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A systems approach to the policy level risk assessment of exotic animal disease: network model and application to classical swine fever

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Abstract

Exotic animal diseases (EAD) are characterized by their capacity to spread global distances causing impacts on animal health and welfare with significant economic consequences. We offer a critique of current import risk analysis approaches employed in the EAD field, focusing on their capacity to assess complex systems at a policy level. To address the shortcomings identified, we propose a novel method providing a systematic analysis of the likelihood of a disease incursion, developed by reference to the multi-barrier system employed for the UK. We apply the network model to a policy level risk assessment of classical swine fever (CSF), a notifiable animal disease caused by the CSF virus. In doing so, we document and discuss a sequence of analyses that describe system vulnerabilities and reveal the critical control points (CCPs) for intervention, reducing the likelihood of UK pig herds being exposed to the CSF virus.

KEY WORDS: exotic animal disease, network, risk, system, import, analysis, classical swine fever

1 INTRODUCTION

Expanding free markets and globalisation have increased countries' exposure to exotic animal disease (EAD). Prevention of EAD incursion is complex and requires the dynamic management of potential entry points, pathways and preventative barriers. Understanding the interactions between these is a focus for governments managing EAD risks [(1)]. Conventionally, risk assessments (RAs) in this field assess the likelihood and impact of an EAD so to inform risk management practice [(2,3)]. Both qualitative and quantitative methods

have been employed. However, in seeking a synthesis of the knowledge on the system of disease incursion, these approaches are often limited. Here, we evaluate current methods for assessing the risk of exposure to EAD and offer an analysis of the merits and limitations of established tools. Building on this, we present an alternative method aimed at improving EAD risk assessments at the policy level. The proposed framework adopts a systems approach and identifies vulnerabilities in the controls in place, presented as critical control points (CCP), across a country's disease management plan. This approach has been developed within the context of EAD protection within the UK.

1.1 Exotic animal diseases

EADs are transboundary hazards, given their capacity to spread substantial distances and cause significant impacts (e.g. direct and indirect economic loss to farmers and governments) at local, national and international scales [4,5]. Concern has been exacerbated by the intensification of agriculture and the expansion of global markets [6]. Recent examples of EADs in the UK include the 2001 and 2007 foot and mouth disease (FMD) and 2000 classic swine fever (CSF) outbreaks [7-11], while avian influenza (AI) and the bluetongue (BT) pandemics represent international examples [12-14]. Prevention of EAD provides substantive economic benefit, and developed countries spend considerable effort preventing and mitigating EADs to maintain a favourable 'disease-free' status [15]; much of this focused at the policy level and requiring intimate knowledge of systemic risk and its reduction. The threat of an EAD incursion is relentless, requiring governments to maintain vigilant management practice. Interaction between the pathways of introduction, the multiple stages of exposure, subsequent impacts and barriers of management is highly complex. Preventative risk management requires a broad understanding of system risk in order to design and implement cost-effective programmes adapted to high-level protection for a heightened state of national preparedness [4,15].

1.2 The UK multi-barrier defence system and failure to prevent outbreak

The UK framework for the prevention and control of exotic animal diseases combines the competences of multiple agencies (e.g. local authorities, Animal Health Agency, Meat and Hygiene Service, HM Revenue and Customs and the UK Borders Agency [1]), each with specific management roles and responsibilities. Mutually independent, the functions of these agencies create a complex network of protection barriers that operate as a whole system. Considering their risk management activities as a 'multi-barrier system', and taken in concert, these barriers protect against the imperfections that exist, even in the most effective of single barriers [16]. However, system failures still occur, and may be due to a rare coincidence of successive failures in multiple defences, which create pathways for hazardous agents to reach susceptible livestock. The more robust the defence network, the more unlikely an incursion is. Nonetheless, incursion remains theoretically possible [16], which is why understanding the complexity of the system is vital for the development of effective and risk-informed interventions [17].

1.3 Key issues for improving prevention of exotic animal diseases

Firstly, EAD outbreaks result from complex interactions between the host, the disease agent, and environmental conditions (e.g. human activities) [18]. Understanding the role each plays is central to identifying weaknesses in the system [17]. The introduction of an EAD is influenced by the agent's unique characteristics influencing the route of import [19] and the complexity of interactions between the environment, hosts (e.g. wildlife and livestock), trade routes, and the level of biosecurity provided by animal production systems (e.g. extensive vs. intensive). This generates a very large number of possible release and exposure pathways [17]. Though multi-barrier systems harbour some redundancy that could improve protection, the efficacy of these systems remains vulnerable to human factors [16,18,20] (Figure 1). Improving these systems is difficult, as evidenced by the investigation of past outbreaks, which are

frequently inconclusive on root causes [2,21]. Consequently, true system failures are difficult to detect and therefore, the performance levels for individual controls poorly documented [2,22]. Understanding the relationship between opportunities for transmission in the context of the efficacy of risk management controls is central to enhancing a nation's level of preparedness.

Secondly, the World Trade Organisation (WTO), under the sanitary and phytosanitary (SPS) agreement, requires the validated scientific rationale and data before increasing protective measures for EAD incursion [23]. Thus, so that that protective measures are not used inadvertently as barriers to trade. Risk assessments provide an evaluation of the risk of introducing an EAD and guidance on the causes for failure, thus must be included in the package of evidence provided to justify the necessity for added measures [3,24,25].

2 IMPORT RISK ASSESSMENTS: A CRITIQUE

By convention, so-called import risk assessments (IRA) are used to assess the likelihood and consequence of an EAD incursion, playing a key role in the identification and classification of risks of introducing an EAD into a disease free country [3,24,25]. Guided by international standards [23], IRAs employ a range of qualitative and quantitative methods, which can be applied under different scopes and objectives. Table II presents a summary of approaches to IRA and their respective strengths and weaknesses. Though these methods are well established, we argue they present methodological limitations in the context of increased system complexity and may fail to provide a sufficiently comprehensive analysis of all the introduction mechanisms and subsequent threats of exposure to an EAD.

IRA tools are divisible in two groups; expert- and scenario-based. The majority of expert-based models are strictly qualitative, [26] such as those applied by Australia and New Zealand [27], and rely on a process of hazard screening, identification and classification and

use descriptors to assess the likelihood and severity of the impact of EAD introduction [28-31]. The Department for Environment, Food and Rural Affairs (Defra) in England and Wales adopts these techniques [32-34]. Expert-based methods rely on multiple sources of information, including expert opinion, to estimate risk [2]. Experts synthesise information from a range of possible events, often providing a single 'score' as a surrogate risk estimate. The approach is suitable for a quick breakdown of the risks although limited in its ability to capture the complexity of the system, offering a pragmatic alternative for assessing events where data is sparse. It enables rapid and inexpensive screening level assessment, allowing decision-makers to discern priorities and design management solutions in short time frames. Other expert-based assessments apply complex elicitation methods, such as conjoint analysis [35-37], or quantitative methods that rely on expert knowledge to support a fuller assessment. These employ more complex and time-consuming processes to strengthen the accuracy of elicited values; though arguably, with limited improvements to the representation of system detail. As an example, Horst (1998) presented an exhaustive list of the importation release and exposure routes, in order to prioritise them according to importance. Though extensive in analysis, the output was a ranked list of risk factors and sources with limited analytical depth. Expert-based models are flexible enough to allow the study of large systems [3,26]. Nonetheless, their highly descriptive nature may fail to offer system oversight, reveal true complexity and/or the full extent of introduction scenarios. Scenario based modelling includes end-point quantitative and mechanistic models, and event-trees [38]. The approach, used quantitative or qualitative, requires the detailed representation of the sequence of events responsible for exposure for source to receptors. The complexity of models increases as analysis moves from single [39,40] to multiple introduction pathways [41-44] or receptors [25,45]. Scenario-based models provide diagnostic detail but often at the cost of extensive preparatory work and input data. This constrains the scale of these assessments [25,45], which can deliver

only a small portion of all available pathways, as acknowledged by their users. This review demonstrates that when used individually, expert-based and scenario-based models have methodological limitations, which result in the development of an incomplete understanding of EAD import mechanisms.

The consensus appears to be that the management of disease incursion combining the insights for expert- and scenario-based IRA perspectives provides an acceptable understanding of EAD import mechanisms and associated risks [3,26]. However, we challenge the extent of systems understanding claimed for. These methods rely heavily on available information from past outbreaks and on predicted pathways of exposure to advise on the scope of the assessment. They require the existence of prior knowledge of the mechanisms involved in creating introduction pathways and the behaviour of system barriers [46,47]. However, for incidences such as the CSF 2000, FMD 2001 and HPAI 2007 outbreaks, Defra identified causal pathways resulting from a conjunction of unlikely events. Such pathways are more difficult to predict and may provide the explanation for a high percentage of inconclusive epidemiological reports associated with EAD (Figure 2). As prior knowledge is often unavailable, such pathways have remained outside the scope of conventional IRA, as has the identification and understanding of the mechanisms involved for creating an incursion opportunity.

3 A SYSTEMS APPROACH TO IMPORT RISK ASSESSMENT

An understanding of system properties and of how controls interact enables us to predict behaviour better [48-50]. We propose a method that integrates network analysis with the so-called features, events and process (FEP) analysis. By combining these approaches, we expand the assessment of potential events that may trigger a barrier failure, so initiating an EAD incursion. Network analysis attempts to understand interactions between species and

the environment [51,52]. Examples exist in the epidemiological and disease transmission literature [53,54]. Functionally, a network is comprised of a number of nodes and the connections that exist between them (arcs). FEPs analysis is used to define relevant exposure scenarios and has previously been applied to nuclear waste repositories and proposed for geological storage of carbon dioxide [55,56]. When applied to a specified EAD, this approach intends provide an assessment of the entire system, unveiling interactions at play that may have historically been overlooked.

3.1 Feature, events and processes list

A FEPs list provides a set of system features, system events and system processes that when combined, generates an exposure scenario [55]. For our purposes, 'features', the components within the system (e.g. farms, fomites, border inspection posts, and human or livestock populations) are represented as network nodes (Figure 1). Nodes include the source of EAD, countries without a disease free status, and receptors, e.g. livestock farms. **'**Processes' represent the opportunities for disease transmission between adjacent nodes, and are represented in the network as arcs. Each arc represents a single process and nodes may be connected to several other nodes. The extent of connectivity between two adjacent nodes is defined as an incidence and is assigned a value. 'Events' are the potential root causes of barrier failure and are not represented graphically. Barrier failure does not necessarily infer disease transmission; rather a situation where transmission is possible. Events are assigned a value that describes the barrier failure rate, reflecting an expert's confidence in barrier efficacy. A complete FEPs list is a comprehensive record of all the values attributed to each process and arc in the network, and of all the description and assumptions associated with them.

3.2 Data collection and modelling challenges

Risk assessment favours the use of quantitative data as a reliable and auditable source of information [3,26]. However, for the study of incursion and exposure of EAD to susceptible receptors, such data is often sparse, incomplete and/or unavailable in the quantities necessary to develop a comprehensive analysis of the mechanisms driving exposure (Figure 2). In these circumstances, expert opinion presents an alternative source of information [3,26]. The systemic model relies on expert judgements to inform the model structure and assign values to the FEP network. The experts provide information on the frequency of movements between nodes and the quality of the barriers preventing transmission. Required from the experts is an evaluation of:

- **Incidence:** the number of times a connection is attempted (frequency), with or without successful transmission during a predefined time interval. The degree of 'challenge' in the system.
- **Barrier failure rate:** the number of times a barrier actually fails to detect and/or eliminate a disease agent, as opposed to the number of times a connection is attempted.
- **Events:** a description of the events provoking barrier failure and their classification according to error type - human and/or system error.

3.3 Scenario simulation, pathway calculation and system properties

A scenario is a described sequence of events; e.g. the sequence of events necessary to allow an EAD to contact a receptor, where a receptor represents an animal from a species susceptible to the EAD considered. Multiple scenarios resulting in a system failure (i.e. disease incursion) may exist. We simulate these using a pre-programmed Excel™ spreadsheet describing the network as an interaction matrix (IM; Figure 3). Here, diagonal cells represent network nodes; off-diagonal cells (where full) represent a connection between

two nodes. The off-diagonal cell [i, j]; with A being the row and B the column, represents the connection between the node [i, i] and the node [j, j], whereas cell [j, i] represents the inverse connection. If an off diagonal cell is empty, there is no connection between two respective nodes. When complete, the matrix represents every possible connection within the system. Using the IM, a scenario simulation analysis (SSA) generates all possible outbreak scenarios, leading from a source node to a receptor. A direct pathway contains two nodes and one arc, whilst indirect pathways contain $\boldsymbol{n}$ nodes and ($\boldsymbol{n}$ *-1)* arcs. A pathway length $\boldsymbol{k}$ refers to the number of arcs present in the pathway *(*$\boldsymbol{k = n - 1}$). (P) represents the likelihood of a pathway being available for causing infection. It results from the estimations of the likelihood of the sequences of transmission between any two adjacent nodes (X) considered in pathways, where and $X_{(i,j)}$ the likelihood of transmission between two random nodes within the network can be described. For direct pathways, where $k = 1$ the value of P is equal to the value of X for the source and receptor node,

$$P_{(s,r)} = X_{(s,r)} \text{ ; and} \qquad \text{(Eq. 1)}$$

for indirect pathways, where $k > 1$ P is calculated using the following equation, which considers a random sequence of adjacent connections from source to receptor node,

$$P^*_{(s,r)} = X_{(s,i_1)}.X_{(i_1,i_2)}.X_{(i_2,i_3)} \ldots . X_{(i_{m-1},i_m)}.X_{(i_m,r)}; \qquad \text{(Eq. 2)}$$

Where, $P^*_{(s,r)}$ is the likelihood of a pathway between a source node (s) and a receptor node (r) and i represent random adjacent nodes from *n* network nodes. Therefore, (P) depends on the likelihood of the adjacent connections. This is calculated by $X_{(i,j)}$, where i and j are any two randomly selected nodes in the network, $Ic_{(i,j)}$ represents the value for incidence associated with the process connecting nodes i and j and $BFR_{(i,j)}$ is the value for barrier failure rate. Incidence provides a comparative assessment of the likelihood of the outgoing connections

from a node and the barrier failure rate how likely is failure to detect and eliminate a disease agent in a specific outgoing connection.

$$X_{(i,j)} = \frac{Ic_{(i,j)}}{\sum_{c=1}^{i-1} Ic_{(i,c)} + \sum_{c=i+1}^{n} Ic_{(i,c)}} . BFR_{(i,j)} \text{ ; for } j \neq i \qquad \text{(Eq. 3)}$$

where $i = 1, \ldots, n$.

The output of the model is a list of all pathways allowing exposure of susceptible receptors to the disease agent. That list includes a description of all the nodes composing the pathways and a respective likelihood (P) value.

3.4 Sensitivity analysis

System vulnerability is evaluated by considering the sum of the likelihoods of all pathways. It represents the likelihood of system failure and defines a base case for system performance. The value represents a snapshot of system vulnerability to the incursion of an EAD and allows the detection of which arcs and associated events promote barrier failure and so pose a greater influence to system vulnerability. This can be achieved by the application of a local 'one at a time' sensitivity analysis to the model, targeting the behaviour of the barriers associated with each arc [57,58] and is valuable later for identifying risk management interventions that are likely to be most effective in times of risk reduction.

4 MODEL APPRAISAL

Clearly, historically high priority pathways for EAD incursion are understood and under active management. However, an increase in system complexity is leading to the possibility of unexpected interactions that generate less predictable pathways of EAD introduction. Current focus is on the occurrence of a sequence of low probability system failures that may result in an incursion [1,16,59]. The approach offered here adopts a bottom-up approach, based

on a belief that the behaviour of the system emerges as a whole, and cannot be understood in full by the atomised analysis of constitutive parts [48,60]. Bottom-up models offer the following advantages: [48,50,51,56,60-63]

a) The model is based on simple local rules that drive the complex behaviour observed at a global level, so understanding the rules governing system behaviour allows for making predictions. This enables the model to infer system resilience, simulating the UKs' overall resilience to a disease introduction.

b) The model allows for interplay between bottom-up and top-down perspectives through several levels of granularity, allowing the analyst to assess the effects of micro behaviour in system performance and weaknesses e.g. at critical control points[64]. These properties make network models suited to large, complex systems where the role of an individual component is not altogether clear [50,51].

Here, pathways are not determined prior to the assessment as in an event tree, but generated from within the system, based on agent / system interactions. This generates a very large number of introduction pathways, from which none can be excluded. In contrast with conventional approaches [3,24,25,45], the model produces an estimation of system behaviour based on the likelihood of all generated pathways and information on to the influence of components within the system [51]. The interplay allows us to examine the sensitivity of the system to the behaviours of individual components [48]. The model also assumes individual barrier failure is not exclusive to one pathway. Nonetheless, increasing control over that failure will decrease the likelihood across a number of pathways, improving system behaviour. For example, a failure (a) may provide agent access to two high likelihood pathways, and a failure (b) to thousands of low likelihood ones. Understanding which failure has greater influence on system behaviour enables the identification of critical control points; key areas where intervention is likely to be more effective [64].

An analysis concentrating on the *features* (components) allows defining priorities at a macro level, and a second analysis focussing on the *processes/events* the identification of key areas to intervene with regard to those priorities. This provides an indication of 'where' to intervene. However, as the causes of barrier failure are captured by the FEP list, it also provides information on 'how' to intervene. Latent failures are a key concept when assessing a multi-barrier system [16,59,65]. Barrier performance is influenced by a multitude of factors, including technological and resource limitations, political and social issues and human factors. Understanding how these influence each individual *process/event* provides insight for the development of risk mitigation strategies, where intervention is possible.

A key feature of our method is its flexibility, which is the capacity of the model to update input data [24,66]. The structure provided by the FEP list and characterization of each process/event allows for updating sections of the input data without influencing the remaining system components. Updating can be performed in light of new, relevant data thus increasing the accuracy of the results. As government policies change and new intervention strategies are implemented, the ability to update is valuable for maintaining relevant political and economic context.

The model's purpose is to develop a comprehensive analyse of the system of controls, expanding the number of scenarios analysed for a specific EAD, and in turn allowing for the comparison of known scenario with previously unknown ones, generating a list of system priorities. Furthermore, used on a regular basis it can provide an estimation of how changes in factors exterior to the system (political economical, new outbreaks) affect system behaviour. In light of the limitations presented by expert- and scenario-based methods, we defend a systemic model complements analyses developed through the conventional approach. We suggest the combined use of all three modelling approaches, improves the

understanding of vulnerabilities to EAD and allows confirmation and validation of the priorities identified, generating increasing accuracy of the results.

Given the exploratory nature of the method developed and the scarcity of data in literature, particular attention was given to model validation. The internal validation process was influenced by publication on IRA good practice [24,25,66]. Furthermore, method development was closely followed by a project-specific Technical Advisory Group (TAG) composed of experts from Defra, Animal Health and Veterinary Laboratory (AHVLA) staff and experts from other institutions, whose role was to challenge the approach and provide alternatives, improving its robustness.

5 APPLICATION OF THE MODELTO CLASSICAL SWINE FEVER DISEASE INCURSION

Development of the modelling approach included its application to the study of vulnerabilities of the system of controls to an EAD. The model proposed is applicable to test systems of different sizes and properties, and can be applied to multiple diseases and/or countries. For a fist application the selected disease was Classic Swine Fever, and applied to England, instead of UK, a decision based on availability and accessibility of expertise for developing the assessment.

5.1 Classical swine fever incursions

Classical swine fever (CSF) is a notifiable animal disease caused by the CSF virus (CSFv) of the genus *Pestivirus* of family Flaviviridae [67,68]. Wild and domestic swine are natural hosts for the disease, and its manifestation varies according to the virulence of the strain, which can cause a range of mild to acute and sub-acute infections [67,68]. CSF is an EAD that continually challenges a nation's defences. It remains present worldwide with positive detections within Europe, Asia, Africa and the Americas from 2005 to 2010. CSF is

endemic in parts of Europe having been detected in Bosnia and Herzegovina, Hungary and Slovakia in 2010 and in Germany in 2009, (Table III).

Though eradicated from the UK since 1966, CSF is highly contagious. Numerous routes of transmission exist (Table IV). The potential introduction of CSF via multiple transmission mechanisms places considerable pressure on the UK's capacity to prevent CSF outbreaks. The diversity and quantity of national and international animal movements, legal or otherwise, further enhances this increase. For example, the UK is exposed to the importation of legal and illegal meat consignments, the movement of people, e.g. tourists and migrant works, and live animal imports, amongst other potential introduction routes [1,41,42]. The detection of CSF in the UK automatically puts in motion a contingency plan focussing on containment and eradication of the disease agent. Measures to prevent disease spread include trade restrictions and the elimination of potential sources through the elimination of livestock [69]. These contribute to the high costs of protection [5,70]. In light of the uncertainties associated with the pathways of CSF introduction, and of the roles played by different components of the system, a systemic analysis is necessary to provide improved insight at the policy level. This application focuses on understanding the sequence of unlikely events that may result in a CSF outbreak, and the influence these events may have on compromising the barriers in place to protect against an outbreak.

5.2 Model application

The network model was used to assess the likelihood of a pathways being available for exposure of English commercial swine herds to CSFv (Figure 4). Definition of the system included several components, including the livestock and meat industries, facilities for trade, human population and pet shops as well as a mix of organisations and controls protecting the England from outbreaks [1]. The model application focus on understanding the causes for exposure of commercial swine herds to CSF. Therefore, the model considers other

susceptible animals in the system, e.g. domestic animals, backyard farms and wildlife, and that these play a role in CSF transmission (Figure 4). However, model application considers commercial swine herds, i.e. outdoor and indoor finishers and breeders, as terminal receptors. Also important is a description of CSFv transmission characteristics that are of importance to system behaviour (Table IV).

5.2.1 System definition

Transmission mechanisms for the introduction and spread of CSFv are summarised in Table IV. The first row describes the transmission modes demonstrated under laboratory condition; the second describes transmission modes detected in epidemiology reports from past outbreaks. The system is the physical components noted above, the regulations and tests used to detect an incursion [(1)]. Transmission between nodes occur through on or more of the possible transmission modes (e.g. live animals, meat products, germplasm – see Table IV). Successful transmission of CSFv between two features depends on an event(s) that enables the agent to avoid detection and elimination. The nature of this is recorded and a likelihood assigned to its potential for occurrence. The interaction matrix [(52)] is presented as Figure 3. An x-y co-ordinate system of four digit codes describes the off diagonal cells. The last two digits indicate the 'origin node' and the first two indicate the 'destination' node. So, cell 0907 describes a connection from node 07 to node 09. The matrix is not symmetrical. Therefore an inverse connection, e.g. node 09 to 07, if existent, is assigned cell 0709.

5.2.2 Elicitation process

Scenarios of CSF introduction are sequences of events that allow CSFv to be exposed to a UK pig herd. The literature is incomplete on the causes for failure of the multi barrier system. To overcome this, the model was informed by CSF transmission data elicited from experts [(71,72)]. Twenty-eight (n = 28) experts informed the exercise according to expertise,

domain background, and availability to provide broad network coverage. By its nature, elicitation was constrained by time and resource limitations [73]. The workshop was 8 hours in duration and included training. This was the sole information gathering exercise, where relationships between 20 features (nodes) in the network were assessed (Figure 4). This required extensive data input, and to reduce workload, small groups were formed according to expertise (minimum 3 people), and allocated relevant nodes. Each group was responsible for assessing all the outgoing connections to the remaining network nodes. For example, the assessment of node 07 (livestock vehicles) required assessments of all connections (arcs) adjacent to this node, hence the cells 0107, 0207, up to 2007. For each connection experts answered the following questions: 1) Is the connection between node A to node X possible where A is the node allocated to the expert and X any other node present in the network? YES or NO; 2) If YES how frequent are movements between node A and X, using left side scale (Figure 5)? 3) If YES how efficient are the barriers preventing the movement of contaminated goods between them, using right side scale (Figure 5)? 4) Assuming the existing barriers are not 100% efficient, what is in your opinion the cause for barrier failure, using in the comments section. Therefore, for each cell, experts estimated the incidence and barrier efficacy (Figure 5) and provided commentary on the causes of failure and the best and worst case assessment. Each expert group was provided with a booklet containing a description of the network and forms (figure 5) where expert introduced the values and comments requested. Mediators were present to ensure expert rationale was in line with the data requirements for the assessment. Data collected from the workshop was introduced into an interaction matrix coded into the pre-programmed Excel ™ spreadsheet. The model was used to generate all scenarios of CSFv introduction, accompanied by a sensitivity analysis to determine the *process/event(s)* posing greatest influence on system performance. Follow up sessions, via email and telephone conferences dealt with data verification issues; for example,

missing values, comments and corrections. Results were validated by a sub-group of experts to ensure inputs and outputs were valid and within scope.

5.2.3 Sensitivity analysis

To analyse the sensitivity of the model's output to changes in the input, the probability of transmission in the input parameters was changed using a sensitivity analysis [57,58]. The barrier failure rate associated with the process/events enabling transmission between nodes was nominally reduced by 50% (i.e. barriers made less susceptible to failure), simulating an improvement to the controls of the disease. Two analyses were then performed: a) the effects caused by individual barrier improvement, using a 'one-at-a-time' sensitivity analysis; and b) the improvement of clusters of barriers associated with the nodes. For each increase in barrier integrity, a new system performance was estimated and compared to the base case. Nodes or arcs presenting higher percentage values represent the greater influence on network behaviour. At these nodes, policy intervention is likely to have the greatest impact on reducing the vulnerability of the system to a future CSF outbreak.

5.2.4 Model output

For this case study, a single set of core principles was adopted for scenario generation. First, a scenario was defined as starting in one of the three available source nodes, i.e. 01 - Third Countries; 02 - EU Positive; 04 – Laboratories (Figure 3). Next, the scenario was deemed to terminate when the disease agent reached one of four termination nodes, defined as the point where a single domestic livestock pig is infected. The terminal nodes are 17 - indoor finishers; 18 - outdoor finisher; 19 - farm breeder; 20 - animal gatherings. Finally, the scope of the scenario was managed by limiting the maximum length of each pathway (or number of nodes visited) to k = 5, where k denotes the length of pathway [52]. This value was based on available computing capacity. Even then, the model produced 56,269 theoretically

plausible introduction scenarios (pathways) derived from three sources. Each scenario represents a failure to detect and eliminate the disease agent prior to exposure to pig herds and thus a failure of the multi-barrier system. A probability estimate is presented for each scenario, which ranged from 10^{-3} and below. The pathway scores and the overall system performance do not consider on-going outbreaks in foreign countries or the quantity of imported goods at any given moment. Critically for readers, this does not represent a measure of the current residual risk of CSF exposure to pig herds. Rather, used comparatively at the policy level, it provides a diagnostic opportunity to assess the influence of exposure scenarios and failure in the barrier between two adjacent nodes in the exposure to CSF thus enabling the identification of risk drivers.

The interaction matrix presents a systemic risk map of the network indicating the key network sensitivities. A colour scheme was used to classify the results of the sensitivity analysis and indicate the influence that process/events have on system behaviour (Figure 3). The columns represent all incoming connections (upstream) into a particular feature, while the rows represent all outgoing connections (downstream). Upstream interventions represent preventative measures while downstream interventions represent containment measures. For example, feature 01 represents a disease source where the only intervention measure is through containment. Similarly, for features representing receptors, 17, 18, 19 and 20, only preventative measures are available.

The interaction matrix presents a powerful visual tool to identify key arcs that exert greater influence. For example, closer review of node 08 - domestic residence (representing the human population) reveals that cell 0801, which connects the human population to a disease source and cell 1608, which describes the infection of wildlife via domestic residence, e.g. rubbish or scraps in FEP list, are most vulnerable. Also, the matrix identifies wildlife as posing a threat to multiple livestock production units (cells 2018 and 2118) and

thus of exposing livestock to CSFv (Figure 3). Figure 3 displays the worst-case sensitivity analysis. Here, the influence is separated according to three levels. The process/events presenting an influence higher than 10% are in red; for example, the two arcs P outside EU coordinates number (0801) and C wildlife (0816) discussed above. In addition, process/events associated with wildlife and environment, with coordinates 1516 (14%), 1816 (15%), 1916 (15%) and 1915 (14%), also present a significant reduction on risk of livestock exposure (5). The interaction matrix allows easy identification of the most influential nodes and arcs in the network. However, the percentage values have to be retrieved from the data set, as they are unavailable in the matrix; which is a clear limitation.

The results of the node influence analysis are presented in Figure 6. This describes network behaviour, considering a best- and worst-case scenario of barrier performance. For both, the source node outside EU had significant influence on network behaviour, creating a reduction in overall performance of 46% and 49% for worst and best case conditions, respectively. This suggests that intervention at source may be the best control option. Under best-case conditions, animal gatherings (46%) and domestic animals (44%) also proved influential, while worst-case conditions reveal domestic residences (46%), and wildlife (44 %) as most influential. Interestingly, the same nodes - animal gatherings, domestic animals, human population and wildlife - are influential under both best and worst case conditions.

A more detailed analysis of node “05 domestic residence” is available in Figure 7. This focuses on a worst-case assessment of all *process/events* directly associated with domestic residences. The movement of goods between countries outside the European Union (outside EU positive) and the human population were shown to be highly influential to system performance (42%). Similarly, the link between the human population and wildlife (represented by the wild boar population) was also shown to be highly influential (44%). The arc representing movement from European countries had only modest influence (4%). The

arcs (P) outside EU and (C) wildlife, represent the specific movement of goods and animals, where intervention results in a significant reduction in the vulnerability to future CSF outbreaks. The prefix (P) stands for preventative measures and represents incoming movement to the target node. Contrastingly, C represents containment measures, representing outgoing movements. The percentage values, for example 44% for C wildlife, means that an intervention that successfully increases containment reduces the risk of transmission by 50%, produces a reduction by 44% in the likelihood of a future CSF outbreak. Comparing the outputs presented, the interaction matrix allows a systemic perspective of the influence each *process/event* has in the overall system performance however the sequences of Pareto charts (nodes and arcs) communicate the output without loss of information.

6 DISCUSSION

Systemic network models allow for an examination of the interplay between the local and global aspects of a network at the policy level. The Pareto charts provide stakeholders with a top down analysis of the system, consistent with the approach to developing a better understanding of system behaviour using the conventional approach to developing risk assessments [3,26]. Two independent sensitivity analyses were performed to assess vulnerability within the system: at the node level, enabling identification of the features (i.e. nodes) exerting greatest influence on network behaviour and at a process/event (i.e. arc) level, which enabled understanding of those arcs influencing network behaviour as well as providing information about interventions.

6.1 Increasing resilience against a future CSF outbreaks

A study by the European Food Standards Agency (EFSA) suggests that in 2006, countries were no less susceptible to an EAD outbreak than they were 20 years ago [6]. The enormous progress in disease monitoring, surveillance and diagnostics has been offset by the

increase in communication and contact via global trade. Furthermore, CSF is present worldwide with 13 countries declaring outbreaks in 2010; 2 of which were EU partners [21]. The peril of introducing CSF into the UK remains. Our sensitivity analysis reveals that disease containment in third countries produces the greatest increase in system performance and robustness. Nonetheless, eradication of CSF is unlikely to be achieved in the forthcoming decades, and detection and elimination of outbreaks remain the most viable defence options [6]. Surveillance is vital and the UK has in place a system for the early warning and elimination of threats. The system is complex, consisting of multiple controls, each which may be susceptible to failure. Occasional system failure is exemplified by outbreaks in 1971, 1986 and 2000; events' occurring after 1966, the year the disease was officially eradicated from the UK [74].

In assessing system robustness, the analysis identifies a number of known threats as well as previously unidentified ones. This was achieved by assessing the level of influence each individual node has on system behaviour (Figure 4). Even when assigning different weightings to the nodes (assessment under worst and best case conditions), similar nodes were identified as highly influential, although with a variation in the level of influence (Figure 6). This results from a different approach to assessing the efficiency of the barriers preventing transmission of CSF.

Our model also provides enough detail to study the effect of specific events that permit transmission between nodes, thus compromising system robustness. The matrix (Figure 3) displays the upstream and downstream arcs connecting a node. This allows the analysis to detect node frailties, as well as guidance as to where best risk management resource allocations be made. Concerning disease introduction from countries outside the European Union, experts were most concerned with connectivity to domestic residences and with backyard and domestic animals. They believed that *"risk targeted enforcement was unable*

to check all passengers and packages and there was a lack of awareness amongst travellers". With respect to the exposure of livestock, outdoor farms were deemed most vulnerable, particularly those with high contact with wild pig populations and the environment. Concerns with wildlife contact refer to the possibility of a *"wild boar entering the unit or of a young domestic pig escaping from premises into the environment and back [Evidence from Belgium]"*, in FEP list.

6.2 A new approach to assessing risk and strategies to prevent EAD outbreaks

The objective of this work has been to develop a tool requiring minimal expenditure of resources whilst providing significant data for the development of guidelines and strategies for reducing the likelihood of livestock animals to EAD agents at the policy level. Previous studies have also identified the human population as a driver of exposure as well as backyard livestock, restaurants, caterers and food markets, wildlife, livestock lorries, and importation of live animals as risk factors [2,34]. However, conventional scenario-based assessments rely on the research literature and past epidemiological reports to define the pathways of exposure to be included in the assessment [41-43,75] and a significant portion of introduction and exposure pathways will not have been previously assessed. This model provides an alternative approach, which, through the application of a computer model alongside smart use of expert opinion, allows us to consider pathways overlooked by previous assessments and an estimate of the impact particular measures may have on overall system performance.

This said, expert opinion as a source of information exposes the model to the limitations of expert judgments [76,77]. We highlight that data produced is influenced by the dynamic of personalities within each group, motivations, biasing effects such and anchoring, and the capacity to correctly evaluate the data requested in the scale provided, all of which may have a negative influence in the accuracy of the outputs produced [78]. Nonetheless, the processes of selection and allocation of experts in groups, and development of the elicitation

process focussed on minimising the influence of such biasing effects. In light of the scarcity of data associated with the events enabling the introduction of CSFv into the UK, expert opinion stands as the sole source of information available to perform such an assessment. Furthermore, the expert opinion represents the most up to date source of information. Therefore, despite inaccuracies resulting from the capacity to retrieve information from experts, the results produced by the systemic model represent the most current assessment of the control measures applied to prevent the introduction of CSF into the UK.

The model presented develops analyses of the system of controls that differ from that made available using conventional RA methods. We defend a systemic analysis brings benefits to better understanding how controls fail and where to invest in order to significantly improve resilience to an outbreak. However, we acknowledge the model fails to consider specific disease sources (countries or regions) or the outcome following exposure of livestock to CSF (subsequent spread within UK). Thus, the model does not comply with the requirements stated in the WTO's Sanitary and Phytosanitary agreement and the implementation of specific protection measures to address identified movements where improved control increases system resilience, may require further analysis to ensure compliance with WTO [23].

6.3 Validation of the model

The analysis is used in an exploratory model and at the generic policy level to inform decisions on intervention. Therefore, its development follows the OIE risk assessment guidelines and efforts were made for the model to be validated by peer review assuring all assumptions are reasonable and the mathematical computations representative of the system [24,25,66]. The validation comprised of a number of development stages where the model was structured using available documents and information. A number of improvements for future application were highlighted:

- The network considers both legal and illegal movements of potentially threatening materials within the same process. The FEP list identifies and describes the nature of the movement. However, for processes where illegal and legal movements are present, the model does not estimate each individual influence in system robustness.
- For extraordinary situations where control barriers are not in place and common sense actions alone prevent events, such as the relation between livestock vehicles and domestic residences, future applications of the model should capture the effects of both phenomena.
- Extensiveness of the data to be elicited and the short time available to do so resulted in selecting best-case and worst-case approach, as opposed to a more comprehensive format (probability density functions) [25]. Nonetheless, it provides estimates of the level of uncertainty associated with the barrier failure rates elicited [79].
- Adoption of a stochastic approach to modelling the network, which incorporates the level of uncertainty into the outputs produced.

7 CONCLUSIONS

This is the first illustration of a network model within an import risk assessment context for EAD at the policy level. It provides a level of insight not within reach of established IRA methodologies by providing a systemic perspective and the events at the root of a potential CSF outbreak. As such, it has the potential to contribute to the robustness of UK's defence against a CSFv incursion, so informing where to allocate resources to reinforce those defences. The model harbours its own limitations. At its core, the model remains an expert based-assessment and is susceptible to a certain expert bias. In spite of these limitations, this represents the first attempt to develop a systemic perspective over the risk associated with animal disease.

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TABLES

Table I Glossary

Barrier	Any obstacle reducing the chances of disease transmission, these may be physical and biological barriers and activities performed
Barrier Failure rate	Represent the frequency of barrier failure events associated with a specific process
Bottom-up model	Modelling technique, based on the description of the system where system behaviour and pathways systems emerges for a series of rules used to define the EAD agent transmission characteristic
Diagonal cell	In the interaction matrix it represents a network node. In the diagonal cell are also include the sources and receptor nodes
Disease free status	The OIE, mandated by the WTO, officially recognises disease-free areas of countries for trade purposes
Events or barrier failure events	Represent a situation or activity causing the preventative barriers (natural and man-made) associated with a specific process to fail in the detection and elimination of the disease agent, leading to a situation in which transmission is possible.
Exotic Animal Diseases (EAD)	Disease agents included in the list of notifiable disease by the OIE
Expert-based model	A model that relies exclusively on expert opinion a source of information to describe the system and evaluate risks
Feature Events and Processes (FEP) list	Method of recording data, capturing information on all system components and variables, and expert assumptions providing a auditable trail of information
Features	Represent system components where the disease agent may be present. In this models Feature include all sources, all receptors and all component of the system where the disease may be present at any one time.
Incidence	Represents the frequency of a process
Off-diagonal cell	In the interaction matrix it represent an adjacent connection between two network nodes. Each off-diagonal cell is associated with a process (potential transmission) and an event (causing barrier failure) and therefore a process/event.
Process	Represents an activity and/or movement (e.g. live animals, food goods, people, etc.) which present the potential for transmission of the disease agent
Process/event	Represents the interactive behaviour between a process that potentially enables disease transmission between two features and the barriers protecting transmission
Scenario	Characterization of a pathway of exposure, through the description of the sequence of event uniting the disease source to a susceptible receptor
Scenario based model	Model based on a detailed description of the sequence of events responsible for creating a pathways (scenario) connecting a source of a disease agent to a susceptible receptor
System	The source-pathway-receptor relationship
System behaviour	The interactive relationship between an EAD agent and the source-pathway-receptor
Systemic Analysis	A study aiming to analyse the full extent of the source-pathways-receptor relation, by analysing all pathways of exposure connecting source to receptor, regardless of likelihood and impact, that are considered within the adopted definition of system
Top-down model	Modelling technique, where the assessor or experts based on their perception of system behaviour, define the pathway(s) or pathways system used to estimate the impact of exposure

Table II Description of the strengths and weaknesses of the conventional import risk assessment [IRA] methods applied to date and comparison with total system analysis.

Advantages	Disadvantages
Expert-based qualitative model	
Time (enables quick assessments and are adequate to find solution in times of crisis)	Repeatability and validation
Cost (do not require specialist software)	Results are presented in descriptive terms (high, medium and low), low level detail of the output
Use all types of data, thus overcoming data limitations in the research literature	Comparative output
Application to complex open systems	Sensitivity analysis cannot be applied
Scenario-based quantitative model	
Event-tree based models: detail analysis of pathways of exposure and exposure mechanisms	Extensive prior knowledge to select pathways to be assessed
Binomial probability model	Cost and time
In stochastic models, a value for variable uncertainty and/or variability is provided	Data availability (data is not always available and assumptions have to be made, that undermine the value and validity of the model
Repeatability, auditable, and validation	
Sensitivity analysis is applicable	
Data can be updated to account for changes in the system represented	
Model for total system analysis	
Capacity to study large system, represented through the use of an interaction matrix	Repeatability and validation
Use all types of data, thus overcoming data limitations in the research literature	Complex process of elicitation
Results are represented as numerical values	Comparative output
Contextualization provides a descriptive insight the mechanism of disease transmission	Pathways described with an intermediate level of detail, where the multiple mechanisms of disease transmission have no influence in the output
Representation of all pathways and components	It does not allow to estimate uncertainty and/or variablity
Sensitivity analysis is applicable	

Note: Difficult to validate all types of RA

Table III Number of outbreaks and of infected animals worldwide from Jan, 2005 to Jan, 2011; with positive countries within Europe analysed in detail [21]

CSF outbreaks		Year					
		2005	2006	2007	2008	2009	2010
Number of animals testing positive to CSF per year in European countries	Bosnia and Herzegovina	40	35	33			324
	Bulgaria	5	3	3	1	4	
	Croatia		13	112	4		
	Former Yug. Rep. of Macedonia		2	2	4		
	France	1		1			
	Germany	24	52	11		2	
	Hungary				164	27	382
	Montenegro (2007-2011)			16			
	Romania	1075	1438	159			
	Russia	8	2	7	1	4	
	Serbia (2007-2011)			18			
	Serbia and Montenegro (2005-2006)	489	401				
	Slovakia	4	5		3		24
European countries reporting at least one CSF outbreak/year (from 49 countries)		8	9	10	6	4	3
Countries outside Europe reporting at least one CSF outbreak/year (from 139 countries)		17	18	18	14	13	10

Table IV Transmission mechanisms for classical swine fever, classified according to verification laboratory under laboratory conditions and confirmation in historical data.

Transmission modes	**Classical Swine Fever**		
	Proven in Lab	Disease Import	References
Animal movements	+	+	(67,80-85)
Transport vehicles	+	+	(67,68,83-85)
Human contacts	+	+	(80,83,85,86)
Meat based food products	+	+	(83,83,86)
Wild boar	+	+	(67,82,83,87)
Airborne	+	-	(81,83,85)
Other carriers (mechanical vectors)	+	-	(88)
Iatrogenic transmission	+	-	(88)
Artificial insemination	+	+	(81,85,89)
Vertical transmission	+	-	(81,83)

FIGURES

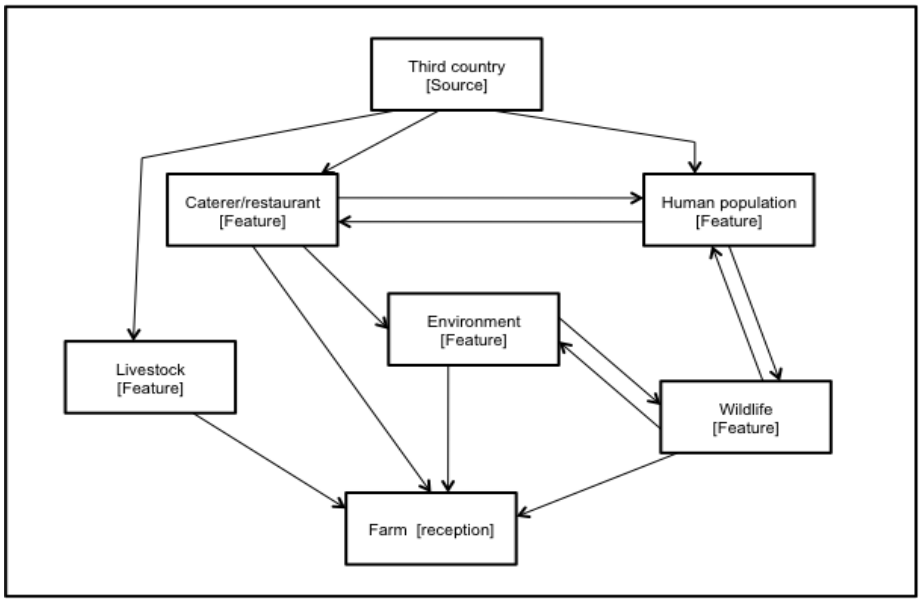

Figure 1 Network representation of the system: Nodes represent the features; arcs represent the process. The [Node Third country] represents the disease source; [Node farm] represents one the terminal node (terminating the simulation); the remaining nodes represent the components contribution to disease transmission; and [Arcs] are represented by the arrows corresponding to movement between two adjacent nodes. Based on the influence diagrams developed by Defra [(1)].

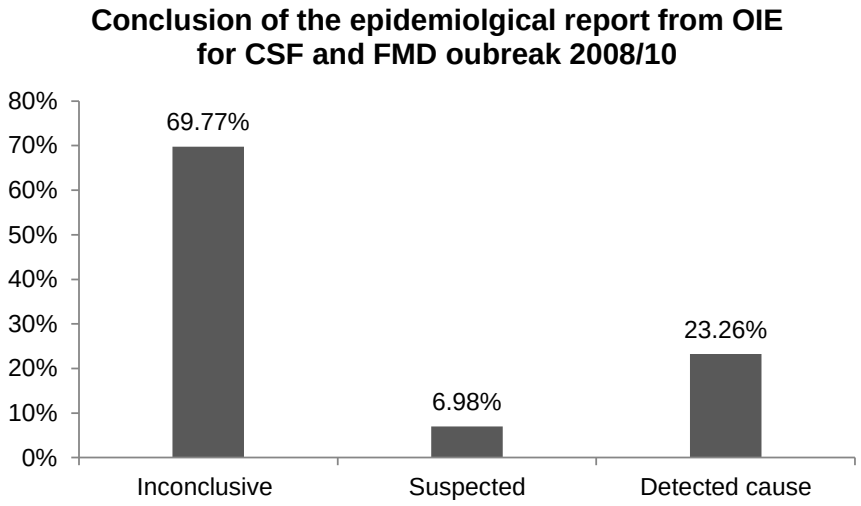

Figure 2 Analysis of the epidemiological reports develop by the OIE [(21)] for CSF and FMD outbreak from 2008 up to 2010. Reports are classified according to the capacity to detect and confirm the pathways of exposure responsible for disease introduction.

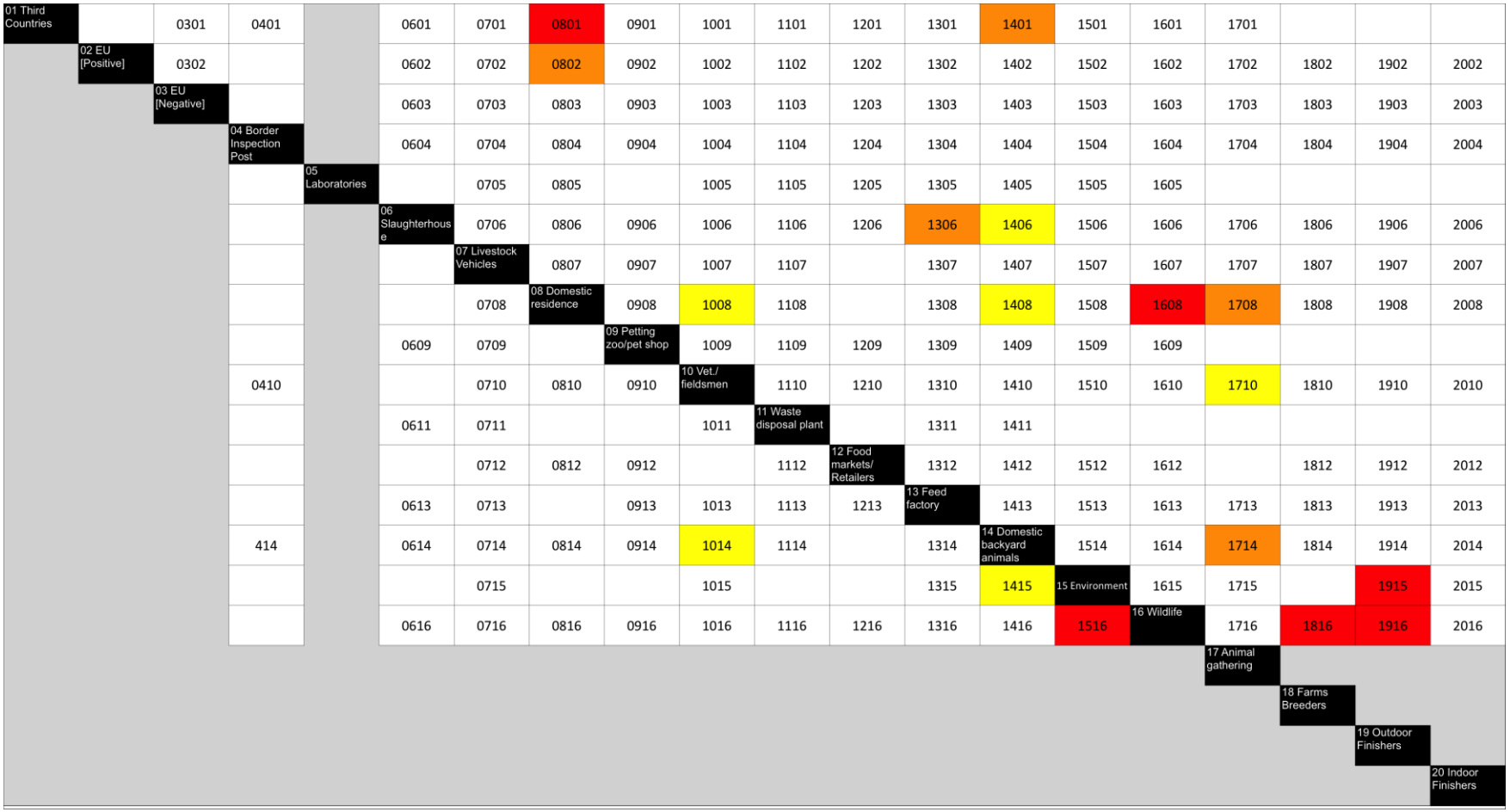

Figure 3 CSF interaction matrix - Diagonal cells (black) network nodes, off diagonal cell (white) network arcs: the first two digits of the coordinates represent the receptive node, whilst the last two the source node. The colour scheme presents the results of the local sensitivity analysis (Red cell represent a reduction in likelihood on system failure > 10 %; orange cells a reduction >1 %; and amber cells reduction > 0.1 %,) , where highlighted cells represent specific process/events where intervention will produce a greater impact in reducing system vulnerability.

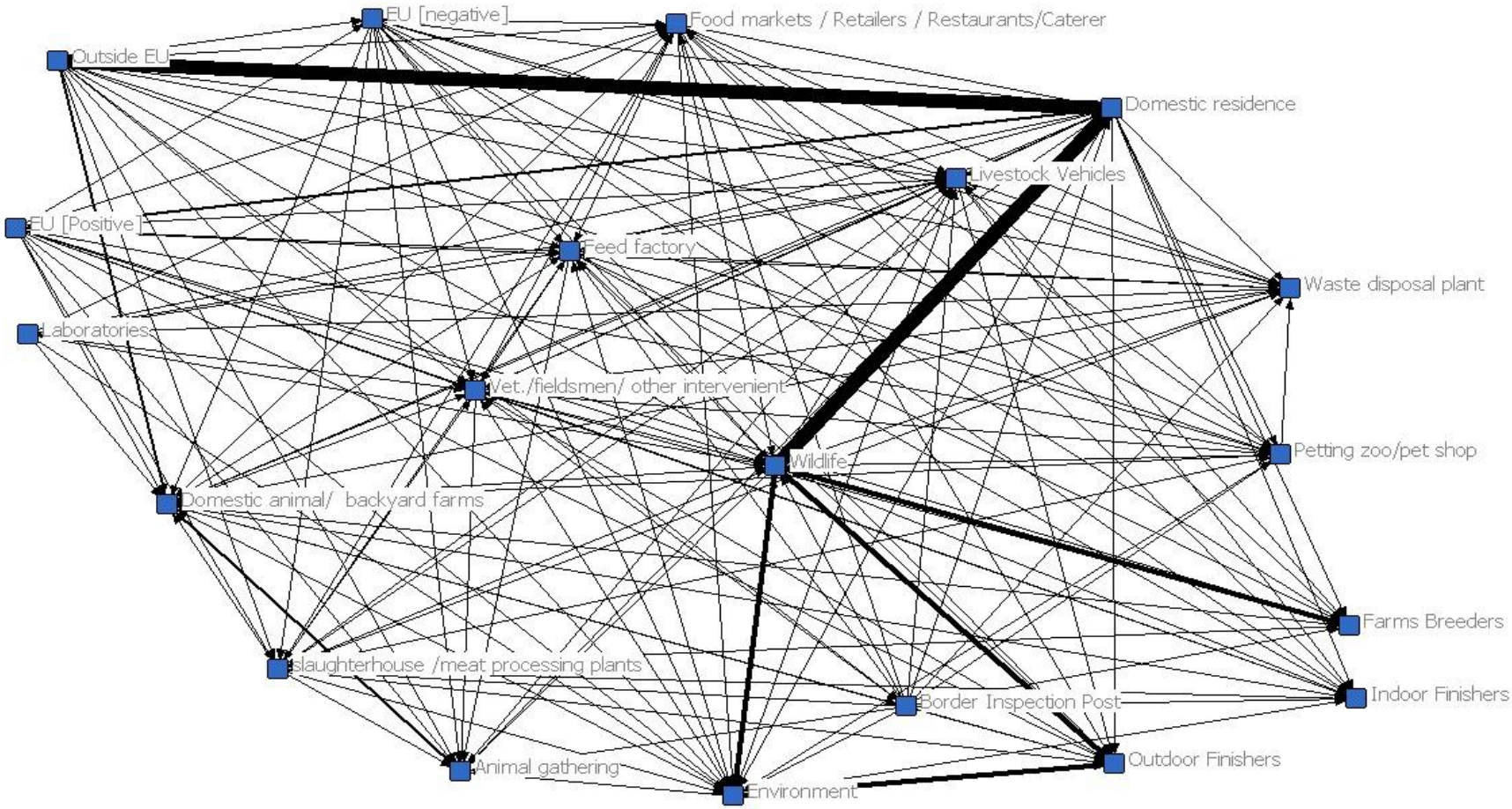

Figure 4 The network system developed for Classical Swine Fever (CSF), based on the data recorded by the FEP list using UCINET 6 ™ and NetDraw ™: the arcs describe movements that may result in transmission, these consider all possible transmission models (Table IV); thickness is associated with the influence of that particular arc in system performance.

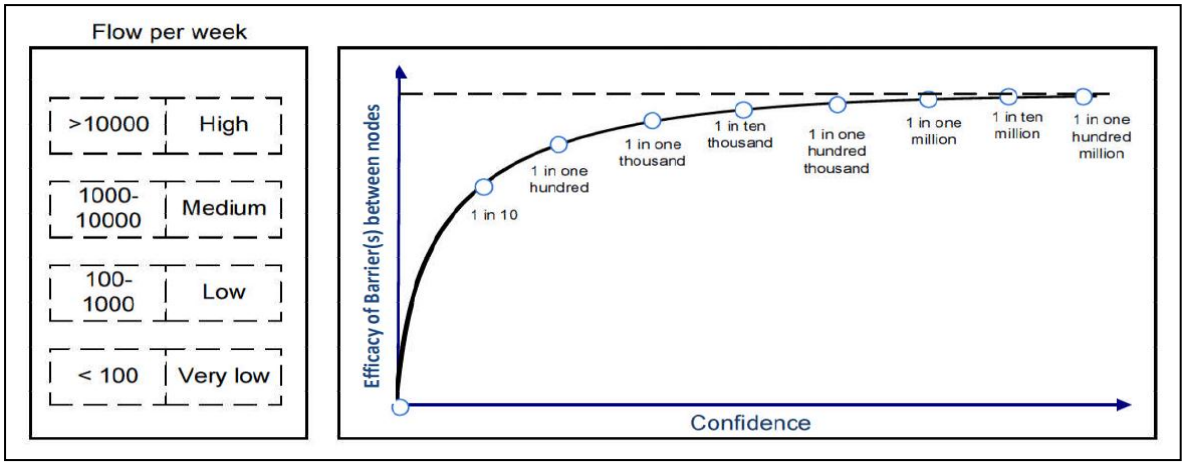

Figure 5 Elicitation form used for assesseing the connection between two adjacent nodes: incidence is captured as a flow per week and barrier failure rate is captured by the efficacy of barrier(s) between nodes.

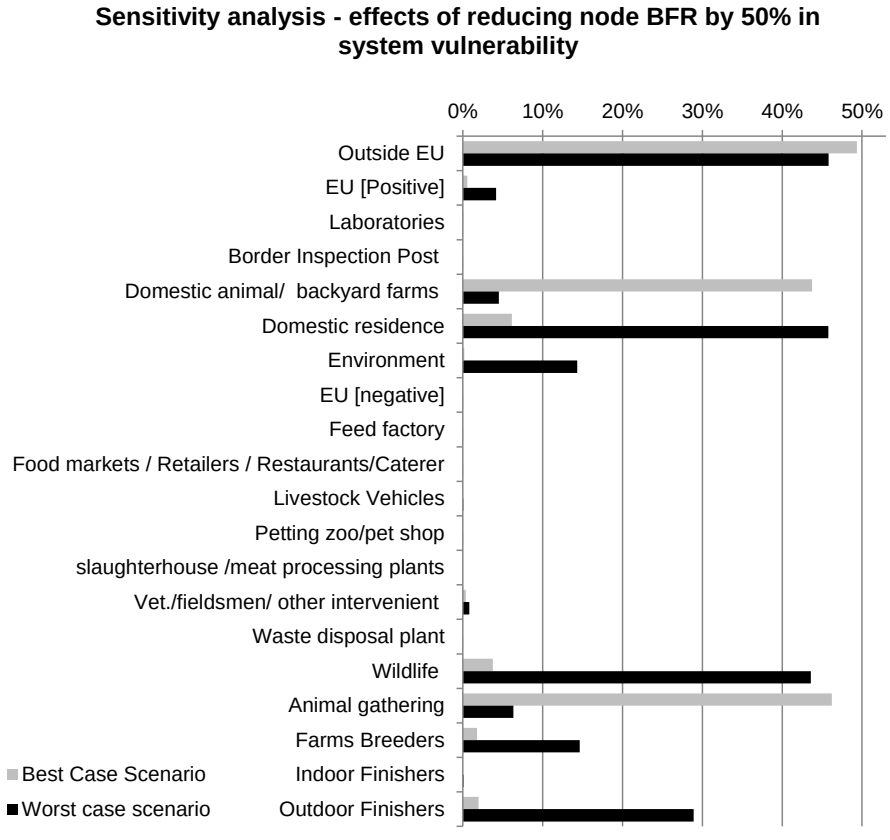

Figure 6 Node sensitivity analysis displays node influence on system behaviour by describing the reduction in performance value by comparison with the base case.

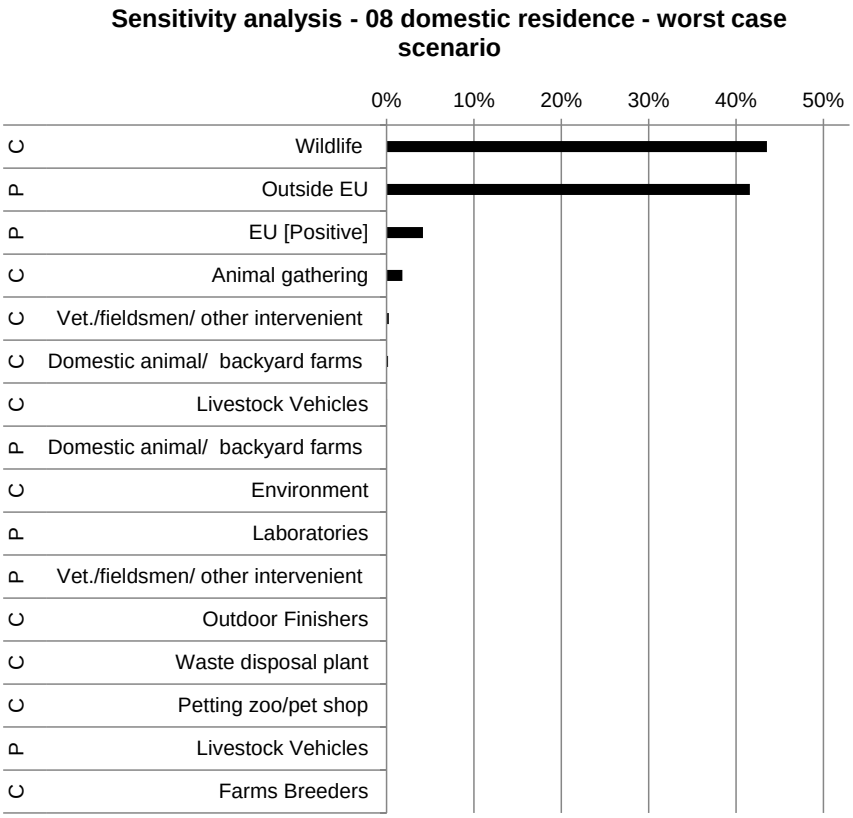

Figure 7 Arc sensitivity analysis – displays the process/events, the arcs of the network, with higher influence on system behaviour. For brevity, the graph describes the 10 most influential arcs associate with 08 domestic residences. The graphic displays all adjacent connections (upstream and downstream) to the 08 domestic residence nodes where (P) preventative representing upstream nodes and (C) contingency representing downstream nodes.

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