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A decision-tree to optimise control measures during the early stage of a foot-and-mouth disease epidemic

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Abstract

A decision-tree was developed to support decision making on control measures during the first days after the declaration of an outbreak of foot-and-mouth disease (FMD). The objective of the tree was to minimise direct costs and export losses of FMD epidemics under several scenarios based on livestock and herd density in the outbreak region, the possibility of airborne spread, and the time between first infection and first detection. The starting point of the tree was an epidemiological model based on a deterministic susceptible–infectious–recovered approach. The effect of four control strategies on FMD dynamics was modelled. In addition to the standard control strategy of stamping out and culling of high-risk contact herds, strategies involving ring culling within 1 km of an infected herd, ring-vaccination within 1 km of an infected herd, and ring-vaccination within 3 km of an infected herd were assessed. An economic model converted outbreak and control effects of farming and processing operations into estimates of direct costs and export losses. Ring-vaccination is the economically optimal control strategy for *densely* populated livestock areas whereas ring culling is the economically optimal control strategy for *sparsely* populated livestock areas.

Keywords: Foot-and-mouth disease; Decision-tree; Control strategies; Livestock densities; The Netherlands

1. Introduction

Foot-and-mouth disease (FMD) is a highly contagious disease that infects many cloven-footed mammals (including cattle, pigs, sheep, goats and deer). The virus has the potential to spread rapidly in susceptible populations. FMD outbreaks generate considerable losses due to costs of disease control, productivity losses and constraints on international meat

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and livestock trade (Power and Harris, 1973; Krystynak and Charlebois, 1987; Berentsen et al., 1992b; Garner and Lack, 1995; Mahul and Gohin, 1999; Mahul and Durand, 2000). Recent examples of the devastating consequences of FMD are the epidemics in Great Britain and The Netherlands in 2001. In Great Britain, nearly four million animals were slaughtered and the disease spread to 2030 livestock farms (Department for Environment, Food and Rural Affairs, 2001). During the Dutch epidemic, about 265,000 animals had to be slaughtered and 26 farms were actually infected (Ministry of Agriculture, Nature Management and Fisheries, 2001). Another example is the epidemic which occurred in 1997 in Taiwan, in which more than four million pigs had to be slaughtered (Yang et al., 1999).

FMD is a difficult disease to control and eradicate because of the various mechanisms by which the virus can be transmitted (Sellers, 1971). The most common mechanism is the movement of infected animals to susceptible animals (Donaldson et al., 2001). Other mechanisms include the movement of contaminated animal products such as meat, offal and milk. FMD virus can also be transmitted mechanically (e.g. by contaminated milking machines, by vehicles, especially those used for transporting animals, and by people). Under certain epidemiological and climatic conditions, FMD virus can be spread by the wind. Of all mechanisms, spread by air is least controllable (Donaldson et al., 2001; Ferguson et al., 2001a; Sørensen et al., 2000, 2001).

Our objective was to develop a tool to support decision making on control strategies during the early stage of an FMD epidemic. (‘‘Early stage’’ means the first few days after the declaration of an outbreak.) Successful eradication of an epidemic mainly depends on the selected control strategy and on the time interval between diagnosis and implementation of the control strategy. Selecting an inadequate strategy can cause large additional economic losses (Mahul and Durand, 2000). Delayed implementation of control measures can cause extensive spread of the disease (Garner and Lack, 1995; Howard and Donnelly, 2000; Ferguson et al., 2001b). This means that it is very important for animal-health authorities to make the right decision immediately after the first diagnosis. Usually, there is no time to gather additional data to support decision making. Therefore, it is absolutely essential to have an overall analytic structure for these kinds of situations beforehand. This paper presents such an analytic structure, comprising a decision-tree modelling approach using all information available in the first 3 days after the declaration of an outbreak. Using this approach, the efficacy of disease-control measures was evaluated in all kinds of scenarios. The efficacy was determined by modelling the epidemiological consequences and calculating the resulting direct costs and export losses. Scenarios were defined by important determinants in the development of epidemics that were found in the literature.

The objective of the decision-tree was to calculate the economically optimal control strategy for each scenario. ‘‘Economically optimal’’ meant that direct costs and export losses were minimised. The results of the decision-tree can be used as yardsticks for deciding on control measures during possible FMD epidemics in the future.

2. Materials and methods

The modelling approach consists of three modules (Fig. 1): an epidemiological module to simulate the disease dynamics, an economic module to convert outbreak and control

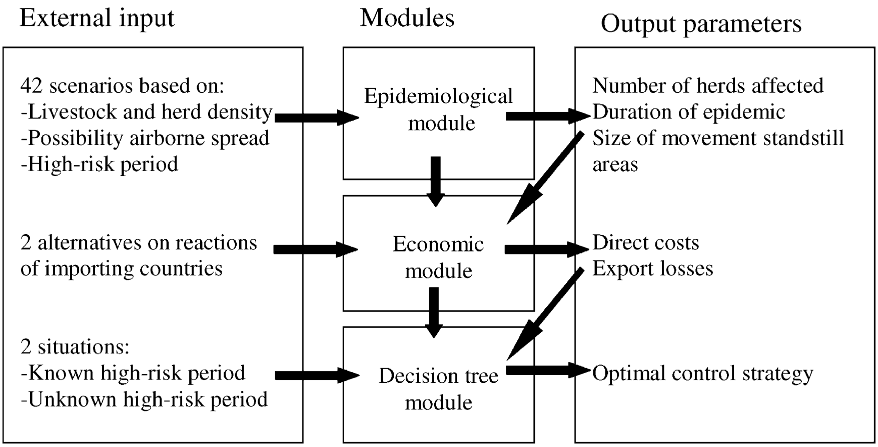

Fig. 1. An overview of the modelling approach.

effects into estimates of direct costs and export losses, and a decision-tree module to optimise decisions on control strategies. Each module used external input, which will be explained in the following sections.

2.1. Choice of virus strain

There are seven immunologically and serologically distinct types of FMD: A, O, C, SAT1, SAT2, SAT3 and Asia 1. Within each serotype, there are several subtypes. The disease caused by different serotypes is clinically indistinguishable, although they vary somewhat in their epidemiological patterns (Sanson, 1993). Some strains of FMD show a degree of natural adaptation to an animal species, with the result that the other species of animals appear to be more difficult to infect. An example of a pig-adapted virus strain was the strain that caused the Taipei China epidemic in 1997—no outbreaks were detected in cloven-hoofed animals other than pigs (Chen et al., 1999).

Our study also confined attention to a pig-adapted FMD virus strain, which is the source of most available data (Sellers, 1971; Salt et al., 1998; Yang et al., 1999). These data made it possible to quantify the FMD transmission between pigs and to estimate the efficacy of vaccination. This meant that the epidemiological module simulated FMD epidemics that mainly affected pigs. Nevertheless, the control strategies included all susceptible species to avoid the risk of transmission in other species. In the first days after the declaration of an FMD outbreak animal-health authorities cannot be sure that it will infect only one species because of the lack of information on the kind of virus strain.

2.2. Control strategies

The size and duration of an epidemic depend largely on the control strategy implemented and on its effectiveness. In 1990/1991, the EU decided to cease routine prophylactic vaccination. The control procedures are now total stamping out[1] of the disease in affected herds and movement control[2] in the surrounding area. These measures are laid down in Council directive 85/511/EEC. However, in certain circumstances, these measures need to be supplemented by other interventions such as ring culling[3] or ring-vaccination.[4] In particular, outbreaks in areas containing high densities of susceptible animals and inadequate manpower or abattoirs for the slaughter and disposal of animals can spread out of control without additional control measures. In this context, ring culling and ring-vaccination strategies target infection hotspots by reducing the density of susceptible herds in the vicinity of diagnosed infections, thereby removing the "fuel" essential to maintaining the epidemic (Scientific Committee on Animal Health and Animal Welfare, 1999; Ferguson et al., 2001a).

Simulated FMD outbreaks in The Netherlands, Australia and France demonstrated that the strategy of stamping out and movement control alone (as laid down in 85/511/EEC) is almost never the economically optimal strategy. Extension of this strategy with culling of dangerous contact herds[5] generally reduced the epidemiological and economic consequences (Berentsen et al., 1992b; Garner and Lack, 1995; Mahul and Durand, 2000). Previous research based on the Dutch classical swine fever (CSF) epidemic of 1997–1998 showed that ring culling also can be an effective strategy to reduce the size of a CSF epidemic, if started in an early stage (Elbers et al., 1998; Nielen et al., 1999; Stegeman et al., 1999). This study suggested that 1 km was an optimal radius from an epidemiological as well as an economic point of view. A model analysis of the recent FMD epidemic in Great Britain (GB) showed that both ring culling and ring-vaccination are highly effective strategies if implemented sufficiently rigorously (Ferguson et al., 2001a). It also was concluded that ring-vaccination policies need to be more extensive than comparable culling policies. In the case of infected but undiagnosed animals, culling eliminates virus replication by removing these animals. Vaccination only reduces the virus replication—thereby limiting the transmission of the virus less than culling does (Sobrino et al., 2001). Another analysis of the GB epidemic (Donaldson et al., 2001) concluded that ring culling is not always effective because of the very wide variation between different species in the quantities of virus excreted, their susceptibility to infections, and the routes by which they are likely to be infected.

Based on the current EU legislation, previously discussed experiments and analyses of recent epidemics, we considered:

(1) stamping out of infected herds (85/511/EEC) and culling of high-risk contact herds (SO);
(2) SO extended with ring culling of all susceptible animals within a radius of 1 km of an infected herd (RC1);
(3) SO extended with ring-vaccination of all susceptible animals within a radius of 1 km of an infected herd (RV1);

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[1] Slaughtering of all the affected and in-contact susceptible animals of the infected herd.

[2] Prohibition of movement of animals and manure within a radius of 10 km of an infected herd.

[3] Slaughtering all susceptible animals within a certain radius of every newly diagnosed case of infection.

[4] Vaccinating all susceptible animals within a certain radius of every newly diagnosed case of infection.

[5] Slaughtering of herds that, although not showing FMD symptoms, are considered to be at high risk of spreading the disease because of proximity to or contact with infected herds.

(4) SO extended with ring-vaccination of all susceptible animals within a radius of 3 km (RV3).

All four strategies include movement control. The last three strategies also take into account the possibility of airborne spread outside implemented rings. Susceptible animals outside a ring but downwind of a virus plume are culled or vaccinated. Vaccinated animals are culled as quickly as possible to keep the necessary period for regaining the status of ‘‘FMD-free country without vaccination’’ as short as possible (see Section 2.6). Here, culling and destruction capacities were the restricting factors.

2.3. Regions

Densely populated livestock area (DPLA) has increased risk of major disease epidemics (Dijkhuizen and Davies, 1995). For our study, The Netherlands was divided into seven regions according to the division method of Stegeman et al. (1997) based on pig density per municipality. This method was useful for the epidemiological module, which calculated the transmission of a pig-adapted FMD strain (see Section 2.1). Statistics were used from the year 1999 and pig densities are based on agricultural land area (Statistics Netherlands, 2001). According to this method, municipalities with >1000 pigs per km^2 were combined to form a pig-dense region. Municipalities that have fewer than 1000 pigs per km^2—but that are surrounded by densely populated municipalities—were included in the pig-dense regions. Fig. 2 shows the seven regions that could be distinguished. The very dark-coloured regions (regions 1, 2 and 3) have >1000 pigs per km^2.

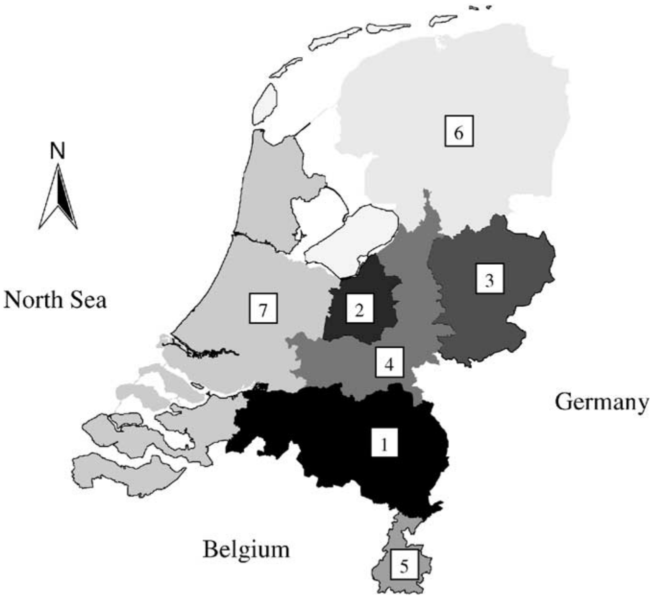

Fig. 2. Subdivision of The Netherlands into seven regions, showing density of pig population.

Table 1
Descriptive statistics for The Netherlands divided in seven regions (Fig. 2) in 1999[a,b]

Variable	Region						
	1	2	3	4	5	6	7
Total livestock per							
Agricultural land (km^2)	3019	2641	1633	1353	563	389	384
Total land (km^2)	1272	701	920	615	275	236	148
Pigs							
Pigs/km^2	2691	1736	1290	916	346	152	175
Herds/km^2	2.30	4.56	2.32	1.24	0.41	0.19	0.31
Herd size	1171	381	555	738	851	798	559
Cattle							
Cattle/km^2	279	838	305	336	166	178	129
Herds/km^2	3.28	7.29	4.69	4.42	2.72	2.05	2.05
Herd size	85	115	65	76	61	87	63
Sheep							
Sheep/km^2	30	47	31	84	42	55	76
Flocks/km^2	1.11	2.24	1.48	2.55	1.56	1.20	1.77
Flock size	27	21	21	33	27	46	43
Goats							
Goats/km^2	19	19	7	16	10	4	5
Flocks/km^2	0.22	0.41	0.35	0.55	0.15	0.31	0.30
Flock size	85	46	20	29	65	13	15

[a] Densities for pigs, cattle, sheep and goats are per km^2 agricultural land.
[b] Source: Animal Health Service (2000) and Statistics Netherlands (2001).

Table 1 lists the densities of susceptible livestock species, herds and flocks per region and the mean sizes of herds and flocks per region. According to the definition of Michel and De Vos (2000),[6] the regions 1–4 are classified as DPLAs.

Not only animal densities vary between regions but also the number of pig and cattle herds per square km vary strongly. Region 2 has by far the most pig herds and cattle herds per square km. In this region, the mean size of pig herds is small but the mean size of cattle herds is large because of a high concentration of veal calves in this area.

2.4. Scenarios in the epidemiological module

Scenarios were defined by important determinants in the development of epidemics that were found in literature. These determinants were (Fig. 1): (a) livestock and herd density in the outbreak region (De Vos et al., 2000; Gerbier, 1999), (b) the possibility of airborne spread (Donaldson et al., 2001), and (c) the high-risk period (HRP; defined as the time interval between first infection and first detection) (Horst, 1998).

For livestock and herd densities, the statistics of Table 1 were used. For airborne spread two possibilities were considered: no airborne spread or maximum airborne spread

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[6] A DPLA for FMD contains >300 pigs per km^2 or >450 susceptible animals per km^2 (total land area).

(see Section 2.5). Finally, for the HRPs three different lengths were chosen: 7, 14 and 21 days. These lengths were based on Horst (1998) and the HRPs during the recent FMD epidemics in Great Britain and The Netherlands. Horst (1998) derived a midpoint estimate of the HRP of 6 days from experts by elicitation techniques. Field data suggest that the estimated mean HRP is higher. During the last epidemic in Great Britain, the HRP was estimated to be around 12 days (Gibbens et al., 2001). During the epidemic in The Netherlands, the HRP was estimated to be 24 days (Abbas et al., 2001). With this knowledge in mind, the chosen HRPs of 7, 14 and 21 days largely covered the possible range of HRPs.

2.5. Epidemiological module

A mathematical model was constructed to estimate the effect of control strategies in the separate regions. A previously described deterministic susceptible–infectious–recovered (*SIR*) model (De Jong, 1995; Stegeman et al., 1999) was applied to describe the transmission of FMD between herds. In this model, S is the number of susceptible herds, I the number of infectious herds and R the number of recovered herds. Because herds are depopulated upon detection, $R = 0$ at all times in this study. In the model, the rate at which susceptible herds become infected is described as: $C = \beta \times SI/N$, in which C is the number of virus introductions per unit of time into a susceptible herd, β the infection rate parameter and N the total number of herds. Furthermore, infected herds are depopulated at the rate $D = \alpha \times I$, in which D is defined as the number of infected herds depopulated per unit of time and α as the depopulation rate parameter. The parameter α is the inverse of T; T is the average period that a herd is infectious. The transmission of FMD between herds can be expressed as the basic herd reproduction ratio R_{h}, which is defined as the average number of outbreaks caused by one initial infected herd in a wholly susceptible population. R_{h} can be estimated from $R_{\mathrm{h}} = \beta/\alpha$ (Stegeman et al., 1999). From the definition of R_{h}, it follows that if R_{h} is <1, the epidemic will fade out automatically. On the other hand, if R_{h} is >1, the virus will continue to spread (De Jong, 1995; Diekmann and Heesterbeek, 2000).

Knowledge and factual information on the precise transmission routes of FMD are scarce. This is in contrast to CSF (see, e.g. Stegeman et al., 1999; De Vos et al., in press). Both diseases are list-A diseases and spread via approximately the same transmission routes (Elbers et al., 1999; Donaldson et al., 2001; De Vos et al., in press). Therefore, to estimate the R_{h}, data collected during the Dutch CSF epidemic in 1997–1998 were used (Stegeman et al., 1999). Five transmission routes were distinguished by which the virus could be transmitted from one herd to another: animal transport, persons, neighbourhood,[7] artificial insemination (AI), and rendering (Elbers et al., 1999; Stegeman et al., 2000). Four types of herds were defined: AI stations, breeding herds, farrow-to-finish herds and finishing herds. The infectiousness of a herd was determined by the virus transmission within the herd (Van Nes et al., 1998). The parameters were adjusted to FMD using data collected from recent FMD outbreaks and data from transmission experiments (Sellers, 1971; Salt et al., 1998; Yang et al., 1999). Thus, based on the available FMD data, we

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[7] Neighbourhood infection is mentioned for those infected farms for which the origin of the virus is unknown and which are situated in the immediate vicinity of another infected herd, the infection date of which proved to be earlier (De Vos et al., in press).

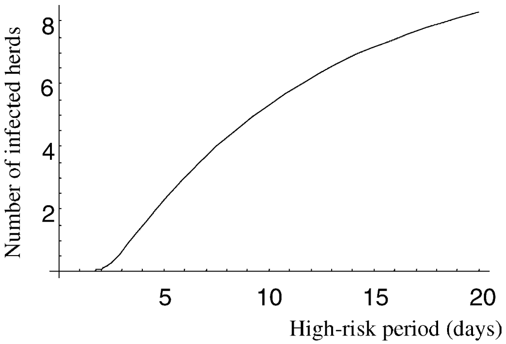

Fig. 3. Expected number of (FMD) infected herds caused by one initial infected breeding herd in region 1 during the HRP.

quantified the infectiousness of a herd over time. The length of the HRP has a strong influence on the infectiousness of a herd. This can be read from Fig. 3, which shows the infectiousness of a breeding herd in region 1 for variable HRP as an example. Clearly, fast detection will lead to much lower transmission (and thus to a smaller outbreak).

For each transmission route and HRP, a transmission matrix was composed to describe the transmission from one herd type to another (Stegeman et al., 2000). These matrices combined the number of contacts and the estimated chance of transmission by a contact. The values in the transmission matrices were made dependent on herd density and mean herd size in the outbreak region, as previously applied in Aujeszky- and CSF-control studies (De Koeijer and Stegeman, 2000; Stegeman et al., 2000; De Koeijer et al., in preparation).

Because the transmission routes were independent of each other, the five matrices could be added to one total transmission matrix. The transmission matrices were composed for each of the seven regions without control measures and after the implementation of the SO and RC1 strategy. Appendix A lists these total transmission matrices for each region in the case of an HRP of 14 days. The matrices show the transmission of FMD within farm types and from one farm type to another. Subsequently, R_h was determined by calculating the dominant eigenvalue of the matrix. The matching eigenvector reflects the proportion of each herd type that got infected (Diekmann and Heesterbeek, 2000). The R_h was determined for each control strategy and each region. In the case of ring-vaccination, we assumed that transmission continued for 1 week after vaccination and after that, transmission stopped in vaccinated herds. The model calculations were programmed in Mathematica 4.0 (Wolfram Research).

The main difference between transmission routes of FMD and CSF is that FMD virus could be spread by wind over long distances under certain weather circumstances[8] (Gloster et al., 1982; Donaldson et al., 2001), although opinions differ about the range of airborne spread. Air currents play a minor role as a transmission route between herds for CSF (Elbers et al., 1999; De Vos et al., in press). Therefore, airborne transmission was

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[8] Most favourable conditions for airborne spread are a constant wind direction, a wind speed of 5 m/s, a high atmospheric stability, no precipitation, and a relative humidity >55% (Donaldson et al., 2001).

calculated separately, and subsequently was added to the R_h for the scenarios with airborne spread (Gloster et al., 1982). For each combination of control strategy and region, a worst-case scenario of airborne spread was modelled (Gloster et al., 1981).

The calculated R_h's were used to derive the number of herds affected, duration of epidemics and areas subjected to movement restrictions for the defined scenarios (see Section 2.4). These outputs were used as inputs to the economic module (Fig. 1).

2.6. Economic module

The purpose of the economic module was to quantify payoffs that then could be used in the decision-tree module as the most important economic consequences of control strategies (see Section 2.7). Payoffs were defined as the direct costs and the export losses of spread and control of an FMD epidemic. Disease-control measures also could have other side effects, but these were not considered (see Section 4.2). The direct costs were defined as the economic implications for: (1) producers in the entire livestock value chain whose income depends on the livestock sector (e.g. farmers, abattoirs, hauliers and meat processors) and for (2) the government that is organising the disease control. Direct costs are generated by the implementation of control measures (such as costs of animal slaughter and vaccination, compensation payments and costs due to movement restrictions and idle production factors) (Berentsen et al., 1992b). An epidemic also could have export losses (Berentsen et al., 1992b; Garner and Lack, 1995; Mahul and Durand, 2000). These losses were defined as the value of livestock and livestock products that could not be exported because of trade restrictions due to the FMD epidemic.

In this module, the direct costs and export losses were calculated in a rather objective way using several statistical databases (Statistics Netherlands, 2001; Product Boards for Livestock, Meat and Eggs, 2000; Product Board for Dairy, 2000). The module was programmed in Excel 97 (Microsoft Corporation).

2.6.1. Input data for direct costs

The economic module used the outputs from the epidemiological module (Fig. 1). To calculate the direct costs, the economic module used the number of affected herds, the duration of epidemics and the size of areas subjected to movement restrictions. The number of culled or vaccinated animals was calculated. These calculations were based on livestock and herd densities in the outbreak region and the estimated number of contact herds (based on the calculated R_h) during the period between first infection and first detection. The duration of epidemics was longer when the culling and rendering capacity was not sufficient. The culling and rendering capacity was set at 16 farms per day for the SO and RC1 strategies and at 36 farms per day for the RV1 and RV3 strategies. This difference was made because biosecurity measures of culling and rendering could be less strict in the case of ring-vaccination because the danger of disease spread had been largely reduced due to vaccination. Vaccinated animals could be slaughtered in slaughterhouses instead of on the farms.

For each scenario, the direct costs were calculated as costs per dairy cow, sow or fattening pig that was culled or put under movement restrictions. Input values to calculate the direct costs are represented in Table 2. These values were calculated on base of statistics

Table 2
Input values for calculating the direct costs per dairy cow, sow and fattening pig (?) caused by an FMD epidemic in The Netherlands

Variables	Dairy cow (including young stock)	Sow (including piglets)	Fattening pig
Organisation costs	136	68	18
Compensation payments	1190	349	66
Idle production factors (per day)	4.95	0.66	0.14
Movement restrictions (per day)	0.07	0.15	0.02
Vaccination costs	9	7	2

of the Agricultural Information and Knowledge Centre and Research Station for Animal Husbandry (2000) and estimates of the National Inspection Service for Livestock and Meat (Meuwissen et al., 1999). Organisation costs refer to costs of diagnosis, valuation of the animals, killing, cleansing and disinfection of stables and equipment and surveillance in the protection and surveillance zones. Compensation payments are governmental payments to farmers whose animals were culled. These payments were calculated as the replacement values of the animals and feed supplies. Costs from idle production factors were calculated as the fixed costs decreased by released labour that could have been deployed elsewhere. The costs of movement restrictions were calculated as the costs for additional feed for maintenance and other supply and delivery problems caused by the restrictions. Vaccination costs included labour and material costs of the vaccination teams (Mangen et al., 2001). For sheep and goats only the replacement values were included because many of these animals are kept as hobby animals.

The losses for supplying, processing and distribution companies were calculated as half of the gross value added of agricultural production that did not take place due to the implemented control strategies. The main reason for this halving was that these companies only had to pay their fixed costs in case of idle production factors. The distribution of the gross value added within the livestock production chain is shown in Appendix B (Koole and van Leeuwen, 2000).

2.6.2. Input data for export losses

The extent of the export losses depends on the duration and size of the epidemic and the reactions of importing countries during and after the epidemic. The studies of Mahul et al. (2000) and Berentsen et al. (1992b) showed that import bans implemented by the importing countries play a key role in the evaluation of economic consequences of an FMD epidemic. The duration and size of the epidemic resulted from the epidemiological module. For the possible reactions of importing countries two alternatives were formulated. One alternative was based on OIE guidelines (Table 3).

According to the OIE International Animal Health Code, countries recover their status of FMD-free zone without vaccination: (i) 3 months after slaughtering of the last infected herd when there is no vaccination strategy implemented (only stamping out and preventive slaughter) or (ii) 3 months after slaughtering of the last vaccinated herd if a campaign of emergency vaccination is applied (Office International des Epizooties, 2000).

Table 3
Import bans during and after an FMD epidemic in The Netherlands in the OIE alternative (OIE) and in the more realistic alternative (REAL)

Ban-imposing region	Product group	During the epidemic	After epidemic (days)	
			Regional	National
OIE alternative (OIE)				
EU	Livestock	National	90	NA[a]
	Meat	Regional	90	NA
	Dairy products	Regional	0	NA
Non-EU	Livestock	National	90	NA
	Meat	Regional	90	NA
	Dairy products	Regional	0	NA
More realistic alternative (REAL)				
EU	Livestock	National	180	NA
	Meat	Regional	180	NA
	Dairy products	Regional	0	NA
Non-EU	Livestock	National	NA	360
	Meat	National	NA	360
	Dairy products	Regional	90	NA

[a] Not applicable.

However, reactions of importing countries during and after epidemics in the past have indicated that these countries did not respect the OIE guidelines. For this reason, a more realistic alternative (REAL) was defined (Table 3), based on international trade restrictions applied during epidemics in the past (e.g. Italy, 1993; Greece, 1994; Great Britain and The Netherlands, 2001). Assumptions on the duration of import bans were based on Berentsen et al. (1992b) and Mahul et al. (2000) and experiences of recent outbreaks (Commission Decisions 2001/172/EC and 2001/223/EC).

In both alternatives, three export-product groups were distinguished: (1) livestock, (2) meat products and (3) dairy products. The importing countries were divided in to EU countries and non-EU countries. Next, for each combination of product group and country group, it was determined how long an import ban was effective and whether the ban was at a national or regional level. A regional import ban means an import ban for products coming from regions around infected farms in radii of 10 km. Because regional export data were not available, the assumption was made that exports were proportional to the regional production (Mahul and Durand, 2000).

2.7. Decision-tree module

Rational economic decision-making models assume perfect markets and perfect information (Mileti, 1999). But in reality, animal-health authorities are faced with sparse information about the probable efficacy of proposed control strategies. A decision-tree analysis offers a formal, structured approach to decision making, taking into account elements of uncertainty (Marsh, 1999). The aim is to make explicit the chronological decision process and to arrive at the best decision given the available information.

Our objective of the decision-tree was to optimise early decisions to control FMD epidemics by calculating the economically optimal control strategy. A multi-attribute decision-tree was built using the expected-value criterion (von Winterfeldt and Edwards, 1986). The two attributes were the direct costs and the export losses and were weighted

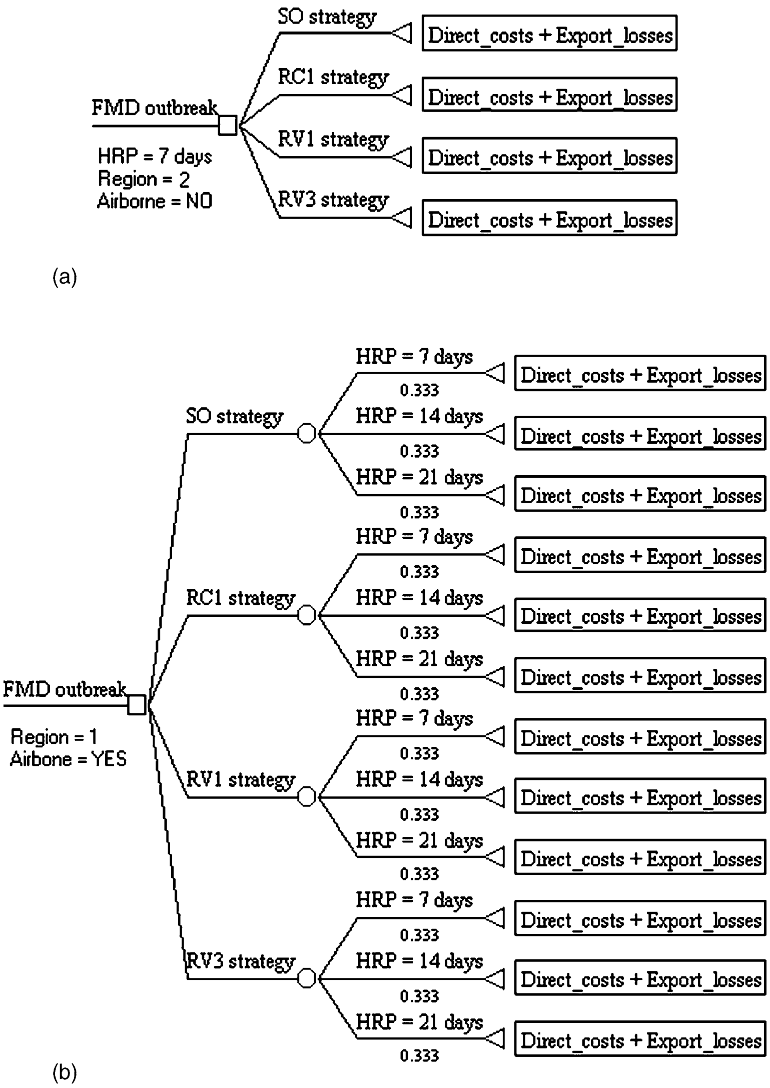

Fig. 4. (a) Example of decision-tree if the HRP is known; (b) example of decision-tree if the HRP is unknown.

equally. For each scenario (Fig. 3), these attributes were calculated from the epidemiological and economic modules.

In the early stages of a possible epidemic, information is available on the outbreak region (livestock density and herd density) and the possibility of airborne spread (weather conditions). Information on the HRP is often sparse, because the source of introduction of FMD in the primary-outbreak herd is often unknown and the analysis of virological and serological samples takes time (Horst, 1998). The decision-tree method is used in two different situations (Fig. 1). In the first situation, the assumption was made that animal-health authorities knew the length of the HRP. This length was either 7, 14 or 21 days (see Section 2.4). For each combination of HRP, region and possibility of airborne spread a decision-tree was set up. In total there were 42 decision trees. An example is given in Fig. 4a. Each combination of HRP, region and possibility of airborne spread was run through four branches (options)—which were the SO, RC1, RV1 and RV3 strategies.

In the second situation, the assumption was made that animal-health authorities did not know the length of the HRP. Three possible HRP lengths were considered. So, the HRP could be one of the three options: 7, 14 and 21 days. The probabilities of these three HRPs were assumed to be equal. In total there were 14 decision trees. An example is given in Fig. 4b. The trees were built in Data 3.5 (TreeAge Software, Inc.). Each combination of region and possibility of airborne spread was run through four branches—which were the SO, RC1, RV1 and RV3 strategies. Each branch had three possible outcomes because the HRP was unknown.

After calculating the optimal control strategies in both situations, the expected value of perfect information was calculated. The expected value of perfect information is the difference between the expected direct costs and export losses calculated both with and without knowledge on the length of the HRP. It provides an upper bound for the expected value of information in general. By considering the expected value of perfect information, animal-health authorities can make better decision about whether to obtain information (Clemen and Reilly, 2000).

3. Results

3.1. Epidemiological results

The epidemiological module generated the herd reproduction ratios (R_h) for each combination of region, control strategy and the possibility of airborne spread (Table 4). When $R_h < 1$, exact numbers are not shown because the epidemic will fade out automatically. The SO-strategy is predicted not to be adequate to stop the epidemic in regions 1, 2, 3 and 4 in the scenarios with airborne spread because the R_h is >1. Additional measures are necessary. In the other three regions, the SO-strategy eradicates the virus because R_h is <1. With additional measures, the R_h could be reduced—and likewise, the number of infected farms and the duration of the epidemic. In case of airborne spread, the RC1-strategy also is not very effective in region 2 because of the high livestock and herd densities and the limited culling capacity. Ring-vaccination is then the only option in this region to eradicate the virus.

Table 4
Basic herd reproduction ratio (R_h) for each region, control strategy and the possibility of airborne spread during an FMD epidemic in The Netherlands

Control strategy	Airborne spread?	Region						
		1	2	3	4	5	6	7
None	No	5.8	3.9	4.0	3.9	4.4	3.2	4.0
Stamping out	Yes	2.0	2.7	1.7	1.1	<1	<1	<1
	No	1.0	1.0	<1	<1	<1	<1	<1
Ring cull 1 km	Yes	<1	1.0	<1	<1	<1	<1	<1
	No	<1	<1	<1	<1	<1	<1	<1
Ring vaccinate 1 km	Yes	<1	<1	<1	<1	<1	<1	<1
	No	<1	<1	<1	<1	<1	<1	<1
Ring vaccinate 3 km	Yes	<1	<1	<1	<1	<1	<1	<1
	No	<1	<1	<1	<1	<1	<1	<1

3.2. Economic results

The economic module calculated epidemic 336 times (42 scenarios per region × four control strategies × two alternatives for possible import bans) the direct costs and export losses of an FMD. To give an indication of the major results, the extremes in sizes and economic consequences within these 336 calculations are presented in Table 5.

Table 5
Extremes in sizes and economic consequences in each region caused by FMD epidemics in The Netherlands (OIE: OIE alternative; REAL: more realistic alternative)

Size and consequences	Region						
	1	2	3	4	5	6	7
Predicted minimum							
Duration (days)	75	72	54	46	47	41	45
Number of infected herds	11	8	7	6	6	4	5
Movement control surface (km^2)	518	483	432	411	416	393	407
Direct costs (in million €)	83	60	36	24	16	4	5
Export losses OIE (in million €)	255	183	179	144	90	81	99
Export losses REAL (in million €)	563	443	453	407	314	315	339
Predicted maximum							
Duration (days)	End.[a]	End.	End.	End.	180	123	119
Number of infected herds	End.	End.	End.	End.	494	159	245
Movement control surface (km^2)	End.	End.	End.	End.	10874	1500	2066
Direct costs (in million €)	End.	End.	End.	End.	1478	63	110
Export losses OIE (in million €)	End.	End.	End.	End.	3051	678	926
Export losses REAL (in million €)	End.	End.	End.	End.	2305	389	573

[a] The epidemic became endemic (duration >1 year).

Table 6
Optimal and next-to-optimal control strategies and the differences in costs and losses (in million €) between these strategies in the scenarios with and without airborne spread if the HRP is known (OIE: OIE alternative; REAL: more realistic alternative)

	Region						
	1	2	3	4	5	6	7
With airborne spread							
HRP = 7							
Optimal strategy	RV3	RV3	RV1	RC1	RC1	RC1	RC1
Next-to-optimal strategy (OIE)	RV1	RV1	RV3	RV1	RV1	SO	SO
Δ costs + losses (OIE)	35	9	3	52	32	45	44
Next-to-optimal strategy (REAL)	RV1	RV1	RV3	RV1	RV1	RV1	RV1
Δ costs + losses (REAL)	51	11	5	61	35	49	49
HRP = 14							
Optimal strategy	RV1	RV3	RV3	RC1	RC1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV1	RV1	RV1	RV1	RV3	RV1
Δ costs + losses (OIE)	29	44	134	20	13	46	41
Next-to-optimal strategy (REAL)	RV3	RV1	RV1	RV1	RV1	RV3	RV1
Δ costs + losses (REAL)	30	55	176	24	14	51	47
HRP = 21							
Optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV1	RV3	RV1	RV3	RV1	RV3
Δ costs + losses (OIE)	404	746	236	71	3	62	51
Next-to-optimal strategy (REAL)	RV3	RV1	RV3	RV1	RV3	RV1	RV3
Δ costs + losses (REAL)	405	766	241	90	5	134	61
Without airborne spread							
HRP = 7							
Optimal strategy	RV1	RV1	RC1	RC1	RC1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV3	RV1	SO	SO	SO	SO
Δ costs + losses (OIE)	5	7	42	33	20	11	39
Next-to-optimal strategy (REAL)	RV3	RV3	RV1	SO	SO	SO	SO
Δ costs + losses (REAL)	7	10	51	46	24	14	24
HRP = 14							
Optimal strategy	RV1	RV1	RV1	RC1	RC1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV3	RV3	RV1	RV1	SO	RV1
Δ costs + losses (OIE)	28	32	7	61	21	25	45
Next-to-optimal strategy (REAL)	RV3	RV3	RV3	RV1	RV1	SO	RV1
Δ costs + losses (REAL)	31	34	9	73	26	30	51
HRP = 21							
Optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV1	RV3	RC1	RV3	SO	RV3
Δ costs + losses (OIE)	219	451	33	63	6	48	76
Next-to-optimal strategy (REAL)	RV3	RV1	RV3	RV1	RV3	SO	RV3
Δ costs + losses (REAL)	259	471	96	83	9	62	90

In regions 1, 2, 3 and 4, the epidemic becomes endemic in the worst-case scenarios. These results also indicate that the export losses are much higher than the direct costs. This is valid for both alternatives, although export losses in the OIE alternative were lower than in the REAL alternative.

3.3. Results of decision trees

As described in Section 2.7, the decision-tree module was used in two different situations: (1) if the HRP is known and (2) if the HRP is unknown (Fig. 4a and b).

3.3.1. If HRP is known

Ring-vaccination is always the economically optimal strategy in regions 1 and 2 (Table 6). The optimal radius of the ring-vaccination depends on the length of the HRP. Ring culling is always the economically optimal strategy in regions 6 and 7. For regions 3, 4 and 5, the economically optimal strategy depends on the length of the HRP and the presence of airborne spread.

The results of the two alternatives of possible reactions of importing countries (OIE and REAL) show almost the same rankings of economically optimal and next-to-optimal strategies (Table 6). The differences in costs and losses between the economically optimal and next-to-optimal strategy generally increase as the HRP is extended.

3.3.2. If HRP is unknown

The economically optimal and next-to-optimal control strategies for each region when the HRP is unknown are shown in Table 7. Ring-vaccination is always the optimal strategy in regions 1, 2 and 3 because ring-vaccination reduces the number of infected herds and the duration of the epidemic.

Table 7
Optimal and next-to-optimal control strategies and the differences in costs and losses (in million €) between these strategies if the HRP is unknown (OIE: OIE alternative; REAL: more realistic alternative)

	Region						
	1	2	3	4	5	6	7
Airborne spread							
Optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV1	RV3	RV1	RV3	RV3	RV3
Δ costs + losses (OIE)	132	256	38	21	1	69	48
Next-to-optimal strategy (REAL)	RV3	RV1	RV3	RV1	RV3	RV3	RV3
Δ costs + losses (REAL)	128	268	23	25	4	81	56
No airborne spread							
Optimal strategy	RV1	RV3	RV1	RC1	RC1	RC1	RC1
Next-to-optimal strategy (OIE)	RV3	RV1	RV3	RV1	RV1	RV3	RV3
Δ costs + losses (OIE)	110	12	7	13	8	57	56
Next-to-optimal strategy (REAL)	RV3	RV1	RV3	RV3	RV1	RV3	RV3
Δ costs + losses (REAL)	94	142	28	42	7	65	66

Table 8
Optimal strategies when HRP is unknown and known and the expected value of perfect HRP information (the totals between brackets are the differences between the direct costs and export losses calculated both with and without the HRP information)

Region	Airborne spread	HRP unknown	HRP known			Expected value of information (€€$\times 10^6$)
			7 days (€€$\times 10^6$)	14 days (€€$\times 10^6$)	21 days (€€$\times 10^6$)	
1	Yes	RV1	RV3 (−51)	RV1 (0)	RV1 (0)	17
	No	RV1	RV1 (0)	RV1 (0)	RV1 (0)	0
2	Yes	RV3	RV3 (0)	RV3 (0)	RV3 (0)	0
	No	RV3	RV1 (−10)	RV1 (−9)	RV3 (0)	6
3	Yes	RV1	RV1 (0)	RV3 (−176)	RV1 (0)	59
	No	RV1	RC1 (−51)	RV1 (0)	RV1 (0)	17
4	Yes	RV3	RC1 (−65)	RC1 (−33)	RV3 (0)	33
	No	RC1	RC1 (0)	RC1 (0)	RV3 (−121)	40
5	Yes	RV1	RC1 (−35)	RC1 (−14)	RV1 (0)	16
	No	RC1	RC1 (0)	RC1 (0)	RV1 (−85)	28
6	Yes	RC1	RC1 (0)	RC1 (0)	RC1 (0)	0
	No	RC1	RC1 (0)	RC1 (0)	RC1 (0)	0
7	Yes	RC1	RC1 (0)	RC1 (0)	RC1 (0)	0
	No	RC1	RC1 (0)	RC1 (0)	RC1 (0)	0

Ring culling is always the optimal strategy in the regions 6 and 7. In these regions, ring-vaccination prolongs the epidemic and enlarges the surface of movement standstill areas.

For regions 4 and 5, the optimal strategy depends on the presence of airborne spread. The results of the two alternatives of possible reactions of importing countries (OIE and REAL) show almost the same rankings of optimal and next-to-optimal strategies (Table 7).

3.3.3. Expected value of HRP information

The results in Table 8 emphasise the importance of retrieving information on the length of the HRP for the situations in which the expected value of perfect information is not zero. Especially in regions 3, 4 and 5, gathering HRP information leads to making better decisions.

4. Discussion

4.1. Epidemiological module

We used available knowledge, so had to restrict the model to a pig-adapted FMD virus strain. There was not much knowledge available on virus transmission in the field between other susceptible species. This means that the results can be interpreted only as the optimal strategies for pig-adapted FMD virus strains.

The ideal that the modelling can be completely based on underlying processes and estimated parameters of these processes could not fully achieved. For that, the data on the precise transmission routes of FMD was too scarce. Nevertheless, the assumed β's were best choices given available data, because data collected during the Dutch CSF epidemic in 1997–1998 was very useful to quantify the transmission of CSF for different sets of control measures that had been applied during the epidemic. Furthermore, the observations on the transmission process under different experimental conditions was helpful to yield further insight. The stochastic model could then be used to arrive at estimators based on observable quantities of the population dynamics (De Jong and Bouma, 2001).

4.2. Economic module

The economic module converted outbreak and control effects into estimates of direct costs and export losses for producers in the livestock value chain and the government. Decision making on control measures should always consider impacts on the most affected stakeholders. In The Netherlands, producers in the livestock value chain and the government are the most affected stakeholders because Dutch livestock farming depends for a large part on the export of livestock, meat and dairy products.

An epidemic could also have effects on the Dutch economy as a whole because of side effects of disease-control measures (e.g. the closure of footpaths harms the tourist sector) and interactions between economic sectors (e.g. price drops for livestock products favours consumers) (Berentsen et al., 1992a; Garner and Lack, 1995; Mahul and Durand, 2000). These 'non-agricultural' effects have not been quantified because the aim was not to carry out a full social cost–benefit analysis. This analysis provides a framework for comparing disease-control strategies but includes also difficulties. Many costs and benefits are by their nature difficult to quantify (e.g. emotional problems of farmers whose animals had to be culled). Assigning monetary values to these costs and benefits is a major problem of cost–benefit analysis and involves making subjective judgements (Ramsay et al., 1999).

A knowledge gap was found for the possible reactions of importing countries. Reactions do not always respect the OIE guidelines. This problem was addressed by using two alternatives for possible reactions—and we found that varying the lengths of import bans had only limited influence on the economically optimal control strategies. A limitation of the calculations is that these were based on changes in quantities due import bans—but not price and substitution effects. Therefore, the results provide upper bounds for the economic costs of an epidemic.

5. Conclusions

The decision-tree is a useful tool to structure and optimise early decisions on control of FMD epidemics in different regions in The Netherlands. The outcomes can be used as yardsticks for deciding on control measures during possible FMD epidemics in the future.

The results showed that not selecting the economically optimal strategy might cause large additional economic losses.

Animal density within the outbreak region is an important determinant in deciding on the optimal control strategy. The results show a considerable regional variation in the size of impacts. Ring-vaccination is the economically optimal strategy for DPLAs because this strategy reduces the number of infected herds and the duration of the epidemic compared to the other strategies. Ring culling is the economically optimal strategy for sparsely populated livestock areas. For livestock areas that are neither very densely populated nor very sparsely populated, the optimal strategy depends on the length of the HRP and the presence of airborne spread.

The duration of an epidemic was one of the most important parameters, which determined the economic impact of an epidemic. This was consistent with previous research (Horst et al., 1999; Mahul and Durand, 2000). In DPLAs, the culling and rendering capacity was the limiting factor causing delays in culling and extension of the epidemic. Therefore, ring-vaccination is the optimal strategy in these areas because it reduces the number of infected farms and likewise the duration of the epidemic.

The results of this study stress the importance of retrieving information on the expected length of the HRP as soon as possible after an outbreak of FMD has been declared, especially in regions that are neither very densely nor very sparsely populated.

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Appendix A

Total transmission matrices for each of the seven regions without control measures and after the implementation of the stamping out strategy and ring culling strategy in the case of an HRP of 14 days. The FMD transmission within and between farm types is shown.

Control strategy	Farm type	AI station	Breeding	Farrow-to-finish	Finishing	AI station	Breeding	Farrow-to-finish	Finishing
		Region 1				Region 2			
No control strategy	AI station	0.000	0.105	0.000	0.000	0.000	0.064	0.000	0.000
	Breeding	0.000	3.563	0.336	0.909	0.000	2.296	0.352	0.694
	Far-to-Fin	0.000	1.021	1.289	0.423	0.000	0.719	0.891	0.322
	Finishing	0.000	2.544	1.341	0.806	0.000	1.639	0.869	0.563
Stamping out	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.321	0.336	0.327	0.000	0.336	0.352	0.342
	Far-to-Fin	0.000	0.232	0.254	0.150	0.000	0.242	0.266	0.157
	Finishing	0.000	0.228	0.134	0.170	0.000	0.238	0.140	0.178
Ring culling 1 km	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.236	0.252	0.289	0.000	0.247	0.263	0.302
	Far-to-Fin	0.000	0.202	0.197	0.140	0.000	0.211	0.206	0.147
	Finishing	0.000	0.168	0.113	0.140	0.000	0.175	0.118	0.146
		Region 3				Region 4			
No control strategy	AI station	0.000	0.070	0.000	0.000	0.000	0.070	0.000	0.000
	Breeding	0.000	2.439	0.290	0.670	0.000	2.387	0.242	0.623
	Far-to-Fin	0.000	0.726	0.909	0.311	0.000	0.692	0.871	0.289
	Finishing	0.000	1.741	0.920	0.571	0.000	1.704	0.899	0.546
Stamping out	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.277	0.290	0.282	0.000	0.231	0.242	0.236
	Far-to-Fin	0.000	0.200	0.219	0.129	0.000	0.167	0.183	0.108
	Finishing	0.000	0.197	0.115	0.147	0.000	0.164	0.096	0.123

Ring culling 1 km	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.204	0.217	0.249	0.000	0.170	0.181	0.208
	Far-to-Fin	0.000	0.174	0.170	0.121	0.000	0.146	0.142	0.101
	Finishing	0.000	0.145	0.097	0.121	0.000	0.121	0.081	0.101
		Region 5				Region 6			
No control strategy	AI station	0.000	0.081	0.000	0.000	0.000	0.057	0.000	0.000
	Breeding	0.000	2.718	0.236	0.677	0.000	1.943	0.210	0.517
	Far-to-Fin	0.000	0.770	0.974	0.315	0.000	0.569	0.715	0.240
	Finishing	0.000	1.940	1.022	0.609	0.000	1.387	0.732	0.448
Stamping out	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.226	0.236	0.230	0.000	0.201	0.210	0.205
	Far-to-Fin	0.000	0.163	0.179	0.105	0.000	0.145	0.159	0.094
	Finishing	0.000	0.160	0.094	0.119	0.000	0.143	0.084	0.106
Ring culling 1 km	AI station	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Breeding	0.000	0.166	0.177	0.203	0.000	0.148	0.158	0.181
	Far-to-Fin	0.000	0.142	0.138	0.099	0.000	0.126	0.123	0.088
	Finishing	0.000	0.118	0.079	0.098	0.000	0.105	0.070	0.088
		Region 7							
No control strategy	AI station	0.000	0.073	0.000	0.000				
	Breeding	0.000	2.471	0.223	0.622				
	Far-to-Fin	0.000	0.703	0.889	0.289				
	Finishing	0.000	1.764	0.929	0.556				
Stamping out	AI station	0.000	0.000	0.000	0.000				
	Breeding	0.000	0.213	0.223	0.217				
	Far-to-Fin	0.000	0.154	0.169	0.099				
	Finishing	0.000	0.151	0.089	0.113				
Ring culling 1 km	AI station	0.000	0.000	0.000	0.000				
	Breeding	0.000	0.157	0.167	0.192				
	Far-to-Fin	0.000	0.134	0.131	0.093				
	Finishing	0.000	0.111	0.075	0.093				

Appendix B

Distribution of the gross value added (in billion €) within the livestock production chain in The Netherlands (mean value of 1995 and 1998).

Production aspect[a]	Grassland-based livestock farming		Intensive livestock farming		Total	
	Billion €	%	Billion €	%	Billion €	%
Livestock farms	3.0	41	0.7	22	3.7	35
Supply industry	1.4	19	0.7	22	2.1	20
Processing industry	2.2	30	1.3	40	3.5	33
Distribution industry	0.7	10	0.5	16	1.2	12
Total	7.3	100	3.1	100	10.5	100

[a] Source: Koole and van Leeuwen (2000).

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