achieved with the Meta-X approach (15%). To increase the overall permeability of the network, the optimization algorithm focused on improving a path from the south patch to the north patch along the corridors SOUTH 1, ROAD 2 and NORTH 1. The key patch is the linkage of the SOUTH 1 and ROAD 2 corridors. Except for SOUTH 2 the optimization algorithm applied costs for reducing the resistance rate to all corridors at this linkage point. For this linkage point the improvements lead to a mean probability of 0.51 for successfully reaching a neighboring patch, whereas in the unoptimized case the mean probability is 0.372.

	Unoptimized		Optimized		Cost distribution	
Corridor	R	M	R	M	SimapD	MetaX

SOUTH 0	0.4665	0.00	0.4665	0.00		
SOUTH 1	0.6298	0.00	0.3423	0.00	0.8	0.55
SOUTH 2	0.3588	0.00	0.3588	0.00		
NORTH 0	0.3588	0.00	0.3588	0.00		0.12
NORTH 1	0.4665	0.00	0.3987	0.00	0.2	0.39
NORTH 2	0.3588	0.00	0.3588	0.00		0.09
ROAD 0	0.7118	0.27	0.7118	0.27		
ROAD 1	0.7692	0.33	0.6770	0.33	0.2	0.39
ROAD 2	0.6527	0.23	0.5282	0.23	0.3	
ROAD 3	0.7118	0.27	0.5020	0.27	0.5	

Table 1: Corridor attributes (R = resistance rate, M = mortality rate) before and after applying the optimization procedure; cost distribution allocated by the SimapD optimization and, for comparision, by the Meta-X optimization

For comparison, the corridor cost distribution yield by the Meta-X approach is mentioned in Table 1, too. Since Meta-X assigns a minor amount of costs also for patch improvements, the total sum of the values given in Table 1 is slightly below 2.0. Anyway, it stands out that the main amount of costs is applied to the same corridors SOUTH 1 and NOTH 1 by both models, but by Meta-X only ROAD 1 is optimized, whereas SimapD suggests improving the resistance rate for three road-affected corridors. It can be presumed that this is caused by Meta-X considering only the corridor distance for evaluation. Reducing the longest corridor distance significantly will result in a reasonable improvement. Corridor ROAD 1 is by far the one with the longest distance in Meta-X (Grüning and Sonnenschein 2005). In comparison SimapD distinguishes resistance and mortality rates. A reduced resistance rate will increase the permeability, but only when the individuals will not be killed by the disturbance too often. Therefore, the optimization algorithm reduced the resistance rate for corridors having a relatively low mortality rate. Altogether the selection of road-affected corridors done by a SimapD based optimization seems to be reasonable.

As a consequence of these results, measurements should be concentrated at the suggested path SOUTH 1, ROAD 2, and NORTH 1. For SOUTH 1 and NORTH 1 possible measurements would be to adapt the environment to the requirements of the examined species (e.g. reforestation). For the road-affected corridors ROAD 2 or ROAD 3, a green bridge may be sensible, that connects the south with the north compartments. However, concrete measurements depend on the species or species family examined.

6   Optimization quality

The results so far were all obtained by using the meta-model to determine the network permeability index λ_k. Therefore, the quality of the optimization process depends on the quality of the meta-model. In turn, the quality of the svm model depends on the appropriateness of the training data.
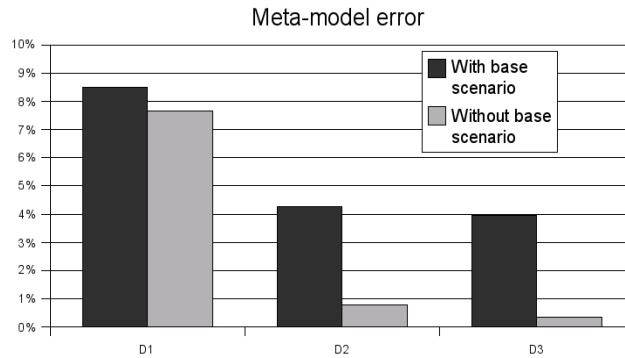

Figure 3: Mean error of predicted λ_k-values in relation to simulation outputs for three kinds of training data (see text for explanation)

Figure 3 shows the mean prediction error of the meta-model in comparison to the simulation outcomes for three different kinds of cost distributions to train the meta-model. For D1 random costs from the [0, 2.0] interval have been applied to each corridor attribute to create training scenarios. For the D2 distribution 0.1 costs were allocated to a random corridor, until the total amount of 2.0 costs were reached. The D3 distribution allocated a random fraction of the available costs to a random corridor. For D2 and D3 the sum of all applied costs is 2.0. The different training sets were used to train three svm-models and these have been used for optimization. The predicted λ_k values for the base scenario (no cost allocation), the initial solution scenario, and the best solution scenario of the optimization were then compared with the appropriate values achieved by simulation. The comparison of the mean λ_k prediction error regarding these three scenarios is depicted in Figure 3. All three meta-models do not predict the lambda value for the base scenario very well, because they are trained to modified networks with applied costs. For D2 and D3, the support vectors are limited to the search space of the tabu-search algorithm for the optimization, causing mean prediction errors of less than 1% for the initial and best solution scenarios. Since the D3 trained meta-model has been used in the example addressed in section 5, it is assumed that the results are highly accurate compared to the simulation model.

Since Grüning and Sonnenschein (2005) missed a similar comparison, no statement can be made about the quality of the optimization approach for Meta-X.

7   Conclusions

It is an important task to improve the overall permeability of habitat networks to aid the migration requirements for a lot of species. Our proposed individual-oriented simulation method is a promising approach to identify regions of high conflict potential between wildlife needs and human requirements. By explicitly incorporating important anthropogenic disturbances (like roads) into the model, a detailed insight of the effects of these artificial obstacles regarding network permeability can be obtained. The λ_k measure, resulting from the simulation, eases the comparison of different development scenarios.

The optimization procedure applied in this paper helps to place mitigation measures where they are most effective. This is especially important in terms of limited financial resources. The presented example obtained reasonable results, built up on a high accuracy of the meta-model predictions. The use of a meta-model makes the algorithmic optimization feasible in the first place, since the simulation based evaluation of all cost allocations during the optimization process would be much too time consuming.

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