



Identification of Response Cost Analysis of Alternative Early Responses to Foot and Mouth Disease Outbreaks in Dairy Cattle in Malang District, Indonesia

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Abstract | Delays in disease reporting by farmers and delayed response by officials cause Foot and Mouth Disease (FMD) to spread rapidly in the population. This impacts the amount of economic losses in the form of control costs that the government must bear. This study evaluates the control costs incurred with various alternative responses at the beginning of the FMD outbreak. The location of the research model is Malang District, with three simulation areas with low, medium, and high levels of dairy cattle population density. Disease transmission was simulated using the mathematical model susceptible-exposed-infected-recovered or dead-vaccinated-culled (SEIRVC) through three HRP of 7, 14, and 21 days. Each scenario was then paired with five alternative control programs, namely (1) cull of infected and exposed animals (CIE); (2) cull of infected animals and pre-emptive culling of susceptible animals within 1 km of the outbreak site (CIE 1 km); (3) cull of infected animals and pre-emptive culling of susceptible animals within 3 km of the outbreak site (CIE 3 km); (4) cull of infected animals and vaccination of susceptible animals within 3 km of the outbreak site (CIV 3 km); and (5) cull of infected animals and vaccination of susceptible animals within 10 km of the outbreak site (CIV 10 km). The cost of control was then calculated for all scenarios. The lowest total cost of control was then considered the optimal control strategy. Surveys were also conducted to determine the probability of HRP days and farmer acceptability of each region's culling program. The expected monetary value (EMV) was calculated by multiplying the probability of HRP and the probability of culling acceptability by the optimal control cost. Simulation results show that the most optimal initial response to FMD outbreaks in low-density areas is the CIE program with an EMV of eradication costs of 67 (65-113) thousand USD; medium-density areas is the CIV 3 km program with an EMV of eradication costs of 194 (188-200) thousand USD; and high-density areas is the CIE program with an EMV of eradication costs of 89 (85-92) thousand USD. The extension of the HRP, the postponement of control measures, and the lack of farmer acceptance of the culling program will increase the number of infected animals, the duration of the outbreak, the number of animals affected by control, and an increase in control costs.

Keywords | SEIRVC model, Economics evaluation, FMD control strategies

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The Foot and Mouth Disease (FMD) is attributed to a virus belonging to the *Aphthovirus* genus of the *Picornaviridae* family (McLachlan and Dubovi, 2017). It stands out as one of the most highly transmissible ailments affecting livestock and is considered the most economically burdensome. FMD manifests typical symptoms, including lesions or blisters on the oral region, such as the tongue, gums, inner cheeks, and lips, as well as blisters or erosions on all four feet, including the heels, hoof crevices, and along the coronary bands (Adjid, 2020). Although the mortality rate associated with FMD is relatively low, the economic losses attributable to it encompass a range of factors including diminished milk production, reduced livestock growth rates, decreased fertility, and increased abortion rates, elevated neonatal-calves mortality rates, expenses related to livestock treatment, and labor productivity losses following infection (Ringa and Bouch, 2014a; Baluka, 2016). Furthermore, the potential economic ramifications of FMD extend beyond the individual farmer level, impacting the nation due to government expenditures on disease control measures and disruptions in domestic and international trade activities (Baluka, 2016; Naipospos and Suseno, 2017).

According to the Direktorat Kesehatan Hewan, Kementerian Pertanian (2022), when an FMD outbreak occurs in an area of Indonesia, the FMD outbreak response policy is to immediately control and eradicate the disease and prevent losses to farmers by using several strategies in combination, namely: quarantine and restriction of movement of livestock, livestock products, and other infectious materials from all village areas and farms suspected of having FMD; tracing and surveillance; control of wild animals (especially rodents); decontamination; culling (stamping out) of infected and suspected infected animals; vaccination (if the disease cannot be controlled by culling alone and the outbreak has spread widely); and risk communication through communication, information and education activities. Several countries that have regained FMD-free status have implemented one or more control strategies to eradicate the disease (Garner *et al.*, 2007). The UK regained FMD-free status after depopulation of infected farms and a 3 km ring cull around them. Ireland implemented a similar policy, including the tracing and culling wild goats and deer in the ring cull area to break transmission through the sylvatic chain. The Netherlands implemented stamping out and ring vaccination (Tildesley *et al.*, 2009; Boklund *et al.*, 2013). The success of these countries in eradicating FMD by culling infected animals and surrounding susceptible animals can provide important guidance for the Indonesian government's FMD eradication program.

FMD triggered by the serotype O virus (ME-SA topotype, Ind-2001e genotype) was introduced to Indonesia in

late April and officially declared as an outbreak on May 5, 2022, in the East Java Province (Silaban and Wibawa, 2022; Suryadiningrat, 2022). The cause of the re-introduction of FMD in Indonesia is not known for certain, but it is thought to be due to lax regulations on the import of livestock (Grehnson, 2023). The East Java Province is one of the most densely populated regions for cattle breeding and boasts the highest livestock count in Indonesia (BPS, 2023). Indonesia's lack of preparedness, owing to 36 years of being free from FMD, resulted in the emergence of a widespread epidemic of the disease. As of the end of 2022, the statistics indicated a total of 591,42773,246 affected animals, 12,3804,145 fatalities, 6,72012,726 animals conditionally culled, and 226,28715,594,813 animals vaccinated, all amidst the ongoing FMD epidemic (Crisis Center PMK, 2023).

As policymakers, governments encounter various challenges when addressing highly contagious disease outbreaks like FMD. These challenges encompass resource constraints in expertise, finances, logistics, and social factors. Additionally, there may be a need for more information available to determine which mitigation strategies should be promptly implemented (Conrandy *et al.*, 2023). The improper selection of disease eradication strategies can result in significant additional economic losses, whereas the delayed implementation of control measures can lead to the extensive dissemination of the disease (Tomassen *et al.*, 2002). Analyzing disease transmission dynamics is a crucial preliminary step in devising disease control strategies. Epidemiological modeling is a valuable tool for comprehending the mechanisms of disease propagation, offering insights into potential responses during an outbreak, and assessing which control policies hold the greatest relevance (Hayama *et al.*, 2013; Probert *et al.*, 2016). Simulation models also facilitate the exploration of control strategies that may seem risky or too costly to test in practice while simultaneously enabling the calculation of cost estimates associated with each control option (Milner-Gulland *et al.*, 2001; Kao, 2002; Probert *et al.*, 2016).

This research examined the outbreak simulation and control using the SEIRVC mathematical model, which stands for Susceptible-Exposed-Infected-Removed-Vaccinated-Culled. This model is commonly known as the mean-field approach as it typically assumes that the population members are uniformly mixed or distributed, thus neglecting the spatial spread of the disease (Brauer, 2006; Bunwong, 2010; Ringa and Bauch, 2014a). Subsequently, a decision tree model was constructed and employed to assess the costs associated with five distinct FMD control programs within the specified model area of Malang District, located in the East Java Province. Malang Regency, with an area of approximately 3,473.50 km², is situated in the second-largest region in East Java Province, preceded

only by Banyuwangi Regency. East Java is the Indonesian province that produces the most livestock products. Malang Regency is a significant contributor to fresh milk production, with a total dairy cow population of 86,986 and a yield of 160,643.46 tonnes of milk in 2020. This figure increased in 2021 to 87,943 dairy cows with a milk yield of 168,401.09 tonnes (BPS, 2023). Following the incursion of FMD into the district of Malang, there was a significant decline in milk income. Despite the recovery of infected cows from FMD, the level of milk production remained below normal.

This evaluation focused on the initial stages of the outbreak, specifically the weeks following the diagnosis of FMD. This research aims to conduct an economic assessment of different disease control strategies during the initial phases (1-3 weeks after the first infection appears) of an FMD outbreak. This assessment is based on scenarios involving livestock density within a region, the length of the high-risk period (HRP), and the willingness of farmers to cull. It is hypothesized that the length of time farmers take to report to officials is directly proportional to the length of the HRP, thus affecting the coverage of animals affected by FMD. The simulation outcome estimates the Expected Monetary Value (EMV) that the government must cover in each scenario. The study aimed to evaluate the control costs of various FMD control alternatives in the early stages of an outbreak in low, medium, and high-density areas.

MATERIALS AND METHODS

ETHICAL APPROVAL

This research received approval from the Human Research Ethics Committee of Bogor Agricultural University under reference number 1075/IT3.KEPMSM-IPB/SK/2023.

TIME AND PLACE OF RESEARCH

The research was conducted from June to August 2023, and data were collected in Malang District, East Java Province. This data was obtained through in-depth interviews with veterinarians at the Livestock and Animal Health Service Office of Malang District and several dairy farmers. Farmers were selected as research participants using a purposive sampling method with specific criteria in place. These criteria included that the farmer must have experienced an FMD outbreak on their farm, be a cooperative or livestock group member, and have access to animal health services to cross-check the data obtained for veracity. The sample size was calculated based on a 95% confidence level, a presumptive prevalence of 13%, and a 6% error rate, using WinEpi software (Ignacio de Blas. Facultad de Veterinaria, Universidad de Zaragoza ©2006; <http://www.winepi.net>). This calculation yielded a minimum required sample size of 121 farmers. In this research, a total of 126 farmers were selected. Primary data collected in the research were

the ability of dairy farmers to detect clinical symptoms of FMD, the reporting time of farmers when they found sick animals, the attitude and compliance of farmers with the control program that has been running, the time needed for officers to come to handle farmers' reports, the time needed to confirm laboratory tests and the attitudes and practices of farmers towards cull and vaccination controls that have been carried out to cope with FMD outbreaks. The secondary data used are the area and sub-districts in Malang District, data on the dairy cattle population in 2021, which is the time before the outbreak, the components and costs of controls that have been carried out, and the ability of officers to cull and vaccinate animals per day. The model operates under the assumption that Indonesia is free from FMD, and it simulates a scenario where the disease is reintroduced, with the initial case occurring in Malang District, East Java. Furthermore, the model specifically concentrates on dairy cattle farms as affected by the largest losses and is one of the nation's largest sources of milk, thus excluding consideration of the impact of FMD on other susceptible animal species.

OUTBREAK AREAS AND RESEARCH POPULATIONS

In this research, the level of livestock density was determined by calculating the ratio of the dairy cattle population in 2021 to the area of each sub-district within Malang District. The sub-districts used in the model are those with low, medium, and high densities based on relative calculations. Based on these calculations, sub-districts with a dairy cattle population ≤ 63 cows/km² are categorized as low-density areas; sub-districts with a dairy cattle population of 64–126 cows/km² are categorized as medium-density areas; and sub-districts with a dairy cattle population > 126 cows/km² are categorized as high-density areas. Table 1 lists the sub-districts selected for the model and the area, population, and livestock density per sub-district.

Table 1: Data on low, medium and high density areas based on area, population and livestock density in Malang District 2021.

Variable	Density Low	Medium Density	High Density
Subdistrict	Karangploso	Hanging out	Pujon
Area (km ²)	58.74	147.70	130.75
Dairy cattle (head)	2,002	17,621	24,598
Dairy cattle / km ²	34	119	188

Source : Malang Regency Animal Husbandry and Health Service.

EPIDEMIOLOGICAL MODEL

In this research, the transmission and control of FMD were investigated using the SEIRVC mathematical model developed by Ringa and Bauch (2014b). This model is implemented through stochastic simulation, considering

individual animals as singletons. The model in this research is non-spatial, so it does not consider spatial distribution. It is only based on calculating the transition rate between proportions of a population. The disease host population is divided into several compartments, namely susceptible (S), exposed (E), infectious (I), recovered (R), vaccinated (V), and culled (C) so that $N=S+E+I+R+V+C$. The assumptions used in this model are that the distribution of livestock is considered homogeneous; there are no births and deaths of animals only caused by FMD disease; there is no animal movement; the population is constant (closed) so that susceptible animals (S) and simulated outbreak control do not exceed the research area boundaries and livestock re-stocking is carried out after control is complete; the entire livestock population is considered adult animals, and the total population (N) is limited to dairy cattle only. Vaccine efficacy was assumed to be 100% after animals were vaccinated.

The model simulation begins with an infected dairy cow that is not separated from other cattle. Disease transmission in the simulation persists without any control measures until a case is reported to the animal health authority, specifically the Livestock and Animal Health Service Office of Malang District. This period is denoted as the *high-risk period* (HRP). The HRP is the time to detection from infection start and detected, which in this research was divided into 3 periods: 7 days, 14 days, and 21 days. This period is based on the calculation of the median estimate with the elicitation method of experts and the calculation of FMD epidemics that have occurred in the Netherlands and the UK (Horst, 1998; Gibbens *et al.*, 2001; Tomassen, 2002). After that, a delay of 2 days is needed for the animal health authority (Livestock and Animal Health Service Office of Malang District) to start taking disease control measures in the field. Without delaying other controls, it was simulated that FMD vaccination was initiated 7 days after the disease was detected. This is related to the timing of vaccine ordering, logistics preparation, vaccine matching tests with field cases, and organizing resources (experts) to conduct vaccination (WOAH, 2018).

This research proposes five control options based on previous research (Tomassen *et al.*, 2002; Yoon *et al.*, 2006; Boklund *et al.*, 2013; Probert *et al.*, 2016). The options proposed in the research are 1) Cull of infected and exposed animals (CIE); 2) Cull of infected animals and pre-emptive culling of vulnerable animals within 1 km radius of the outbreak site (CIE 1 km); 3) Cull of infected animals and pre-emptive culling of susceptible animals within 3 km radius of the outbreak site (CIE 3 km); 4) Cull of infected animals and vaccination of susceptible animals within 3 km of the outbreak site (CIV 3 km); and 5) Cull of infected animals and vaccination of susceptible animals within 10 km of the outbreak site (CIV 10 km). It was assumed in

this research that infected livestock would remain infectious until all infected animals were culled. The parameters utilized in this research are outlined in Table 2.

Table 2: Parameters SEIRVC modeling.

Parameter	High Density	Medium Density	Density Low	Units	Source
Transmission rate ^a	1.4 (0.5-2.2)	1 (0.5-2.2)	0.6 (0.5-2.2)	per day	Conrady <i>et al.</i> , 2023; Hayama <i>et al.</i> , 2013; Ringa and Bauch 2014b
Latency rate ^a	0.25 (0.07-0.5)	0.25 (0.07-0.5)	0.25 (0.07-0.5)	per day	Ringa and Bauch 2014b; WOA, 2019
Rate recovered ^b	0.07-0.1	0.07-0.1	0.07-0.1	per day	Conrady <i>et al.</i> , 2023
Mortality rate ^a	0.019 (0.01-0.05)	0.019 (0.01-0.05)	0.019 (0.01-0.05)	per day	WOAH, 2019; Crisis Center PMK, 2023.
Number of susceptible cattle culled ^a	265 (64-591)	168 (41-375)	48 (12-107)	head per day	Proposed amount
Number of infected and exposed cattle culled ^a	265 (64-591)	168 (41-375)	48 (12-107)	head per day	Proposed amount
Vaccination ^a	2000 (1800-2100)	2000 (1800-2100)	150 (140-160)	head per day	Interview officer service

Description : (a) distribusi Pert: most likely (minimal-maximal), (b) distribusi uniform.

PROBABILITY OF HIGH-RISK PERIOD (HRP)

The early detection of the disease in the field is typically dependent on case reporting by farmers. Therefore, the variables used to calculate the *high-risk period* (HRP) in this research are based on the following factors: 1) the ability of dairy farmers to recognize clinical symptoms of FMD; 2) the speed at which farmers report cases; 3) the efficiency of officers in handling farmer reports; and 4) the time required to confirm laboratory results. While the type and timing of clinical symptoms may vary among individuals, this research will use specific symptoms as a reference point to estimate the incubation time of clinical symptoms during the risk period. The assumptions used in this research are as follows:

- If a farmer identifies two or more of the early symptoms of FMD, such as high fever, loss of appetite, drooling, and sometimes foaming, along with a significant reduction in milk production, then the estimated risk period is 3-5 days.

- If the farmer fails to identify at least two of the early symptoms of the disease but recognizes two or more of the late symptoms of FMD, which include blisters, blisters and lesions around the mouth, tongue, and gums, teeth grinding or rubbing of the mouth, blisters, blisters and lesions around the muzzle and nostrils, limping, nail wounds, and sometimes detached nails, and increased livestock lying down, as well as blisters, blisters, and lesions around the teats and udders, then the estimated risk period is 7-8 days.

Considering the farmer's capability to identify clinical symptoms, the research determined the number of days it took for the farmer to report. In cases where the farmer did not report, the risk period was categorized into the 21-day HRP group, assuming that an officer would identify the case in the field. The time it takes for officers to respond to the location to handle the reporting is also calculated in units of days. After the officer responds to the location, it is modeled that the officer will immediately collect samples and conduct laboratory testing. According to the Livestock and Animal Health Service Office of Malang District, the time needed to act on the report, collect samples, and confirm the laboratory testing results is around two days.

This research did not undertake serological surveys since no active cases were reported during the research period. Serological testing is most effective during the initial stages of disease onset in livestock and is less efficient for animals that have recovered from the disease or have been vaccinated. This is primarily due to the challenges associated with estimating the time of infection, as FMD antibody titer levels can persist for many years post-infection, and vaccinations further complicate interpretation (Paton *et al.*, 2014). Surveys based on clinical symptoms offer a low-cost alternative. They are more feasible in resource-limited settings, although they do not replace the need for serosurveillance in understanding FMD epidemiology (Nyaguthii *et al.*, 2019). The risk period formula proposed in this research is as follows:

$$\text{Risk period} = \text{DCSF}(t) + \text{SRF}(t) + \text{SHR}(t) + \text{CLT}(t)$$

The parameter descriptions in the formula are as follows: DCSF is the time for detection of clinical symptoms by farmers (days); SRF is the speed of reporting by farmers (days); SHR is the speed of staff handling reporting (days); and CLT is time for confirmation of laboratory tests (days). Risky periods with values ≤ 7 were included in the 7-day HRP; risky periods with values 8-14 were included in the 14-day HRP; and risky periods with values ≥ 15 were included in the 21-day HRP. The results obtained were then proportioned to determine the probability of each HRP in high, medium, and low-density areas. These probabilities will then be fitted in the decision tree analysis.

ACCEPTABILITY OF THE CULLING PROGRAMME

All the farmers participating in this research were queried regarding their level of agreement and adherence to the government's vaccination and culling programs. The interview included simple questions such as 1) Whether the respondent agreed with the FMD vaccination program; 2) Whether the respondent's livestock had been vaccinated; 3) Whether the respondent agreed to have their livestock culled by the veterinary authority during FMD control; and 4) Whether the veterinary authority culled any of the respondent's livestock during control. Farmers who do not agree to cull but still comply with the full program will be considered 'agreeing to cull.' Farmers who did not agree to the vaccination and cull programs will be categorized as 'agreed to vaccination' because, according to the government, vaccination is mandatory whether farmers agree or not. The results were then proportioned to see the probability of applying the cull (CIE, CIE 1 km, CIE 3 km) and vaccination (CIV 3 km, CIV 10 km) programs in a decision tree to adjust the appropriate control in each simulation area. As additional data, each respondent was also asked for their opinion on what compensation they would like if their animals had to be culled as part of the control program. This data can be used as input and a comparison with the compensation currently provided by the government.

PROGRAM AND COST CONTROL

The control program strategy employed in this research is based on the Indonesian Veterinary Emergency Preparedness for FMD series (KiatVetindo PMK) established by the *Direktorat Kesehatan Hewan, Kementrian Pertanian* (2022), as well as control recommendations from the World Organization for Animal Health (OIE) (WOAH, 2019). The FMD control and eradication efforts involve the implementation of a combination of the following programs:

- Quarantine and restriction of movement of livestock, livestock products, and other infectious materials from all village areas and farms suspected of having FMD.
- Tracing and surveillance to determine the source of disease, the level of disease transmission, and tracking new cases, as well as the basis for determining infected or infected areas, threatened areas, and eradication areas.
- Control of wild animals, namely rodenticides, adapted to the historical conditions of FMD in Indonesia.
- Decontamination.
- Risk communication through communication, information, and education (IEC) activities, especially to smallholder farmers, livestock companies, and related industries.
- Culling of infected and suspected infected animals, compensation for culled animals, and sanitary disposal of culled carcasses.

- Vaccination and permanent identification of vaccinated animals.

At the outset of the outbreak, not only the infected area but the entire Malang District was designated as a control area, and a 14-day lockdown was enforced. During this period, the movement of all susceptible animals and their products in and out of Malang District was prohibited. Subsequently, quarantine measures were limited to the control area or model area. The duration of the quarantine and surveillance period would be adjusted once the disease-free status is achieved, as determined through modeling.

The costs assessed in this research pertain solely to the control expenses borne by the government. These costs are computed for each control option and adjusted to account for the control duration as simulated. The cost components are a combination of controls the government has implemented in response to the outbreak and additional proposed components. The price of each control cost used refers to the costs incurred by the Livestock and Animal Health Service Office of Malang District, the Wates Veterinary Centre, the regulation of the Minister of Finance of the Republic of Indonesia on standard input costs for fiscal year 2024, and market prices at the time of the research. Details of these costs are presented in Table 3.

DECISION TREE ANALYSIS

Decision tree analysis calculates the Expected Monetary Value (EMV) associated with a decision. EMV represents the anticipated monetary value of each potential action, considering the presence of uncertainty or the probability of specific events occurring (He and Guan, 2021). To calculate the EMV for each decision, one multiplies the monetary outcome of each branch by the probability of that specific outcome and then sums the various outcomes after considering the chance node. The formula for EMV is defined as follows (Sari and Arfi, 2021):

$$EMV = \sum_{n=1}^N Value_n \times Probability_n$$

Decision tree analysis offers a chronologically structured approach based on often limited available information. At the onset of an outbreak, the basic information available is generally only the outbreak's location, the area's total livestock population, and the number of provisionally reported sick animals. The decision tree analysis in this research was modeled for each region to suggest programs and estimate FMD control costs based on information about 1) the area of first disease occurrence, i.e., low, medium, or high density; 2) the probability of HRP; and 3) the acceptability of cull programs. Considering budgetary constraints, the control strategy with the lowest total cost of control is then

Table 3: Costs control FMD disease.

Cost category	Description	Value
Quarantine and traffic restrictions (check points) on land routes	Disinfectant for vehicles entering and leaving the outbreak area	IDR 1,250,000/ point partition per day
	Disinfection equipment	IDR 260,000/ point bulkhead
	Guard at the sealing point (daily allowance and consumption)	IDR 162,000/person per day
Wild animal control	Rodenticide	IDR 1,000,000/ village per month
Decontamination	Disinfecting the surrounding environment and cages of infected animals	IDR 1,250,000/ village per day
	Disinfection equipment	IDR 260,000/ village
	Decontamination/ burning of contaminant items	IDR 1,000,000/ activity per village
Surveillance and testing	Animal testing costs	IDR 50,000/ head ELISA IDR 500,000/ PCR head
	Sampling equipment	IDR 60,000/ head
	Transport for surveillance activities to Malang District (regardless of the number of farms)	IDR 3,800,000/ activity
Vaccination	Lab officer per visit (regardless of number of farms)	IDR 310,000/person per day
	Vaccination costs	IDR 35,000/ head
	Eartag installation	IDR 25,000/ head
Culling	Vaccination equipment	IDR 37,000/ head
	Compensation for culled animals	IDR 10,000,000/ head
	Mobilisation of animals from pen to burial site	IDR 1,500,000/ day
Communication, Information and Education (KIE)	Burial costs	IDR 2,663,000/ day
	Excavator mobilisation and demobilisation	IDR 3,000,000
	Officer meetings and training	IDR 14,280,000/ meeting
	Socialisation materials	IDR 5,400,000/ print leaflets per month IDR 10,000,000/ billboard per month

considered the optimal control strategy. This value was then multiplied by the probability of farmer acceptability of the program and the probability of HRP length occurring in each simulation area.

SENSITIVITY ANALYSIS AND MODEL RESULTS

Obtaining factual information regarding the suitable FMD transmission rate, latency, mortality, and recovery parameters in Indonesia poses a significant challenge. This challenge arises from the scarcity of resources dedicated to documenting outbreak details and ongoing research efforts to establish the required parameters. Consequently, the FMD parameters utilized in this research were adapted based on data obtained from existing literature. Therefore, the results may exhibit disparities with the actual incidence of cases observed in the field. However, this approach is considered optimal with the available resources. Based on interviews with agency staff, the control parameters refer to the currently available staff resources and historical FMD outbreak control in Malang 2021–2022. The number of animals culled is assumed to be within a radius of 0.33 km², 0.67 km², and 1 km² of the outbreak site based on available human resources in Malang District, even though it was not applied in past outbreak control. The values used in the research are optimistic, so changes in density, capacity, or availability of skilled resources will result in different values.

We conducted sensitivity analyses through Monte Carlo simulations consisting of 10,000 iterations, and a significance level of $p < 0.05$ was established. The outcomes in this research are reported as the median, along with the 10th and 90th percentiles. The SEIRVC model was analyzed using Palisade @Risk statistical computing version 8.5.2 (Palisade Lumivero, Raleigh, USA). In contrast, decision tree analysis was conducted using PrecisionTree version 8.5.2 (Palisade Lumivero, Raleigh, USA).

RESULTS AND DISCUSSION

EPIDEMIC SIMULATION

In this research, we conducted a disease transmission simulation (without any control measures) over 30 days in all three areas of the model. This simulation allowed us to observe key time points at days 7, 14, and 21, which serve as benchmarks for the High-Risk Period (HRP), and days 10, 17, and 24, which are benchmarks indicating when control measures were initiated. Figure 1 presents a graphical representation illustrating the relationship between population density within an area and the transitions between different population compartments. As depicted in Figure 1, it becomes evident that as the population density in the area increases, the rate of decline in the number of healthy animals (susceptible animals) accelerates. Area

density is also directly proportional to the increased number of exposed and infected animals, so the denser the area, the faster the disease will spread. A summary of the number of FMD-infected animals at each HRP point and day of control is presented in Table 4. Simulation results show that extending the HRP from the minimum (7 days) to the maximum (21 days) causes a 28-fold increase in infected animals in low-density areas, 65-fold in medium-density areas, and 120-fold in high-density areas. Control that required a 2-day delay also led to an average 1.8 (1.5–2.1) times increase in infected animals from when the field staff detected the disease. Based on these results, the speed of disease detection and control will affect the number of animals affected by FMD.

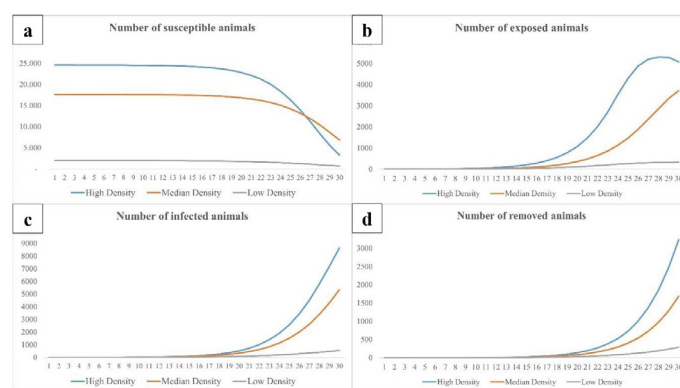


Figure 1: SEIR simulation of FMD disease in low-density, medium-density, and high-density areas (in median values). Figure (a) shows a graph of the decrease in susceptible animals. Figure (b) shows the graph of increasing animals exposed to FMD disease. Figure (c) shows the graph of increasing FMD infected animals. Figure (d) shows the graph of increasing FMD removed (recovered and dead) animals.

PROBABILITY OF HIGH-RISK PERIOD (HRP)

In this research, the determination of the HRP relies on several factors, including farmers' capacity to identify clinical signs, the promptness with which farmers report these signs to authorities, the speed at which officers respond to such reports, and the outcomes of laboratory test confirmations. As suggested by Yano *et al.* (2018), the suspicion of FMD infection arises if, on a given farm, at least one animal exhibits two or more clinical signs. It was found that 78% of respondents in low-density areas could recognize at least two clinical symptoms of FMD that appeared early in the infection period. 98% of respondents reported immediately (day 0) if they found their animals sick, and 2% said they would not report. In medium and high-density areas, 100% of respondents could recognize two or more clinical symptoms of FMD at the onset of infection. 98% of respondents in medium-density areas said they would report the disease immediately (day 0), and 2% said they would not report it at all. In high-density areas, 100% of respondents reported disease. All reported respondents stated that

100% of officers would come on the same day (day 0) after receiving the report. Officers must carry out simulated laboratory tests and require 2 days to confirm the results to obtain the HRP probability, as presented in Table 5.

Table 4: Summary results simulation spread disease.

Simulation area	HRP (day)	Number of infected animals			Start of control (day)	Number of infected animals at the beginning of control	
		Median	10th -90th percentiles			Median	10th -90th percentiles
Low density	7	4	2-6	10	6	4-12	
	14	20	8-61	17	32	12-114	
	21	101	28-469	24	157	39-701	
Medium density	7	5	3-8	10	9	5-18	
	14	40	13-117	17	72	21-249	
	21	311	60-1,564	24	555	91-3,050	
High density	7	6	4-10	10	13	7-25	
	14	69	23-209	17	135	37-491	
	21	726	132-3,728	24	1,395	217-7,280	

Table 5: Probability high risk period (HRP) in each simulation region.

Simulation area	HRP (day)	Median	CI 90%
Low density	7	0.77	0.66-0.86
	14	0.20	0.12-0.32
	21	0.04	0.01-0.11
Medium density	7	0.96	0.90-0.99
	14	0.015	0.001-0.06
	21	0.04	0.01-0.10
High density	7	0.98	0.93-1.00
	14	0.02	0.001-0.07
	21	0.02	0.001-0.07

CI: confidence interval.

ACCEPTABILITY OF CULLING PROGRAMS

The outcomes from interviews with farmers regarding their consent and adherence to the government's vaccination and culling programs are displayed in Table 6. Farmers residing in regions with high population densities exhibited a greater inclination towards consenting to culling. They expressed the view that, even in cases where dairy cattle are treated (rather than culled), milk production only recovers to approximately 50-70% of its previous level after the cows have recuperated. This is considered detrimental, so they will follow any government program if it can help the outbreak end quickly. In addition to economic factors, the community's proximity to officials is also a supporting factor for community compliance. However, they complained

that the compensation money provided by the government was too small. This result contrasts with farmers in medium-density areas who completely rejected the cull policy. Farmers who rejected culling on average reasoned that 1) they were worried that the government would not replace their culled livestock, 2) the compensation given to culled livestock was too small, and 3) they did not know and care that sick FMD livestock transmitted diseases to other livestock even though they were being treated. Meanwhile, only 0.6 (0.5-0.7) farmers agreed to cull in low livestock density areas. Areas with high livestock densities tend to receive attention from the government, resulting in better communication between the government and the farmers.

Table 6: Consent and compliance society under control.

Simulation area	Agree on Culling		Agree on Vaccination	
	Median	CI 90%	Median	CI 90%
Low density	0.6	(0.5-0.7)	0.4	(0.3-0.5)
Medium density	0.0	(0-0.10)	1.0	(0.9-1.0)
High density	0.8	(0.7-0.9)	0.2	(0.2-0.4)

CI: confidence interval.

On the other hand, areas with lower livestock densities only receive occasional visits and, therefore, have less trust in the government than areas with high livestock densities. Areas with low densities that are growing or increasing in density interact more frequently with the government and, therefore, have slightly better trust than medium-density areas. Based on the interview results, on average, farmers in Malang District asked for heifers or the price of the cow (approximately 15-20 million rupiah or 965-1,287 USD) as minimum compensation for culled animals.

SIMULATION RESULTS AND ECONOMIC IMPACT OF CONTROLLING

In this research, the duration of outbreak control is computed starting from the initial day of implementing control measures until no infected animals remain in all three areas of the model. In the case of vaccination programs, such as those within 3 kilometers (CIV 3 km) and 10 kilometers (CIV 10 km), the duration of control was determined by the time it took to complete the second round of vaccination. Rapid culling of infected and exposed animals resulted in the fastest outbreak control duration even though the control point started on day 24. The CIE control option can stop an outbreak in a day when the program starts on day 10. If the program is implemented on day 17, the outbreak will stop in all simulated regions in ≤ 3 (1-7) days. CIE is also still the best option for shortening the duration of the outbreak when the control program starts on day 24 in low and medium-density areas. As for high-density areas,

Table 7: Summary of the number of cattle affected by different disease control models.

Simulation area	Control program	Disease control time (day)	Number of animals culled		Number of animals vaccinated	
			Median	10 th -90 th percentiles	Median	10 th -90 th percentiles
Low density	CIE	10	12	10-24	-	-
		17	49	42-209	-	-
		24	198	165-1.137	-	-
	CIE 1 km	10	144	138-154	-	-
		17	225	225-435	-	-
		24	1.373	758-1.385	-	-
	CIE 3 km	10	1.036	1.031-1.062	-	-
		17	1.537	1.290-1.623	-	-
		24	1.952	1.199-1.967	-	-
	CIV 3 km	10	6	4-6	1.018	1.016-1.043
		17	29	17-55	1.699	1.194-1.699
		24	146	64-461	1.838	1.316-1.924
	CIV 10 km	10	5	4-6	1.997	1.996-1.998
		17	29	17-57	1.970	1.940-1.983
		24	157	64-478	1.824	1.260-1.924
Medium density	CIE	10	25	12-51	-	-
		17	205	57-301	-	-
		24	2.999	246-9.437	-	-
	CIE 1 km	10	432	416-461	-	-
		17	895	650-1.424	-	-
		24	3.958	2.222-5.996	-	-
	CIE 3 km	10	3.495	3.465-3.533	-	-
		17	4.478	3.964-5.163	-	-
		24	8.282	5.265-15.181	-	-
	CIV 3 km	10	16	13-33	3.465	3.465-3.470
		17	92	75-401	4.081	4.062-4.103
		24	2.313	275-4.900	6.355	2.204-8.609
	CIV 10 km	10	18	16-38	17.603	17.582-17.605
		17	110	85-482	17.497	17.085-17.526
		24	1.232	492-3.134	16.127	10.041-17.057
High density	CIE	10	38	20-72	-	-
		17	433	123-1.666	-	-
		24	9.194	755-14.301	-	-
	CIE 1 km	10	673	650-701	-	-
		17	1.629	1.118-2.485	-	-
		24	3.866	1.834- 6.770	-	-
	CIE 3 km	10	5.492	5.446-5.545	-	-
		17	7.395	6.453-8.627	-	-
		24	12.071	7.210-24.495	-	-
	CIV 3 km	10	32	16-61	5.456	5.417-5.504
		17	366	103-1.431	6.920	6.099-8.055
		24	4.418	681-6.611	15.707	6.136-23.834
	CIV 10 km	10	37	19-72	24.561	24.525-24.579
		17	401	113-2.248	24.167	22.074-24.473
		24	4.338	682-6.590	15.514	5.941-23.842

the outbreak control program on day 24 will be faster using the CIE 1 km option. The simulation results of disease control in the form of affected animals and the number of animals culled and vaccinated are presented in Table 7.

Table 8: Summary of economic results of control costs of various disease control models.

Simulation area	Control program	Disease control time (day)	Control duration (day)	Control costs (thousand USD)	
				Median	10 th -90 th percentiles
Low density	CIE	10	1 (1-1)	66	62-70
		17	1 (1-5)	104	89-131
		24	3 (3-22)	282	202-440
	CIE 1km	10	3 (3-7)	158	153-162
		17	4 (4-13)	236	218-270
		24	19 (19-65)	992	886-1.044
	CIE 3km	10	45 (38-51)	859	847-874
		17	30 (30-74)	1.168	1.108-1.219
		24	40 (40-86)	1.427	1.303-1.492
	CIV 3km	10	45 (45-45)	159	150-167
		17	47 (46-48)	193	182-204
		24	50 (41-51)	310	258-382
Medium density	CIE	10	1 (1-1)	75	71-81
		17	3 (1-6)	233	173-343
		24	33 (2-40)	2.689	1.541-3.587
	CIE 1km	10	6 (6-9)	378	352-378
		17	13 (12-14)	700	631-792
		24	58 (37-102)	2.732	2.436-3.276
	CIE 3km	10	46 (45-61)	2.501	2.491-2.517
		17	89 (74-89)	3.272	3.142-3.405
		24	112 (107-121)	5.390	5.192-7.451
	CIV 3km	10	47 (47-47)	192	181-203
		17	47 (46-47)	267	237-322
		24	44 (39-47)	1.786	1.040-2.588
High density	CIE	10	1 (1-1)	89	79-92
		17	3 (1-7)	192	192-600
		24	34 (4-34)	6.866	4.248-7.394
	CIE 1km	10	5 (5-7)	508	508-524

	17	16 (12-16)	1.214	1.066-1.394
	24	28 (17-29)	2.363	2.255-3.352
CIE 3km	10	52 (43-62)	3.871	3.829-3.871
	17	95 (67-95)	5.702	4.988-5.702
	24	117 (92-124)	7.027	7.027-10.880
CIV 3 km	10	40 (40-40)	187	173-200
	17	41 (41-42)	482	319-721
	24	42 (38-50)	3.013	1.955-3.919
CIV 10 km	10	51 (51-51)	259	244-274
	17	51 (49-51)	632	395-1.012
	24	42 (39-50)	2.984	1.931-3.900

The economic model for calculating the costs of outbreak control was applied to 45 instances, corresponding to the number of disease control scenarios considered in this research. These scenarios encompassed three HRP scenarios, each occurring within three distinct simulation regions and five FMD control strategies for each of these scenarios. The economic module interprets the effects of outbreak duration and proposes alternative control programs for monetary values. This analysis provides an overview of the estimated costs to be prepared by the government under each scenario. In addition to the operational cost of eliminating the disease, the additional cost of surveillance to demonstrate disease-free status is also calculated. However, the duration is not included in the disease control duration. The duration of surveillance will match the WOAHP rules based on the program implemented: stamping out (8.8.7 1a) or vaccination (8.8.7 1c). The duration and economic burden of control are presented in Table 8.

DECISION TREE

The hierarchical order within the decision tree can be subject to variation based on the specific objectives of a program or the frequently restricted availability of information. These variables and their relative rankings can be modified to align with diverse interests, considerations, and discussions that involve policymakers and stakeholders. In this research, the ranking of the decision tree based on the probability of HRP, acceptability of culling by farmers, and the lowest cost or most efficient control program option is shown in Figures 2, 3, and 4. The EMV values for each region are summarised in Table 9.

Foot-and-mouth disease (FMD) is an extremely contagious virus. Therefore, controlling its further transmission becomes challenging once it has spread to an area. The resurgence of FMD in previously unaffected regions or cases where it was believed to be eradicated should be a matter of grave concern to all stakeholders. This is due to the substantial economic losses associated with the disease,

estimated to be around 1.37 billion USD for the Indonesian economy (Pambudy *et al.*, 2023). The global strategy for FMD control developed by the World Food and Agriculture Organisation (FAO) and the World Organisation for Animal Health (WOAH) states that FMD control in a country must go hand in hand with improved animal health services. Responding to this disease requires continuous vigilance (Naipospos, 2022), which should not only be imposed on health workers but also include disease reporting in the field by farmers.

pivotal role in determining the extent to which the virus disseminates unchecked within the environment. Hiesel *et al.* (2016) mentioned that extending the HRP will significantly change the number of cases and areas of FMD infection. Figure 1 illustrates the impact of HRP length on reducing the number of healthy animals and increasing the number of infections, especially in high-density areas.

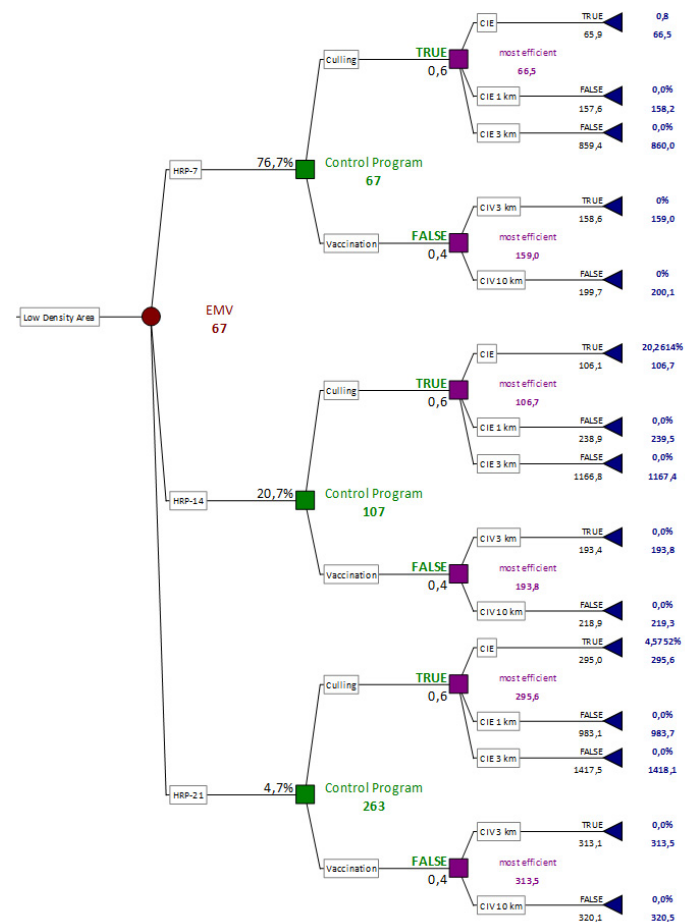


Figure 2: Decision tree for FMD disease control at low density. CIE control is the best alternative at all HRP times. Values in the decision tree are presented as median (50th percentile).

The study aimed to evaluate the control costs of FMD control alternatives in the early stages of an outbreak in low, medium, and high-density areas. Several evaluation stages are needed before determining how much the government will need to eradicate the outbreak. The initial step is to determine the probability of HRP. An assessment of the acceptability of culling programs among farmers follows this: the cost of FMD control must be calculated. HRP timeframe encompasses the duration commencing from the initial onset of infection until a case is identified, during which control measures have not yet been implemented (Iriarte *et al.*, 2023). The length of the HRP plays a

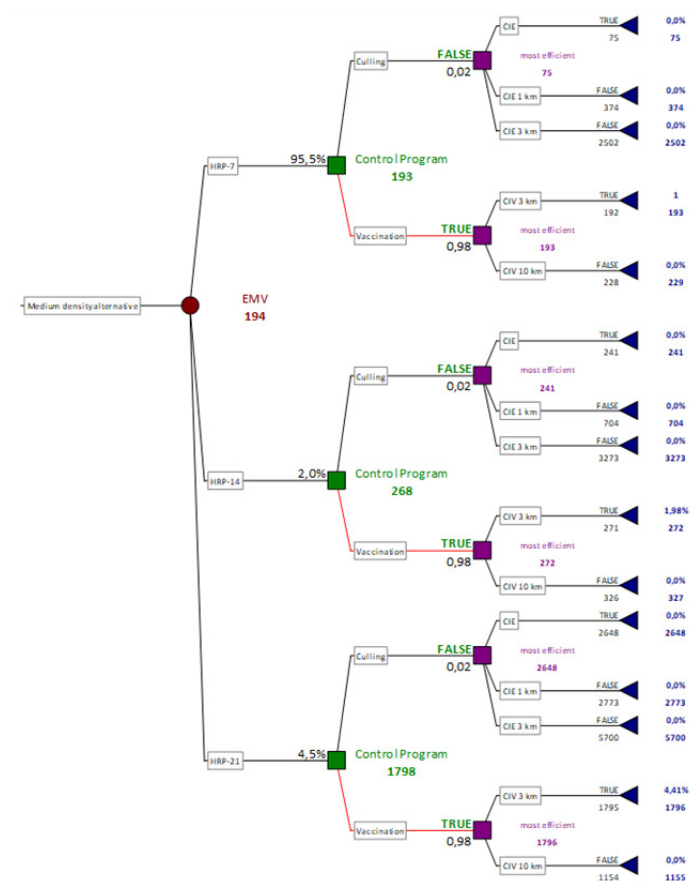


Figure 3: Decision tree for FMD disease control at medium density. CIV 3 km is the best alternative control at all HRP times if vaccination is forced. Values in the decision tree are presented as median (50th percentile).

There was a 5-fold increase in the average number of infected animals in low-density areas, 8-fold in medium-density areas, and 11-fold in high-density areas each week (Table 4). This shows that despite having the same HRP length, there are still differences in the number of cases in each area depending on the density. In comparison, the number of cattle infected with FMD on day 21 was 726 (132-3,728) in high-density areas and only 101 (28-469) in low-density areas. This difference is influenced by the speed of disease transmission and the location of the index case based on cattle density, so although the length of the HRP is a factor in increasing the number of cases, the impact of the disease cannot be generalized across all regions (Carpenter *et al.*, 2011; Hayama *et al.*, 2013; Conrady *et al.*, 2023). The change in animal health status in the SEIR mathematical simulation is the movement or transition of members from

one compartment to another, for example, from susceptible to exposure or from infectious to recovered. The SEIR mathematical model in this study can be applied to other regions and types of livestock with some adjustments, namely by considering the livestock density component in the region and changing the parameters according to the type of livestock. However, since this model is *singletons* and for cattle, adjustments are needed if the transmission model is applied to mixed livestock species. For example, transmission between cattle and pigs would require a SEIR *pairs* model. The SEIR mathematical model used in this study has advantages and disadvantages. The advantages of the model, which uses a mean-field approximation, are that it is suitable for describing a large system, such as at the district, province, or country level, but ignores the scale of individual interactions (Bunwong, 2010), making it unsuitable for application in small areas (e.g., between farms) with specific characteristics. Therefore, the choice of model should be tailored to the purpose of its use.

Passive surveillance, or surveillance predicated on community reporting, represents the most effective form of surveillance for identifying cases and promptly detecting diseases in the field (Sudarnika *et al.*, 2014). Nevertheless, as this surveillance hinges on farmers as the primary frontline for detecting cases, it necessitates their awareness and willingness to report and their proficiency in recognizing disease symptoms. The ability of farmers to detect and find clinical symptoms will affect the recording of outbreak investigations by veterinary authorities (Lamberga *et al.*, 2020). All respondents interviewed in high and medium-density areas had excellent detection skills in recognizing clinical symptoms of FMD, and the majority immediately reported when their animals were sick. This resulted in a day 7 HRP probability of 0.98 (CI: 0.93-1.0) in high-density areas and 0.96 (CI: 0.90-0.99) in medium-density areas. Although farmers in low-density areas had a high initiative to report, 0.23 respondents needed better detection skills for early FMD symptoms in their animals. This resulted in a day 7 HRP probability of only 0.77 (CI: 0.66-0.86).

It is not exceptional for dairy farmers in Malang District to demonstrate proficiency in FMD detection, which can be attributed to three key factors: 1) their extensive farming experience, 2) their participation in guidance and educational programs conducted by governmental, organizational, and livestock group entities, and 3) the relatively limited number of dairy cattle holdings that are always housed. The interviews indicated that 86.5% of the respondents had received formal counseling on FMD and obtained non-formal information from animal health officers when treating cows. Counseling activities, farm visits, or group meetings effectively disseminate information and provide insight to farmers (Mulatmi *et al.*, 2016). Most dairy farmers (94.4%) in Malang District have been engaged in agricultural ac-

tivities for ten years. In general, the respondents indicated that they had commenced involvement in livestock care relatively early, citing the necessity to assist their parents as the primary motivation. In addition to knowledge, this long farming experience also affects farmers' proximity to animal health officers and vice versa.

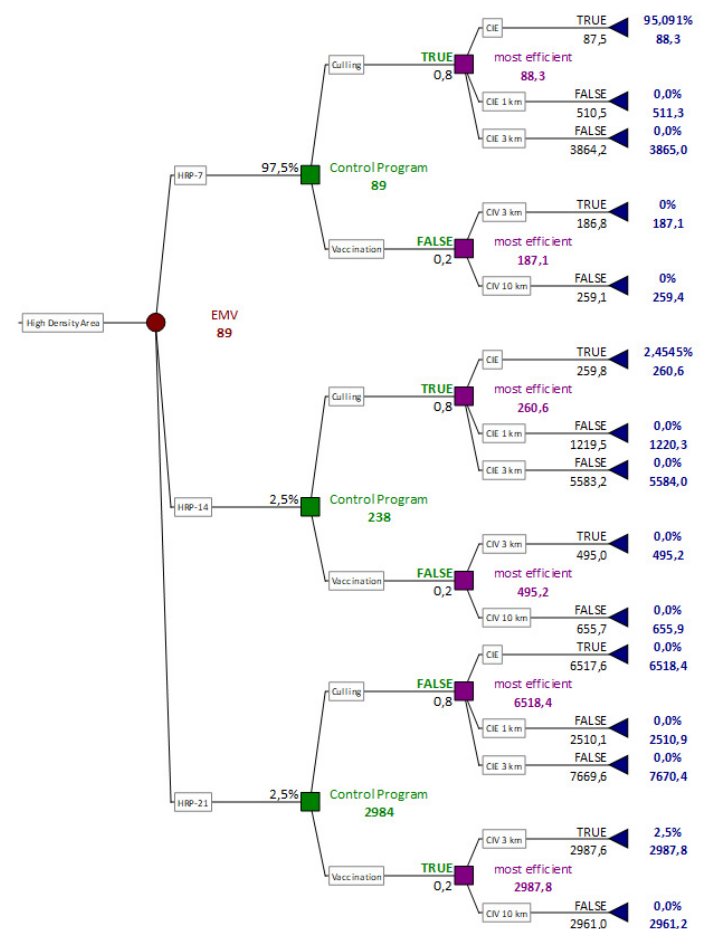


Figure 4: FMD disease control decision tree at high density. CIE control is the best alternative at HRP days 7 and 14, while CIV 3 km is the best alternative at HRP day 21. Values in the decision tree are presented as median (50th percentile).

The relatively short HRP of FMD in dairy farms in Malang District may be different if applied to other types of farms and other regions of Indonesia due to differences in the characteristics of farmers and the speed of officers in responding to reports. However, apart from these things, the key to the short HRP value in this study is the immediate laboratory testing simulation. The importance of using simulated laboratory testing in this study is due to the lessons learned from the first outbreak in Gresik, East Java. Although farmers reported sick animals quickly and officers arrived on the reporting day, the disease was misidentified with BEF (Bovine ephemeral fever), with symptoms similar to FMD. When tests were finally done and confirmed, FMD had already affected 402 cattle in 22 villages in five sub-districts. This delay in index case detection

prolonged the HRP and undoubtedly hindered the effectiveness of locally applicable first control measures that are important in determining epidemic progression (Iriarte *et al.*, 2023).

The results of the disease transmission simulation were then paired with various control program options. The five control programs we proposed showed that during the initial phases (1-3 weeks after the first infection) of an FMD outbreak, rapid culling of infected and exposed animals (CIE) resulted in the fastest duration of outbreak control in all simulation areas. This result is similar to the research of Dürr *et al.* (2014), who stated that when a small-scale FMD outbreak occurs, the first control effort should be made is culling, restricting movement, and tracing the disease rather than vaccination. Culling sick animals will reduce disease transmission and the outbreak's size because the presence of sick animals that are a source of FMD transmission is immediately eliminated. This is because if cattle are not culled immediately or treated for FMD, the transmission of the virus will continue. This is evidenced by the occurrence of FMD reinfection in several areas in Malang, even after implementing the government's vaccine program. This is due to the persistence of the source of infection and its continued maintenance.

The UK has implemented culling decisions, and Ireland depopulated infected farms and pre-emptive culling 3 kilometers from the outbreak site when FMD occurred in 2001 (Tildesley *et al.*, 2009; Boklund *et al.*, 2013). However, in developing countries, in addition to duration, another factor that needs to be considered is the acceptability of culling livestock by the community. The design of control measures to achieve FMD-free should discuss targets, resource availability, and logistics costs and constraints that may arise in the program, such as community resistance as part of the stakeholders. Large-scale livestock culling policies are generally culturally inappropriate and less accepted by smallholder farms in Southeast Asia, so the selection of this control needs extensive discussion with affected actors (Blacksell *et al.*, 2019). In Indonesia, particularly in the Malang District, traditional farmers predominantly do dairy farming. The primary source of income for these families is derived from the sale of milk and feeder cattle, including calves and heifers. Consequently, disease control measures involving the culling of animals, especially healthy ones, can provoke social unrest. This makes the acceptability of culling programs one of the factors we consider in determining which controls are suitable, as well as opening the discussion on whether stamping out can be applied to reduce the duration of the outbreak.

The results of our study indicate that two of the three regions (i.e., high and low-density areas) under consideration were in favor of and more likely to comply with the

culling program for the reasons previously outlined. The results showed that basically, the rejection of dairy farmers in Malang District to the culling program was related to the nominal compensation that was considered too low, the lack of trust in the government, and the closeness of the community to the field officers. These shortcomings can still be corrected and adapted to the community's needs if the government is willing to improve the current conditions. However, as dairy cows are one of the community's main income sources, the government should compensate the farmers ethically accordingly. Suppose the government's budgetary constraints preclude the possibility of offering adequate compensation. In that case, the Indonesian Cattle and Buffalo Breeders Association (PPSKI) has proposed that Bulog (Indonesia Logistics Bureau) be requested to purchase cattle or buffalo owned by farmers for carcass acquisition and incorporation into Bulog stock (Catriona and Ika, 2022).

Besides culling, vaccination is presented as an alternative control program in this research. However, the simulation results suggest that implementing vaccination at the outset of an outbreak may not be cost-effective. Rejecting the culling program can lead to issues such as prolonging the duration of control, enlarging the population of animals affected by the program, and escalating the overall cost of control. This is especially true if FMD control can be implemented on days 10 and 17 post-infection. For example, simulation results in a medium-density area show that FMD control on day 10 with the CIE program only requires 1 day of outbreak control duration and a control cost of 75 (71-81) thousand USD. The program requires culling 16 (13-33) sick animals and 9 (1-18) healthy animals exposed to sick animals. Suppose farmers refuse to cull animals and only want a vaccination program. In that case, the duration of outbreak control will be 47 days, cost 192 (181-203) thousand USD to control, and the government will have to vaccinate 3,465 (3,465-3,470) animals in addition to culling 16 (13-33) sick animals. Culling of sick animals should still be done as a way of localizing the outbreak so that the outbreak does not spread outside the simulated area or Malang District. Still using the example of a medium-density area, in the scenario of FMD control on day 17, the CIE culling program and the CIV 3 km vaccination program did not have a large difference in cost but were significantly different in the duration of disease control. The CIE program can control the disease in 3 (1-6) days, while the CIV 3 km program takes 47 (46-47) days. The duration mentioned does not even compare the surveillance duration required to prove FMD-free: 3 months for cull programs and 6 months for vaccination programs (WOAH, 2019). Another challenge is to ensure that vaccinated animals are always under surveillance or not sold by the farmer so that it is easy to trace them back in the future. However, if a vaccination program must be chosen to

Table 9: EMV results by livestock density (values are presented as median and 10th-90th percentile).

Simulation area	HRP (day)	Optimal Path			EMV (thousand USD)
		Control strategy	Value (thousand USD)*	Probability of HRP	
Low density	7	CIE	66 (62-70)	0,77 (0,66-0,86)	67 (65-113)
	14	CIE	104 (89-131)	0,20 (0,12-0,32)	
	21	CIE	282 (202-440)	0,04 (0,01-0,11)	
Medium density	7	CIV 3 km	192 (181-203)	0,96 (0,90-0,99)	194 (188-200)
	14	CIV 3 km	267 (237-322)	0,015 (0,001-0,06)	
	21	CIV 3 km	1.786 (1.040-2.588)	0,04 (0,01-0,10)	
High density	7	CIE	89 (79-92)	0,98 (0,93-1,0)	89 (85-92)
	14	CIE	192 (192-600)	0,02 (0,001-0,07)	
	21	CIV 3 km	3.013(1.955-3.919)	0,02 (0,001-0,07)	

*: values are shown in median (10-90th percentile).

reduce the number of animals culled, it is best implemented when the control program starts ≥ 17 days.

While the data may indicate the general condition of Kabupaten Malang, it is important to recognize that the results may be different from farmers based on area density (low, medium, and high). This is because only one subdistrict is sampled from each area density category. Consequently, there is a possibility of bias, whereby the results obtained only represent the characteristics of that area. Furthermore, the results of the HRP probability and acceptability of culling programs may vary significantly if tested in other areas, among farmers who are not members of livestock groups or cooperatives, those who face difficulties in contacting animal health officers, and in other types of farms, such as those raising beef cattle, pigs, goats, and sheep. Therefore, further specialized research and studies are necessary for more accurate data.

Table 9 demonstrates that, apart from the probability of entering the HRP, the willingness of farmers to accept culling also impacts the magnitude of the Expected Monetary Value (EMV). In regions with medium population density where the community rejects culling, the EMV is higher compared to high-density areas where culling is accepted. In addition to economic considerations, biosecurity on smallholder cattle farms in Indonesia still needs to be improved. There is no land for isolation cages, no designated area for cleaning before and after entering the cage, and all kinds of people can enter the cage area. Without immediate removal of sick source animals, FMD will spread to other areas within days (as it has), for vaccination is often delayed (both in delivery and availability) and not accompanied by culling of sick animals, so FMD continues to spread. Understandably, stamping out can be very damaging to the owners of affected animals, both economically and emotionally. However, this policy is designed to protect public 'goods,' so the health and economic well-being of the human community takes precedence over individual

interests. Thus, aggressive and pre-emptive culling is our preferred efficient infection control strategy economically, if not ethically.

Therefore, if the government deems it necessary to implement a culling policy to efficiently manage control time and budget in order to maintain an FMD-free status, it becomes crucial to consider compensation that aligns closely with the community's expectations and to engage in regular education and counseling efforts on the benefits of the culling program, even in the absence of the disease. However, if this is not possible due to the limitations of many aspects, it is necessary to strengthen early detection of the disease accompanied by laboratory tests. These two things are needed as one of the factors that can minimize the HRP period of FMD. The smaller the HRP, the smaller the chance of the disease spreading so that disease management can be carried out at the local level and can reduce costs incurred by the government.

Fundamentally, a decision tree serves the purpose of determining the most suitable course of action by taking into account the specific information provided and its considerations. Therefore, the role of the model in aiding the decision-making process only sometimes leads to a singular recommended solution, such as opting for the least expensive control method. While it is acknowledged that the scenario in this research is somewhat artificial, as it models an ideal situation, the research's outcomes can still effectively demonstrate the significance of disease detection, culling, and vaccination in influencing the duration and cost of outbreak management.

In this research, the model generates multiple outputs, including a description of disease transmission, proposed control measures, the duration required for outbreak control, the number of livestock affected by these measures, and the associated costs for each option. These outputs

can demonstrate to policymakers the existence of various alternatives for managing FMD outbreaks. They also facilitate communication between the government, a policymaker, and the community, including stakeholders. The policy choice may impact the speed of outbreak control, stakeholder interests, cost-efficiency, and potential economic benefits (Dürr *et al.*, 2014; Truong *et al.*, 2018). Not everyone will be satisfied with the decisions made, but engaging in open discussions about animal welfare, ethics, and sustainability goals can help minimize the likelihood of rejection and negative sentiments among stakeholders (Lederman *et al.*, 2021).

CONCLUSIONS AND RECOMMENDATIONS

In handling FMD outbreaks, delayed detection and reporting of FMD cases will lead to higher control costs incurred by the government in handling outbreaks. Delays in responding to reports, delays in implementing control measures, and farmers' acceptability of the culling program are other factors that can lead to increased costs. Recommendations for FMD control in the early stages of an outbreak in Malang District for low-density areas is culling of infected and exposed animals (CIE) with control costs of 67 (65-113) thousand USD; Medium-density areas are culling infected animals and vaccinating livestock within a 3 km radius (CIV 3 km) with a control cost of 194 (188-200) thousand USD; and high-density areas are culling infected and exposed animals (CIE) with a control cost of 89 (85-92) thousand USD. Although the EMV value in medium-density areas is higher than the EMV value in high-density areas, this result is the best value, assuming that the acceptability of livestock culling is an important factor considered in the selection of control programs.

It is important to note that the recommendations in this study are contingent upon the results of a simulation model. Consequently, several prerequisites must be met, including 1) policymakers (in this case, the local office) must be aware of the probability of HRP, necessitating immediate laboratory testing when handling suspected FMD cases; 2) the acceptability of culling by farmers as stakeholders must be established; and 3) there must be sufficient resources of animal health officers available for stamping out and vaccinating. In addition, it is important to note that simulation models simplify real-world phenomena, provide a general overview of field conditions, and inevitably encompass inherent uncertainties and constraints. Engaging in discourse with stakeholders and government decision-makers is crucial to ascertain the most appropriate applications of the model outputs. Nevertheless, this simulation will provide valuable insights that will inform decision-making processes in the control of FMD outbreaks and will also

give rise to several new discussions on the various aspects that need to be considered in the control of FMD disease.

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NOVELTY STATEMENT

This study is the first economic analysis to quantify the various responses to FMD control at the beginning of an outbreak in Indonesia. The results of this study can be a valuable reference for the government in setting policies related to FMD control at the beginning of an outbreak and a guideline for local governments in responding to first-time outbreaks.

AUTHOR'S CONTRIBUTIONS

Atsmarina Widyadhari contributed to collecting data, data analysis, and preparing the original manuscript. Chaerul Basri and Etih Sudarnika contributed to the study design, revised the manuscript, and supervised. All authors read and approved the final version of the manuscript in the present journal.

CONFLICT OF INTEREST

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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