Discrete-event simulation of emergency movement permitting during foot-and-mouth disease outbreaks

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Abstract

Foot-and-mouth disease (FMD) is a high-consequence infectious disease affecting cloven-hoofed animals, including livestock and wildlife. Although not currently present in the U.S., an outbreak poses significant animal welfare and economic risks. In the event of an FMD outbreak, livestock movement decisions impact disease spread risk, animal welfare, and livestock business continuity. Permitted movements could help animal health officials balance these conflicting objectives. Successful movement control depends on a permitting system capable of reviewing large volumes of livestock movement requests under time pressure. Existing epidemic models typically represent movement restrictions as policy switches and do not capture the operational realities of staffing limits, queues, corrections, and delays. This study develops a discrete-event simulation model to evaluate the emergency movement permitting workflow for cattle movements in Kansas during a potential FMD outbreak. Movement requests are generated from InterSpread Plus, a detailed epidemic simulation model populated with representative cattle industry data. The discrete-event simulation model represents workflows for inter- and intra-state movement requests, specialized personnel required for different tasks, the potential need for rework due to errors in movement request documents, and applicant response delays. By varying model parameters including task completion time distributions, rework probabilities, and staff capacities, the simulation supports what-if analysis of permit request turnaround time, queue formation, number of requests completed, and staffing bottlenecks. The study also evaluates a control-zone-informed permitting policy in which movements associated with a control zone undergo the full review process, while movements outside the control zone follow an expedited review pathway. This allows the operational effects of alternative permitting policies on processing times, number of requests completed, and resource utilization to be

examined. The proposed framework provides emergency planners with a decision support tool to quantify resource requirements, test alternative permitting policies, and balance disease containment with continuity of livestock commerce during high-consequence animal health emergencies. Although developed for FMD movement permitting, the simulation framework could be adapted to other animal disease outbreaks that require movement restrictions and permitting, with appropriate modifications to disease-specific requirements and review procedures.

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Chapter 1. INTRODUCTION

1.1 Background and Problem Context

Foot-and-mouth disease (FMD) is a highly contagious viral illness that affects cloven hoofed animals, including cattle, pigs, sheep, goats, and deer. It is recognized as one of the most serious worldwide threats to livestock health, production, and trade (1). The disease is caused by the foot-and-mouth disease virus (FMDV), which can spread quickly through direct animal contact, contaminated feed, tools, and clothing. In some cases, the virus can also move short distances through the air, making outbreaks especially hard to control (2). Once infected, animals usually show signs such as fever, blisters, and lesions on the mouth and hooves, leading to excessive salivation, lameness, sharp drops in milk yield, weight loss, and, in young animals, sometimes death (3). Human infection with FMDV is very rare and, when it occurs, the disease is generally mild and self-limiting (9). The economic impact on farming, however, is extremely serious. Outbreaks often lead to strict trade restrictions, large-scale culling, and major productivity losses (4). To stop the spread of FMD, several layers of protection are required. These include strong biosecurity, early detection, fast response, and sometimes vaccination. Among these, one of the most important defenses is strict control of animal movement between farms, which helps keep the virus from reaching new herds or regions (5).

Because of this, well organized coordination and operational planning become vital to ensure these control measures are implemented efficiently during an outbreak. This requires close interaction among veterinary services, government authorities, farmers, and, where appropriate, other organizations to support consistent decision making, communication, and resource allocation during an outbreak. Key operational responses include farm level and regional movement restrictions, setting up quarantine areas, selective depopulation, rigorous

disinfection, and vaccination campaigns where justified (6). On the ground, field teams are central to surveillance, diagnosis, and hands on interventions, while reliable communication channels ensure that case data, policy directions, and logistical needs flow quickly across all levels (7). When stringent movement restrictions are combined with a coherent, coordinated framework, response teams are far more capable of curbing spread, reducing economic fallout, and supporting the quicker restoration of livestock industries and trade (8).

Movement control refers to the restrictions and regulatory measures used to manage the movement of animals, animal products, vehicles, equipment, and other potentially contaminated materials during an outbreak. Its purpose is to reduce opportunities for disease transmission between premises and geographic areas (9). However, completely stopping movement for an extended period can also create serious animal welfare and economic consequences. Movement permitting is therefore an important component of movement control. Rather than allowing unrestricted movement or prohibiting all movement, a permitting system allows specific movements to occur after required disease risk and biosecurity conditions have been reviewed (15, 16). The permitting process must therefore balance two competing objectives: limiting the risk of disease spread while maintaining necessary livestock movements and continuity of business (9, 15, 16).

The United States has remained free of FMD since its last outbreak in 1929. Because there has been no recent domestic outbreak from which to evaluate response operations, federal and state agencies and livestock industries rely on preparedness plans, training, and simulation exercises to test how an FMD response would function in practice. These activities are important because a future introduction of FMD could have major animal health, economic, and trade consequences (9).

In the United States, preparedness for a potential foot-and-mouth disease (FMD) outbreak is managed through a federal-state partnership. State agencies hold the main responsibility for applying movement restrictions, enforcing biosecurity, and overseeing the emergency movement permitting system. These permits allow the controlled movement of animals, animal products, and other potentially risk-associated materials when applicable outbreak surveillance, biosecurity, and permitting requirements are satisfied. This approach supports disease containment while allowing necessary livestock, trade, and animal welfare movements to continue when appropriate (9).

In Kansas, the Department of Agriculture (KDA) has placed FMD readiness at the center of its emergency program. The agency conducts simulation and functional exercises involving multiple partners to evaluate preparedness and improve response strategies. The Pathways functional exercise, conducted in December 2023, gathered more than 175 participants representing 53 agencies, organizations, associations, and industry groups, including federal and state agencies, industry representatives, and members of the Kansas legislature. The scenario simulated a complex outbreak across jurisdictions and activated both the KDA Incident Management Team and the State Emergency Operations Center. Participants were tasked with carrying out epidemiological tracing, coordinating communications, and handling movement permits under fast-changing outbreak conditions (10).

These recent activities build on a longer tradition of preparedness in Kansas. For instance, the 2019 functional exercise tested decision making on livestock movement control, depopulation measures, and communication during a simulated emergency (11). Such drills highlight the difficulty of the permitting process, which depends on timely review of disease status information, movement records, and other permitting data maintained within the USDA

APHIS Emergency Management Response System (EMRS2). EMRS2 is the official federal platform for animal health emergencies and supports permitting, tracing, and data analysis. However, some states keep their own systems and must transfer premises data into EMRS2 for integration with federal response (12, 13, 14).

To meet these challenges, Kansas has aligned its movement permitting with the Secure Beef Supply (SBS) and Secure Milk Supply (SMS) programs. Producers requesting permits must provide a valid SBS or SMS certificate. This requires an enhanced, operation-specific biosecurity plan, prepared with a veterinarian's input. Producers must also keep detailed records of every movement of animals, vehicles, equipment, and people across the farm's line of separation for the time period required by state regulations. In addition, they must show written confirmation from a veterinarian or biosecurity manager that the approved biosecurity steps are being carried out on site (15, 16).

These permitting requirements not only decrease the risk of spreading disease during allowed movements but also improve traceability if new cases appear. The scope of movement control during an FMD outbreak extends beyond live animals and may include animal products, vehicles, equipment, and other potentially contaminated fomites (9, 17).

1.2 Problem Statement and Importance

Preparedness exercises in Kansas have highlighted the substantial personnel, technical expertise, and information management requirements associated with movement permitting (10, 11). However, the scale of these operational requirements has not been well quantified. Identifying these requirements is important for implementing movement controls efficiently during an actual outbreak while limiting both disease spread and economic disruption. How far and how fast FMD spreads depends heavily on the success of movement control. If controls fail,

the virus can spread to new areas much more quickly. This can expand the outbreak and enlarge control zones, which are geographically defined areas around infected or high-risk premises where additional movement restrictions and disease control measures are applied (9). Modeling from earlier epidemics shows that even a few uncontrolled movements in the early stages can sharply increase the number of infected premises and prolong the crisis (18).

The consequences are not only epidemiological but also economic. Delays or bottlenecks in permitting can affect disease free farms because livestock markets, dairies, and processors depend on timely movement to maintain normal production. Extended movement restrictions can increase feed and labor costs, create animal welfare concerns, disrupt milk and livestock marketing, and reduce the value of agricultural products (4).

The financial impact is significant. The 2001 outbreak in the United Kingdom caused an estimated £8 billion (~$11 billion USD) in losses, most of it due to movement restrictions and market shutdowns rather than direct disease effects (19). U.S. models project similar scales of loss, with scenarios showing multibillion dollar damage depending on how long an outbreak lasts, how effective movement control proves to be, and the severity of trade restrictions (20).

From an operational standpoint, states with large livestock sectors such as Kansas could experience a substantial surge in movement permit requests during an FMD outbreak. Without adequate staff, technology, and coordination, backlogs could develop quickly, increasing processing delays and potentially disrupting necessary livestock movements. Recognizing these operational constraints is therefore important for Kansas and other livestock producing states preparing for an FMD response.

1.3 Research Gap

The ability to control animal movement during a foot-and-mouth disease (FMD) outbreak is one of the strongest tools available to slow the spread of the virus. Still, movement control cannot operate on its own. It depends on a permitting system that can quickly review, approve, and track large volumes of requests, often under tight time pressure. Running such a system requires significant staff time, technical expertise, and reliable data platforms. However, the staffing requirements, processing times, and operational capacity needed to manage large volumes of movement permit requests have not been well quantified in the reviewed literature. Without this information, agencies may have difficulty estimating the personnel and resources required to maintain an effective permitting process during an outbreak.

1.4 Research Objective and Proposed Approach

This project is designed to close that gap. The study develops a discrete-event simulation modeling framework that estimates the resources needed to review and issue animal movement permits during an FMD outbreak. The application focuses on beef and dairy cattle movements involving Kansas, including movements within Kansas, movements entering Kansas from another state, and movements leaving Kansas for another state. However, the framework is designed to be general enough to apply to other livestock species, products, and regions. The model is based on three key inputs:

1-A detailed process map of the permitting workflow

The permitting process is represented from request arrival through final approval or denial. The principal personnel categories represented in the model are administrative staff, trained staff, and trained veterinarians. Administrative staff perform data review and approval

activities, trained staff perform data review, route review, and approval activities, and trained veterinarians review the Exposure Questionnaire.

2-Time estimates for each step

Processing time distributions are assigned to the major review and approval activities to represent natural variation in task duration. These values are informed by work measurement principles (21), input from Kansas Department of Agriculture experts, and observations from FMD preparedness exercises.

3-Animal movement request data

Livestock movement data are generated using InterSpread Plus (ISP) (22). The ISP livestock network incorporates representative cattle industry information, including county level farm and livestock population data from the National Agricultural Statistics Service (NASS), movement characteristics from National Animal Health Monitoring System (NAHMS) data, and simulated farm locations. The resulting movement records provide the basis for generating permit request arrivals and classifying movements according to their origin and destination.

1.4.1 Model Structure

The model is implemented as a discrete-event simulation (26). This method is particularly well suited for systems in which processes occur in steps with defined start and finish points. It is especially useful for evaluating operations where task times vary and multiple resources may need to be used at the same time. By representing the permitting workflow in this way, the model can realistically capture how staffing, technology, and task overlap affect performance.

For each permitting policy, the simulation evaluates system performance under different staffing and operating conditions. The model reports measures including processing time,

number of requests completed, and resource utilization, allowing the operational consequences of alternative staffing levels and permitting policies to be examined.

1.4.2 Scenario Testing

The model supports what-if analysis by allowing key operating conditions and permitting policies to be varied. The simulation evaluates changes in staffing levels, processing times, rework rates, and routing policies to determine how these factors affect permitting system performance. In particular, the study compares a base case permitting policy, in which control zone status does not affect the level of review, with a control-zone-informed policy that directs control zone related movements through the full permitting workflow while allowing movements outside the control zone to follow an expedited review pathway. These scenarios allow changes in system metrics, including processing time, number of requests completed, and resource utilization to be evaluated under different operating conditions.

1.5 Research Contributions

This study contributes a decision support framework for evaluating emergency livestock movement permitting during an FMD outbreak. The discrete-event simulation represents permit request arrivals, review activities, staffing constraints, queues, corrections, rework, and approval processes within a single model. These findings can help animal health authorities identify possible improvements to the permitting process, such as adjusting staffing levels, improving processing efficiency, and implementing alternative permitting policies. The model can also support workforce planning by estimating the number of trained personnel needed under different operating conditions.

The model also provides a quantitative way to identify potential bottlenecks, estimate resource utilization, evaluate permit processing delays, and compare alternative permitting

policies before an actual outbreak occurs. By doing so, the study supports preparedness planning and helps decision makers assess how movement control requirements can be implemented while maintaining necessary livestock movements and continuity of business. For example, animal health authorities could use the simulation results to estimate the number of administrative staff, trained personnel, and veterinarians needed to process an expected volume of permit requests. They could also evaluate alternative permitting procedures, such as expedited review for movements outside the control zone.

1.6 Thesis Organization

The remainder of this thesis is organized as follows. Chapter 2 reviews the literature on FMD outbreaks, movement control and permitting, economic impacts, disease modeling, and discrete-event simulation. Chapter 3 describes the discrete-event simulation model of the FMD movement permitting process, including the permitting workflow, model inputs and parameters, personnel resources, base case routing logic, control-zone-informed routing, and rework processes. Chapter 4 presents the simulation experiments and analyzes the effects of staffing levels, processing times, rework rates, and control-zone-informed permitting policies on system performance. Chapter 5 summarizes the main findings, discusses their implications, identifies study limitations, and outlines opportunities for future research.

Chapter 2. LITERATURE REVIEW

2.1 Overview

Foot-and-mouth disease (FMD) is one of the most widely studied livestock diseases because of its ability to disrupt production systems, international trade, and national economies. This chapter reviews how researchers have examined FMD outbreaks, evaluated control strategies, and planned for future responses. The discussion covers historical outbreak experiences, movement control and permitting policies, economic consequences, analytical and modeling methods, operational challenges, and the role of simulation. A key gap emerges from this literature: although movement permitting has repeatedly been identified as an important and resource intensive part of outbreak response, the staffing needs, processing times, and operational capacity required to manage large volumes of permit requests have not been well quantified. This study uses discrete-event simulation as a tool to address this gap.

2.2 Historical Outbreak Experiences and Lessons Learned

Several control strategies can be used during an FMD outbreak. Stamping out, also referred to as culling or depopulation, involves the removal of infected herds to eliminate sources of virus transmission. In countries where FMD is not endemic, this generally involves depopulating all susceptible animals in an infected herd rather than only those showing clinical signs. Depending on the outbreak situation and control policy, depopulation may also extend to dangerous-contact herds that have been exposed or are considered at high risk of infection, even if they do not show clinical signs. Large-scale depopulation can raise societal concerns, particularly regarding public acceptance and animal welfare. In addition, the loss of livestock can severely disrupt farm operations, reduce production capacity, and threaten the business continuity of affected producers (9).

Vaccination is used to reduce animals' susceptibility to infection and limit transmission, particularly when disease spread cannot be controlled effectively through culling alone. Movement control restricts the movement of animals, animal products, vehicles, equipment, and other potentially contaminated materials between premises or geographic areas to reduce opportunities for disease spread. These strategies may be used individually or in combination depending on the characteristics and scale of the outbreak (9, 33).

Vaccination practices differ among countries and regions. Many countries that are recognized as FMD free do not routinely vaccinate susceptible livestock, whereas some countries and zones maintain FMD free status while using systematic vaccination. In areas where FMD remains endemic, vaccination may be used routinely as part of disease control programs. Countries that do not routinely vaccinate may also introduce emergency vaccination during an outbreak when additional control is needed. Therefore, the role of vaccination in FMD control depends on the disease status and control policy of each country or region (55).

FMD remains an active and evolving global animal health threat. In 2025–2026, the World Organization for Animal Health (WOAH) reported the spread of FMD serotype SAT1 beyond its historical African range, with detections across Africa, the Middle East, Asia, and Europe. Recent reports included outbreaks or new occurrences in countries such as Lesotho, Egypt, Iraq, Kuwait, Israel, Palestine, China, Mongolia, Cyprus, Greece, Türkiye, and Lebanon (55). The Food and Agriculture Organization of the United Nations (FAO) also identified continued risk of further SAT1 spread across North Africa; Central, South and Western Asia; and Southeastern Europe (56). These developments demonstrate that the geographic distribution of FMD remains dynamic and highlight the continued importance of preparedness, including in areas that have historically been free of the disease (55, 56).

The 2001 outbreak of FMD in the United Kingdom is often used as a benchmark for studying large scale animal health crises. Control efforts led to the slaughter of roughly four million animals for disease control purposes. In addition, more than two million animals were slaughtered for welfare reasons because movement restrictions prevented normal movement and marketing. The economic costs were immense. Agriculture and the food chain lost an estimated £3.1 billion, while tourism related businesses lost between £2.7 and £3.2 billion. Although the estimated reduction in national GDP was less than 0.2%, this national level figure masks the much more severe economic effects experienced by agriculture and rural communities (19). Modeling work from this outbreak showed the importance of timely action. Delays in detection and movement restrictions increased the scale of the epidemic, while rapid, well targeted culling reduced transmission significantly (27).

Asian outbreaks illustrate the use of different FMD control strategies. In Japan's 2010 Miyazaki epidemic, culling was used extensively, with approximately 276,000 animals culled, while additional at-risk herds were vaccinated (28). In South Korea's 2010–2011 epidemic, emergency vaccination played a larger role in the response. This reduced the need for mass culling but was followed by delays in reopening export markets (29). In Taiwan's 1997 outbreak, large scale depopulation resulted in the destruction of more than four million pigs, while pork exports, particularly to Japan, were suspended for an extended period (30).

In South America, FMD outbreaks in Argentina and Uruguay during the 1990s and early 2000s led to the implementation of different disease-control strategies. During Uruguay's 2001 outbreak, authorities initially used stamping out but discontinued this approach early in the epidemic, shifting toward widespread vaccination and movement restrictions. These measures helped bring the outbreak under control relatively quickly, and Uruguay has continued routine

FMD vaccination since then. However, the outbreaks and associated trade restrictions also resulted in prolonged disruption to export market access (31). In Africa, FMD control is complicated by the continued circulation of multiple serotypes, including SAT1, SAT2, and SAT3, as well as by wildlife reservoirs such as African buffalo. Resource constraints and wildlife–livestock interactions can make sustained disease control and eradication particularly difficult (32).

Collectively, these experiences indicate that the effectiveness of culling, vaccination, and movement restrictions depends on timely implementation, consistent enforcement, and supporting systems such as permitting and surveillance. These operational factors can substantially influence the effectiveness of outbreak containment.

2.3 Control Strategies: Movement Restrictions and Permitting

Experience from other countries has shown that movement restrictions are important for controlling FMD but can also cause substantial economic and social disruption. U.S. preparedness plans address these competing concerns through risk-based permitting under the Secure Food Supply programs. The Secure Beef Supply and Secure Milk Supply plans require enhanced biosecurity measures, veterinary involvement, and movement records to support permitting decisions while allowing eligible movements to continue under disease-control requirements (34, 35).

Within a risk-based permitting framework, movement restrictions can also be differentiated according to the disease risk associated with the location of the premises and the proposed movement. A control zone is a geographically defined area around infected or high-risk premises where additional movement restrictions and control measures may be applied (9). Movements associated with the control zone may require greater scrutiny because they can

present a higher risk of disease spread, whereas movements occurring completely outside the control zone may be eligible for a reduced level of review when applicable disease-control requirements are satisfied.

This distinction is also important operationally. Applying the same level of permit review to all movements can increase workload and cause lower-risk requests to compete for the same administrative staff, trained staff, and veterinary resources needed to review higher-risk movements. Differentiating permitting pathways based on control zone status therefore provides a basis for evaluating how alternative review procedures affect the operational performance of the permitting system.

2.4 Economic and Social Consequences of Movement Control

Movement restrictions can create substantial indirect economic losses by limiting access to markets, disrupting trade, and interrupting livestock supply chains. These indirect costs may exceed the direct production losses caused by FMD. Pendell et al. (36) estimated that a U.S. outbreak could result in substantial regional economic losses depending on the scale and duration of the outbreak. Rich and Perry (38) found that movement restrictions can reduce smallholder income by limiting access to livestock markets.

The operational consequences of movement restrictions also differ across livestock sectors. Dairy operations are particularly sensitive to movement disruptions because milk must continue to move through the supply chain while disease control requirements are maintained (35). Beef operations can also face operational and economic challenges when normal cattle movements are delayed or restricted (34). These examples illustrate why prolonged movement restrictions can affect disease free premises as well as infected operations and why business continuity planning is an important part of FMD preparedness.

Models have been used to estimate the economic consequences of FMD outbreaks and associated movement restrictions. Partial equilibrium approaches focus primarily on changes within livestock and agricultural markets, while broader economic models can capture effects that extend to related sectors and the wider economy (37). These economic consequences also demonstrate the importance of an effective movement permitting system. Permitting allows necessary movements from eligible premises to continue under disease control requirements, helping animal health officials balance the need to reduce disease spread risk with the need to maintain livestock business continuity.

2.5 Operational Challenges in Permitting Systems

Movement permitting is an important operational component of foreign animal disease response because it allows necessary movements to occur while managing disease spread risk. Umber et al. (45) describe a risk based permitting framework designed to balance disease control with continuity of business. The framework establishes criteria and decision rules for evaluating movement requests, but it does not quantify the staffing requirements, processing times, or operational capacity needed to implement the permitting process at scale.

Kansas functional exercises provide a practical perspective on these operational demands. State agencies and industry groups reported that permit processing under simulated outbreak conditions required substantial personnel effort, including participation from veterinarians, information technology staff, and administrative personnel working under significant time constraints (10, 11). These experiences highlight the importance of evaluating whether available staffing and system capacity are sufficient to support movement permitting during a large-scale outbreak.

Information system coordination is another operational consideration. The Emergency Management Response System 2.0 (EMRS2) is USDA's information management system for foreign animal disease investigations and response activities (9). During an outbreak, information needed for movement permitting must be recorded and coordinated within the response information system, creating an additional information management requirement for the permitting process.

Movement control measures are also used in other agricultural disease control settings. For example, management of citrus greening has included restrictions on the movement of potentially infected plant material (46). Although this example involves plant rather than livestock disease, it illustrates the broader use of movement controls to reduce disease spread while maintaining necessary agricultural activities. However, the reviewed literature does not provide quantitative estimates of the staffing requirements, processing times, or operational capacity needed to manage movement permits during an FMD outbreak.

2.6 Simulation Approaches in Disease Preparedness

Simulation models play an important role in FMD preparedness because they allow researchers and decision makers to examine how disease may spread and how alternative control strategies may affect an outbreak. Epidemiological models such as InterSpread Plus (ISP), the North American Animal Disease Spread Model (NAADSM), and the Australian Animal Disease Spread model (AADIS) represent disease transmission across livestock populations and can be used to evaluate interventions such as movement restrictions, vaccination, quarantine, and depopulation (22, 39, 40).

More recent research has examined how livestock traceability and movement information can influence FMD outbreak response. Smith and Sanderson (57) used InterSpread Plus to

evaluate alternative levels of cattle traceability during simulated FMD outbreaks. Their results showed that improved traceability can reduce outbreak size and duration under some conditions and can also affect the number of premises requiring tracing and surveillance. This work further demonstrates the importance of livestock-movement information in outbreak modeling and response planning.

The structure and assumptions of these models can strongly influence projected outbreak outcomes. Halasa et al. (41) show that changes in assumptions about transmission between herds can lead to substantially different epidemic sizes. Buhnerkempe et al. (23) demonstrate how livestock shipment networks can contribute to long distance disease spread, while Yang et al. (42) show that contaminated livestock trucks can provide an additional pathway for transmission. Other modeling studies examine how early epidemic indicators may inform vaccination or depopulation decisions (43, 44).

Agent based models provide a more detailed representation by simulating individual actors such as farms, animals, or vehicles and their interactions. This level of detail can reveal transmission pathways that more aggregated approaches may overlook, although it generally requires more detailed data and greater computational effort. Other large-scale simulation approaches have also been used to evaluate disease response strategies and support policy planning. For example, Germann et al. (47) use a large-scale simulation to examine pandemic response strategies.

These approaches primarily address questions about disease transmission and the effects of control policies. They are less suited to representing operational processes such as permit request arrivals, staff assignments, queues, processing times, and resource constraints. This

distinction motivates the use of discrete-event simulation for examining the operational performance of an emergency movement permitting system.

2.7 The Role of Discrete-Event Simulation (DES)

2.7.1 What DES Offers

Discrete-event simulation (DES) models represent a system as a sequence of events occurring over time. It is particularly useful for processes involving queues, limited resources, and variable processing times. In an FMD movement permitting system, DES can represent permit arrivals, review activities, staff availability, and delays that occur when demand exceeds processing capacity. Because arrival and processing times can vary, DES can also be used to estimate workload, waiting times, resource utilization, and system performance under different operating conditions (48, 49, 50, 51).

DES therefore complements epidemiological models. Epidemiological models such as ISP, NAADSM, and AADIS focus primarily on disease transmission and the effects of outbreak control strategies (22, 39, 40), whereas DES provides a process level representation of workflows, queues, resource use, and processing delays. This makes DES well suited for evaluating the operational capacity and performance of an emergency movement permitting system.

The distinction is important because the modeling approaches address different questions rather than replacing one another. Epidemiological models help estimate how an outbreak may develop and how disease control strategies may affect transmission, while DES can evaluate whether the operational processes and resources needed to implement those strategies can handle the resulting workload.

2.7.2 Applications in Related Domains

Discrete-event simulation has been widely applied in healthcare, where uncertain arrivals, limited resources, queues, and variable service times create complex operational challenges. Healthcare simulation studies have examined patient flow, staffing, resource allocation, diagnostic services, and other process design decisions. Reviews of the literature show that DES is commonly used to evaluate patient flow, waiting times, resource utilization, and alternative system configurations before changes are implemented in practice (48, 49, 50). More recent reviews also demonstrate extensive use of DES and related simulation approaches in emergency departments, where demand, processing times, and resource availability can vary considerably (51).

Simulation and operations research modeling have also been used in public health preparedness, particularly for vaccination and mass dispensing operations. Lee et al. (52) demonstrate how modeling can support vaccine prioritization and pandemic response decisions, while the RealOpt platform has been used to support the planning and configuration of large-scale emergency dispensing operations (53). Related work on drive through mass vaccination clinics shows how simulation can be used to evaluate staffing arrangements, lane configurations, waiting times, and throughput before an emergency clinic is deployed (54). Together, these applications illustrate how simulation can help planners evaluate alternative operational designs under uncertain and time sensitive conditions.

A common finding across these healthcare and public health applications is that system performance depends not only on the total amount of available resources but also on how those resources are allocated across individual processing activities. Changes in staffing levels or processing times at one stage can affect downstream queues, waiting times, and overall system

throughput. DES is particularly useful for examining these relationships because it explicitly represents individual events, queues, resources, and processing activities (48, 49, 50, 51, 54).

Similar operational characteristics are present in emergency movement permitting during an FMD outbreak. Permit requests arrive over time, pass through multiple review activities, compete for limited personnel, and may accumulate in queues when demand exceeds processing capacity. The healthcare and public health preparedness literature therefore provides a methodological basis for examining movement permitting operations using DES. However, the reviewed literature provides limited quantitative analysis of the staffing requirements, processing times, queues, and operational capacity associated with large-scale FMD movement permitting.

2.7.3 The Research Gap

Preparedness exercises have identified movement permitting as an operationally demanding component of FMD response (10, 11). However, the staffing requirements, processing times, and system capacity needed to process large volumes of permit requests during an outbreak have not been well quantified in the reviewed literature. Existing risk based permitting research provides guidance for evaluating movement requests but does not quantify the resources and time required to implement the permitting process at scale (45).

Existing epidemiological models address other important questions, such as how disease may spread and how control strategies may affect outbreak outcomes. These models complement, rather than replace, analysis of the operational processes needed to implement movement controls. The reviewed literature does not provide a detailed quantitative representation of permit request workflows, queues, staffing constraints, and processing delays.

This study addresses that operational gap using discrete-event simulation. DES is used as a methodological tool to estimate staffing needs, processing times, resource utilization, delays, and system capacity under different outbreak and permitting policy conditions.

2.8 Summary

The literature demonstrates the substantial animal health, economic, and operational consequences associated with FMD outbreaks and movement restrictions. Existing research has advanced understanding of disease transmission, control strategies, economic impacts, and risk-based movement permitting. However, the operational requirements of large-scale movement permitting, including staffing needs, processing times, queues, resource utilization, and system capacity, have not been well quantified in the reviewed literature. Discrete-event simulation provides an appropriate approach for examining these operational questions because it can represent permit arrivals, processing activities, limited personnel resources, queues, and variable task times. The present study uses DES to address this operational gap by evaluating the performance and resource requirements of an FMD movement permitting system under different staffing, processing, rework, and permitting policy conditions.

Chapter 3. DISCRETE-EVENT SIMULATION MODEL OF THE FMD MOVEMENT-PERMITTING PROCESS

3.1 Introduction

Traditional epidemiological models of foot-and-mouth disease (FMD) primarily represent disease transmission and the effects of control strategies, but they do not typically account for the time and personnel required to implement movement permitting. Animal movements are an important pathway for FMD transmission, making the effective implementation of movement controls and permitting an important part of outbreak response. To address this gap, this chapter presents a discrete-event simulation that represents permit processing activities, staffing roles, queues, corrections, approvals, and rework, allowing delays and the effects of alternative policy choices to be evaluated. The model is designed around the permitting workflow used in Kansas and its interactions with other states, allowing alternative procedures and capacities to be tested under realistic demand. In doing so, the model helps evaluate how permitting policies affect operational performance while supporting the balance between disease control requirements and continuity of agricultural operations.

3.2 Permit Review Process

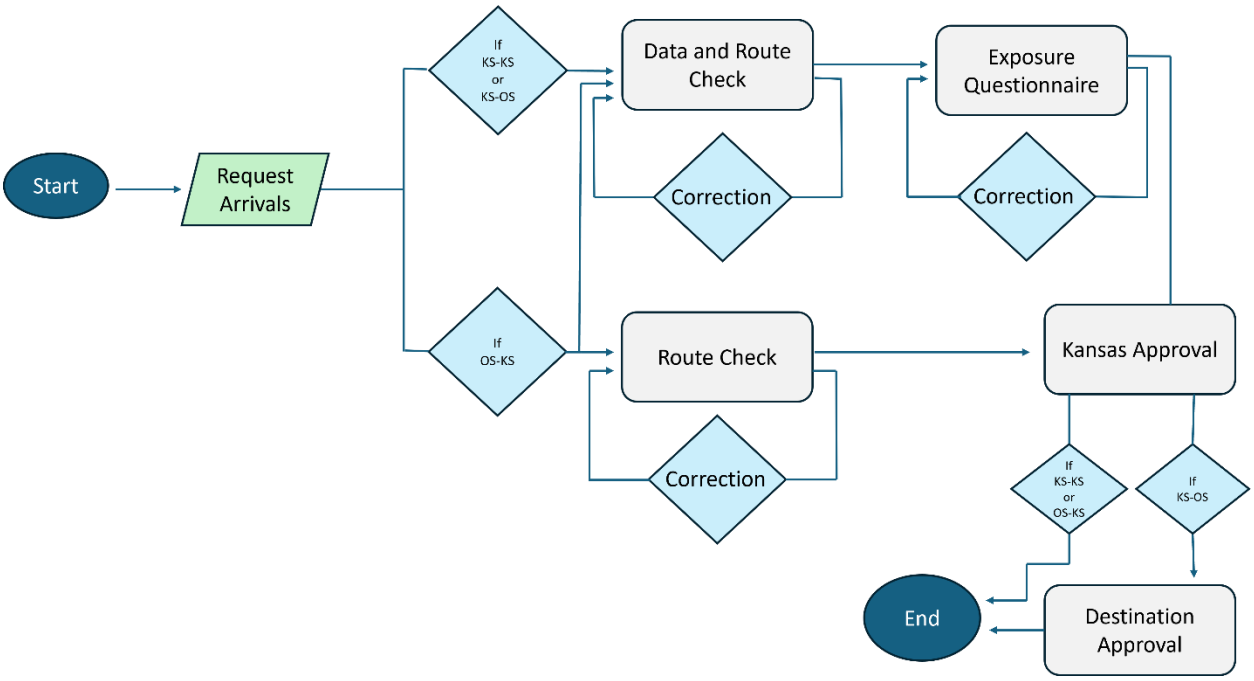


Figure 3.1. Review process for emergency livestock movement permit requests based on origin and destination.

Figure 3.1 depicts the process currently proposed by Kansas for reviewing movement permit requests in an FMD outbreak. The required steps depend on the origin and destination of the proposed movement. Movements are thus grouped into three categories: Kansas-to-Kansas (KS–KS), Kansas-to-other-state (KS–OS), and other-state-to-Kansas (OS–KS). The review requirements differ across these categories because interstate movements may require coordination between Kansas and the other state involved.

For KS–KS and KS–OS movements, the review begins with a Data Check and a Route Check. During the Data Check, administrative staff or trained staff review the submitted information for completeness and accuracy. During the Route Check, trained staff review the proposed movement route and determine whether it satisfies applicable movement restrictions. If missing or incorrect information is identified in either check, the request must be corrected before it can continue through the review process.

After the initial checks are completed, the request proceeds to the Exposure Questionnaire. A trained veterinarian reviews the information associated with the proposed movement. If additional information or clarification is required, the request is returned for correction or further review. Once the Exposure Questionnaire is completed satisfactorily, the request proceeds to Kansas Approval.

For a KS–KS movement, Kansas Approval completes the review because both the origin and destination are within the state. For a KS–OS movement, the request also requires Destination Approval from the receiving state before the movement can be authorized. For OS–KS movements, Kansas is the receiving state. Depending on the information and review already completed by the originating state, the request may proceed through the full Kansas review process or may require only Kansas route verification. Because Kansas is the destination state, a separate Destination Approval from another state is not required. The review conducted in Kansas may also account for verification already completed by the originating state.

The principal worker roles in the permitting process are administrative staff, trained staff, and trained veterinarians. Administrative staff support Data Check and approval activities; trained staff conduct route review and may also support Data Check and approval activities; and trained veterinarians are responsible for reviewing the Exposure Questionnaire.

3.3 Model Overview

The discrete-event simulation model was implemented in Simio, Version 17.261.39190 (Simio LLC 2024). The model uses sources, servers, a sink, and personnel resources to represent the permitting workflow and staff availability. Movement requests are generated from an external input table that provides the arrival time and request characteristics used to classify and route each request through the model.

The simulation represents the permitting process from request arrival to final approval or denial. Requests enter the model over time from the preprocessed movement table and proceed through the applicable review activities, correction pathways, Exposure Questionnaire, and jurisdictional approval stages. Permit requests follow different routing requirements based on their origin and destination.

Personnel resources are explicitly represented and constrained, allowing queues and delays to develop when demand exceeds available capacity. This structure allows the model to evaluate processing time, number of requests completed, queue development, and resource utilization under different staffing levels and permitting policies.

3.4 Model Inputs and Parameters

3.4.1 Movement Data and Processing

The livestock movement data used in this study are generated using InterSpread Plus (ISP) (22), a spatial and stochastic epidemiological simulation model. The ISP livestock network is based on representative cattle industry data, including county level farm and livestock population information from the National Agricultural Statistics Service (NASS), movement characteristics from National Animal Health Monitoring System (NAHMS) data, and simulated farm locations. These inputs allow ISP to generate livestock movements between premises during the simulated outbreak period.

The ISP output contains individual livestock movement records for a 30-day period. For each movement, the information used in this study includes the movement day, origin farm type, origin state, destination farm type, and destination state. These variables are used to determine when a movement occurs and whether its origin and destination are located within or outside Kansas.

The ISP output is preprocessed in an external spreadsheet before being imported into the discrete-event simulation model. Each movement is converted into a permit request, and only the information required by the permitting model is retained or derived. The processed dataset contains an event time, an origin state indicator, a destination state indicator, and a request class based on the origin–destination combination. Kansas is coded as 0 and another state as 1 for the origin and destination indicators. Based on these indicators, each request is classified as Request A (KS–KS), Request B (OS–KS), or Request C (KS–OS).

ISP identifies the day on which each livestock movement occurs but does not provide the exact arrival time required by the DES model. Therefore, the movements assigned to each day are distributed evenly across the 1,440 minutes of that day. Movements occurring on Day 1 are evenly distributed across the first 1,440 minutes of the simulation, movements occurring on Day 2 are evenly distributed across the following 1,440-minute interval, and the same procedure is applied to subsequent days. This conversion creates the event time variable while preserving the number of movements occurring on each ISP simulation day.

The resulting Processed Movements table is imported into Simio and used to generate permit request arrivals. The event time variable determines when each request enters the model, while the assigned request class determines the applicable permitting path. The origin and destination indicators are retained in the input table for verification of the request classification. Figure 3.2 illustrates the overall process of converting the InterSpread Plus livestock movement output into the input data used by the discrete-event simulation model.

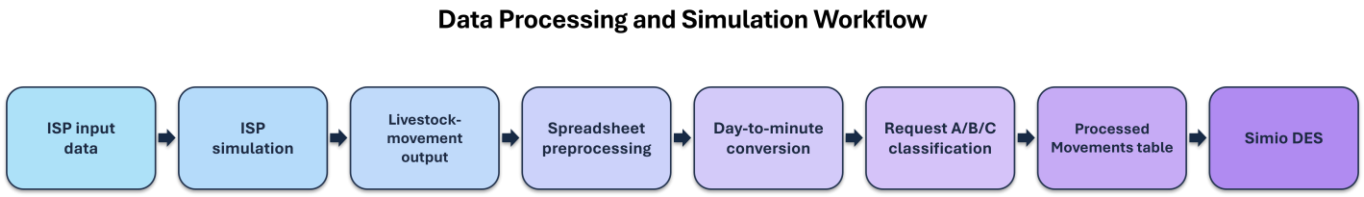


Figure 3.2. Conversion of InterSpread Plus livestock movement output into discrete-event simulation input data.

3.4.2 Processing Time and Rework Parameters

In addition to the movement request input data, the simulation requires parameters describing processing times, rework, routing, and personnel availability. Table 3.1 summarizes the model parameters and the values used in the base case configuration. The processing-time estimates were developed using principles from work measurement literature (21), information obtained during Kansas Department of Agriculture (KDA) foot-and-mouth disease preparedness exercises, and input from experienced animal health officials. The Data Check and Route Check times were estimated based on observations of one administrative staff member and one trained staff member, both experienced in related tasks and systems, during an exercise. Both activities required the use of the custom KDA web-based permitting tool. The Route Check also involved cross-referencing information in the permitting tool with control zone maps in the Emergency Management Response System 2 (EMRS2) to determine whether proposed movement routes were allowable. Although these observations did not constitute a formal time study, the estimated processing times were reviewed with animal health officials to confirm their reasonableness.

The Exposure Questionnaire review involves evaluating information about potential disease exposure, animal movements, and biosecurity practices. Because actual processing time data were unavailable, estimates were developed based on input from animal health experts

familiar with the permitting process. Their input provided an indication of how long the review could take and was used to establish the processing time assumptions for the simulation.

Table 3.1. Base case processing time distributions and routing parameters.

Process	Processing Time Distribution
Data Check	Triangular (4,6,9) min
Route Check	Triangular (5,7,10) min
Exposure Questionnaire	Pert (10,20,30) min
Kansas Approval	Triangular (2,3,4) min
Destination Approval	Triangular (2,3,4) min
Additional Correction	Constant 4 hours

Process Sequence Option	Proportion
Proportion of Request B (Other State to Kansas) permits that require route check only	50%
Proportion of permits denied at each step	1%

In the base case configuration as shown in Table 3.1, the Route Check follows a Triangular (5, 7, 10) minute distribution, while the Data Check follows a Triangular (4, 6, 9) minute distribution. The Exposure Questionnaire is represented using a Pert (10, 20, 30) minute distribution. The Pert distribution was selected because, compared with a triangular distribution using the same minimum, most likely, and maximum values, its conventional formulation assigns less probability to values near the minimum and maximum and more probability to the central range. This reflects the assumption that extremely short or long Exposure Questionnaire review times are less common. Kansas Approval and Destination Approval are each represented using a Triangular (2, 3, 4) minute distribution. Correction and rework activities include a four-hour delay to represent the time required for additional information or applicant response.

3.4.3 Resource Capacities and Routing Parameters

Personnel capacities and selected routing and rework parameters are also configurable. The base case staffing levels provide the reference configuration for the experiments, while alternative values are evaluated in Chapter 4. Similarly, rework probabilities and applicable routing proportions are varied across scenarios to examine their effects on processing time, number of requests completed, and resource utilization.

3.5 Request Classes and Resources

The model uses three request classes (entity type):

- **Request A**: movements within Kansas;
- **Request B**: movements into Kansas from another state;
- **Request C**: movements from Kansas to another state.

These classes encounter different routing and approval requirements, particularly with respect to destination approvals for outbound shipments.

Human resources are represented by three worker categories that correspond to the permitting activities described in Section 3.2:

- **Administrative staff** can perform the Data Check, Kansas Approval, and Destination Approval.
- **Trained staff** can perform the Data Check, Route Check, Kansas Approval, and Destination Approval.
- **Trained veterinarians** perform the Exposure Questionnaire review.

Where both administrative staff and trained staff are eligible for a task, the model preferentially assigns administrative staff. Exposure Questionnaire is restricted to trained veterinarians. This arrangement reflects the specialization and priority rules used in practice.

The experiments considered two staffing configurations, with either 20 or 30 personnel assigned to each of the three resource categories. These values were selected to evaluate the

sensitivity of system performance to changes in personnel capacity rather than to represent documented staffing levels available during an actual outbreak.

3.6 Model Implementation

Two versions of the discrete-event simulation model were developed in this study. The first represents the base case permitting in which control zone status is not used for routing, while the second incorporates control zone information to evaluate an alternative permitting policy.

In both models, permit requests enter the system using the arrival information and request classifications described previously. Requests proceed through the applicable review activities according to their request class and the permitting policy being evaluated. In the control-zone-informed model, requests first undergo the Data Check and Route Check. The model then determines whether the movement is associated with the control zone. Control zone related requests continue through the full permitting workflow, including the Exposure Questionnaire and applicable approval stages, while requests outside the control zone follow an expedited pathway to an approval or denial decision.

In the event of an FMD outbreak, officials will implement the review process for movement permit requests. Thus, the permitting system will start empty, and requests will arrive over time for as long as permit requirements remain in place. For this reason, the simulation models likewise begin with no requests in the system, and arrivals occur over time. All system configurations are simulated for 30 days. This is done to provide insight about system performance during the initial outbreak response. This choice does not imply that an actual outbreak response would conclude in 30 days.

3.6.1 Base Case Model and Routing Logic

Two permitting policies are compared in the simulation: the base case model and the control-zone-based model. The base case model does not use control zone status to determine the level of review, whereas the control zone-based model uses this information to distinguish between full review and expedited permitting pathways. Both models are evaluated under the same demand and staffing conditions to examine how incorporating control zone information into permit routing affects system performance.

Routing in the base case model is determined primarily by the request class. Request A (KS–KS) and Request C (KS–OS) enter the full permitting workflow. Request B (OS–KS) can follow either the full review process or the reduced Route Check pathway, depending on the specified routing proportion.

Within the full workflow, additional routing decisions occur after the Data Check and Route Check. Depending on the review outcome, a request may require Data Correction, Route Correction, both corrections, or may proceed directly to the Exposure Questionnaire. After the required review steps are completed, the request proceeds to the applicable approval stages. Destination Approval is required only for outbound KS–OS movements. Figure 3.3 presents the overall Simio implementation of the base-case permitting model. Figures 3.4 through 3.9 illustrate the individual model components, including request arrivals, review activities, correction pathways, and approval stages.

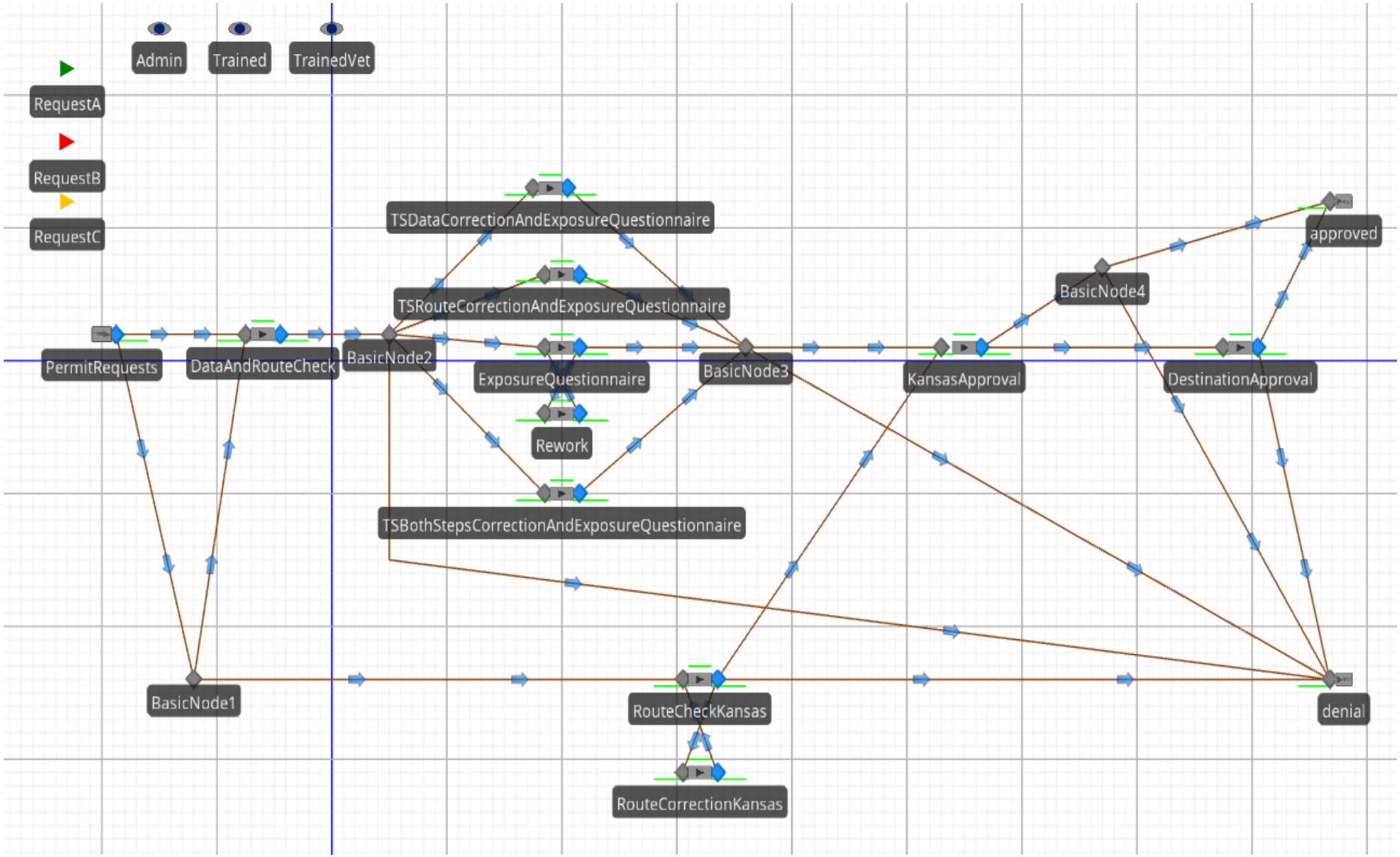


Figure 3.3. Screenshot of Simio implementation of the base case emergency movement permitting model.

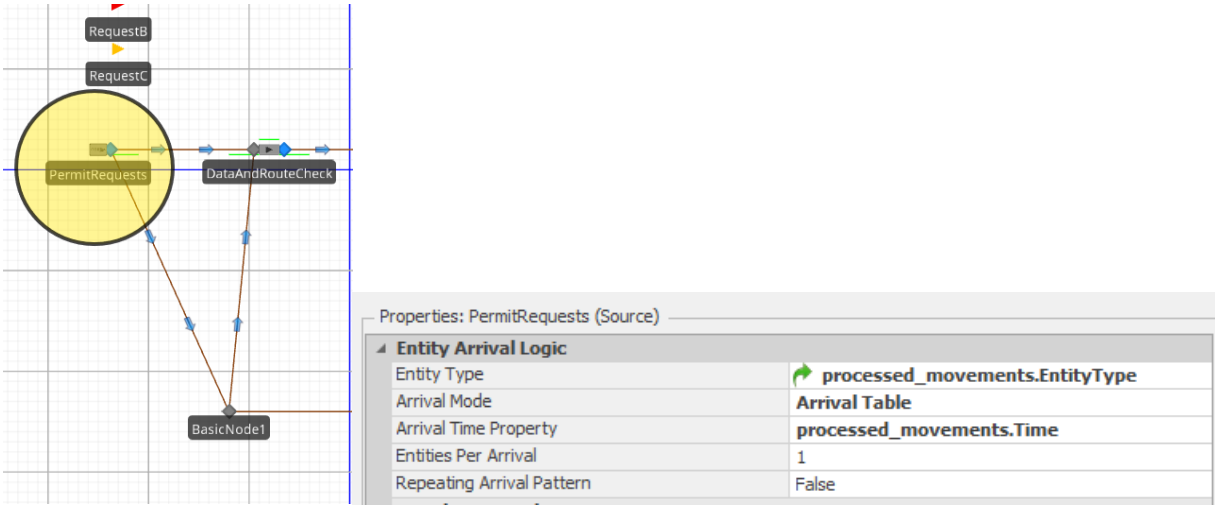


Figure 3.4. Simio Source node configuration for permit request class and arrival time.

- Requests enter the system at a Simio Source node that reads entity type (request class) and arrival time directly from the movement table.

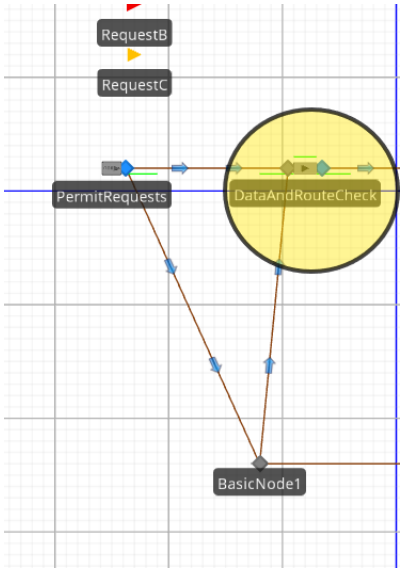


Figure 3.5. Simio configuration of the combined Data and Route Check stage.

- The first major processing stage is a combined Data and Route Check server is shown in Figure 3.5, where data checks and route checks run in parallel, drawing on the relevant resource lists (administrative staff /trained staff for data; trained veterinarians for route).

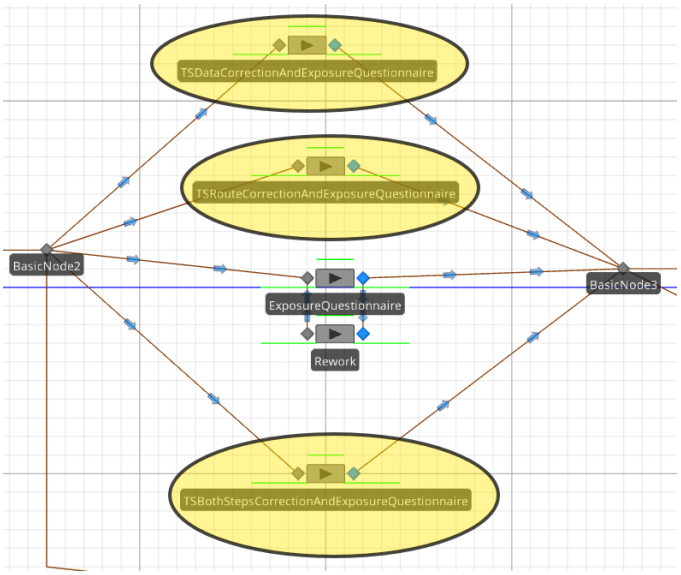


Figure 3.6. Simio configuration of permit correction pathways and Exposure Questionnaire processing.

- If issues are detected, the request is routed to one of three correction pathways: Data Correction + Exposure Questionnaire, Route Correction + Exposure Questionnaire, or Both Corrections + Exposure Questionnaire. Each is modeled as a task sequence with explicit precedence constraints, meaning that the required correction must be completed before the request proceeds to subsequent review activities. Figure 3.6 demonstrates these steps.

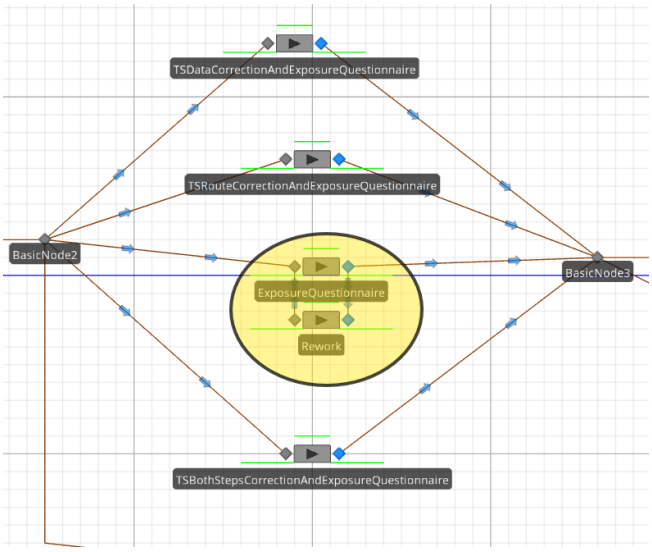


Figure 3.7. Simio configuration of the Exposure Questionnaire review and rework pathway.

- When no correction is needed, the request proceeds directly to the Exposure Questionnaire. Rework may occur after the initial review if additional information is required; in that case, the model includes a user response delay before the request returns for review.

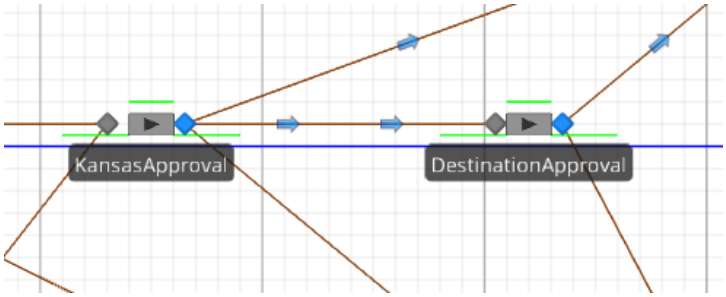


Figure 3.8. Simio configuration of Kansas and destination approval stages.

- Jurisdictional approvals are modeled explicitly. In Figure 3.8, Kansas Approval represents the in state authorization step, while Destination Approval represents the external jurisdiction's decision for outbound movements from Kansas.

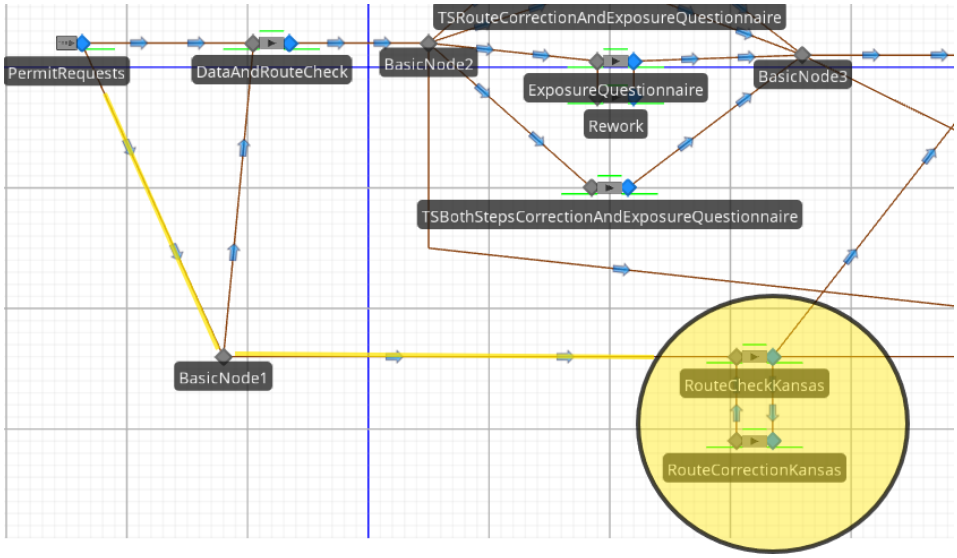


Figure 3.9. Simio configuration of the specialized Route Check Kansas pathway.

- Figure 3.9 illustrates a specialized lane, Route Check Kansas, handles cases that require only Kansas route verification. Modeling these as separate servers allows the simulation to express different capacities, processing times, and queues for each step.

3.6.2 Control-Zone-Informed Model and Routing Logic

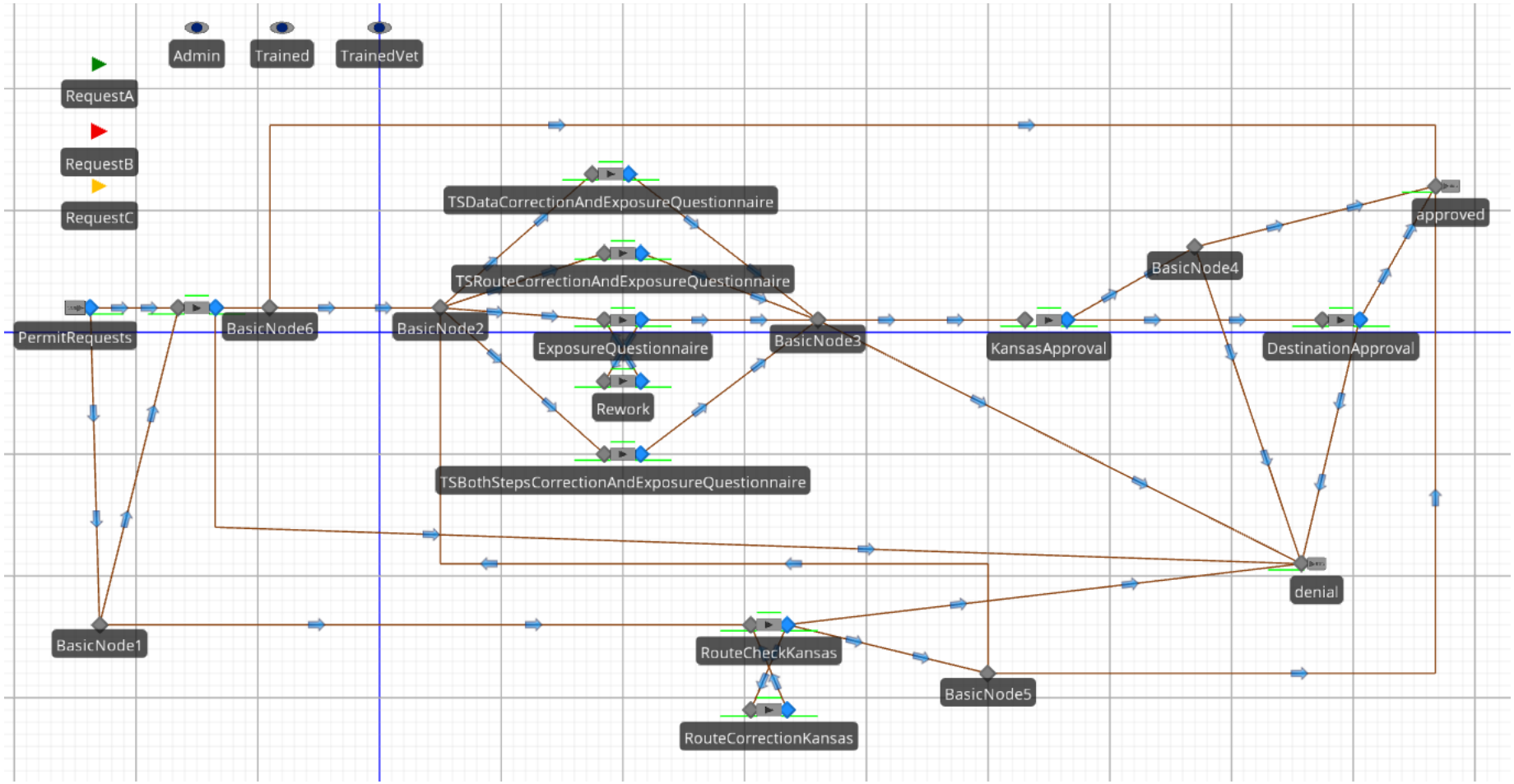


Figure 3.10. Screenshot of Simio implementation of the control-zone-informed emergency movement permitting model.

A second version of the discrete-event simulation model was developed to incorporate control zone information into the permitting process. The control-zone-informed model retains the same request classes, processing activities, and personnel resources as the base case model but adds a control zone routing decision. This allows the simulation to evaluate whether requests associated with the control zone should receive a different level of review from requests occurring outside the control zone. Figure 3.10 shows the Simio implementation of the control-zone-informed permitting model.

Permit requests enter the control zone-based model using the same arrival data and Request A, B, and C classifications described previously. Requests first undergo the Data Check and Route Check. Movement information is then used to determine whether the request is associated with a control zone. To represent control zone status, an additional binary indicator was included in the processed movement dataset for each permit request. A value of 0 identifies a request as control zone related, whereas a value of 1 identifies a request as outside the control zone. This indicator is read by the simulation and used in the routing logic to direct control zone related requests to the full permitting workflow and requests outside the control zone to the expedited pathway. Requests associated with the control zone proceed through the full permitting workflow, including the Exposure Questionnaire, Kansas Approval, and, when required for KS–OS movements, Destination Approval. Requests outside the control zone follow an expedited pathway that leads directly to an approval or denial decision without completing the full review process.

The Request A, B, and C classifications remain relevant because they determine the jurisdictional approval requirements after the control zone routing decision. In particular, Destination Approval is required only for movements from Kansas to another state. The control

zone classification therefore changes the level of review required, while the origin–destination classification continues to determine the applicable approval steps. Figure 3.11 compares the routing procedures used in the base case and control-zone-informed permitting models.

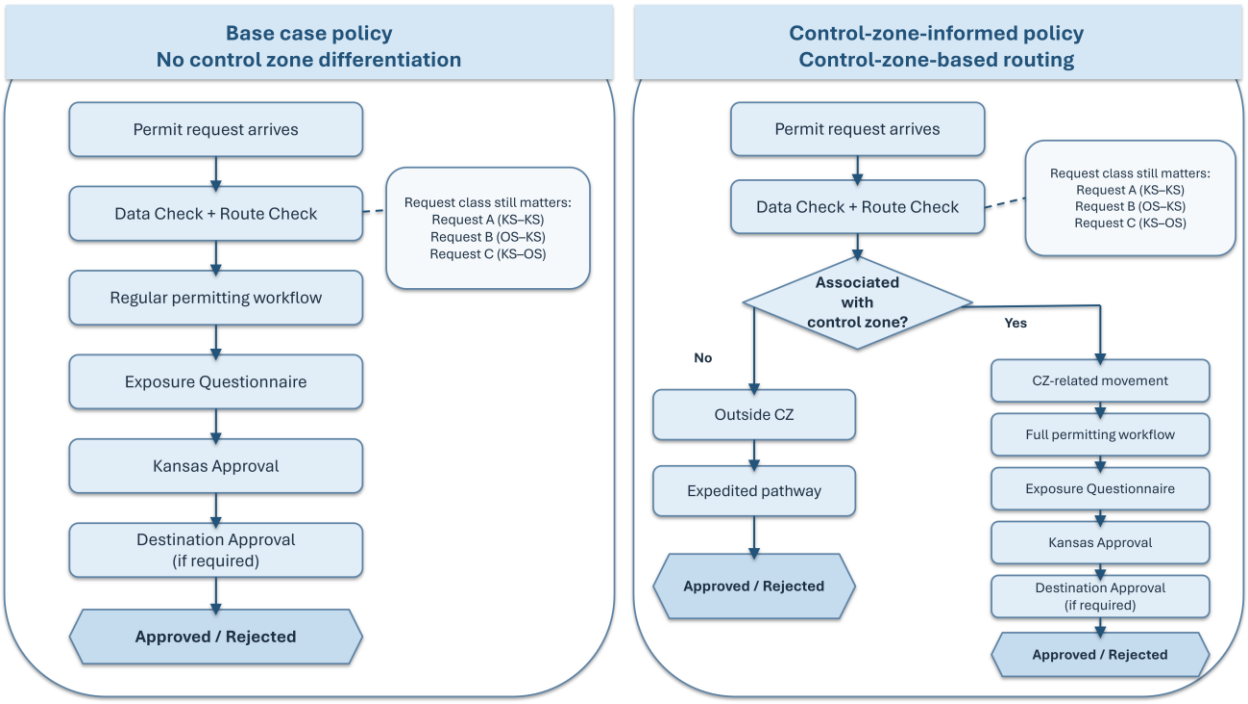


Figure 3.11. Comparison of base case and control-zone-informed permit routing policies.

3.7 Task Precedence and Rework

Each correction pathway enforces precedence: a correction must be completed before the associated review can continue, and Exposure Questionnaire rework can occur only after the initial questionnaire review has been completed. Rework does not occur for every request; instead, it is represented using a specified probability. This probability can be varied across simulation scenarios to examine how different levels of rework affect processing time, queues, number of requests completed, and resource utilization. When rework is required, the model adds a delay to represent the applicant's response time before the request returns for review.

3.8 Summary

This chapter presents the discrete-event simulation model developed to represent the FMD movement permitting process. The model captures permit request arrivals, request classes, review activities, personnel resources, correction and rework pathways, queues, and jurisdictional approvals. Two model configurations were described: a base case model and a control-zone-informed model that uses control zone status to distinguish between full review and expedited permitting pathways. The simulated movement patterns and modeling assumptions were reviewed with two Kansas Department of Agriculture experts to assess whether they were reasonable for the Kansas cattle industry. The model parameters and routing logic are configurable, allowing the effects of alternative staffing levels, processing times, rework rates, and permitting policies to be evaluated in the simulation experiments presented in Chapter 4.

Chapter 4. RESULTS AND ANALYSIS

This chapter presents the results of simulation experiments designed to evaluate how different operating conditions and permitting policies affect the performance of the emergency movement permitting system. Two permitting policies are examined: a base case policy, in which control zone status does not determine the level of review, and a control-zone-informed policy, which allows requests outside the control zone to follow an expedited pathway. The experiments examine the effects of four factors: rework rate, Exposure Questionnaire processing time, staffing level, and permitting policy. The results are evaluated using average permit processing time, number of requests completed, and resource utilization to understand how these factors influence the system's operational capacity.

4.1 Base Case

The base case represents the reference scenario used to evaluate the performance of the simulation model under a defined set of standard conditions. It provides a consistent benchmark for the study, allowing the results from alternative test scenarios to be compared with the same starting condition. Changes in model parameters can therefore be evaluated relative to the base case to determine how they improve or degrade the overall performance of the permitting process.

4.1.1 Base Case Assumptions

The base case simulation is conducted over a 30-day planning horizon, during which movement permit requests are received and processed under the assumed FMD outbreak conditions. During this period, each worker is assumed to be available for eight hours per day and five days per week to perform the tasks represented in the model, with a one-hour break scheduled in the middle of each workday. This work schedule is used to define the daily

processing capacity of the personnel involved in reviewing and handling permit requests. Requests may continue to enter the system outside normal working hours and remain in the queue until the appropriate personnel become available. Two staffing configurations were evaluated to examine the sensitivity of permitting system performance to personnel availability. The first configuration included 20 administrative staff, 20 trained staff, and 20 trained veterinarians, while the second included 30 personnel in each category. These levels were selected as hypothetical resource-capacity scenarios to represent a lower and a higher staffing condition and to evaluate the effect of a 50% increase in personnel availability across the three resource categories. Comparing these configurations allows the analysis to quantify changes in permit processing times, number of requests completed, and resource utilization as staffing capacity increases. The selected staffing levels are experimental assumptions and do not represent verified staffing availability or official staffing recommendations from the Kansas Department of Agriculture.

4.1.2 Data Input for Base Case

The original InterSpread Plus (ISP) dataset contains 101,296 livestock movements involving Kansas over the 30-day simulation period. Based on origin and destination, the full dataset includes 42,819 Request A movements (42.27%), 34,527 Request B movements (34.09%), and 23,950 Request C movements (23.64%).

This analysis focuses on the system's capacity to process movement permit requests with animal-welfare implications. Therefore, a subset was selected from the 101,296 livestock movements generated by ISP. Movements were retained if their destination was a slaughter facility or if they originated from a dairy operation and were directed to a dairy heifer calf operation or cattle dealer. These criteria were used to identify movements likely to have animal-

welfare implications. After applying the criteria, 21,537 movements were retained and represented as permit requests in the simulation experiments described here.

These 21,537 retained movements form the base demand for the simulation and provide the common workload used to evaluate processing time, number of requests completed, and resource utilization under different operating conditions.

Within the 21,537 filtered movements, Request A represents movements from one location in Kansas to another location in Kansas: these account for approximately 42% of the permit requests. Request B includes movements originating in another state and entering Kansas (approximately 36%), while Request C represents movements originating in Kansas and traveling to another state (approximately 22%). This classification is important because each request class can follow a different review and approval pathway in the simulation, affecting processing time, staffing requirements, and overall system workload.

The resulting filtered movement dataset and associated modeling assumptions were reviewed with Kansas Department of Agriculture subject matter experts and deemed reasonable for representing cattle movements relevant to emergency permitting in Kansas.

4.2 Test Scenarios

The simulation experiments evaluate how changes in rework probabilities, processing time distributions, staffing levels, and permitting policies affect system performance. Each scenario varies one or more model parameters relative to the base case configuration to evaluate the operational effect of alternative conditions. Processing time, number of requests completed, and resource utilization are used to evaluate the simulation results. Average permit processing time is the average time between receiving a permit request and making a final decision to approve or deny it, calculated for requests completed within the 30-day planning horizon.

Number of requests completed is the total number of permit requests that complete the review process, either through approval or denial, during the planning horizon. Resource utilization is the proportion of available working hours that personnel in each resource category spend performing permit review tasks.

Several test scenarios were developed to evaluate how changes in key model parameters affect the performance of the movement permitting process. First, the percentage of permit requests requiring rework was varied at 3%, 7%, and 10% to determine how incomplete or corrected requests could affect workload and create additional delays in the permitting process.

The processing time for the Exposure Questionnaire was also varied to represent uncertainty in the amount of time required to complete this activity. Three Pert distributions were evaluated: Pert (10, 20, 30), Pert (8, 15, 25), and Pert (5, 12, 20) minutes, representing different assumptions regarding minimum, most likely, and maximum processing times.

The number of workers available for each resource type, administrative staff, trained staff, and trained veterinarians, varied across two staffing levels of 20 and 30 workers. This makes it possible to examine how workforce capacity influences permit processing time, waiting time, queue formation, and overall system performance. Personnel utilization was calculated as the proportion of on-shift time spent busy, using Time Busy/(Time Busy + Time Idle). Ten simulation replications were conducted for each scenario. The adequacy of the replication count was evaluated using the precision of the confidence intervals for the primary simulation outputs, as described below.

Two permitting policies were evaluated: the base case policy and the control-zone-informed policy. Under the base case policy, permit requests follow routing procedures based on their origin and destination, without using control zone status to determine the level of review.

Under the control-zone-informed policy, requests associated with the control zone follow the full permitting workflow, while requests outside the control zone follow an expedited pathway. These policies were compared to evaluate how control-zone-based routing affects processing time, number of requests completed, and resource utilization.

The nine parameter combinations shown in Table 4.1 were evaluated under both the base case and control-zone-informed permitting policies, with staffing levels of 20 and 30 workers in each resource category. For the control-zone-informed policy, two additional levels of control zone demand were examined: 2,000 and 5,000 control-zone-related requests.

Table 4.1. Experimental scenarios for Exposure Questionnaire processing time and rework rate.

Scenario	Exposure Questionnaire processing time distribution (min)	Rework Rate
S1	PERT (10,20,30), long	3%, low
S2	PERT (8,15,25), moderate	3%, low
S3	PERT (5,12,20), short	3%, low
S4	PERT (10,20,30), long	7%, moderate
S5	PERT (8,15,25), moderate	7%, moderate
S6	PERT (5,12,20), short	7%, moderate
S7	PERT (10,20,30), long	10%, high
S8	PERT (8,15,25), moderate	10%, high
S9	PERT (5,12,20), short	10%, high

The reported results represent averages across replications conducted using the same parameter settings. This approach reduces the influence of random variation within an individual

simulation run and allows the effects of staffing levels, questionnaire processing times, and rework rates on the performance of the permitting system to be compared more consistently.

For the control zone experiments, the number of control-zone related requests was set at either 2,000 or 5,000 while maintaining the total demand of 21,537 permit requests. The control zone requests were allocated among Requests A, B, and C according to the approximate proportions observed in the filtered movement dataset: 42%, 36%, and 22%, respectively. Within each case, the control-zone-related requests were distributed evenly across the 30-day simulation period.

4.3 Replications

4.3.1 Method

Ten independent simulation replications were conducted for each experimental scenario to account for variability arising from stochastic processing times and routing decisions. Replication adequacy was evaluated using the confidence-interval half-width method described in *Simulation Modeling and Analysis* by Law (58). This method assesses the precision of an estimated mean by comparing the half-width of its confidence interval with a specified precision target. Performing more replications increases the precision of estimates derived from the simulation results at the expense of added computation time. For each scenario, Simio reports a summary mean and a 95% confidence-interval half-width based on the ten replications. The relative half-width was calculated as:

$$\text{Relative half-width} = \frac{h}{\bar{x}}\ x\ 100,$$

where h is the confidence-interval half-width and $\bar{x}$ is the sample mean.

A relative half-width threshold of 2% was selected as the study-specific precision criterion. The corresponding target absolute half-width was calculated as:

$$d = 0.02\bar{x}.$$

The relationship between the confidence-interval half-width h, the sample standard deviation, and the number of independent replications n_0 is given by:

$$h = t_{0.975,n-1}\frac{s}{\sqrt{n_0}},$$

where $t_{0.975,n_0-1}$ is the critical value from Student's t distribution for a two-sided 95% confidence interval with $n_0 - 1$ degrees of freedom. Simio directly reports the confidence-interval half-width for the ten replications, this relationship was used to calculate the sample standard deviation from the reported half-width. Standard deviation is then used to examine the precision that could be achieved with fewer replications.

Using the standard deviation, the minimum replication count for the example output was evaluated by identifying the smallest integer n for which the estimated confidence-interval half-width $\hat{h}_n$ met the selected precision criterion:

$$\hat{h}_n = t_{0.975,n-1}\frac{s}{\sqrt{n}} \leq d.$$

4.3.2 Example Calculation

As an example, Scenario 1 of the base case model with 20 personnel in each resource category was considered for Request A. Based on ten simulation replications, Simio reported an average time in system of $\bar{x} = 6.876$ days and a 95% confidence-interval half-width of $h =$ 0.043 days.

The relative half-width was calculated as:

$$\textit{Relative half-width} = \frac{0.043}{6.876}\ x\ 100\ =\ 0.63\%$$

The calculated relative half-width of 0.63% is below the selected 2% precision criterion, indicating that the ten replications provide sufficient precision for this output measure.

The corresponding target absolute half-width for the selected 2% precision criterion was:

$$d = 0.02\bar{x} = 0.02(6.876) = 0.13752 \text{ days.}$$

The calculated value of 0.13752 days represents the maximum acceptable confidence interval half-width under the selected 2% precision criterion. Since the half-width reported by Simio was 0.043 days, the ten-replication result satisfied this criterion.

The confidence-interval half-width reported by Simio was used to calculate the sample standard deviation, which was then used to determine the minimum number of replications needed to meet the selected precision criterion.

$$s = \frac{h\sqrt{n_0}}{t_{0.975,n_0-1}} \quad \text{with} \quad h = 0.043,\ n_0 = 10,\ t_{0.975,9} = 2.262$$

$$s = \frac{0.043\sqrt{10}}{2.262} = 0.0601 \text{ days}$$

Using this standard deviation, the estimated confidence-interval half-width for three replications was:

$$\hat{h}_3 = t_{0.975,3-1}\frac{s}{\sqrt{3}} = 0.1493 \text{ days.}$$

This corresponds to approximately 2.17% of the estimated mean, exceeding the selected 2% precision criterion.

For four replications, $\hat{h}_4 = 0.0956$ days

This corresponds to approximately 1.39% of the estimated mean, satisfying the precision criterion. Therefore, four replications were estimated to be sufficient for this particular output measure, based on the sample standard deviation estimated from the ten-replication experiment.

4.3.3 Summary of Implications for the Study

The precision of the average time-in-system estimates was examined for Requests A, B, and C across the experimental scenarios. The evaluated results satisfied the selected 2% relative

half-width criterion. Although the example calculation indicated that four replications would be sufficient for the selected output measure, ten replications were retained consistently across the experimental scenarios to provide a common basis for comparing staffing levels, Exposure Questionnaire processing times, rework rates, and permitting policies.

4.4 Results of Experiments

4.4.1 Effect of Rework Rate

4.4.1.1 Effect of Rework Rate with 20 Resources

The first comparison examines the effect of increasing the rework rate while maintaining a constant workforce of 20 administrative staff, 20 trained staff, and 20 trained veterinarians. To isolate the effect of rework, scenarios with the same Exposure Questionnaire processing time distribution are compared. The results show that increasing the rework rate reduces the number of permit requests completed within the 30-day simulation period. With 20 personnel in each resource category and the Exposure Questionnaire processing time held at Pert (10, 20, 30), the number of completed requests decreases from 12,011 in S1 (3% rework) to 11,967 in S4 (7% rework) and 11,949 in S7 (10% rework), as shown in Table 4.2. A similar pattern is observed for Pert (8, 15, 25), where completed requests decrease from 14,064 in S2 to 13,884 in S8, and for Pert (5, 12, 20), where they decrease from 16,381 in S3 to 14,774 in S9. These results indicate that additional rework places greater demands on the available personnel and reduces the number of requests that can be completed during the simulation period.

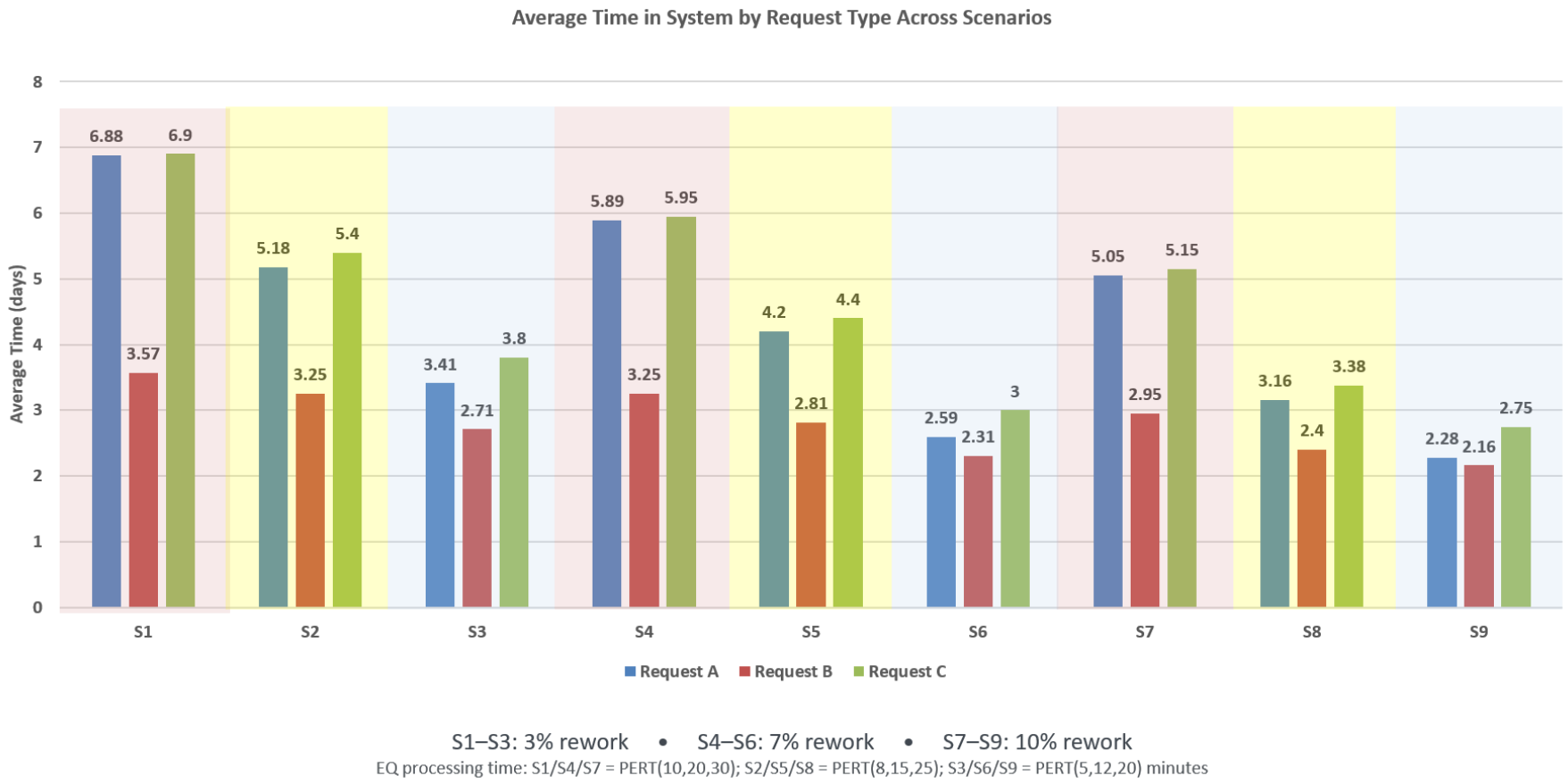


Figure 4.1. Average permit processing time (days) by request type for base case scenarios with 20 personnel in each resource category

Table 4.2. Permit outcomes and total requests processed across base case scenarios with 20 personnel in each resource category.

Scenario	Exposure Questionnaire Processing Time	Rework Rate	Approved	Denied	Total Requests Processed
S1	Long	Low	11603	407	**12011**
S2	Moderate	Low	13607	457	**14064**
S3	Short	Low	15885	495	**16381**
S4	Long	Moderate	11555	413	**11967**
S5	Moderate	Moderate	13466	467	**13932**
S6	Short	Moderate	15320	491	**15811**
S7	Long	High	11538	411	**11949**
S8	Moderate	High	13428	456	**13884**
S9	Short	High	14289	485	**14774**

A secondary observation is that the average time in system for completed requests also decreases as rework increases, as illustrated in Figure 4.1. For example, under Pert (10, 20, 30), the average times for Requests A, B, and C decrease from 6.88, 3.57, and 6.90 days in S1 to 5.05, 2.95, and 5.15 days in S7, respectively. These averages include only requests completed within the 30-day simulation period. Consequently, the decrease should not be interpreted as an improvement in overall system performance, particularly because fewer requests are completed under higher rework rates.

4.4.1.2 Effect of Rework Rate with 30 Resources

The next comparison examines the effect of increasing the rework rate while maintaining a constant workforce of 30 administrative staff, 30 trained staff, and 30 trained veterinarians**.** To

isolate the effect of rework, scenarios with the same Exposure Questionnaire processing time distribution are compared.

The same relationship between rework and the number of completed requests is observed when staffing increases to 30 personnel in each resource category. As shown in Table 4.3, under Pert (10, 20, 30), the number of completed requests decreases from 16,348 in S1 to 16,215 in S4 and 15,477 in S7 as the rework rate increases from 3% to 7% and 10%. Under Pert (8, 15, 25), completed requests decrease from 18,624 in S2 to 15,883 in S8, while under Pert (5, 12, 20), they decrease from 19,147 in S3 to 15,887 in S9. The latter represents 3,260 fewer completed requests over the same 30-day period. These results show that increasing rework reduces the number of requests completed even with additional staffing.

Figure 4.2 also shows a decrease in the average time in system among requests completed during the simulation period. For example, under Pert (10, 20, 30), the average times for Requests A, B, and C decrease from 3.67, 2.27, and 3.76 days in S1 to 1.95, 1.50, and 2.01 days in S7, respectively. However, these averages reflect only completed requests and do not account for the time accumulated by requests remaining unfinished at the end of the simulation. The reduction in completed requests is therefore the more important indicator of the effect of increasing rework on system performance.

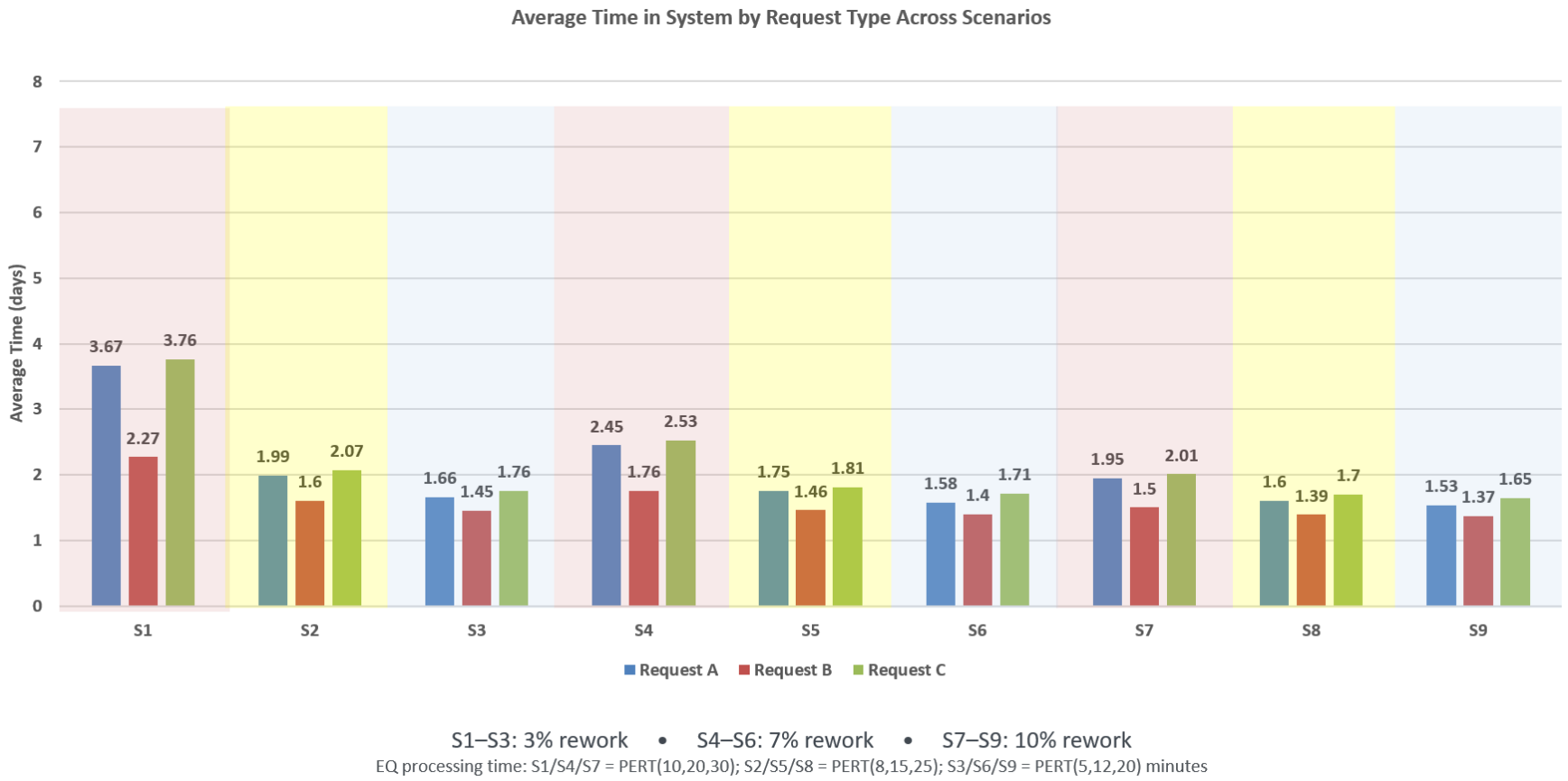


Figure 4.2. Average permit processing time (days) by request type for base case scenarios with 30 personnel in each resource category

Table 4.3. Permit outcomes and total requests processed across base case scenarios with 30 personnel in each resource category.

Scenario	Exposure Questionnaire Processing Time	Rework Rate	Approved	Denied	Total Requests Processed
S1	Long	Low	15851	497	**16348**
S2	Moderate	Low	18070	554	**18624**
S3	Short	Low	18592	555	**19147**
S4	Long	Moderate	15721	494	**16215**
S5	Moderate	Moderate	16553	518	**17070**
S6	Short	Moderate	16835	520	**17355**
S7	Long	High	15000	477	**15477**
S8	Moderate	High	15397	486	**15883**
S9	Short	High	15403	484	**15887**

Therefore, the average processing time and number of requests completed again need to be interpreted together. Although the reported average processing time decreases as the rework rate increases, the system simultaneously completes fewer requests. That is, increasing rework reduces the effective processing capacity of the permitting system because requests requiring rework consume additional staff resources.

4.4.1.3 Cumulative Permit Request Arrivals and Completions

To further examine the temporal behavior of the permitting system, cumulative arrivals and completions were analyzed for Scenario S1 of the base case model with 30 administrative staff, 30 trained staff, and 30 trained veterinarians. The analysis used the full arrival schedule of

21,537 permit requests over the 30-day simulation period and individual entity-level completion records from two replications.

Figure 4.3 presents the cumulative number of requests entering and completing the permitting process over time. The solid line represents all scheduled arrivals, which are identical across the two replications, while the dashed and dash-dotted lines represent the completed requests in Replications 1 and 2, respectively.

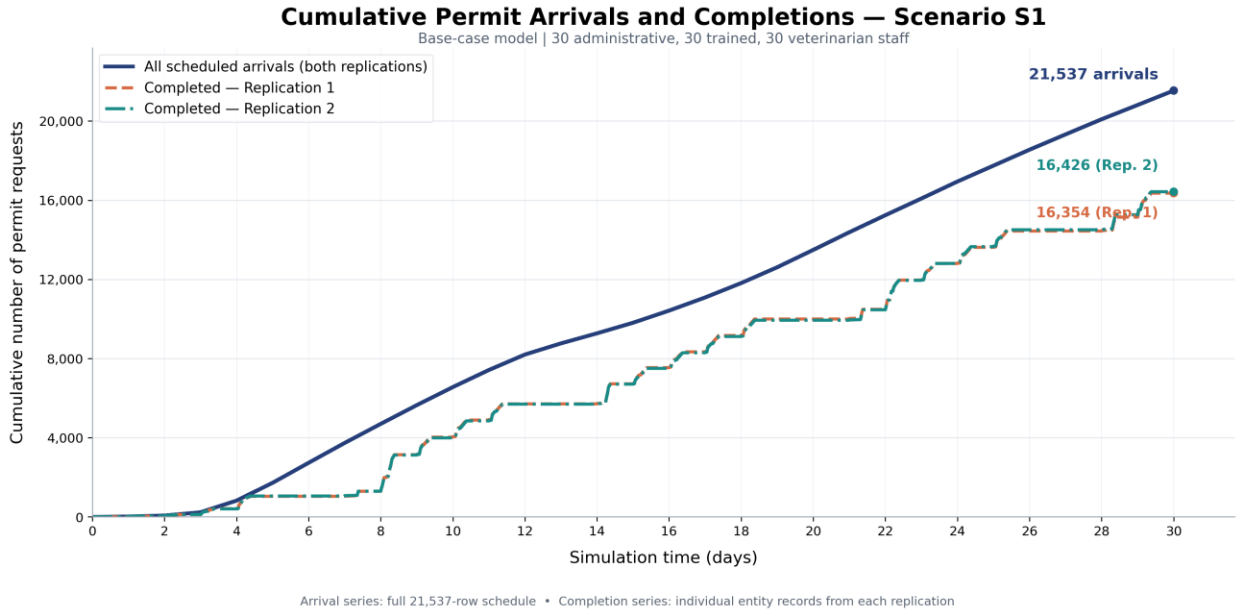


Figure 4.3. Cumulative permit request arrivals and completions over the 30-day simulation period for Scenario S1 of the base case model with 30 resources in each personnel category, Replications 1 and 2.

As shown in Figure 4.3, cumulative arrivals increase throughout the simulation period, reaching 21,537 requests by Day 30. In contrast, the number of completed requests reaches 16,354 in Replication 1 and 16,426 in Replication 2, corresponding to approximately 75.93% and 76.27% of total arrivals, respectively. At the end of the simulation period, 5,183 requests in Replication 1 and 5,111 requests in Replication 2 had not completed processing. These results

demonstrate that the available personnel capacity was insufficient to complete all incoming requests within the 30-day period under Scenario S1.

The cumulative completion curves exhibit periodic horizontal segments during Days 6–7, 13–14, 20–21, and 27–28. These intervals correspond to weekends in the model's five-day working schedule, during which administrative staff, trained staff, and trained veterinarians are not scheduled to process requests. Consequently, cumulative completions remain unchanged during these periods, while permit arrivals continue according to the predefined arrival schedule.

The separation between cumulative arrivals and completions illustrates the accumulation of requests that have entered the system but have not yet completed processing. This difference reflects the combined effects of personnel capacity, processing requirements, queueing delays, and the working schedule. The similar completion patterns across the two replications also indicate relatively consistent number of requests completed under the same scenario conditions.

This time-based analysis complements the average processing times and total completed requests presented in the preceding sections by demonstrating how unfinished requests accumulate throughout the simulation period.

4.4.2 Effect of Exposure Questionnaire Processing Time

4.4.2.1 Effect of Exposure Questionnaire Processing Time with 20 Resources

This section describes the effect of reducing the Exposure Questionnaire processing time**,** while keeping both the workforce and rework percentage constant. This comparison provides a particularly clear pattern.

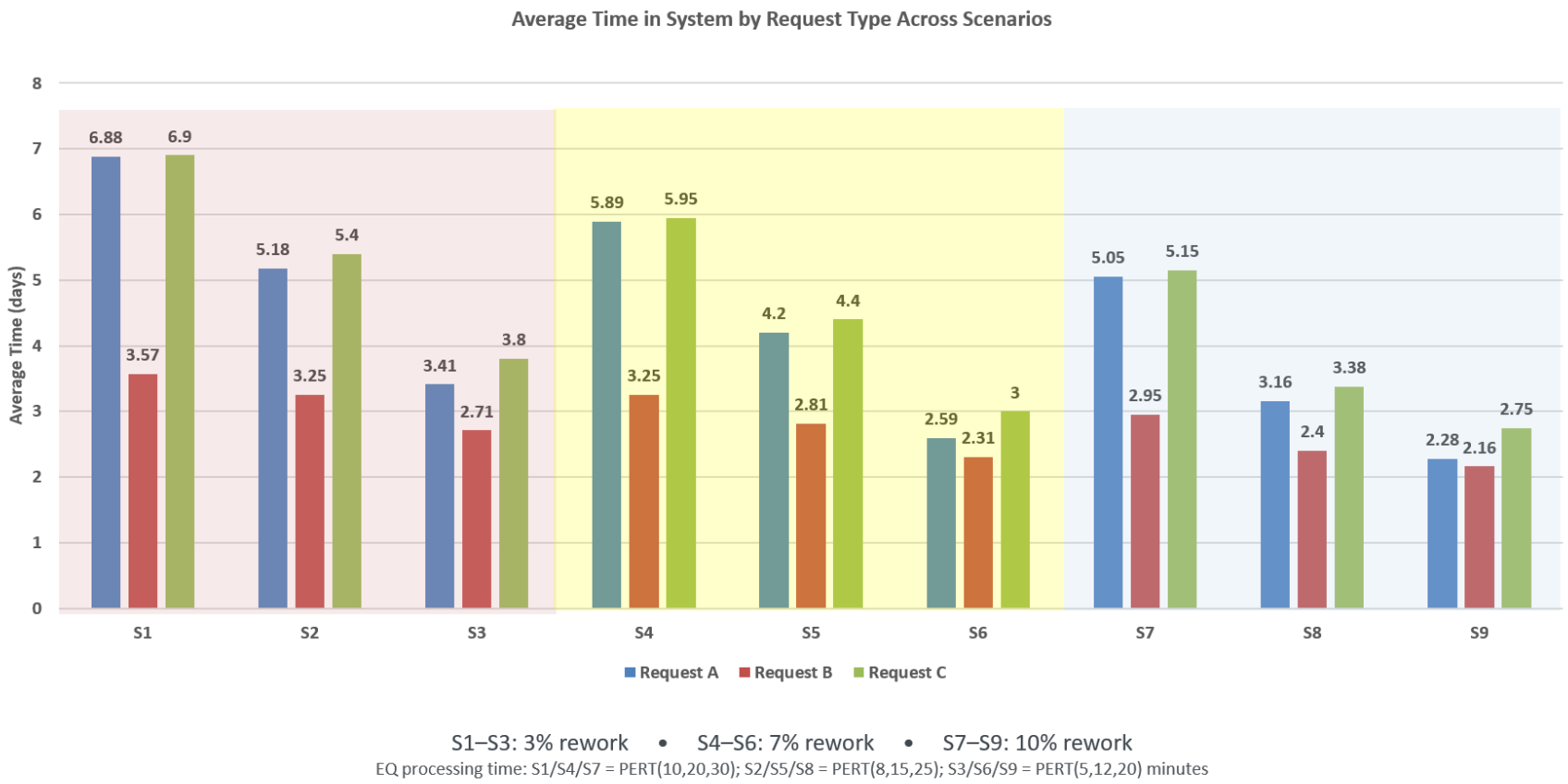


Figure 4.4. Effect of Exposure Questionnaire processing time (minutes) on average permit processing time (days) for base case scenarios with 20 personnel in each resource category.

At a 3% rework rate, scenarios S1, S2, and S3 use the same workforce of 20 workers of each type, while the Exposure Questionnaire completion times decrease; these times follow Pert (10,20,30), Pert (8,15,25), and Pert (5,12,20), respectively.

As shown in Table 4.2, as Exposure Questionnaire processing time decreases, the total number of completed requests increases from 12,011 in S1 to 14,064 in S2 and 16,381 in S3. At the same time, as shown in Figure 4.3, the average processing time for Request A decreases from 6.88 to 5.18 and 3.41 days, Request B decreases from 3.57 to 3.25 and 2.71 days, and Request C decreases from 6.90 to 5.40 and 3.80 days.

The same general relationship is observed at the other rework levels. At 7% rework, total requests processed increase from 11,967 in S4 to 13,932 in S5 and 15,811 in S6 as Exposure Questionnaire processing time decreases. At 10% rework, number of requests completed similarly increases from 11,949 in S7 to 13,884 in S8 and 14,774 in S9. Average processing times also decline across these comparisons. Therefore, unlike the rework comparison, the Exposure Questionnaire results show improvement in both major performance measures simultaneously: requests are completed more quickly, and a larger number of requests are processed within the same 30-day period.

4.4.2.2 Effect of Exposure Questionnaire Processing Time with 30 Resources

The next comparison examines the effect of reducing the Exposure Questionnaire processing time while keeping the workforce and rework percentage constant. At 3% rework, scenarios S1, S2, and S3 provide the clearest comparison. As the processing time distribution decreases from Pert (10,20,30) in S1 to Pert (8,15,25) in S2 and Pert (5,12,20) in S3, the average processing time for Request A decreases from 3.67 to 1.99 and 1.66 days. Request B decreases

from 2.27 to 1.60 and 1.45 days**,** while Request C decreases from 3.76 to 2.07 and 1.76 days as shown in Figure 4.4**.**

The number of requests completed results show a corresponding improvement. At 3% rework, the total number of requests processed increases from 16,348 in S1 to 18,624 in S2 and 19,147 in S3**.** Therefore, reducing Exposure Questionnaire processing time allows the same 30 worker workforce to process substantially more permit requests while simultaneously reducing average processing time.

The same overall relationship is observed at higher rework rates as shown in Table 4.3. At 7% rework, total requests processed increase from 16,215 in S4 to 17,070 in S5 and 17,355 in S6, while average processing times also decrease. At 10% rework, number of requests completed increases from 15,477 in S7 to 15,883 in S8 and 15,887 in S9, again accompanied by reductions in average processing time. However, the improvement becomes progressively smaller as rework increases. For example, at 3% rework, changing from Pert (10,20,30) to Pert (5,12,20) increases number of requests completed by 2,799 requests, whereas at 10% rework the corresponding increase is only 410 requests. This suggests an important interaction: improving Exposure Questionnaire processing time is most beneficial when the rework rate is also kept low.

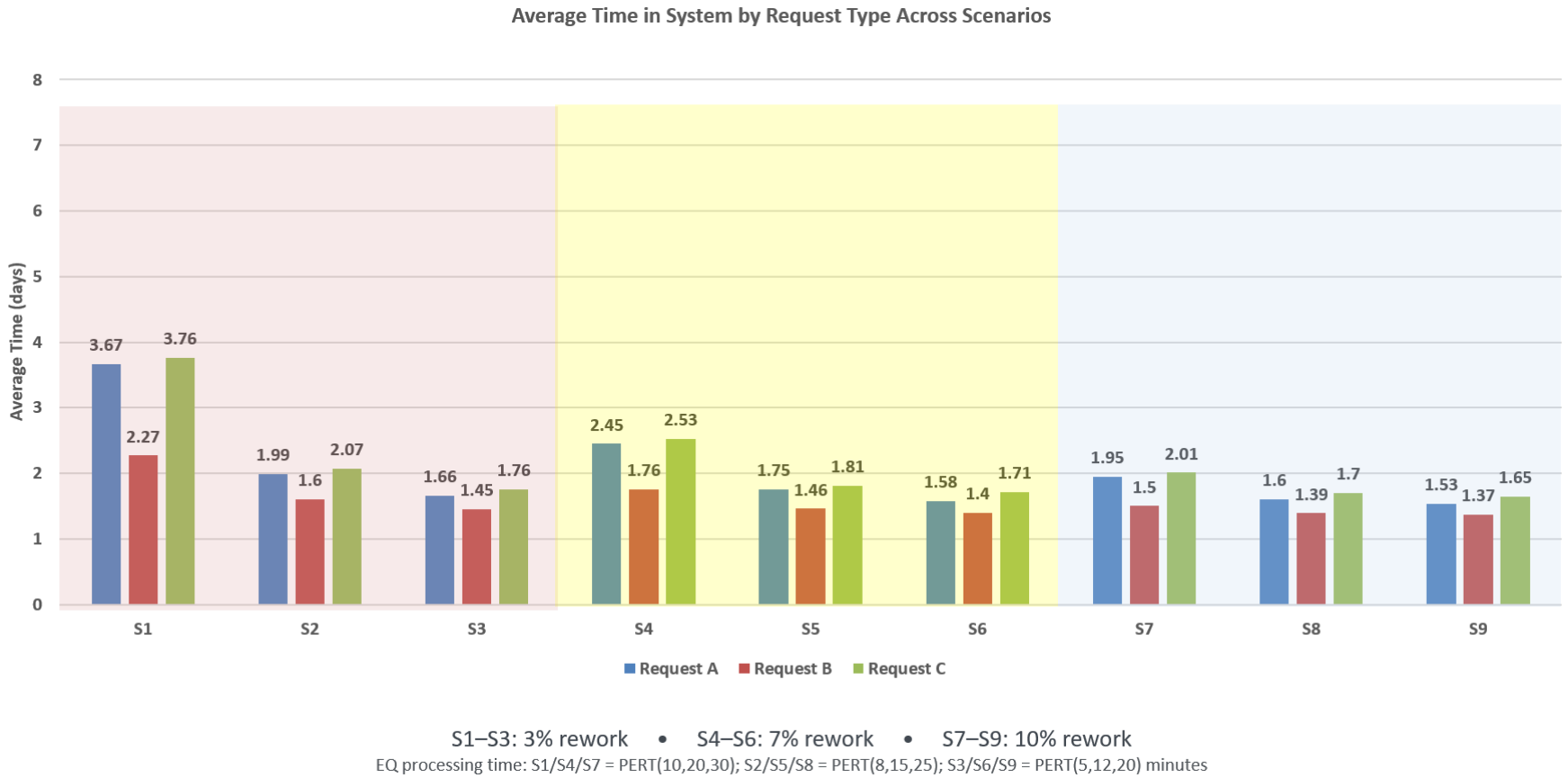


Figure 4.5. Effect of Exposure Questionnaire processing time (minutes) on average permit processing time (days) for base case scenarios with 30 personnel in each resource category.

4.4.3 Worker Utilization

4.4.3.1 Worker Utilization with 20 Resources

Another important result is the consistently high utilization of all worker categories. Across the nine scenarios, administrative staff, trained staff, and trained veterinarians remain above 90% utilization as shown in Table 4.4**.** With only 20 workers of each type available, the system is operating close to its available capacity throughout the simulation. Consequently, even relatively small increases in rework can consume capacity that would otherwise be available for processing additional permit requests. These findings suggest that reducing rework could improve the overall number of requests completed by the permitting system, particularly when staffing resources are already highly utilized.

Table 4.4. Worker utilization across scenarios with 20 resources.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.916	0.919	0.942
S2	0.918	0.918	0.932
S3	0.917	0.919	0.923
S4	0.915	0.919	0.941
S5	0.915	0.919	0.927
S6	0.915	0.919	0.917
S7	0.914	0.918	0.933
S8	0.915	0.918	0.923
S9	0.915	0.918	0.912

4.4.3.2 Worker Utilization with 30 Resources

Table 4.5. Worker utilization across scenarios with 30 resources.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.916	0.918	0.943
S2	0.916	0.918	0.930
S3	0.916	0.918	0.922
S4	0.913	0.919	0.939
S5	0.915	0.919	0.926
S6	0.914	0.919	0.916
S7	0.914	0.919	0.933
S8	0.913	0.918	0.920
S9	0.914	0.918	0.910

Worker utilization remains consistently high across all nine scenarios, even with 30 workers available in each resource category. Table 4.5 shows administrative staff utilization ranges from approximately 91.3% to 91.6%, while trained staff utilization remains particularly stable at approximately 91.8% to 91.9%. Trained veterinarian utilization shows greater variation, ranging from approximately 91.0% to 94.3%, depending on the scenario. Therefore, all three resource categories remain above 90% utilization throughout the simulation, indicating that the permitting system continues to operate at a high level of resource use despite the increased workforce.

The trained veterinarian results show a consistent relationship with Exposure Questionnaire processing time. At a 3% rework rate, trained veterinarian utilization decreases from approximately 94.3% in S1 to 93.0% in S2 and 92.2% in S3 as the Exposure Questionnaire

processing time distribution decreases from Pert (10,20,30) to Pert (5,12,20). A similar pattern occurs at 7% rework, where utilization decreases from approximately 93.9% in S4 to 92.6% in S5 and 91.6% in S6, and at 10% rework, where it decreases from approximately 93.3% in S7 to 92.0% in S8 and 91.0% in S9. In comparison, administrative and trained staff utilization changes relatively little across the scenarios.

When these utilization results are considered together with average processing time and number of requests completed, they show that the additional workforce does not leave substantial unused capacity. Instead, the 30-worker system continues to operate above 90% utilization while processing a larger number of requests and generally achieving shorter average processing times. This suggests that the additional personnel are being effectively used to increase the capacity of the permitting system rather than simply creating excess staffing capacity.

4.4.4 Control Zone Experimental Results

The control-zone-informed model was evaluated using two levels of control zone demand: 2,000 control zone related requests and 5,000 control zone related requests, while maintaining the same total demand of 21,537 permit requests. Requests associated with the control zone follow the full permitting workflow, whereas requests outside the control zone follow the expedited pathway. Results were evaluated for staffing levels of 20 and 30 workers in each resource category.

4.4.4.1 Control Zone Results with 20 Resources

With 20 administrative staff, 20 trained staff, and 20 trained veterinarians, the control-zone-informed policy allows a substantially larger number of requests to be completed than the base case permitting model. In Table 4.6, under S1, the model completes 20,537 requests when 2,000 requests are associated with the control zone, compared with 12,011 requests in the

corresponding base case scenario. Average processing times also decrease substantially, from 6.88, 3.57, and 6.90 days for Requests A, B, and C in the base case model to 1.24, 1.34, and 1.25 days, respectively as shown in Figure 4.5.

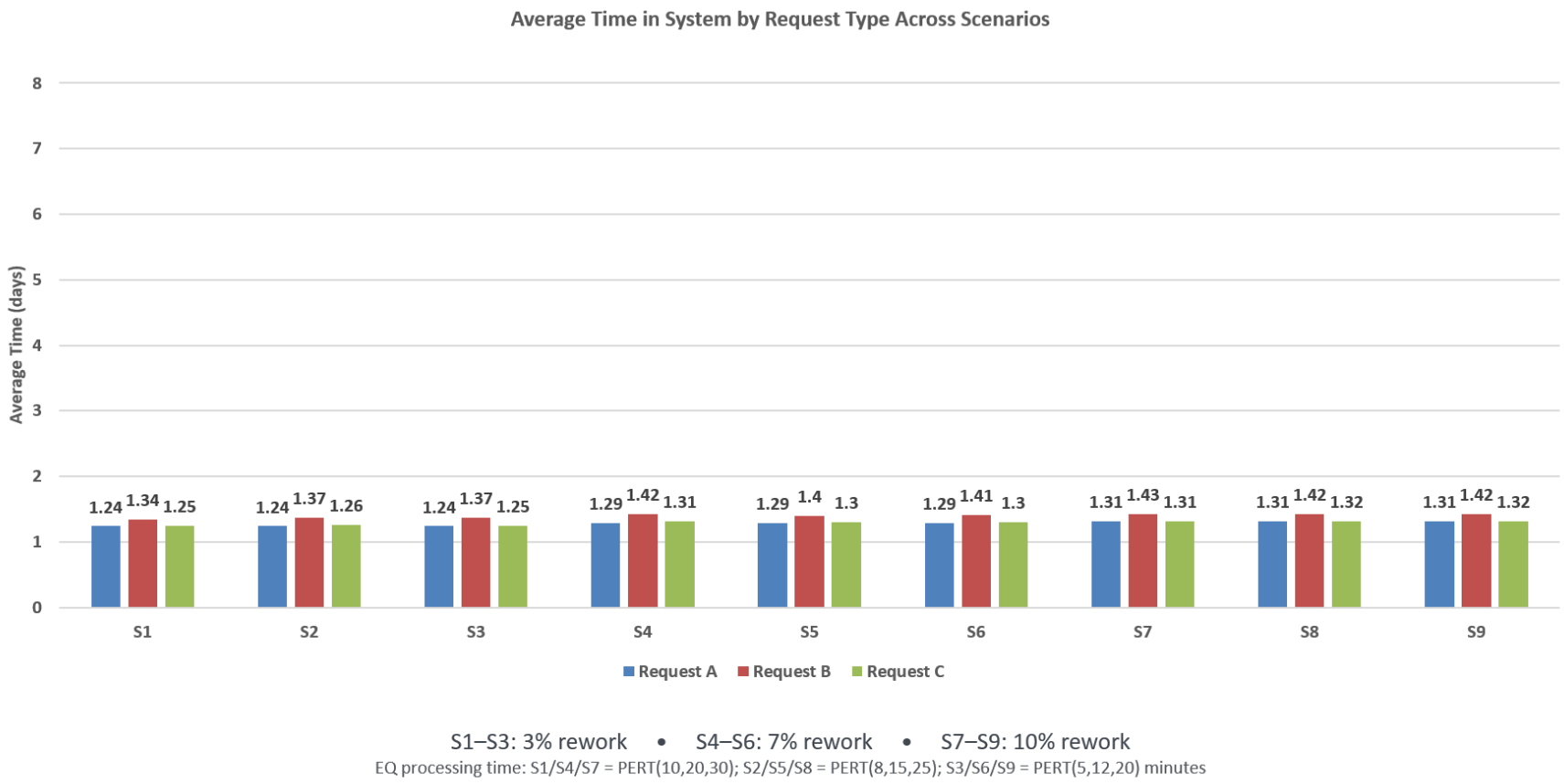


Figure 4.6. Average permit processing time across scenarios with 2,000 control zone related requests and 20 personnel in each resource category.

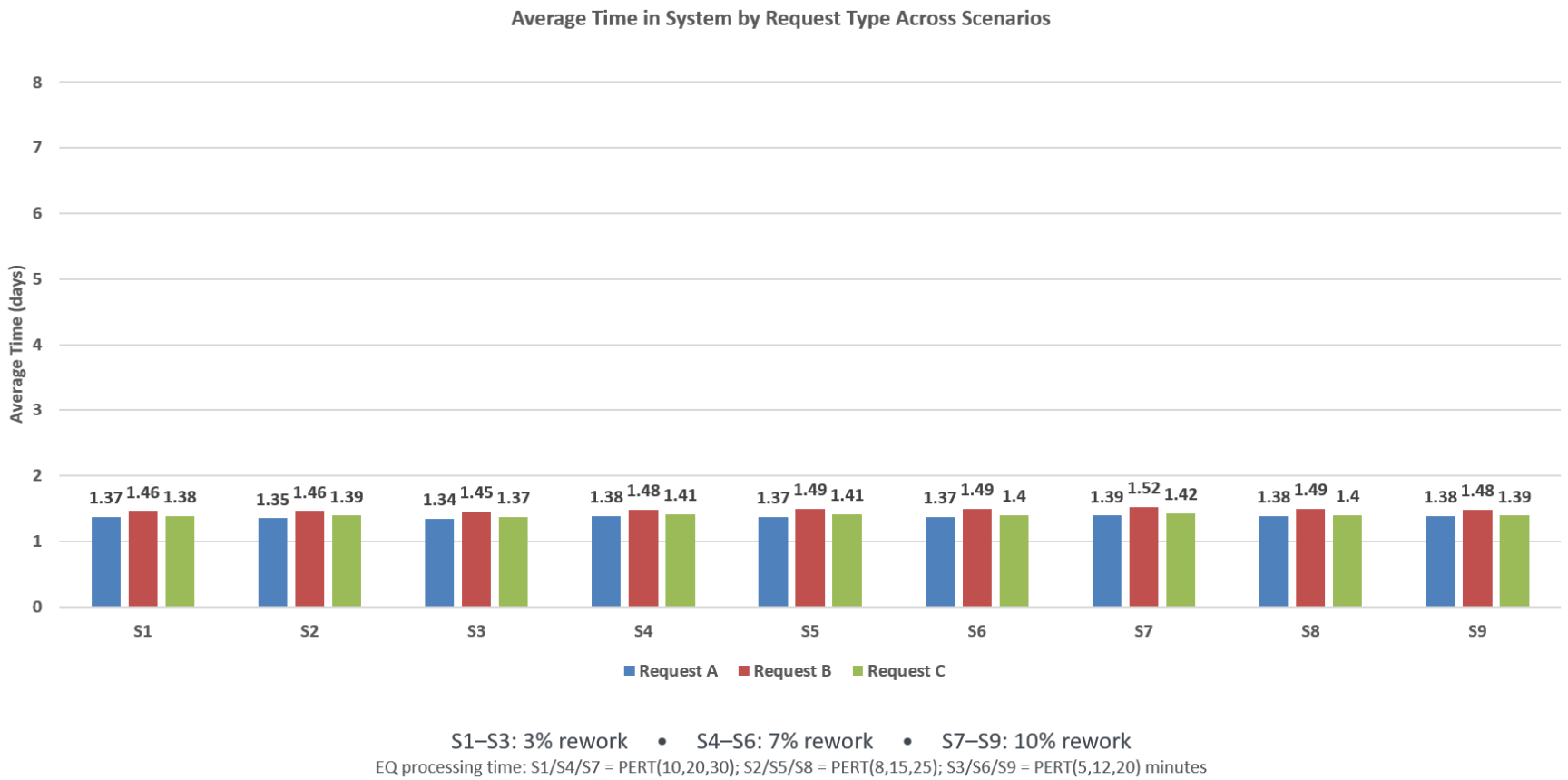


Figure 4.7. Average permit processing time across scenarios with 5,000 control zone related requests and 20 personnel in each resource category

Increasing the number of control zone related requests from 2,000 to 5,000 increases the workload associated with the full permitting pathway. In Table 4.6, under S1, number of requests completed decreases from 20,537 to 20,287 requests, while average processing times increase from 1.24, 1.34, and 1.25 days to 1.37, 1.46, and 1.38 days for Requests A, B, and C in Figure 4.6. The effect becomes more pronounced as rework increases. At 10% rework, S7 processes 20,177 requests with 2,000 control zone requests, compared with 19,284 requests with 5,000 control zone requests.

Table 4.6. Permit outcomes across scenarios with 2,000 control zone related requests and 20 personnel in each resource category.

Scenario	Approved	Denial	Total
S1	20286	252	20537
S2	20279	251	20530
S3	20291	245	20537
S4	20099	232	20331
S5	20096	241	20337
S6	20103	240	20343
S7	19948	229	20177
S8	19942	232	20174
S9	19936	239	20175

Table 4.7. Permit outcomes across scenarios with 5,000 control zone related requests and 20 personnel in each resource category.

Scenario	Approved	Denial	Total
S1	19991	299	20287
S2	19990	299	20289
S3	19992	295	20287
S4	19431	292	19723
S5	19451	289	19740
S6	19441	289	19730
S7	19005	280	19284
S8	19023	277	19299
S9	19029	277	19305

In Table 4.8 and Table 4.9, the resource utilization results help explain this difference. Administrative and trained staff remain highly utilized in both control zone settings, generally above 90%. However, trained veterinarian utilization increases substantially when more requests are routed through the full review process. Under S1, veterinarian utilization increases from approximately 49.5% with 2,000 control zone requests to 72.8% with 5,000 control zone requests. This reflects the increased number of requests requiring Exposure Questionnaire review.

Table 4.8. Worker utilization across scenarios with 2,000 control zone related requests and 20 personnel in each resource category.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.909	0.918	0.495
S2	0.910	0.919	0.409
S3	0.910	0.918	0.351
S4	0.907	0.919	0.465
S5	0.907	0.918	0.389
S6	0.908	0.919	0.336
S7	0.905	0.919	0.433
S8	0.908	0.919	0.372
S9	0.906	0.919	0.318

Table 4.9. Worker utilization across scenarios with 5,000 control zone related requests and 20 personnel in each resource category.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.913	0.918	0.728
S2	0.914	0.919	0.626
S3	0.913	0.919	0.548
S4	0.911	0.919	0.689
S5	0.911	0.919	0.593
S6	0.913	0.919	0.525
S7	0.909	0.919	0.653
S8	0.911	0.918	0.566
S9	0.910	0.919	0.507

4.4.4.2 Control Zone Results with 30 Resources

Increasing staffing to 30 workers in each resource category further reduces processing time and increases number of requests completed. In Table 4.10, with 2,000 control zone related requests, S1 completes 21,017 of the 21,537 requests, with average processing times of 0.84, 0.98, and 0.86 days for Requests A, B, and C as shown in Figure 4.7. When the number of control zone related requests increases to 5,000, Table 4.11 shows that number of requests completed decreases slightly to 20,791 requests, while average processing times increase to 0.94, 1.06, and 0.97 days as shown in Figure 4.8.

The same pattern is observed at higher rework rates. At 10% rework, S7 completes 20,678 requests with 2,000 control zone requests, compared with 19,788 requests when 5,000 requests are associated with the control zone. Average processing times also increase from approximately 0.92–1.05 days to approximately 1.00–1.10 days.

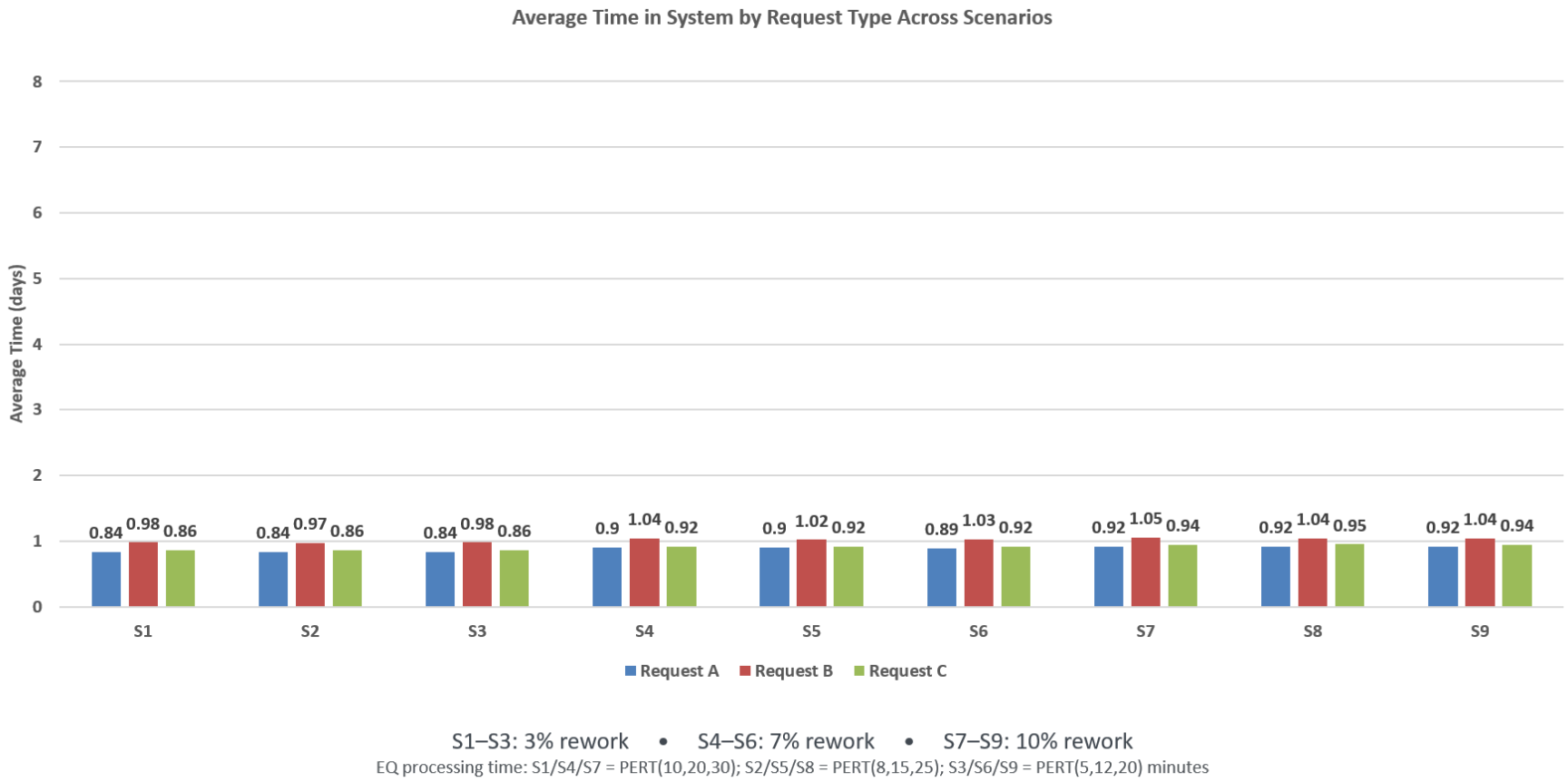


Figure 4.8. Average permit processing time across scenarios with 2,000 control zone related requests and 30 personnel in each resource category.



Figure 4.9. Average permit processing time across scenarios with 5,000 control zone related requests and 30 personnel in each resource category

Table 4.10. Permit outcomes across scenarios with 2,000 control zone related requests and 30 personnel in each resource category.

Scenario	Approved	Denial	Total
S1	20753	264	21017
S2	20771	254	21025
S3	20765	256	21021
S4	20599	248	20847
S5	20609	246	20855
S6	20602	242	20843
S7	20431	247	20678
S8	20449	243	20692
S9	20433	238	20671

Table 4.11. Permit outcomes across scenarios with 5,000 control zone related requests and 30 personnel in each resource category.

Scenario	Approved	Denial	Total
S1	20478	313	20791
S2	20472	317	20788
S3	20480	310	20790
S4	19930	301	20231
S5	19927	295	20222
S6	19925	295	20220
S7	19496	292	19788
S8	19463	287	19750
S9	19488	284	19772

As in the 20 worker experiments, administrative and trained staff remain highly utilized, while veterinarian utilization is much more sensitive to the number of control zone related requests. Under S1, veterinarian utilization is approximately 47.8% with 2,000 control zone requests in Table 4.12, and 73.1% with 5,000 control zone requests in Table 4.13. This indicates that the Exposure Questionnaire becomes increasingly important as a larger proportion of permit requests is required to complete the full review pathway.

Table 4.12. Worker utilization across scenarios with 2,000 control zone related requests and 30 personnel in each resource category.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.905	0.919	0.478
S2	0.907	0.918	0.407
S3	0.907	0.919	0.342
S4	0.904	0.919	0.463
S5	0.906	0.919	0.391
S6	0.905	0.919	0.337
S7	0.904	0.919	0.441
S8	0.904	0.919	0.373
S9	0.903	0.919	0.323

Table 4.13. Worker utilization across scenarios with 5,000 control zone related requests and 30 personnel in each resource category.

Scenario	Admin (% Time Busy)	Trained (% Time Busy)	Trained Vet (% Time Busy)
S1	0.910	0.919	0.731
S2	0.912	0.919	0.659
S3	0.911	0.919	0.601
S4	0.908	0.919	0.710
S5	0.909	0.919	0.641
S6	0.909	0.919	0.584
S7	0.905	0.919	0.685
S8	0.908	0.918	0.617
S9	0.908	0.919	0.561

Overall, the control-zone-informed policy substantially improves system performance by allowing requests outside the control zone to bypass portions of the full permitting workflow. The benefit is greatest when relatively few requests are associated with the control zone. As the number of control zone related requests increases, number of requests completed decreases, processing times increase, and trained veterinarian utilization rises because a larger share of requests requires the full review process. Increasing staffing from 20 to 30 workers reduces these effects, but the results continue to show that both the size of the control zone workload and the rework rate influence overall permitting system capacity.

4.4.4.3 Sensitivity Analysis of Trained Veterinarian Capacity

An additional sensitivity analysis was conducted to evaluate the effect of reduced trained veterinarian availability on permitting system performance under the control-zone-informed

policy. The experiment considered 5,000 control zone related requests, with 30 administrative staff and 30 trained staff, while reducing the number of trained veterinarians from 30 to 5. All other scenario parameters were maintained, including the Exposure Questionnaire processing time distributions and rework rates.

Table 4.14 compares the results for Scenario S1 under three staffing configurations. When the number of trained veterinarians was reduced to 5, while maintaining 30 administrative and 30 trained staff, the total number of completed requests decreased to approximately 18,357, compared with 20,791 requests under the configuration with 30 workers in each resource category. This represents a reduction of approximately 11.7% in completed requests.

The average time in system also increased. With 5 trained veterinarians, average processing times were 1.70, 1.77, and 1.66 days for Requests A, B, and C, respectively, compared with 0.94, 1.06, and 0.97 days under the original 30-worker configuration. Trained veterinarian utilization increased substantially, indicating that the reduced veterinarian workforce was operating close to its available capacity.

These findings suggest that trained veterinarian availability can become an important operational constraint when the number of veterinarians is substantially reduced. Even with sufficient administrative and trained staff, limited veterinarian capacity can reduce number of requests completed and increase processing delays. This highlights the importance of considering the distribution of personnel across resource categories rather than relying only on the total number of available workers.

Table 4.14. Comparison of permit processing performance under Scenario S1 with 30 and 5 trained veterinarians for 5,000 control zone related requests.

Performance Measure	30/30/30 Staff	30/30/5 Staff
Administrative staff	30	30
Trained staff	30	30
Trained veterinarians	30	5
Total requests processed	20,791	18,357
Average time – Request A (days)	0.94	1.70
Average time – Request B (days)	1.06	1.77
Average time – Request C (days)	0.97	1.66
Trained veterinarian utilization	73.1%	95.5%

4.5 Discussion

The results indicate that Exposure Questionnaire processing time is an important constraint on the capacity of the permitting system. With staffing fixed at 20 administrative staff, 20 trained staff, and 20 trained veterinarians, reducing the time required for this activity allows the same workforce to process substantially more requests while also reducing the time experienced by individual permit requests. In contrast, increasing rework consumes already highly utilized staff capacity and reduces total number of requests completed. Thus, the results suggest that improvements to the permitting process should consider not only the number of available workers but also process efficiency and the reduction of rework, since both directly influence how effectively a fixed workforce can respond to a large volume of permit requests.

The 30-worker experiments reinforce two important findings. Reducing Exposure Questionnaire processing time increases the number of completed requests, while increasing rework reduces the number completed within the 30-day simulation period. Although the average time in system among completed requests decreases under higher rework rates, this is a secondary result and does not indicate improved overall permitting performance. The results also suggest that process improvements should not be considered independently: the benefit obtained

from faster questionnaire processing can be substantially reduced when a larger proportion of requests requires rework. The cumulative arrival and completion analysis further showed that the base case permitting system was unable to complete all 21,537 incoming requests within the 30-day simulation period under Scenario S1, with approximately 24% of requests remaining unfinished. The periodic interruptions in cumulative completions also highlight the influence of the five-day personnel working schedule on system performance.

The simulation experiments show that permitting system performance is strongly influenced by staffing capacity, Exposure Questionnaire processing time, rework, and the proportion of requests requiring the full review pathway. Increasing staffing and reducing processing time generally improve number of requests completed and reduces permit processing time, while higher rework reduces effective system capacity. The control-zone-informed policy further improves performance by allowing lower risk requests outside the control zone to follow an expedited pathway. The additional trained veterinarian capacity sensitivity analysis further demonstrates the importance of balancing staffing across resource categories. Reducing the number of trained veterinarians from 30 to 5, while maintaining 30 administrative and 30 trained staff, reduced the number of completed requests and increased average processing times under the 5,000-control zone request configuration. This suggests that increasing administrative and trained staff capacity alone may not be sufficient when veterinarian availability becomes a limiting factor. Therefore, workforce planning should consider the staffing requirements of individual review activities rather than only the overall number of personnel.

Chapter 5. CONCLUSION

5.1 Summary of Main Findings

This study used discrete-event simulation to evaluate the operational performance of an emergency livestock movement permitting system under rework, processing time, different staffing, and permitting-policy conditions. The results show that system performance is influenced by all these factors.

Increasing the rework rate consistently reduced the number of permit requests completed within the 30-day simulation period. Requests requiring additional review consumed staff capacity, leaving fewer resources available to process other requests. A secondary observation was that the average time in system among completed requests decreased as rework increased. However, this measure excludes requests that remained unfinished at the end of the simulation period. Therefore, the reduction in average time for completed requests should not be interpreted as improved system performance. The primary consequence of increasing rework was a reduction in the number of completed permit requests.

Reducing the processing time required for the Exposure Questionnaire improved both number of requests completed and average permit processing time. This effect was especially clear when rework remained low. These results suggest that improving the efficiency of the Exposure Questionnaire review can increase system capacity without necessarily increasing the number of personnel.

Increasing staffing from 20 to 30 workers in each resource category generally improved number of requests completed and reduced average processing times. At the same time, administrative staff, trained staff, and trained veterinarians remained highly utilized in the base

case permitting experiments. This indicates that the additional personnel were actively used to increase system capacity rather than creating substantial unused staffing capacity.

The control-zone-informed permitting policy produced substantial operational improvements by allowing requests outside the control zone to follow an expedited pathway while directing control zone related requests through the full permitting workflow. For both 2,000 and 5,000 control zone related requests, the control-zone-informed policy substantially increased the number of completed permit requests and reduced average processing times compared with the corresponding base case scenarios. The magnitude of these improvements varied with staffing levels, rework rates, and Exposure Questionnaire processing times. When the number of control zone related requests increased from 2,000 to 5,000, number of requests completed decreased, average processing times increased, and trained veterinarian utilization increased. This demonstrates that the proportion of requests requiring full review can strongly influence overall system performance. An additional sensitivity analysis showed that substantially reducing trained veterinarian availability decreased permit number of requests completed and increased average processing times, even when administrative and trained staff capacity remained unchanged. This finding emphasizes the importance of maintaining sufficient veterinarian capacity when a large number of requests requires the full permitting review process.

Overall, the findings indicate that effective emergency movement permitting depends not only on staffing levels but also on reducing rework, improving review efficiency, and directing the most resource intensive review activities toward requests that require the highest level of scrutiny.

5.2 Research Contributions

This study contributes a quantitative framework for evaluating the operational requirements of emergency livestock movement permitting during an FMD outbreak. While previous research has largely focused on disease transmission, movement restrictions, and risk based permitting policies, the operational capacity required to process large numbers of movement permits has received limited attention.

The first contribution is the development of a discrete-event simulation model that represents the movement permitting process at the operational level. The model captures permit arrivals, review activities, personnel constraints, queues, corrections, rework, and jurisdictional approvals, allowing processing delays and staffing requirements to be evaluated within a single framework.

A second contribution is the integration of livestock movement demand generated by InterSpread Plus with the permitting simulation. This connects outbreak related movement activity with the operational workload experienced by the permitting system and allows permit demand to reflect realistic origin-destination movement patterns rather than an assumed number of requests.

The study also provides a systematic way to evaluate how staffing levels, processing times, and rework rates affect permit processing time, number of requests completed, and resource utilization. This allows emergency planners to identify potential bottlenecks and examine whether improvements should focus on additional personnel, faster review activities, reduced rework, or a combination of these strategies.

Finally, the study evaluates a control-zone-informed permitting policy in which requests associated with the control zone receive the full review process while requests outside the control

zone may follow an expedited pathway. This provides a quantitative way to examine how risk-based routing can influence workload, processing time, number of requests completed, and personnel utilization while preserving more intensive review for movements requiring greater scrutiny.

Although the simulation model was developed using cattle movement data and permitting procedures relevant to Kansas, its structure is not limited to this setting. The model allows users to modify key inputs, including permit request arrivals, processing time distributions, staffing capacities, rework probabilities, and routing rules. With appropriate changes to the permitting workflow, resource requirements, and movement data, the framework could be adapted to other jurisdictions, livestock species, or animal disease emergencies. This flexibility allows the model to serve as a foundation for evaluating permitting operations under different regulatory and operational conditions.

5.3 Implications for Practice

The simulation results highlight four areas that warrant consideration in emergency movement permitting: staffing capacity, processing times for review activities, rework, and permitting policy. These areas provide a basis for identifying potential operational improvements and evaluating preparedness strategies for a foot-and-mouth disease outbreak.

One important consideration is the availability and allocation of trained personnel. The simulation results indicate that staffing levels influence the number of permit requests completed and the time required to process them. Emergency preparedness planning should therefore consider not only the total number of available personnel but also the specific tasks that different worker categories are qualified to perform. Cross-training eligible personnel and identifying additional staff who could be mobilized during an outbreak may provide opportunities to

improve processing capacity. However, the feasibility of these approaches would depend on training requirements, staff availability, and the responsibilities assigned to each worker category.

Another consideration is the time required to complete individual review activities, particularly the Exposure Questionnaire. The simulation experiments demonstrate that changes in questionnaire processing time can affect overall permitting performance. In practice, opportunities to reduce review time might include clearer application instructions, standardized review procedures, improved information organization, and electronic forms that make required information easier to locate. These changes would need to preserve the information necessary for disease risk assessment rather than simply shortening the review process.

Reducing rework may also improve permitting operations. Requests that contain missing or incorrect information can require additional review and applicant responses, increasing the workload placed on permitting personnel. Clear submission requirements, validation checks in electronic forms, and guidance for applicants could help prevent avoidable errors before requests enter the review process. Training personnel to identify common documentation problems consistently may also reduce unnecessary repeated reviews. These approaches represent potential operational improvements that could be evaluated in future simulation experiments.

The comparison of permitting policies also has practical implications. The control-zone-informed model evaluates an alternative approach in which requests associated with a control zone undergo the full review process, while requests outside the control zone follow an expedited pathway. This distinction illustrates how differentiating review requirements according to control zone status may reduce the workload associated with requests that do not require the same level of review. However, any expedited permitting procedure would need to remain

consistent with applicable disease-control requirements and decisions made by animal health authorities.

Overall, the model can support emergency preparedness by allowing decision makers to evaluate alternative staffing arrangements, processing procedures, and permitting policies before an outbreak occurs. Rather than providing a single recommended staffing level or permitting procedure, the simulation offers a configurable framework for examining how operational changes affect permitting system performance under different assumptions.

5.4 Limitations and Future Work

This study has several limitations that should be considered when interpreting the simulation results. First, the application focuses on cattle movements involving Kansas. Although the modeling framework can be adapted to other livestock species and regions, differences in permitting procedures, livestock industries, staffing structures, and outbreak response policies may affect results in other settings.

Second, several model parameters, including activity processing times and rework assumptions, are based on work measurement principles, expert input, and observations from preparedness exercises rather than observations from an actual U.S. FMD outbreak. Because the United States has not experienced a recent FMD outbreak, direct operational data for validating large-scale emergency permitting are not available.

The movement arrival data also involve a simplifying assumption. ISP provides the day on which each livestock movement occurs but not the exact time within that day. Therefore, movements occurring on the same day are distributed evenly across the 24-hour period. Actual permit requests during an outbreak may arrive unevenly, including periods of concentrated demand that could produce larger short-term queues and workload peaks.

The model also assumes defined personnel availability and work schedules. In the current experiments, personnel work eight hours per day with a one-hour break, while requests may continue to arrive outside working hours and wait until the required personnel become available. Actual emergency operations may use overtime, multiple shifts, temporary personnel, or changing staffing levels as outbreak conditions evolve.

Another limitation is the assumption that the personnel required for permit processing are already available and appropriately trained. During an actual FMD outbreak, mobilizing additional administrative staff, trained personnel, and veterinarians may require considerable time and resources. Some permitting activities also require specialized knowledge that cannot be acquired immediately. Future research could incorporate personnel mobilization and training delays to evaluate how these constraints affect permitting system performance during the early stages of an outbreak.

Future research could extend the model by incorporating time-varying request arrivals, alternative work schedules, dynamic staffing policies, and additional livestock species or geographic regions. The model could also be validated further using detailed data from future FMD preparedness exercises or, if available, actual emergency permitting operations. Additional analysis could examine alternative control zone sizes and routing policies and evaluate how changes in outbreak conditions affect both permit demand and the resources required to process requests.

5.5 Conclusion

This study developed a discrete-event simulation framework to evaluate the operational performance of emergency livestock movement permitting during a potential FMD outbreak. The model represents permit request arrivals, review activities, staffing constraints, queues,

rework, and approval processes, allowing the operational consequences of different staffing and permitting strategies to be examined quantitatively.

The simulation results show that permitting system performance depends on more than staffing levels alone. Rework, processing efficiency, and the proportion of requests requiring the full review pathway can substantially affect number of requests completed, processing time, and personnel utilization. The control-zone-informed policy demonstrates how directing lower risk requests through an expedited pathway can reduce workload on the full permitting process while maintaining more intensive review for control zone related movements.

Overall, the framework provides a practical decision support tool for examining whether available personnel and permitting procedures are sufficient to manage large numbers of livestock movement requests during an FMD response. The model can also support future planning by allowing agencies to test alternative staffing levels, processing assumptions, and permitting policies before an actual outbreak occurs.

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