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Road and Trail Network Optimisation for Low-intensity Selective Logging in Tropical Forests

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Abstract

Selective logging operations in natural tropical forests often involve a very limited number of commercial tree species and if the density of these species is low, the number of trees felled may be only a few per ha. Consequently the costs of road and trail networks have a significant impact on the overall profitability of forest use. Furthermore, the damages resulting from inappropriate routing of skid trails may be severe and, therefore, the need for optimisation of the transport network layout is evident. However, optimisation involves deciding what trees to cut, designing the best possible road and trail network and choosing the best possible winding route for each trail segment and is therefore a difficult task. In this study a self-organising procedure is tested as a means of optimising the temporary road and trail network in a heterogeneous terrain with scattered trees. The paper outlines the method and presents preliminary test results for a hypothetical forest area.

Keywords: Self-organisation, ant colony algorithm, swarm intelligence, skid trails, forest operations

1. Introduction

Selective harvesting in tropical forests has been observed to cause considerable damage to the remaining trees and soil of stands with relatively high densities of commercial trees (Gullison & Hardner 1993, Webb 1997). For example, in a study where reduced-impact logging was carried out in a humid tropical forest in Bolivia and 4.35 trees/ha were felled it was found that, for every tree that was extracted, 44 trees with DBH greater than 10 cm were damaged (Jackson et al. 2002). However, usually the damages can be limited by careful planning of skid trails and logging roads, directional felling, cutting of lianas prior to felling, etc. (d'Oliveira & Braz 1995, Douglas 1998, Sist 2000). Nevertheless, in a comparative study in East Kalimantan in Indonesia it was found that, although reduced-impact logging reduced damages by 50% compared to conventional logging, 25% of the original tree population was damaged when the felling intensity was 8 trees/ha (Sist et al. 1998). Moreover, the effectiveness of reduced-impact logging techniques in reducing the damages decreases when the logging intensity increases (Gullison & Hardner 1993, Sist et al. 1998). The area covered by skid trails and the resulting disturbance of the topsoil also depends on the way that harvest is planned and executed. For example, in a study in Malaysia it was found that in an area where conventional, uncontrolled harvest had been carried out 17% of the area was covered by roads and skid trails whereas, in an experimental area with reduced-impact logging, only 6% of the area was disturbed (Pinard et al. 2000).

The applied felling regime and the associated planning effort have repeatedly been shown to have a significant impact upon drainage, water runoff, soil erosion and stream water quality in tropical forests (Yusop et al. 1987; Nik & Harding 1992; Hartanto et al. 2003). The main

sources of sediments in stream waters of logged-over forests are logging roads and skid trails. For example, Baharuddin et al. (1995) found that the surface runoff from skid trails and logging roads were 14.5% and 20.3% of the total annual rainfall, respectively, compared to 2.3% for an undisturbed area of forest. Similarly, in the first year after logging the soil loss from skid trails and logging roads was 22 and 29 times greater, respectively, than from an undisturbed forest. The difference gradually diminished from one year after logging when secondary vegetation started covering gaps and trails. According to Nik & Harding (1992) the adverse effects of logging can to some extent be ameliorated by proper planning of the road network, installation of cross drains and use of buffer strips.

Studies like those of Barreto et al. (1998) and Ahmad et al. (1999) have shown that the economics of selective logging is improved considerably when logging operations and road construction are properly planned. On a per cubic metre basis it appears that planning reduces costs of all work elements of selective logging, including the number of working hours used on tree felling, the number of machine hours used on opening logging roads and log landings and the number of hours used on skidding. In addition, the number of logs that are wasted, either because they are damaged due to poor felling techniques or because machine operators do not find them, is reduced when logging operations are properly planned. The cumulative effects of the increased productivity in felling and skidding more than compensate for the cost of planning (Barreto et al. 1998, Ahmad et al. 1999). Nevertheless, as also mentioned by Howard et al. (1996), there are a number of barriers to the application of sustainable management practice, including a high interest rate and the lack of enforcement of forestry regulations.

1.1 Road and trail network planning

An important element in the planning of selective logging is the design of road networks. Traditional models used to plan forest road networks are based on rigid simplifying assumptions, e.g. that the forest is spatially homogeneous with respect to volume or value, and the optimal distance between roads is determined by minimising the transportation cost per cubic metre. The optimum is found where the construction cost per unit volume served by the road equals the travelling portion of the skidding and forwarding costs expressed in the same unit (FAO 1977, Wijngaard & Reinders 1985, Yeap & Sessions 1989). Under the condition that road density is constant and that distance is the only important concern, the road network layout can be optimised using geographical optimisation techniques such as the one described by Ishikawa et al. (1995). Other studies operate with more complicated conditions where spatial structure, existing roads, topography (Wijngaard & Reinders 1985, Dean 1997), differential costs (Setyabudi 1994) and environmental constraints (Richards & Gunn 2000) are taken into account. In such cases heuristic solvers or combinations of tools (e.g. GIS and linear programming) are used to identify the optimal road network.

When designing a road and trail network the risk of erosion, deteriorated drainage and long-term degradation of forest productivity is greatly influenced by the extent to which topography, soil conditions and location of major watercourses are taken into account. However, the task of designing an optimal road and trail network that includes secondary forest roads and skid trails with links to every single tree is tremendous, particularly if differential costs and risks of damages are to be taken into account.

The optimal road and trail network problem shares basic characteristics with the classic Travelling Salesman Problem, where each of a number of points must be visited once and only once by following the shortest possible route, and with the Vehicle Routing Problem where

products must be delivered to a number of points by vehicles starting at a common source point while keeping the sum of the travel distances at a minimum. In the road network problem the points to be visited are trees, the routes all go from a timber landing to the tree and back, and apart from horizontal distance, the transportation cost depends on slope, soil conditions, density of vegetation and occurrence of obstacles such as rivers, swamps and pools. The objective is to minimise a cost function that may include both direct costs and indirect costs associated with anticipated damages. At least three variants of the problem may be distinguished, (I) a simplified (restricted) version where every relevant tree is felled, (II) a version where only those trees that yield a positive contribution margin are felled and (III) a 'complete' version where only those trees are felled for which the sales value exceeds the cost of felling and transportation plus the (discounted) opportunity cost resulting from damages to soil and remaining vegetation. Model I is a pure road network optimisation model whereas (II) and (III) are combined harvest and road network optimisation models. A fourth model that may be considered is one that emphasises harvest and road networks both at the current point in time and in the future (IV). Obviously, to apply such a model reliable growth forecasts and estimates of entry costs and opportunity costs must be available. Based on optimisation in such a model one may both decide how much and how often to harvest, and how to design permanent and temporary road and trail networks. In this paper the emphasis will be on the comparatively simple Model I.

As illustrated by the study of Richards & Gunn (2000) a tabu search procedure can handle quite large road network design problems. On the other hand, as mentioned by Bonabeau et al. (1999), with respect to the Travelling Salesman Problem collaborative, self-organising optimisation procedures known as ant-based algorithms may obtain performance similar to that of the best heuristics, such as tabu search. Ant colony optimisation is one variant of what is also known as 'swarm intelligence' and owes its name to an analogy with the foraging behaviour of ants, where positive feedback is obtained through pheromone deposits indicating the routes previously followed by other ants.

In Section 2 a self-organising procedure will be outlined, which is designed to solve complex multi-objective road and trail network problems. The 'ants' can be thought of as agents, or 'contractors', who communicate their experiences (costs) to other agents. For example one may imagine that each contractor draws a sketch map showing what route he has followed, writes a note on his transport costs and that any contractor has access to the sketch maps and notes provided by all of his predecessors. The optimisation procedure is intended for application on data from Bolivian concession areas but, so far, it has only been applied to idealised examples. To illustrate the potential of the procedure preliminary results are presented for a hypothetical forest area including all the features considered in the model.

2. Basic features of models and methods

We will consider a forest area that is divided into square cells using a regular quadratic grid. Each cell is assigned eight properties, six of which are static. First, some cells hold a commercial tree while others are 'empty'. This is indicated by the binary function $T(cell)$ which is 1 if a tree is present and 0 if the cell is empty. The contribution margin associated with visiting the cell and felling the tree is assumed known and is given by the real-valued function $W(cell)$. If no tree is found in a cell, $W(cell) = 0$. The location of existing permanent roads is indicated by the binary function $R(cell)$, which has the value 1 if the cell is part of an existing road and 0 if it is not. Similarly, the location of protected areas that must be avoided

completely is indicated by the binary function $P(cell)$, which is 1 in protected areas and 0 otherwise. The cost of accessing a given cell and using it for transportation is indicated by the real-valued transport difficulty function $D(cell)$. Similarly, the present value of the long-term opportunity cost, that is assumed to be associated with damages caused when using a cell, is indicated by the sensitivity function $S(cell)$. Finally, at any given time the amount of positive feedback from previous visitors is expressed by the function $F(cell)$ and the number of previous visits by the current agent, the associated type of road or trail and the resulting costs of using the cell this time is expressed by $U(cell)$.

As regards the moves of the skidders (agents), four different schemes can be distinguished, [i] one where a skidder is allowed to move to any of the eight cells surrounding it, [ii] one where the skidder is allowed to move in any direction except back to where it came from, [iii] one where the angle between the direction in which the skidder arrived and the direction of the next move cannot exceed 90 degrees, and [iv] one where the angle cannot exceed 45 degrees. In the example presented here the third scheme including five different moves is applied.

As mentioned in Section 1.1 four different problems can be specified. Only the simple Model I will be considered here. In Model I the aim is to minimise the total direct cost of the road and trail network plus the present value of the opportunity cost associated with damages to soil and vegetation. Leaving out details the objective function can be outlined as:

$$C_I^* = \min \left\{ \sum_{trees} \left(\sum_{cells} U(cell) + D(cell) + S(cell) \right) \right\} .$$

The undesirability of moving to a particular cell (j) is measured using an inconvenience function $I(j)$. This function includes the three cost elements of the objective function (U, D, S) plus weighted effects of distance to nearest tree (DIS_N) and distance to the value-weighted centre of the spatial distribution of the trees (DIS_w) minus positive feedback from previous visitors to the cell (F):

$$I(j) = U(j) + D(j) + S(j) + DIS_N(j) + DIS_w(j) - F(j) .$$

At any time the direction of move is determined randomly using a probability function based on the relative desirability of choosing a particular move (j). The probability function can be expressed as:

$$\pi(j) = \frac{\left(\max_{m'} \{I(m')\} - I(j) \right)^\beta}{\sum_{m=1}^M \left(\max_{m'} \{I(m')\} - I(m) \right)^\beta} ,$$

where $\hat{\alpha}$ is an adjustable parameter, $M = 5$ is the number of allowed directions, and $\max\{I(m')\}$ is the maximum inconvenience value observed in any of the allowed directions.

3. Example

A hypothetical forest area has been created to test the self-organising algorithm. The area is rectangular (600×480 m; 28.8 ha) and includes 40 commercial trees and examples of

all other features considered in the model. Figure 1 illustrates the economic properties of the forest area. The passability landscape to the left shows the variation of the transport difficulty function $D(\cdot)$. Similarly, the sensitivity landscape to the right shows the variation of the sensitivity function $S(\cdot)$. The dark high-difficulty, high-sensitivity band snaking its way through the area is a river that must be bridged to get access to trees in the northeast corner of the area. The dark patches in the passability landscape can be thought of as marshy areas or backwaters of the river. Similarly, the dark areas in the sensitivity landscape are mainly areas close to the river, which are likely to be damaged severely when logged and/or ought to be protected to avoid heavy soil erosion.

The left-hand part of Figure 2 shows the passability landscape overlaid by a network of shortest possible paths to the existing road. Although such a network is not the poorest solution one might imagine, it still crosses the river in two places, crosses three swampy areas, and by comparing the network with the sensitivity landscape in Figure 1 it also appears that a considerable part of the network is located in highly sensitive areas along the river. Of course it is unlikely that difficult and sensitive areas can be avoided completely but at least it must be ascertained that a well-considered and balanced compromise solution is used. This is the aim of the methods described here.

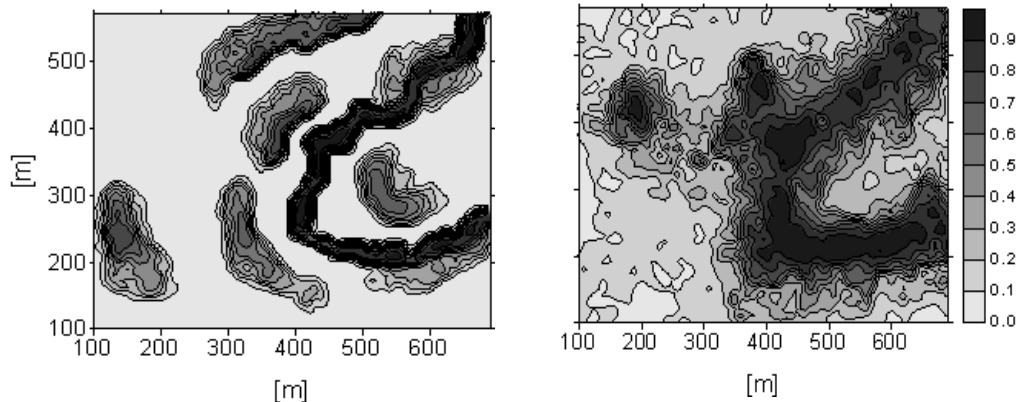
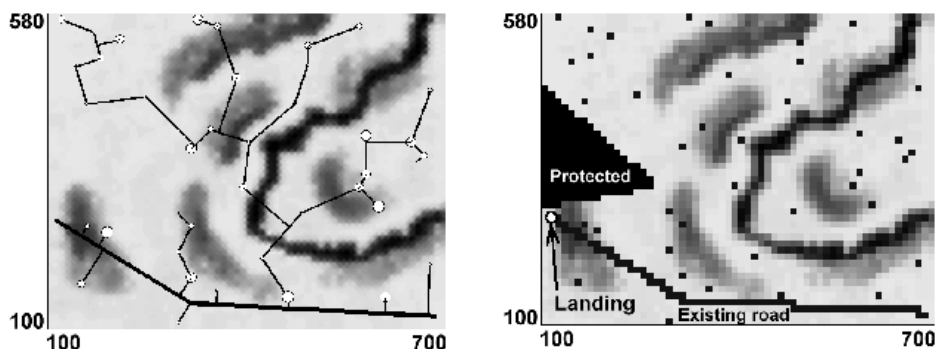


Figure 1. Left: Passability landscape, $D(\cdot)$; dark areas are rivers or swamps that are difficult (expensive) to pass. **Right:** Sensitivity landscape, $S(\cdot)$; dark areas are particularly sensitive and skidding is associated with considerable opportunity costs.

Figure 2. Left: Passability landscape, $D(\cdot)$, with shortest path trail network overlaid.



The thick line is an existing road; other lines are suggested skid trails. Circles are trees and their diameter is proportional to stumpage value. **Right:** Passability grid $D(\cdot)$ with protected area $P(\cdot)$, trees $T(\cdot)$ and existing road $R(\cdot)$ overlaid.

In the optimisation runs all agents start at the landing, see right-hand part of Figure 2. At every step they evaluate the desirability of each of the five allowed moves according to the principles described above. When moving they record the cost and when they end up in a cell with a tree they receive the stumpage value of this tree and return to the landing following the route they used on their way out. When an agent has visited all trees the objective value is evaluated and compared to the current best result. The better the relative performance of the agent, the more positive feedback (experience) is left behind as guidance for other agents. In the run presented below 50 agents are applied and when all 50 agents have finished their search the feedback pattern, $F(\cdot)$, is weakened by multiplying all values by 0.85. In that way the effect of inferior solutions diminishes over time. In addition the feedback function is bounded, implying that its effects on the agent's decisions, compared to other components of the probabilistic decision model, remain within a certain range.

4. Results

In this section the results of a single optimisation run including 4000 iterations are described. As mentioned above the hypothetical forest area is 600×480 m and in this run a spatial resolution of 60×48 cells was applied, each cell thus having a size of 10×10 m. Clearly, 10 metres is considerably more than the width of a skid trail (3-4 m according to Jackson et al. 2002, Table 5), and therefore, the area disturbed by roads and trails will not be examined here. The optimisation algorithm was written in Borland Delphi; the optimisation was executed on a PC with a 1 GHz processor and the 4000 iterations took 14 minutes. In initial test runs it was observed that the improvement of the solution was very slow when fixed optimisation parameters were applied and, hence, the results presented here are based on a schedule where the agents become more focused over time and, conversely, exhibit less explorative behaviour.

The development of the objective function is illustrated in Figure 3. The graph shows both the current solutions (thin line) and the current best solution (thick line) and it appears from the graph that the algorithm continues to improve the solution to the very end of the optimisation run. Thus, it is evident that the algorithm was not really allowed to converge completely. This is a consequence of the mentioned parameter adjustment schedule that forces the agents to become more focused but, on the other hand, does not allow them to fully explore the range of possibilities at any particular stage.

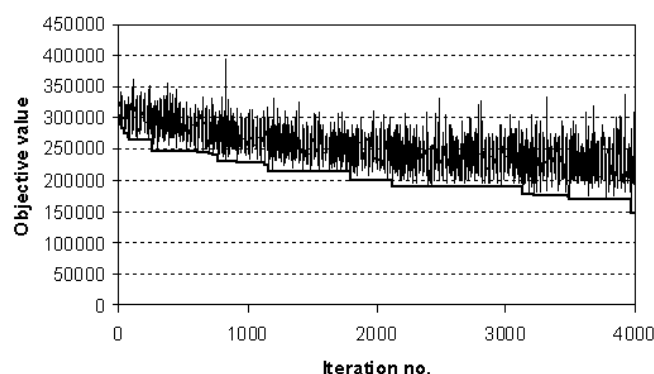


Figure 3. Development of the objective value for an optimisation run with 4000 iterations. The bold line indicates the objective value of the current best solution

Figure 4 shows the accumulated number of visits to each cell at the end of the optimisation run (iteration 4000). Firstly, it appears that due to the low cost of using the existing road, cells that form part of this road have very high frequencies of visits, at least for those parts of the road that are situated close to the timber landing (cf. right-hand part of Fig. 2). Secondly, it appears that due to the fact that many trees are situated north and northeast of the protected area, cells immediately south of the protected area are used very often. It is also interesting to note that, due to the high cost of passing the river and the marshy areas, cells in these areas are not visited very often. The river is most frequently crossed at the three points marked A, B and C. At these points it is relatively narrow (A, B) or trees are located on either side, near the banks (A, B, C). Finally, it should be noted that with the weights applied here, the agents usually prefer to pass a swampy area (marked D) to reach the northernmost trees in the middle, instead of taking the slightly longer route to the west (marked E).

In Figure 5 the development of the feedback function $F(\cdot)$ is shown at six stages of the optimisation. It appears that in the beginning of the process (iteration 50) no spatially continuous feedback pattern has formed and the pattern appears highly erratic. During the next one thousand iterations evidence accumulates, but at iteration 1000 it is still difficult to judge what paths will eventually be preferred although certain routes have indeed been ruled out, e.g. the one marked E in Fig. 4. Finally, during the last 3000 iterations the most preferable paths gradually crystallise. However, at iteration 4000 there are still many alternative routes that have not yet been ruled out.

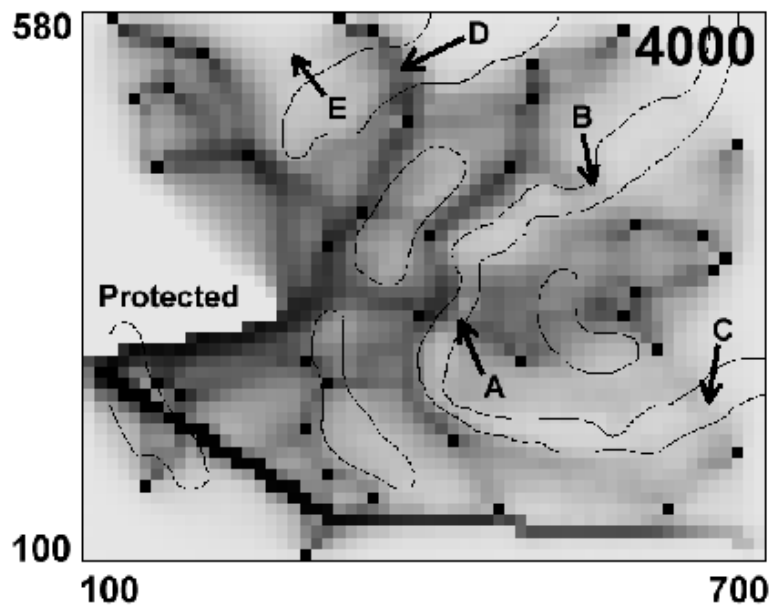


Figure 4. Accumulated number of visits at iteration 4000. Most frequently visited areas are darkest. Location of river and (marshy) areas with low passability are marked with thin black lines.

The current best solutions are shown in Figure 6 and confirm the impression already obtained from Figure 5, namely that the explorative behaviour of the agents continues at least to iteration 1000 and that, only after then, they become so focused that less muddled solutions gradually result. The solution obtained at iteration 4000 clearly underlines the fact that the

process was not allowed to fully converge. The overall structure of the solution may be close to the optimum but even if this is the case, it still includes a couple of doubled routes and a considerable number of cells that are visited for no apparent reason.

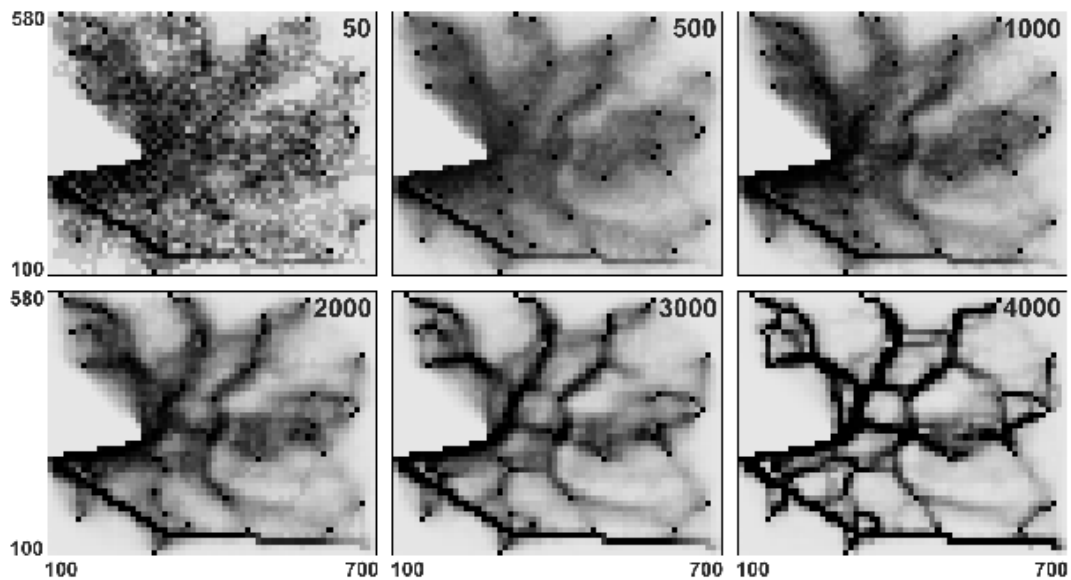


Figure 5. Intensity of feedback from previous passes $F(\cdot)$ at iterations 50, 500, 1000, 2000, 3000 and 4000. Shading is proportional to $F(\cdot)$, darker areas being more attractive.

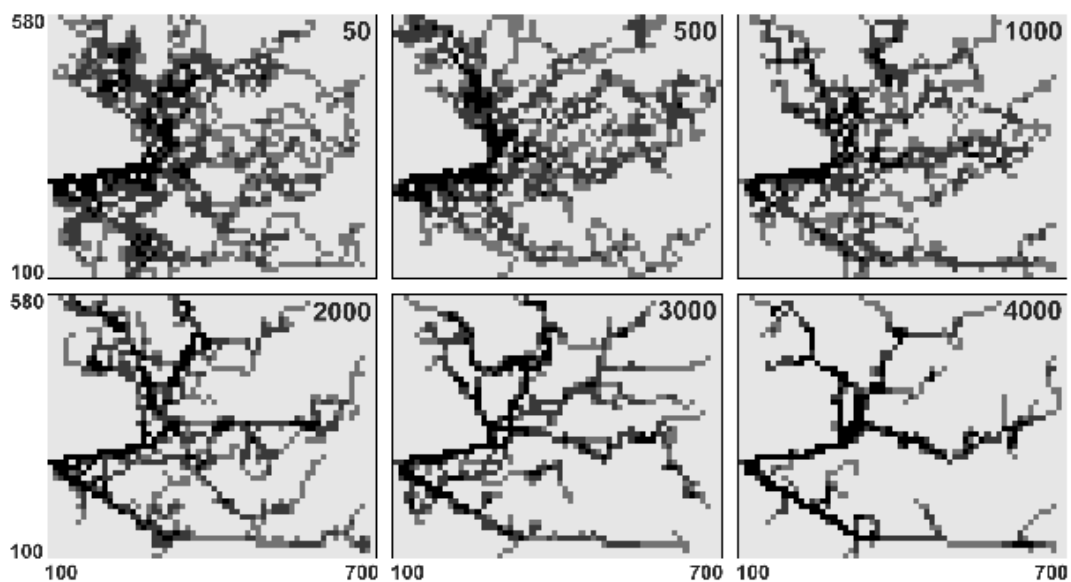


Figure 6. Current best trail networks at iterations 50, 500, 1000, 2000, 3000 and 4000. Shading indicates intensity of use (light grey: not in use; black: used more than three times).

5. Discussion

A self-organising algorithm for road and trail network optimisation has been outlined and applied to a hypothetical forest area. The next step is to apply the algorithm to a real forest and to compare the results with those obtained using other methods. Moreover, still a considerable amount of work needs to be done to identify ideal optimisation schedules that ensure that near-optimal solutions are invariably found within the lowest possible number of iterations. However, it may emerge that the ideal optimisation schedule is problem-specific, implying that an adaptive parameter adjustment procedure should be developed. At any rate the method is considered promising as it allows all elements of a transportation network to be handled within one common framework.

In this paper a constrained version of the 'real' optimisation problem has been considered, i.e. a version where all trees included must be felled (Model I). This is a considerably simpler problem than one which both involves identifying the optimal road and trail network, and sorting out those trees that are too costly to reach or imply unacceptable damages to soil and vegetation. To solve this problem each agent must report on its achievements for each tree individually as well as for the whole set of trees, and the applied algorithm must be modified to exclude trees that are not profitable to fell. However, the cost of choosing a particular route to a tree depends on whether a trail has already been opened. Therefore, the cost of reaching a tree depends both on the chosen path to this particular tree and on the paths chosen to other trees, and consequently, for any suggested primary solution (trail network) a secondary, combinatorial optimisation problem arises in which the optimal combination of trees to fell must be identified. As the number of different solutions is exponential in number of trees this problem becomes hard to solve even for a relatively small area. For example, the hypothetical forest area used in this paper includes 40 trees so the number of different combinations would be $2^{40} = 1.1 \times 10^{12}$. Therefore, for each primary solution it will be necessary to accept approximate solutions to the secondary problem. However, also in this context it may be possible to make use of feedback from previous iterations, implying that the secondary optimisation problem may prove less demanding than it currently appears.

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