Appendix

Section A: Transport data

Each location (farm, slaughterhouse or slaughtering company) is identified with a production place number (PPN) in the databases. Here we will refer to PPNs as farms, although it is possible for a farm to have several PPNs. To make the following sections more comprehensible we refer to a single report (line) in the database as report, with movement we mean the movement of one single animal between two PPNs and with transport we mean the transport of one or several animals between two PPNs. Cattle movements to slaughter are reported twice on individual level. Both sending farm and the receiving slaughterhouse reports date, cattle ID-number, the PPN of the other facility and the type of event (we are interested in slaughter transports). The reporting slaughter company also specifies at which slaughterhouse the cattle are slaughtered. The extracted data contained 1.76 million reports of 0.88 million cattle movements to slaughter during the period from January 2007 to December 2008. Movements where farm and/or slaughterhouse did not agree on the PPN-number of the sending or receiving facility were corrected (about 6-8% of the reports). Single reported cattle movements (< 0.5% of the reports) were removed. Cattle movements with more than 2 reports were removed (< 0.015% of the reports). Reports to or from a PPN not present in the holding database were removed (< 0.065% of the reports). All movements between two specific PPNs on a specific date were considered as one transport. This resulted in 103 110 cattle transports (429 thousand animals) during 2008.

Pig transports are only reported by the sending farm. The PPN of the sending farm, PPN of the destination, date and number of pigs are reported. Transports to non-existing PPN were disregarded (at most 2.5% of the transports). Transports to PPNs that are slaughterhouses in the holding database are regarded as slaughter transports. This resulted in 45 191 transports (3.1 million pigs) to slaughter 2008.

Section B: Geographical data

The holding database contains coordinates, postal codes and production types (for example slaughter) of farms and slaughterhouses in Sweden.

There were 23 372 active farms that sent cattle to slaughter during the period from January 2007 to December 2008 and 2 619 farms that sent pigs. Coordinates are missing in the holding database for 1.25% of all pig farms and 6.75% of all cattle farms. Farms without coordinates are randomly assigned the same coordinates as one of the other farms in the same county. This gives realistic random coordinates, and we avoid impossible coordinates, for example in middle of a lake. The most error affected region is for cattle transports in the county of Västmanland where 10.15% of the farms lack coordinates in the database.

Data on the amount slaughtered cattle and pigs for all active slaughterhouses during the years 1998-2007 (the slaughter capacity database) were provided by the National Food Administration. Slaughterhouses are identified by KS-number at National Food Administration. Coordinates for slaughterhouses in the capacity database were obtained by searching for the address at the search engine Eniro (www.eniro.se). The KS-number and PPNs were matched using postal codes, geographical coordinates and the capacities from 2007. The 17 slaughterhouses without coordinates in the holding database were assigned the coordinates for their match in the capacity database for the analysis. Coordinates for two slaughterhouses only operating 2008, were found using postal codes and google to connect them with their corresponding company. Coordinates for one slaughterhouse (very low capacity) were found on Eniro (www.eniro.se) from its address in the holding database.

Section C: NVDB — Road database and distances

Compute the distances between farms and slaughterhouses is not straightforward. There exist road databases, but these are restricted to the state and governmental roads in Sweden which are a considerably smaller part of the entire road network. A majority of the roads are private and information about these is not easily accessible. Many of the farms are connected to or use the private road network. To deal with this problem, the Swedish National Road database (NVDB) was developed in collaboration between the Swedish National Road Administration, the Central Office of the National Land Survey, the Swedish Association of Local Authorities and the forest industry. The database contains digital information about all Swedish roads: the state road network, the municipal road and street network, and private road networks. All roads, approximately 560 000 km, are described geometrically, topologically, and with detailed information about each road segment (Figure I).

NVDB includes the road manager (owner), road classification, road designation, height restrictions, load bearing obstacles, surface material, width and traffic regulations. For transportation on forest roads, of which there is more than 200 000 km, there are also special details about accessibility, special forest roads, turning radius, barriers etc. When the forest trucks reach cities, there are some special routes for driving heavy loads inside cities, and the last part to mill. These details are handled as an add-on to NVDB, forming the Forestry National Road database (SNVDB). During the past decade, the Swedish forest companies have made large investments in order to collect all the necessary data. Animal trucks have similar size and prefer similar routes as logging trucks.

We have used SNVDB to calculate the distances between farms and slaughterhouses. In our application, some additional limits have been enforced. The limitations used are a minimum height (bridges) of 4.4 meters, minimum allowed vehicle weight of 60 metric ton and a minimum road width of 2.5 meters. SNVDB is structured as a network and to find shortest distance between two pairs of nodes it is possible to use for example a Dijkstra algorithm. Efficient implementations of Dijkstra in Geographical Information Systems (GIS) are described in (Zeng and Church, 2009[1]). However, this distance is often not the distance that the animals have traveled. In a study by the Forest Research Institute of Sweden the difference between the shortest path and the preferred and driven distance is as large as 7.4% (Flisberg *et al*., 2010[2]). The reason is because drivers prefer to drive longer distances on a higher quality road. To find a balance, the forest industry initiated the project ”Krönt Vägval” project (in English, Calibrated Route Finder) in 2007 by SDC and the Forest Research Institute of Sweden described in Flisberg *et al*., (2010).

[1]**Zeng and Church** 2009 Finding shortest paths on real road networks: the case for A*. International Journal of Geographical Information Science, 23(4), pp. 531-543.

[2]**Flisberg P, Lidén B, Rönnqvist M and Selander J** 2012 Route Selection for best distances in road databases based on drivers' and customers' preferences, Canadian Journal of Forest Research, Vol 42, No 6, 1126-1140.

Section D: Optimization model

Parameters:

I: set of farms

J: set of slaughterhouses

A: set of animals

T: set of time periods

ℓ_{ij}: distance between farm i and slaughterhouse j

c_{ij}: unit transportation cost between farm i and slaughterhouse j

f_j: fixed cost for slaughterhouse j

d_{ja}: capacity for slaughterhouse j for animal type a

s_{ita}: supply from farm i in time period t for animal type a

t^{max}: nominal max transportation time for animals

c^{time}: penalty cost for exceeding the max transportation time

p: max number of slaughterhouses

We define a support set X which is used to define all connections that do not satisfy the maximum transport time:

$$X = \{(i,j): i \in I, j \in J, \ell_{ij} > t^{max}\}$$

The variables are defined as

$$y_j = \begin{cases} 1, & \text{if slaughterhouse } j \text{ is open} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij} = \begin{cases} 1, & \text{if farm } i \text{ uses slaughterhouse } j \\ 0, & \text{otherwise} \end{cases}$$

w_{ij} = penalty due to exceeded transport time between farm i and slaughterhouse j

u_{ja} = added extra capacity to slaughterhouse j for animal type a

The full model is:

$$\min z = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c_{ij}x_{ij} + \sum_{j\in J} f_j y_j + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c^{time}\, s_{ita}w_{ij} \qquad (1)$$

$$s.t. \quad \sum_{i\in I} s_{ita}x_{ij} \leq d_{ja}y_j + u_{ja}\,, \; j \in J, t \in T, a \in A \qquad (2)$$

$$u_{ja} \leq d_{ja}y_j\,, j \in J \qquad (3)$$

$$\sum_{i\in I} x_{ij} = 1\,, j \in J \qquad (4)$$

$$\sum_{j \in J} y_j = p \quad (5)$$

$$\left(\ell_{ij} - t^{max}\right) x_{ij} \leq w_{ij,} \, (i,j) \in X \quad (6)$$

$$\sum_{j \in J} u_{ja} = \sum_{j \in J} d_{ja} \left(1 - y_j\right), a \in A \quad (7)$$

$$x_{ij} \in \{0,1\}, i \in I, j \in J \quad (8)$$

$$y_{ij} \in \{0,1\}, j \in J \quad (9)$$

$$w_{ij} \geq 0, (i,j) \in X \quad (10)$$

$$u_{ja} \geq 0, j \in J, a \in A \quad (11)$$

The objective function that have been minimized consists of three parts; i) transportation distances, ii) a fixed cost when a slaughterhouse is used and iii) a penalty cost if maximum transportation time is exceeded. This latter part is included in order to find a solution for all farms and model the correct capacity usage at the slaughterhouses.

The constraints sets can be described as follows:

(1) capacity limitation for each slaughterhouse and time period,

(2) capacity limitation of extra capacity for each slaughterhouse and time period,

(3) each farm must be assigned to one slaughterhouse,

(4) a specific number of slaughterhouses must be open,

(5) model the time that exceeds the maximum transportation time,

(6) overall extra capacity is the same as the capacity of closed down slaughterhouses,

(7) and (8) binary restrictions for the allocation between farms - slaughterhouses and the usage/closing of slaughterhouses,

(9) and (10) non-negativity restrictions of the penalty variables and the transfer of capacity