Double Ant Colony System to Improve Accessibility after a Disaster

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Keywords: Accessibility Problem, Road Repair, Ant Colony System.

Abstract: We propose a novel double ant colony system to deal with accessibility issues after a natural or man-made disaster. The aim is to maximize the number of survivors that reach the nearest regional center (center of economic and social activity in the region) in a minimum time by planning which rural roads damaged by the disaster should be repaired given the available financial and human resources. The proposed algorithm is illustrated by means of a large instance based on the Haiti natural disasters in August-September 2008.

1 INTRODUCTION

Natural disasters have a huge impact on human life, as well as on the economy and the environment. In spite of the advances in forecasting and monitoring the natural hazards that cause disasters, their consequences are often devastating.

Disaster management activities can be categorized into five generic phases: prediction, warning, emergency relief, rehabilitation and reconstruction. The last three phases are generally associated with the post-disaster effort and involve both response and recovery activities (Moe and Pathranarakul, 2006). The response activities during the emergency relief phase aim to provide assistance during or immediately after a disaster to ensure the preservation of life and the basic subsistence needs of the victims.

Activities during the rehabilitation and reconstruction phases include decisions and actions taken after a disaster in order to restore or improve the living conditions of the affected community, but also activities related to mitigation and preparedness.

One of the main problems relief teams face after a natural or man-made disaster is how to plan rural road repair work to take maximum advantage of the limited available financial and human resources. In this paper we account for the accessibility issue, which is defined in (Donnges, 2003) as the degree of difficulty people or communities have in accessing locations for satisfying their basic social and economic needs. It is defined in (Lebo and Schelling, 2001) as the minimum level of rural transport infrastructure network service required to sustain socioeconomic activity. Specifically, we maximize the number of survivors that reach the nearest regional center (center of economic and social activity in the region) in a minimum time by planning which rural roads should be repaired given the available financial and human resources.

This is a combinatorial problem since the number of connections between cities and regional centers grows exponentially with the problem size, and exact methods are no good for achieving an optimum solution. In order to solve the problem we propose a novel adaptation of the *ant colony system* (ACS), the *double ant colony system* (DACS). In the DACS we consider pairs formed by an explorer and a worker ant. The aim of the *explorer* ant is to build paths from cities to their nearest regional centers, whereas the goal of the *worker* ant is to identify the optimal repair plan to maximize net accessibility.

The two ants always work concurrently in pairs to build the paths and repair roads simultaneously. Candidate roads for repair have to be previously selected by the explorer ant in a transition rule, whereas the possibility of repairing a damaged road has to be taken into account when deciding which node to visit next.

In Section 2, we introduce the mathematical model of the accessibility problem. A literature review focused on accessibility problems and their solution on the basis of metaheuristics is provided in Section 3. In Section 4, we describe the *double ant colony system*. An example based on the Haiti natural disasters in 2008 illustrates the DACS in Section 5. Finally, some conclusions are provided in Section 6.

Sacristán, V., Jiménez-Martín, A. and Mateos, A.
Double Ant Colony System to Improve Accessibility after a Disaster.
DOI: 10.5220/0005651900790086
In *Proceedings of 5th the International Conference on Operations Research and Enterprise Systems (ICORES 2016)*, pages 79-86
ISBN: 978-989-758-171-7

2 PROBLEM MODELLING

Let $G = (N, \varepsilon)$ be an undirected graph where $N = \{N_1 \cup N_2 \cup N_3\}$ is a node set and ε is an edge set. N is partitioned into three subsets: N_1, regional centers; N_2, rural towns; and N_3, road intersection points. Edges in ε represent roads with an associated binary level l_e (1 if the road is operational and 0 otherwise).

The subset of roads $\varepsilon_r \in \varepsilon$ is composed of roads that are not operational and can be repaired. The initial level for these roads is $l_e = 0$. There is a financial budget B and a person-hour budget H allocated to road repair, whereas a financial cost c_e and a manpower requirement m_e are associated with each road $e \in \varepsilon_r$.

A measure of accessibility is defined for each node $i \in N_2$: the shortest travel time from i to the closest regional center in N_1, which depends on which roads are singled out for repair. The time to traverse an edge is t_e when the road is operational and $t_e + M_e$ when it is not. M_e represents a penalty factor for using another means to traverse e (e.g., using animal-powered transport).

Three types of decision variables have to be considered in this accessibility problem. First, the binary variables x_e indicate whether ($x_e = 1$) or not ($x_e = 0$) road $e \in \varepsilon_r$ is repaired. Variable y_e^{ij} is assigned the value 1 when road e is used on the path from $i \in N_2$ to $j \in N_1$ and 0 otherwise. Similarly, variable b_k^{ij} is given the value 1 when node k is visited on the path from $i \in N_2$ to $j \in N_1$.

A **mathematical integer program** for this accessibility problem (Campbell et al., 2006; Maya and Sörensen, 2011) is described below.

The *objective function* minimizes the weighted sum of the shortest routes for all $i \in N_2$ to the nearest regional center $j \in N_1$ as follows:

$$f(x) = min \sum_{i \in N_2} (w_i \times min_{j \in N_1} \{\sum_{e \in \varepsilon} d_e y_e^{ij}\}) \quad (1)$$

where

$$d_e = \begin{cases} t_e + (1 - x_e)M_e, & \forall e \in \varepsilon_r \\ t_e, & \forall e \in \varepsilon \setminus \varepsilon_r \end{cases} . \quad (2)$$

The weight w_i associated with each node $i \in N_2$ represents its relative importance and is usually a function of the number of inhabitants of the rural town associated with that node.

The constraints to be considered in the optimization problem are as follows. First, the following constraints ensure, respectively, that there is exactly one road leaving i on the path from i to j and that there is exactly one road entering j on the path from i to j:

$$\sum_{e \in \varepsilon(i)} y_e^{ij} = 1, \quad \sum_{e \in \varepsilon(j)} y_e^{ij} = 1 \quad \forall i \in N_2, \forall j \in N_1, \quad (3)$$

where $\varepsilon(i)$ is the set of roads adjacent to node i.

We must also ensure that the path from i to j is connected:

$$\sum_{e \in \varepsilon(k)} y_e^{ij} = 2b_k^{ij} \quad \forall k \in N \setminus \{i, j\}, \forall i \in N_2, \forall j \in N_1. \quad (4)$$

Additionally, budget limitations regarding road repair also have to be taken into account:

$$\sum_{e \in \varepsilon_r} c_e x_e \leq B, \quad \sum_{e \in \varepsilon_r} m_e x_e \leq H, \quad (5)$$

where B and H are the above financial and the person-hour budgets, respectively.

3 LITERATURE REVIEW

The reconstruction or repair of the road network after a natural disaster has been studied by several authors considering different objectives and using diverse approaches.

(Sato and Ichii, 1996) developed a hybrid *genetic algorithm* (GA) to decide the priority of components to be restored in a restoration process of lifelines damaged by earthquakes. They also applied a single populated GA to distribute restoration teams at damaged sites in order to optimize the restoration process of lifeline networks.

A GA was also proposed in (Chen and Tzeng, 1999) to solve a fuzzy multi-objective model for reconstructing the post-quake road network, aimed at minimizing the total travel time over the road network during reconstruction, the individual reconstruction time of any work team, and the idle time between work teams.

(Feng and Wang, 2003) proposed a multi-objective model focused on network repair over the first 72 hours after the disaster to maximize the performance of emergency road rehabilitation and the number of people that benefit, and to minimize the risk to rescuers. A case study was conducted presenting the 1999 Chi-Chi earthquake in Taiwan. (Lee, 2003) also deals with repairing the post earthquake road networks. A GA was used to solve a scheduling problem. Specifically, the sequence for repairing disaster spots in a first model was determined on the basis of a fuzzy ranking method, whereas a second model assumed that the travel times are deterministic and allowed each disaster spot to be handled by one or more construction teams.

In (Liao, 2005) the damaged infrastructure repair problem considered both the overall efficiency and total completion time. An upper-level subproblem maximizes the overall efficiency of the repair work, whereas the lower-level subproblem minimizes the total completion time subject to the time constraint for each disaster spot.

(Wang, 2008) formulated a series of mixed integer programming problems for a multi-depot vehicle-routing problem with time windows. A two-stage solution algorithm was proposed, using the *nearest/farthest insertion method* for generating an initial solution, and the *2-opt, swap, and or-opt methods* for improving that solution, respectively.

(Yan and Shih, 2009) considered minimizing the length of time required for both emergency roadway repair and relief distribution, as well as the related operating constraints, to develop a model for planning emergency repair and relief distribution routes and schedules within a limited time. A multi-objective mixed-integer multiple-commodity network flow model was proposed which was efficiently solved by a weighting method based heuristic.

(Chen et al., 2011) addressed the task of repairing damaged infrastructures as a series of multi-depot vehicle-routing problems with time windows in a time-rolling frame by a *take-and-conquer* strategy.

In (Maya and Sörensen, 2011) the *greedy randomized adaptive search procedure* (GRASP) in combination with *variable neighborhood search* (VNS) was used to solve exactly the same accessibility problem considered in this paper. We will use the same instance to illustrate our proposal and analyze its performance in Section 5.

(Zhang and Lu, 2011) established a fuzzy multi-objective model for road rush-repair scheduling. The model based on VRP, containing time window, took the sum time of the repair work, the time of the work group in transit and the risk of the rush-repair. A GA was developed to solve the problem.

(Yan and Shih, 2012) employed an ACS algorithm coupled with a threshold accepting technique (ACSB) for solving and applying an emergency roadway repair time-space network flow problem to different instances using data from the Chi-Chi earthquake.The objective was formulated as a *minimax* function to minimize the time duration for finishing all repair work.

More recently, (Muñoz et al., 2015) used an adaptation of the ACS to solve exactly the same accessibility problem considered in this paper. In the ACS adaptation the construction of paths from each city to its nearest regional center and the road repair decisions were carried out independently.

Finally, (Zheng et al., 2015) survey the research advances in evolutionary algorithms and other metaheuristics applied to disaster relief operations.

4 DOUBLE ANT COLONY SYSTEM

The *double ant colony system* (DACS) is bio-inspired in *Atta* ant colonies from Costa Rica, commonly known as *leaf-cutter* ants. These ants work in pairs. While one ant carries a leaf, a smaller one climbs on the back of the leaf to inspect its quality and protect the carrier ant from a type of parasitic fly.

In DACS we consider pairs formed by an explorer and a worker ant. The aim of the *explorer* ant is to build paths from cities to their nearest regional centers, whereas the goal of the *worker* ant is to identify the optimal repair plan that maximizes net accessibility.

The two ants always work concurrently in pairs to build the paths and repair roads simultaneously. Candidate roads for repair have to be previously selected by the explorer ant in a transition rule, whereas the possibility of repairing a damaged road has to be taken into account when deciding which node to visit next.

However, although the explorer and worker ants work simultaneously, they each use different information to select the next node to be visited and to decide whether or not a road is repaired. Thus, different pheromone matrices will be considered for the explorer and worker ants.

Moreover, we also consider that the construction of paths from each city to its nearest regional center as independent problems. Whereas it could be a good decision to use a specific road to build a path from city i to its nearest regional center, this could be a bad decision if another city j is considered. Thus, we propose using different pheromone matrices for the construction of paths from each city to its nearest regional center.

Note that if only one pheromone matrix is used then the pheromone level for a road might be very high because this road is in the path from a city to its nearest regional center and, consequently, is visited by many ants when building this road. However, this road might not originally be in the path from another different city to its nearest regional center, but could be included due to its high pheromone level.

Besides, as the available budgets concern the repair process for the whole accessibility problem, involving n cities, only one pheromone matrix will be used by worker ants.

Thus, in an accessibility problem with n cities, $n+1$ pheromone matrices would be used, n by the explorer ants and 1 by the worker ants.

The basic idea of DACS (Sacristán, 2015), see *Algorithm 1*, is as follows. First, both explorer and worker pheromone matrices are initialized. Then, we consider m pairs of ants in each iteration, formed by an explorer and a worker ant. For each pair of ants, k, we first initialize the respective available budgets $B_k = B$ and $H_k = H$. Then, the pair of ants builds a path for each city n in N_2 to its nearest regional center and simultaneously decides on the repair of the respective roads. Note that some decisions to repair are taken during the construction of such paths, but we will not have a complete repair plan until all n cities have been analyzed.

Algorithm 1: Double ant colony system (DACS).

Initialization: τ_0^{expl}, τ_0^{worker}, T.
repeat
  for (each pair of ants k, $k = 1,...,m$) **do**
    Initialize budgets $B_k = B$ and $H_k = H$
    for ($n \in N_2$ cities (randomly selected)) **do**
      repeat
        Ant k^{expl} performs transition rule
        if (the road is damaged) **then**
          Ant k^{worker} decision to repair
          Update B_k and H_k if necessary
        end if
        Local pheromone trail update
      until a path is build for city n
    end for
  end for
  Identify *IterationSol* (best accessibility value)
  if *IterationSol* better than $best\text{-}so\text{-}far$ **then**
    Update $best\text{-}so\text{-}far$
  end if
  Global pheromone trail update
until maximum number of iterations

The order in which cities in N_2 are analyzed by the m pairs of ants in each iteration is selected at random.

The explorer ant (k^{expl}) builds the path according to a transition rule. Once a road is selected by the explorer ant, the worker ant (k^{worker}) comes into play and decides whether or not to repair that road, if possible, i.e. if the road is damaged and the person-hour and financial budget available at the time is sufficient. If the road is singled out for repair, the remaining budgets (B_k and H_k) are updated. The new available budgets together with the roads repaired have to be taken into account when building paths for the remaining cities in N_2 by the pair of ants.

Local pheromone trails are updated by both explorer and worker ants in the corresponding matrices while paths are built.

Once the pair of ants has analyzed the n cities we have a possible solution, consisting of the paths from each city n in N_2 to its nearest regional center and a repair plan. Note that the accessibility value of a solution implies recomputing the accessibility of each path built taking into account all the roads repaired in the repair plan. Even if a road included in a path for a specific city is not repaired, it may be decided to repair the road if it is considered again during the analysis of another city and included in the path from that city.

Of the m solutions derived from the m pairs of ants, the one with the highest net accessibility value is the solution for the current iteration (*IterarionSol*). If the solution of the current iteration is better than the global solution ($best\text{-}so\text{-}far$) in terms of net accessibility, then the global solution is updated.

Finally, global pheromone trails are updated, where only the pair of ants corresponding to the *best-so-far* solution deposit pheromes. The explorer ant updates the corresponding explorer pheromone matrices taking into account the paths in the *best-so-far* solution, whereas the worker ant updates the worker pheromone matrix taking into account the corresponding repair plan.

We now describe the algorithm phases in detail.

4.1 Initizalization Phase

First, a matrix T containing the minimum distance between each pair of nodes in the net is computed using the *Floyd-Warshall algorithm* (Cormen et al., 1990).

Pheromone levels are then initialized in the matrices corresponding to explorer ants as follows:

$$\tau_0^{expl} = 1/m \times L_n, \tag{6}$$

where m is the number of ants and L_n is the length of the path from city n to its nearest regional center in T and assuming that no road has been repaired.

A similar expression to (8) is used to compute the initial pheromone in the matrix corresponding to worker ants. However, the elements to be considered account for accessibility rather distance issues, i.e. $\tau_0^{worker} = \frac{1}{m \times A}$, where A is the accessibility value corresponding to a suboptimal solution computed using a *sequential forward selection* (SFS) algorithm that we propose.

SFS is very similar to the *insertion algorithm* (IA) proposed in (Maya and Sörensen, 2011). In the IA, see *Algorithm 2*, matrix T containing the minimum distance between each pair of nodes in the net and matrix P including the paths associated with the minimum distances in T are first computed using the *Floyd-Warshall algorithm*.

Then, roads whose repair leads to a greater improvement in net accessibility are iteratively repaired until the budget is depleted. The time saved by repairing a given road is computed according to the following expression:

$$saving(e) = \sum_{l \in N_2} \Big(min_{k \in N_1} \{T[k,l]\} - min_{k \in N_1} \{T[k,i] + f_t(e,1) + T[j,l]\} \Big), \tag{7}$$

where $T[i,j]$ represents the shortest travel time from i to j and $f_t(e,1)$ gives the time to traverse edge e when the road is repaired.

Algorithm 2: Insertion algorithm (IA).

Require: Consider initial **x**, B, H, T, P, $saving = 0$
  repeat
    for $(e \in \varepsilon_r \mid l_e = 1, c_e \leq B, m_e \leq H)$ **do**
      Estimate insertion saving for e, $saving(e)$
      if $saving(e) > saving$ **then**
        $saving = saving(e)$, $candidate = e$
      end if
    end for
    Improve candidate: Update **x**, B, H, T and P
    $saving = 0$
  until no insertion candidate is found

The difference between IA and the SFS algorithm that we propose is that the SFS algorithm recomputes the saving for all the unrepaired roads in each iteration, since these values depend on the state of the net. So, when a road is repaired in an iteration, the net has changed and the saving corresponding to the roads that are still unrepaired may have changed too. Recomputing the saving values throughout the iterations in the IA algorithm outputs a more accurate solution.

Another difference between IA and the SFS algorithm is that the expression proposed by Maya and Sorensen for the *saving* may include negative elements in the summation. However, we think that not repairing a road would never mean a loss in the net accessibility or lead to longer path between a city and its nearest regional center. Therefore, we consider only the positive elements in the summation.

4.2 Path Construction and Repair Decisions

As already mentioned, the aim of *explorer ants* is to build the paths from each city to its nearest regional center. To do this, we use the *pseudorandom proportional rule* used in the original ACS algorithm (Dorigo and Gambardela, 1997a; Dorigo and Gambardela, 1997b) to decide which node to visit next when building the paths. An ant currently at node i chooses the road

$$e = \begin{cases} argmax_{e \in \varepsilon(i)} \{[\tau_e^{expl}], [\eta_e^{expl}]^\beta\}, & \text{if } q \leq q_0 \\ J, & \text{otherwise} \end{cases}, \tag{8}$$

where $\varepsilon(i)$ is the set of roads adjacent to city i and J is randomly generated according to the following probabilities:

$$\frac{[\tau_e^{expl}] \times [\eta_e^{expl}]^\beta}{\sum\limits_{l \in \varepsilon(i)} [\tau_l^{expl}] \times [\eta_l^{expl}]^\beta}. \tag{9}$$

q is randomly generated from a uniform distribution in $[0,1]$ and q_0 ($0 \leq q_0 \leq 1$) is a parameter that models the degree of exploration and the possibility of concentrating the search around the *best-so-far* solution or exploring other paths. It is usually initialized with a high value ($0.8 \leq q_0 \leq 0.9$).

Note that the higher parameter β is, the more relevant the heuristic information regarding the pheromone trails is. The heuristic information used in the pseudorandom proportional rule, η_e^{expl}, is the inverse of the distance in time units to traverse the corresponding road e when it is operational (t_e). However, when the road is damaged the time to traverse it is $t_e + M_e$. Therefore, we propose using a value within the interval $[t_e, t_e + M_e]$ according to the probability of that road being repaired. This is computed on the basis of the *saving*, see Eq. (10). Roads with a low *saving* (low probability of being repaired) with respect to the other roads under consideration will be proportionally assigned a value on the right of the interval, whereas a high *saving* will mean that a value on the left of the interval will be assigned.

Note that the pheromone level in the above expressions, τ_e^{expl}, corresponds to an explorer ant and depends on the city from which the path is being built since we are considering different pheromone matrices for the paths from each city to its nearest regional center.

Besides, the aim of *worker ants* is to identify a road repair plan that maximizes net accessibility. Although the decision on whether or not to repair a road is different to deciding which node to visit next when building the paths, it has been modeled as a path selection problem too. Specifically, a path will mean repair whereas the other will mean do nothing.

Therefore, the *pseudorandom proportional rule* used in the ACS algorithm can be reused as the *repair rule*, but including pheromone values corresponding to worker ants (τ_e^{worker} rather than τ_e^{expl}) and different heuristic information (η_e^{worker} rather than η_e^{expl}).

Now, η_e^{worker} is expressed in terms of accessibility rather than distance since the decision is aimed at maximizing net accessibility. Thus, η_e^{worker} corresponding to the path in which the road is not repaired is the net accessibility when no road has been repaired, otherwise (we decide to repair the road) the net accessibility when that road is repaired is used. This is computed using the *saving* expression.

4.3 Pheromone Update

Pheromone update works in a similar way to the ACS algorithm. However, we must take into account that different pheromone matrices are being used for explorer and worker ants. Moreover, different pheromone matrices are also being used in the construction of the paths from each city to its nearest regional center.

According to ACS, only the explorer ants corresponding to the *best-so-far* solution add pheromone in the *global pheromone trail update* after each iteration as follows:

$$\tau_e^{expl}(t) = (1-\alpha)\tau_e^{expl}(t-1) + \alpha\Delta\tau_e^{expl},$$

where $0 < \alpha < 1$ is the global pheromone evaporation parameter and

$$\Delta\tau_e^{expl} = \frac{1}{C(S_{best-so-far}^{expl})},$$

where $C(S_{best-so-far}^{expl})$ is the length of the shortest path found up to that point between the respective city and its nearest regional center.

Regarding worker ants, the expression for $\tau_e^{worker}(t)$ is analogous, and $C(S_{best-so-far}^{worker})$ now refers to the net accessibility value associated with the *best-so-far* solution.

The *local pheromone trail update* is applied by ants immediately after having traveled a road during the path construction and is aimed at allowing a more diversified search since it improves the probability of the pair of ants following different paths:

$$\tau_e(t) = (1-\rho)\tau_e(t-1) + \rho\Delta\tau,$$

where ρ $(0 < \rho < 1)$ is the local pheromone evaporation parameter and $\Delta\tau$ is τ_0^{expl} or τ_0^{worker} (initial pheromone levels) depending on whether the ant is a worker or an explorer, respectively.

5 ILLUSTRATIVE EXAMPLE

We used the instance of the real natural disaster that occurred in Haiti described in (Maya and Sörensen, 2011) to illustrate the proposed DACS and check its performance. Moreover, the problem-solving method based on GRASP and VNS metaheuristics proposed in (Maya and Sörensen, 2011) was used for comparison.

Within weeks at the end of August and beginning of September 2008, four hurricanes and tropical storms hit Haiti. Up to 800,000 people were directly affected and many main roads and bridges across the country were destroyed or blocked, compounding logistics operations (OCHA-UN, 2008).

The considered instance is based on this case using the information gathered from diverse sources. Data from GISDataDepot (http://data.geocomm.com) was used to define the road network in a GIS, whereas the status of the network after the natural disaster is based on the information published by Mapaction (www.mapaction.org) and Reliefweb (www.reliefweb.com), and demographic information was obtained from Falling Rain Genomics Inc. (www.fallingrain.com).

In this accessibility problem instance we have three regional centers (Port Au-Prince, Les Cayes, and Cap Haitien), 101 rural towns, 110 road junctions and 281 roads (30 of which were damaged after the disaster), see Fig 1. Solid and dashed lines represent operational and damaged roads, respectively. Moreover, damaged roads are numbered.

The penalty factor for traversing a non-operational road, M_e, is the same for all $e \in \varepsilon_r$, the sum of the length of all the roads in ε_r, 336.58. Table 1 shows the financial cost (c_e) and the manpower requirement (m_e) associated with the repair of each road $e \in \varepsilon_r$.

Table 1: Financial cost (c_e) and manpower requirement (m_e) for repairing roads.

road	c_e	m_e	road	c_e	m_e	road	c_e	m_e
1	5.6	5	**2**	6.5	9.3	**3**	0.9	3.6
4	2.5	5.1	**5**	7.1	7.7	**6**	7.1	3.7
7	2.8	3.7	**8**	4	1	**9**	3.8	1.4
10	7	5.8	**11**	4.9	5.8	**12**	4.2	2.6
13	2.8	0.9	**14**	4	3.8	**15**	3.2	2.7
16	3.8	4.2	**17**	3.6	2.4	**18**	2.8	3.4
19	2.5	3.6	**20**	3	4.2	**21**	6.5	6.2
22	4.4	5.1	**23**	4.3	4.6	**24**	3.3	2.1
25	4.4	4.2	**26**	2.7	5.5	**27**	4.4	6.5
28	1.7	5.1	**29**	3.7	3.3	**30**	2.7	5.6

Following (Maya and Sörensen, 2011) we have considered three different scenarios in which 25%, 50% and 75% of the total monetary and person-hour budgets required to repair all roads ($B = 120$, $H = 128$) are available, respectively.

The values fixed for parameters in the DACS algorithm are as follows: the number of pairs of ants used is $m = 10$ and the number of iterations is 100.

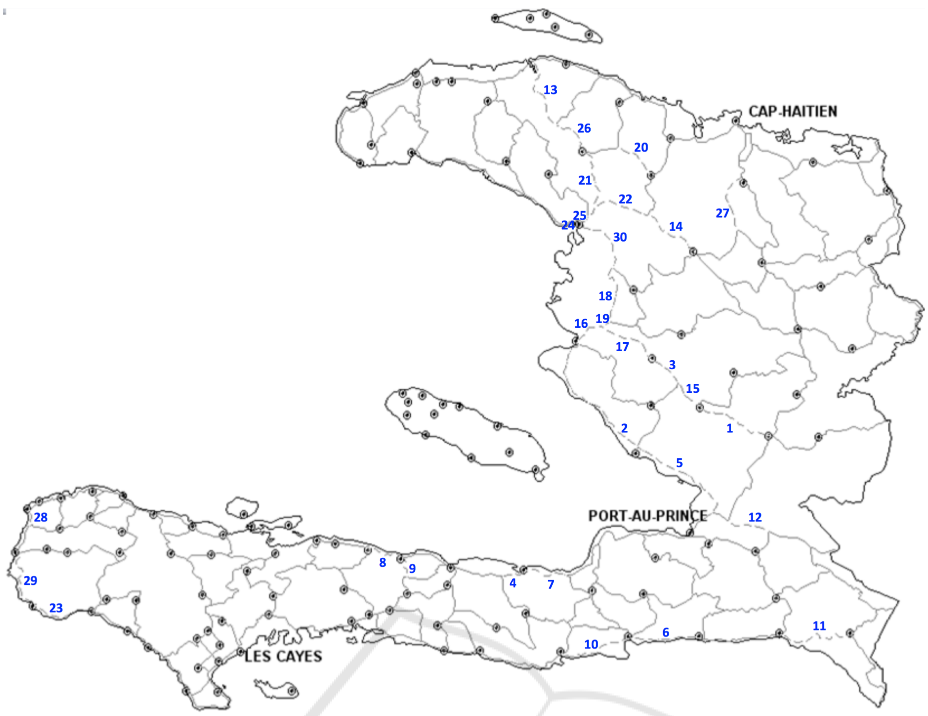

Figure 1: Road network after the natural disaster.

The initial pheromone level for worker ants depends on the scenario under consideration since the *sequential forward selection* algorithm that we propose uses the available budgets. Specifically, $\tau_0^{worker}(25\%) = 0.0077$ and $\tau_0^{worker}(50\%) = \tau_0^{worker}(75\%) = 0.00786$.

Besides, 101 initial pheromone levels were computed for explorer ants since 101 pheromone matrices were considered for explorer ants. However, these initial pheromone levels for explorer ants are the same in all three scenarios.

Local and global evaporation parameters are $\alpha = \rho = 0.1$. In the *pseudorandom proportional rule* for path construction $\beta = 2$ and $q_0 = 0.9$.

Table 2 shows the repaired roads and the total traverse time associated with the paths from the 101 rural towns to their closest regional center in the three scenarios under consideration.

Table 2: Solutions for the three scenarios.

	Repaired roads	Traverse time
25%	{23,5,3,22,25,7,24}	125,449,501.62
50%	{5,24,20,25,22,3,27,7,23,1,2,9,11}	121,055,243.50
75%	{25,22,23,24,5,27,11,1,7,29,3,2,20,29}	120,995,327.08

When the budgets are set to 25% of the total requirements only seven out of the 30 damaged roads are repaired (see Table 2). This recovers 58.1% of the accessibility with respect to the conditions before the disaster. If we consider 50% of the total requirements, then 13 out of the 30 damaged roads are repaired, recovering 96.8% of the accessibility. Finally, with 75% of the total requirements, the network can be totally recovered with respect to accessibility. To do this, only 14 out of the 30 damaged roads have to be repaired.

Regarding the affected towns and people, 774,432 persons (14.8% of the total population) were affected by the natural disaster. Specifically, the shortest path for 364,259 of them to their nearest regional center was longer than before the disaster, whereas there was no path connecting the other 410,173 persons to a regional center.

In the three above scenarios we established a path connecting all people to a regional center, and the percentage of people whose shortest path to their nearest regional center is longer than before the disaster was reduced from 14.8% to 7.6%, 0.2% and 0.0%, respectively.

The solutions described above are fully consistent with findings by (Maya and Sörensen, 2011). Moreover, the simplest scenario considering 25% of the total monetary and person-hour budgets was exactly solved, and the optimal solution matched with the one achieved using DACS. Thus, we can conclude that both the the solution method based on GRASP and VNS and the DACS algorithm find the optimal solution for the considered accessibility problem.

6 CONCLUSIONS

We have proposed a novel double ant colony system (DACS) to deal with an accessibility problem after a natural disaster aimed at maximizing the number of survivors that reach the nearest regional center in a minimum time by planning which rural roads should be repaired given the available financial and human resources.

The performance of the proposed algorithm has been analyzed in an instance related to Haiti natural disasters in 2008, and the results demonstrate that the optimal solution is found.

Regarding future research lines, a possible parallelization could be incorporated to DACS, and it should be compared with other heuristics, such as artificial bee colony, on several instances. Besides, the DACS approach could also be used for the repair of the road network after a natural disaster which involves additional concerns, such as minimizing the length of time required for road repair or minimizing risk to rescuers.

ACKNOWLEDGEMENTS

The paper was supported by the Spanish Ministry of Science and Innovation project MTM2011-28983-C03-03 and the Spanish Ministry of Economy and Competitiveness MTM2014-56949-C3-2-R.

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