Livestock Evacuation Planning for Natural and Man-made Emergencies

Chrysafis Vogiatzis  
University of Florida

Ruriko Yoshida  
University of Kentucky

Ines Aviles-Spadoni  
University of Florida

Shigeki Imamoto  
Shinjo Veterinarian Clinic  
and

Panos M. Pardalos  
University of Florida

Email: ruriko.yoshida@uky.edu

On March 11, 2011, Japan was struck by the Great East Japan earthquake followed by a 23-foot tsunami, which crippled the Fukushima Daiichi nuclear plant. Because of a lack of plans for livestock evacuation in the case of a nuclear power plant accident, local farmers in the Fukushima exclusion zone had significant losses. Development of a rigorous and mathematical formulation of an evacuation plan for livestock in a case of disasters is essential for producers to lessen the financial and emotional impacts. Thus, we propose two mathematical models for evacuation plan for livestock in the area around a nuclear power plant using integer programming over networks. Since solving an evacuation problem on a time dynamic network is NP-hard, we propose algorithms to estimate an optimal solution for our problem. The methods and models discussed herein apply not only to nuclear plant related disasters, but also to a variety of other emergencies.

Keywords: animal evacuation plan, livestock, nuclear power accidents, natural and man-made disasters
Introduction

Various papers have proposed the salvageability of livestock after a nuclear crisis to avoid disruption in the economic stability of that sector. For example, a report of the United States Department of Agriculture, Animal and Plant Health Inspection Congressional Research Service (UDSA/APHIS) recommended avoiding “panic slaughter” because livestock that have survived exposure to radiation must be preserved to rebuild healthy and viable populations after a nuclear crisis (Berger et al. 1987). This report also gives detailed steps on how to decontaminate livestock exposed to radioactive material. In the wake of growing concerns by pet owners and livestock producers for animals remaining in the 20 km exclusion zone, the International Fund for Animal Welfare (IFAW) in May 2011 made specific recommendations to the Japanese government that animals should be rescued, decontaminated and provided relief (IFAW 2011). Moreover, a protocol for handling livestock externally contaminated by radioactive material has recently been proposed based on the degree of exposure, the cost of decontamination, the demand for that food product, and the economic impact to the producer (McMillan et al. 2011). Even though the authors of the document have strongly stated the importance of establishing a concrete evacuation plan for livestock in the area around a nuclear power plant, they have not discussed a mathematical and statistical formulation for such a plan. Development of a rigorous and mathematical formulation of an evacuation plan for livestock around a nuclear power plant is essential for producers to lessen the financial and emotional impacts related to losing their animals (Carroll et al. 2006; Wilson et al. 2009).

Modeling an efficient evacuation plan from the disaster zone is essential in order to save livestock before they are externally or internally contaminated by radionuclides such as cesium or iodine. External and internal contamination of livestock by radionuclides is produced in a variety of ways such as radioactive material in air or rain and via internal contamination by ingesting contaminated feed and water (Berger et al. 1987). For example, cesium 137 and iodine are important radionuclides because cesium has a half-life of 30 years and settles into the bone marrow, while iodine because of its relatively large mass and effect on the thyroid. (www.ncrponline.org/Publications/Press_Releases/161press.html)

Apart from the financial damage introduced by the sudden loss of the livestock of a specific area, there are also a number of emotional and social welfare losses associated with losing companion animals or livestock. These factors, weighed in from a sociological point of view, are stressed in Zottarelli (2010). Therein, the author points out the emotional distress caused by the loss of companion animals during Hurricane Katrina.

From the above, it is easy to note that a scheme for fast evacuation of livestock from the disaster zone is vital. Also it is imperative to save as many livestock as possible. Traffic flows for transporting livestock can be seen as flows in a network, a directed
graph $G = (N, A)$ where $N$ is the set of nodes and $A$ is the set of arcs. Therefore, in this paper we formulate an evacuation plan for livestock in a case of a nuclear power plant as an optimization, minimizing the evacuation time as well as maximizing the number of transportation of livestock in an evacuation, i.e., flows in a network.

In general, solving a network flow problem is set up as an integer programming (IP) problem, however it belongs to a specially structured set of problems that can be tackled in polynomial time (Papadimitriou and Steiglitz 1998). Integer programming, on the other hand, belongs in general in the set of NP-hard problems (Schrijver 1986). In the case of a time expanded network, as is the case in our work, where we are not only interested in a static network, but in a time dependent one, the problem becomes NP-hard. This means solving the integer program might be intractable in the large scale and, thus, employing an exact solver is impractical. For this reason, people usually try to estimate the IP solution using linear programming (LP) techniques, which can be solved in polynomial time, by relaxing the integral condition of the solution. In this paper, we will discuss the exact IP solutions and compare them with the solution obtained using an augmented Lagrange multiplier heuristic approach.

In this paper, we focus on the lessons learned from the Fukushima Daiichi nuclear plant meltdown and subsequent evacuation process. However, our models and methods can be universally applied to evacuation frameworks that include a known disaster source. It is not always the case that the source of a disaster can be well defined in the setting of the underlying transportation network; in many disasters, though, that is the case. When a hurricane is about to hit an area, the site of landfall can be predicted with substantial accuracy, giving us a clearly defined evacuation area. Of course, the same can be stated in the case of a volcanic eruption. For active volcanoes, the danger source is the volcano itself, while the affected area to be evacuated can be computed through various simulations. In the case of a bioterrorist attack, or a chemical spill, once more the danger source is known, albeit not well in advance. In all the above cases, where the source is known, or can be found after the incident has started, our methodologies can be applied with no alterations in their considerations.

**Formulation and Algorithmic Implementations**

In this section, we will formulate our evacuation plan for livestock in a case of a nuclear power plant accident. Let $G = (N, A)$, where $N$ is the set of nodes and $A$ is the set of arcs, be a network given. Let $S \subseteq N$ be the set of nodes that are considered safe. Let $f_{ij}^t$ be a variable denoting the number of animals at arc $(i, j)$ at the time $t$ and $d_i^t$ be a variable denoting the number of animals at arc $(i, j)$ waiting for rescue at node $i$ at time $t$. Let $p_{ij}^t$ be the known probability that arc $(i, j) \in A$ will be available at time $t$ and let $E$ be the lower bound of the success probability we aim to achieve.
First we consider a maximum flow in a network in order to evacuate as many livestock as possible from the disaster zone.

\[
\text{(1) } \max \sum_{t \in T} \sum_{i \in N/S} \sum_{j \in S} f_{ij}^t
\]

\[
\text{(2) } \quad \text{s.t. } \sum_{t \in T} \sum_{j \in R.S.(i)} f_{ji}^t - \sum_{t \in T} \sum_{j \in F.S.(i)} f_{ij}^t = d_{i}^{t+1}, \quad \forall i \in N/S, \quad \forall t \in T
\]

\[
\text{(3) } f_{ij}^t \leq u_{ij}^t, \quad \forall (i, j) \in A, \quad \forall t \in T
\]

\[
\text{(4) } \sum_{t \in T} \sum_{(i, j) \in A} f_{ij}^t v_{ij}^t \geq \epsilon \sum_{t \in T} \sum_{(i, j) \in A} f_{ij}^t
\]

\[
\text{(5) } d_{i}^t \geq 0, \quad \forall i \in I, \quad \forall t \in T
\]

\[
\text{(6) } f_{ij}^t \geq 0, \quad \forall (i, j) \in A, \quad \forall t \in T,
\]

Where \(R.S. \ (i)\) is the reverse star of node \(i\) and \(F.S. \ (i)\) the forward star. The formal definitions are

\[
R.S. \ (i) = \{ j: (j, i) \in A \}
\]

and

\[
F.S. \ (i) = \{ j: (i, j) \in A \}.
\]

In the formulation, equation (1) is the objective function that is maximized. It corresponds to maximizing the number of animals that are being evacuated from the endangered area (N/S) toward one of the safe zones (S). The constraint presented in equation (2) guarantees that the number of animals waiting to be rescued at a given node and time must be equal to the number of animals that originally were there, plus the ones that visited that node on their way to safety, and minus the ones that have already been evacuated. This is clearly the time expanded version of the flow preservation constraints that are seen in network flow problems.

Thus, equation (3) is a simple link capacity constraint that can drop to zero if the link is permanently destroyed or closed. Since this is a vehicular evacuation, it is fair to assume that there exists an upper bound on the number of animals that can be evacuated using a specific arc at each given time. Also, the constraints in equations (5) and (6) are simply there to enforce the non-negativity of demands and flows.

A closer look at equation (5) reveals that it is highly unrealistic to assume that all links will be fully functional throughout the evacuation. Especially when it comes to catastrophic events, several roads of the underlying transportation network could either be closed by officials or destroyed by the hazard agent while people and
animals are still being evacuated. However, with modern simulation techniques, we can obtain reasonable expectations about these events. After these simulations, we have at our disposal a series of probabilities that a certain link will be functional at a certain time $t$ in the future. In this constraint, we require that the selection of routes satisfies a certain probability. With that constraint, we ensure a high probability of the evacuee animals reaching the safe zones within the time horizon given.

The solution vector obtained by the first formulation will be in the form of a vector $x_{ij}^t$. This vector would represent the number of animals using arc $(i, j) \in A$ at time/period $t \in T$. At this point, it is important to note that the solution vector is not easily applicable to a realistic representation of the livestock evacuation problem. However, it is used a starting point for more applicable mathematical formulations, such as the one that follows. A second formulation based on the vehicle routing problem can be adopted to render the underlying model more realistic. The problem can then be formulated as:

(7) \[ \text{min} \sum_{(i,j) \in A} \sum_{k \in K} c_{ij} x_{ij}^k \]

(8) \[ s.t. y_i^k \leq \sum_{j: (j,i) \in A} x_{ji}^k, \quad \forall i \in N, \forall k \in K \]

(9) \[ \sum_{k \in K} y_i^k = 1, \quad \forall i \in N \]

(10) \[ \sum_{i \in N} y_i^k d_i \leq C^k, \quad \forall k \in K \]

(11) \[ 0 \leq y_i^k \leq 1, \quad \forall i \in N, \forall k \in K \]

(12) \[ x_{ij}^k \in \{0, 1\}, \quad \forall (i,j) \in A, \forall k \in K. \]

In this problem we have a fleet of vehicles ($K$) and a set of destinations (“clients”) with a given demand $d_i$. Each of the vehicles of the fleet has a capacity $C^k$. In this formulation we have two sets of variables:

\[ x_{ij}^k = \begin{cases} 1, & \text{if arc } (i,j) \text{ is being employed for vehicle } k \\ 0, & \text{otherwise} \end{cases} \]

and $y_i^k$ which is equal to the “percentage” of the demand that vehicle $k$ can serve. Hence, in equation (9) the summation of the percentages that each vehicle contributes
is equal to 1. Also, as indicated in equation (8), a vehicle can serve a node only if it has been assigned to an arc that terminates in that node. In equation (10) the capacity constraint requires that each vehicle cannot surpass its capacity limitation $C^k$. Last, equations (11) and (12) ensure that $y^k_i$ will remain between zero and one along with the binary nature of variable $x^k_{ij}$.

Also, as indicated in equation (8), the solution vectors obtained by the second formulation can be easily utilized. The vector $x^k_{ij}$ represents whether arc $(i, j) \in A$ is to be used by vehicle $k \in K$. That will help design the routes that all serving vehicles need to use in order to safely evacuate the maximum number of animals. The second vector, $y^k_i$ represents the percentage of its capacity (storage capacity for livestock) that it can contribute at each of the nodes $i \in N$.

**Algorithmic Design**

The algorithmic design appears to be simple, yet it is highly efficient. In situations where a large-scale evacuation is necessary, it is acceptable that the results be obtained as fast as possible, even if that implies sub-optimality, rather than wasting resources and computational time to reach optimality. This is also the main driver of our implementations. Taking into consideration the recent catastrophic events of Fukushima after the earthquake, it becomes increasingly obvious that a fast and well-organized, yet not perfect, plan is much preferred to a late, optimal evacuation routing model.

The algorithm we are following in this project can be summed in Algorithm (1) below. Notice that in this algorithm, we solve the Lagrange relaxation using a commercial solver (in our case Gurobi 4.6). Then, after we achieve an increase in the number of animals we can successfully evacuate, we stop the optimization phase and turn to the rounding phase. As mentioned before, since we are dealing with a large scale optimization problem, we are primarily interested in retrieving a good quality, feasible solution. Hence, we are applying a simple, yet efficient in the worst case scenario, rounding method. Every one of our fractional flows will be rounded up, implying that at some point we might obtain less node demand than we actually need to satisfy, which does not affect the results.

For the same reasons as before, we applied a similar algorithmic idea to the second formulation. Once more, the latter formulation is a more realistic representation and hence a much more difficult integer program to deal with. The underlying idea for the algorithm is that, if we somehow relax the coupling constraint in equation (8), then we are left with a much easier program that only deals with the $y$-space of the problem. The basic idea is presented in Algorithm (2).
Algorithm 1. The Algorithm Designed for the First Problem Formulation.

\[ z^* \leftarrow \infty, z \leftarrow 0, \epsilon \leftarrow 10^{-2} \]

\textbf{while} \(|z^* - z| > \epsilon\) \textbf{do}

\[ z^* \leftarrow z \]

Solve the Lagrange Relaxation of Problem (1)-(6) and obtain \( z = \sum_{t \in T} \sum_{i \in N} \sum_{j \in S} f_{ij}^t \)

Update dual Lagrange multipliers

\textbf{end while}

Round all flows \( f_{ij}^t \) up.

\textbf{return} \( f_{ij}^t \) \( \forall (i, j) \in A, \forall t \in T \)

Algorithm 2. The Algorithm Designed for the Second Problem Formulation.

\[ z^* \leftarrow \infty, z \leftarrow 0, \epsilon \leftarrow 10^{-2} \]

\textbf{while} \( n \) \textbf{do}

\[ z^* \leftarrow z \]

Solve the Lagrange Relaxation of Problem (21)-(26) and obtain \( z = \sum_{(i,j) \in A} \sum_{k \in K} c_{ij}x_{ij}^k \)

Update dual Lagrange multipliers

\textbf{end while}

Round all binary selection variables \( x_{ij}^k \) up.

\textbf{return} \( x_{ij}^k \) \( \forall (i, j) \in A, \forall k \in K \)

Computational Results

In order to obtain these results, we created a series of networks (ranging from 30-100 nodes and from 10-30 time steps) and applied our algorithm. We compared the results to the ones obtained by Gurobi 4.6 on an Intel Core 2 Duo at 2.0 GHz. For each of the experiments shown in Table 1 and 2, 30 different instances were created and solved. The results appear in the tables.
Table 1. Computational Results Obtained for the First Formulation.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Nodes</th>
<th>Time (sec)</th>
<th>IP Time (sec)</th>
<th>Average Optimality Gap (%)</th>
<th>Maximum Optimality Gap (%)</th>
<th>Minimum Optimality Gap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
<td>3.6</td>
<td>9.0</td>
<td>1.3</td>
<td>2.7</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>8.2</td>
<td>15.0</td>
<td>1.5</td>
<td>1.9</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>22.1</td>
<td>37.0</td>
<td>1.5</td>
<td>2.9</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>8.0</td>
<td>14.2</td>
<td>1.2</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>21.3</td>
<td>39.0</td>
<td>1.2</td>
<td>1.7</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>63.0</td>
<td>109.0</td>
<td>1.9</td>
<td>2.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 2. Computational Results Obtained for the Second Formulation.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Time (sec)</th>
<th>IP Time (sec)</th>
<th>Average Optimality Gap (%)</th>
<th>Maximum Optimality Gap (%)</th>
<th>Minimum Optimality Gap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4.5</td>
<td>19.0</td>
<td>3.3</td>
<td>10.7</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>9.9</td>
<td>34.0</td>
<td>3.5</td>
<td>13.9</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>22.1</td>
<td>69.0</td>
<td>5.5</td>
<td>22.8</td>
<td>0.2</td>
</tr>
<tr>
<td>80</td>
<td>41.2</td>
<td>182.0</td>
<td>4.2</td>
<td>9.4</td>
<td>0.3</td>
</tr>
<tr>
<td>100</td>
<td>75.6</td>
<td>331.4</td>
<td>6.2</td>
<td>16.5</td>
<td>0.0</td>
</tr>
<tr>
<td>200</td>
<td>223.0</td>
<td>1309.0</td>
<td>10.9</td>
<td>22.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

As we can see, our algorithm obtains results that are near optimal at all cases. It is important to note that in almost every one of our cases, there was at least one instance that was solved to optimality using our relaxation approach. It is also very interesting to see that our algorithm is producing results efficiently and rapidly, outperforming the commercial solver in all instances.

In addition to the computations that were performed to empirically demonstrate the success of our modeling and algorithmic efforts, a graph/network based on the Fukushima site was created and put to test. Both formulations produced solutions that were near optimal at all cases (within 5% difference). For the numbers of the animals, we used the official data for the livestock from the Japan Department of Agriculture and the officially recognized farms close to the nuclear plant site. Safety was considered to be reached after reaching a 20 km distance from the plant. Last, a horizon was set to be equal to a 30-minute time step. In our approach, discrete time steps are assumed so as to easily model it as a mathematical program. We assumed that there is a time limit after which no further people, livestock, or vehicles leave the affected area. This time limit was selected to be equal to 12 hours (24 horizons).
As for the second formulation, we assumed that a fleet of 34 vehicles is employed all with a capacity of 10 animals per vehicle. The value of 34 was selected after preliminary examination of the set [25, 40] to identify a set of initial conditions for the problem that are realistic enough, yet provide us with a feasible solution. With these site conditions, all demands could be met and every farm animal from the area could reach safety within the given time limits. For future research and further implementations, we could discuss a non-homogeneous fleet of vehicles with different animal categories. At the moment, all animals are considered homogeneous in order to facilitate the rounding algorithms presented.

The network created consists of 57 nodes and 99 arcs (roads) all of which have distinct, realistic capacities. The capacities are only employed in the first formulation, while in the second one they are replaced by a Steiner forest (vehicle assignment) constraint. The results given by the algorithms are presented in Table 3, where the first solution is given by our algorithmic scheme and the second one is the optimal result produced by the solver itself. The result is characterized optimal from the mathematical programming point of view, while in practice it is a boundary solution (extreme point). Hence, it might prove infeasible due to the road closures and further restrictions that were not disclosed when the evacuation begins. This is the focus of a number of research studies, called robust optimization. For more information, the interested reader is referred to Ben-Tal and Nemirovski (2002) and Beyer and Sendhoff (2007).

### Table 3. Computational Results Obtained for the Practical Application.

<table>
<thead>
<tr>
<th>Implementation Evacuation Scheme</th>
<th>“Optimal” Evacuation Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Formulation</td>
<td>23 horizons</td>
</tr>
<tr>
<td>Second Formulation</td>
<td>34 vehicles</td>
</tr>
<tr>
<td></td>
<td>21 horizons</td>
</tr>
<tr>
<td></td>
<td>29 vehicles</td>
</tr>
</tbody>
</table>

**Application of the Algorithms**

The premise of our work has been greatly affected by the disaster that occurred in Japan in 2011. A similar disastrous scenario could occur in the United States because 20 percent of its energy is generated by 104 nuclear power reactors—of which 52 are about 40 years old and many of which are within states having a considerable livestock industry. For example, a 2007 USDA Agricultural Census shows that there are 33 million beef cattle and 9.2 million dairy cattle in the United States, with Florida, Tennessee and Arkansas having a heavy beef cattle industry and other states in the southeast U.S. having a considerable dairy industry.

In addition to that, applications of the proposed mathematical models include not only a nuclear plant crisis but also emergencies such as natural disasters, exotic...
animal diseases, pests, bioterrorism attacks, and chemical spills. To clarify, the premise of our work might have its roots in the tsunami and the nuclear power plant meltdown in Japan, but it can be generalized to include other situations where an area needs to be permanently or temporarily evacuated. In all cases where a natural or man-made disaster spreads towards an area that humans or animals inhabit, our models can be easily applied to develop an evacuation plan that is guaranteed to be both of high quality (i.e., resources are well-utilized, most animals are evacuated safely, humans are not endangered) and very fast compared to the same solutions provided by a commercial solver.

To apply our models to realistic emergencies, we have been working on two projects:

1. Collaborating with veterinarians in the state of Kentucky for Public Health in order to implement our models in the cases of a natural disaster occurring in the state and

2. Collaborating with local farmers in the Fukushima exclusion zone and collecting the data from the zone in order to learn from the unfortunate experience of the Fukushima Daiichi nuclear power plant accident

In Kentucky, the state Public Health department is highly concerned about developing evacuation plans for natural disasters such as earthquakes and floods. Consequently, they contacted the authors to participate in a meeting where state emergency preparedness was discussed. During the meeting, veterinarians expressed their interest in devising a plan for the state of Kentucky that would guarantee a safe evacuation to the majority of dairy cows, beef cattle, and horses (Linnabary 1993), which are a major economic factor for the state. The second author has been participating in their meetings and communicating with them since April 2012.

Furthermore, Dr. Shigeki Imamoto has been in the Fukushima exclusion zone to conduct research on the status of livestock as an official veterinarian from the Japanese government since April 2011. He has been working with local farmers in the affected area to help support the management of their farms and livestock since then. In working with the local farmers in the Fukushima exclusion zone, we are analyzing what went wrong during the Great East Japan Earthquake and are developing strategies to reduce damage in future disasters. Similar opportunities have arisen for collaborating with researchers who have offered us an opportunity to include them in our work such as the case of a volcanic eruption (Bird et al. 2011; Wilson et al. 2012).

Last, it is very important for human and animal evacuation plans to be integrated. However, it is easy to see that evacuation management for the human population in the risk area should have higher priority than the animal population. Both of the models presented herein treat the livestock evacuation problem in isolation. In the future, livestock evacuation must be examined concurrently with human evacuation,
but ensuring that human evacuation takes precedence at all times. Recently, we have been working on a generalization of the evacuation problem as a whole, including both evacuation of humans and livestock. This problem will have to be formulated as a two-stage mathematical problem in which the optimal solution guarantees that the two evacuation processes do not interfere. That is, human evacuation is always prioritized to ensure the well-being and safety of human population before tackling the livestock evacuation problem.

Discussion

In this paper, we proposed two mathematical models that aim to help solve the evacuation problem of livestock in the case of an emergency. The first model aspires to solve a time-dependent maximum flow problem that maximizes the number of animals that can be evacuated while minimizing the time it takes to do so. The second one assumes that a fleet of vehicles that can transport animals out of the danger zone is available and tries to minimize the number of vehicles that need to be used in order to maximize the number of animals that reach safety. Both models assume that a time limit exists, after which all operations in the risk area cease.

This is not the first attempt to develop a full-scale evacuation plan for livestock during an emergency. However, it is an attempt to mathematically model a problem by employing operations research methods. It has been stressed in the past that evacuation management needs to include livestock, as proposed by Casper et al. (1995) and Mansmann et al. (1992). More recently, jurisdictions such as Brantley GA have adopted animal evacuation practices since 2006.

One important aspect of the livestock evacuation problem that needs to be addressed in the future is the one of obtaining the necessary data. At the moment, there have been efforts to collect all information on cattle numbers and exact locations of the farms where they are kept. However, collecting this information and combining it with data on the local transportation network is still a challenging task. Google Earth can be of assistance, as described by Xin and Hu (2008). In addition, other interesting approaches in data collection can be found in De Silva and Eglese (2000) and Vatsavai et al. (2006).

In order to be able to apply our models to real data sets, we must be able to solve a large IP problem. However, in general, this might prove to be very computationally expensive with a large system. Thus, in this paper, we proposed heuristic methods to estimate an optimal solution of our IP problem. We also used a LP relaxation to approximate an optimal solution but the gap between the IP optimal value of each formulation presented herein and its LP relaxation might be large. Thus, it might be interesting to investigate the size of the gap between the IP optimal value of each formulation and its LP relaxation. When the feasible region (which is called a polytope) is
totally unimodular, an optimal solution of the IP problem over the feasible region equals an optimal solution of its LP relaxation (Schrijver 1986).

This study provides owners of livestock a solution to preserve their animals from an area affected by a nuclear accident. McMillan et al. (2011) initiated this effort by proposing a plan to assess and handle livestock that have been externally contaminated. Our study presents two distinct mathematical models that allow livestock to be successfully evacuated from an area as soon as a nuclear crisis or other life threatening disaster occurs. Future research, a collaboration among scientists from the University of Colorado, University of Kentucky, and the University of Florida, will include studying the effects of radiation on the progeny of animals from an affected zone as well as understanding the public perception, acceptance of livestock, and animal products used for human consumption originating from areas affected by the Fukushima Daiichi nuclear plant. The research team plans to do this by surveying the public and launching an aggressive public relations campaign based on results from physical measurements and data analysis.

The meltdown at the Fukushima Daiichi nuclear power plant as a result of the earthquake and tsunami on March 11, 2011 was indeed one of the worst nuclear disasters in history. While people had several options for evacuating from the affected areas, a systematic and coordinated evacuation plan was not available for owners of livestock, causing many cattle, pigs, horses, and chickens to starve to death while locked in their pens. This is our attempt herein: to provide a scientific solution to minimize the economic impact to the livestock industry in the unfortunate case of a natural or man-made disaster, and to recommend considering farm animals as evacuees in the event of a future crisis.

References


