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Towards a resilient food supply chain in the context of food safety

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ABSTRACT

Global food supply chains have been constantly challenged by various food safety incidents or crisis. Traditional approaches on enhancing robustness of the food supply chain are not sufficient to ensure a safe food supply to the society, while building resilience as a more comprehensive approach has shown to be a good alternative option. With a resilience thinking, the food supply chain is not targeting to achieve a state of zero food safety risks, but rather to pursue the capacity to adapt and manage food safety shocks. A resilient food supply chain can still be vulnerable under the constant pressure of food safety hazards and the changing food chain environment, but has the capacity to adapt to and recover from the shocks. This study aimed to1) provide a clear definition for resilient food supply chains in the context of food safety; 2) provide a procedure to assess food safety resilience; 3) specify how a resilient food supply chain can be quantified and improved by providing a numerical example in a case study. Three dimensions of resilience factors, being time, degree of impacts caused by the food safety shocks, and degree of recovery, are suggested for assessing supply chain resilience. Results of a case study on Salmonella spp. in the pork supply chain show that the proposed framework and modelling allow for selecting the most effective strategies (having alternative suppliers, enhancing animal resilience as examples for the considered case) for improving the resilience of the supply chain for food safety.

1. Introduction

Due to the high social relevance, providing safe food to the society has always been a key topic on the agenda of food industry, policy makers and researchers worldwide. Food safety risks to human health can arise from the presence of residues of chemical substances, zoonotic bacteria, viruses, parasites, or physical hazards in our food. According to a recent estimation of the World Health Organization (WHO, 2019), around 600 million (i.e. 1 in 10 people in the world) people become ill every year due to the consumption of contaminated food. Meanwhile, the global food supply chain has been challenged by various food safety incidents or crises, such as the bovine spongiform encephalopathy (BSE) crisis in the 1990s, the presence of dioxin in chicken feed in the year 1999, and the recurrent outbreaks of foodborne illnesses due to *Salmonella* spp. in eggs (Aung & Chang, 2014). The increasing complexity of the global food supply chain on the one hand, and global threats such as climate change and urbanization on the other hand can lead to emergence of food safety hazards that can increasingly challenge the food supply chain (Leat, 2013). Finding feasible solutions to tackle these challenges is, therefore, important for the global food supply chain to ensure a safe food supply. Food business operators (FBOs) are responsible for ensuring safe food supply (EC/178/2002). Therefore, it is vital that FBOs along the food supply chain align their food safety objectives and collaborate closely to reach the common goal on a safe food supply (Buncic, Alban, & Blagojevic, 2019). Such a collaboration is important since failure of FBOs at one supply chain stage can harm other business operators in other chain stages and, eventually, harm consumers' health (Chammem, Issaoui, Almeida, & Delgado, 2018).

Traditionally, when improving the food safety performance of the food supply chain, the robustness of the food supply chain is prioritized; in other words, the strength to withstand disturbances (hereafter called food safety shocks i.e. unwanted disruptions related to the increasing presence or emergence of food safety hazards) is addressed (Asbjornslett, 1999). Robustness is defined as the ability of a system to resist the shocks and return back to the same stable situation as it has before the shock while keeping the system structure intact (Asbjornslett, 1999). Nevertheless, robustness becomes insufficient when the need for flexibility to adapt to disturbance is inevitable and resilience is, therefore, a more comprehensive concept to adopt for the food supply system nowadays (Stone & Rahimifard, 2018). Pursuing the capacity to adapt to

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and manage food safety shocks is more suitable and practical than trying to achieve a state of zero food safety risks (Nakov et al., 2019). A resilient food supply chain can still be vulnerable under the constant pressure of the presence of known and the emergence of new food safety hazards and the changing food chain environment, but has the capacity to adapt to and recover from the shock (Mumby, Chollett, Bozec, & Wolff, 2014).

The research idea on "resilience" has been discussed intensively in the different fields (e.g. psychology, ecology, supply chain management) for a long time. Holling (1973) indicated that a resilience framework is not about developing a precise capacity to predict the future, rather to have the qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take (Holling, 1973). Meanwhile, resilience has also been discussed in other research domains such as economics and supply chain management. The definition of resilience varies across different research areas and highly depends on the research context (Stone & Rahimifard, 2018). Just to name a few examples, in the field of ecology, resilience is defined as "the ability to rebound from a disturbance while maintaining diversity, integrity and ecological processes"; in the field of psychology, resilience is defined as "the developable capacity to rebound from aversity"(Luthans, Vogelgesang, & Lester, 2006); whereas in the field of supply chain management, resilience is defined as "the ability to react to an unexpected disruption and restore normal supply network operations" (Rice & Caniato, 2003). It is, therefore, important to provide a clear definition of resilience that fits the general resilience concept but can be adopted to the specific research context. Building resilience in the context of food safety, is a new research domain with limited relevant studies. To our best knowledge, Alban, Häsler, Nielsen, and Rüegg (2017) is the one of the few studies that investigates the resilience of food supply chains with the focus on food safety. In that study, the authors adopt the definition used in general systems theory in which resilience is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Alban et al., 2017, p. 29). Nevertheless, since the definition is not specific for food safety, a more clear definition is needed explaining the link between resilience and food safety.

The objectives of this study are: 1) to provide a clear definition for resilience of food supply chains in the context of food safety; 2) to set up a methodology to assess food safety resilience and to illustrate the resilience quantification concept and methodology; 3) to specify how a resilient food supply chain can be quantified and improved by providing a numerical example.

2. Methodology to assess food safety resilience

A recent study (Oliver et al., 2018) stressed the importance of giving an explicit definition of resilience with regard to the resilience 'of what', 'to what', 'for whom' and 'over what timeframe'. Using these elements, we define resilience in the context of food safety as: the recovery and adaptation capacity of the food supply chain to food safety shocks to allow the delivery of safe food over a reasonable lead time. With our definition, we aim to emphasize the importance of building and maintaining resilience throughout the supply chain. In case resilience targets only one stage of the food supply chain, emerging issues might arise on other stages of the chain. For instance, resilient animals which do not have clinical symptoms at the farm stage might cause food safety shocks at the slaughtering stage (Scherer et al., 2008). Therefore, resilience needs to be incorporated in the full supply chain.

To evaluate and improve the resilience of the food supply chain to food safety shocks, we present a diagram of an essential procedure that is based on existing literature on resilience. Besides being based on a literature study, the procedure was developed and validated through a series of in-depth discussions with six experts who are senior researchers from different fields (i.e. resilience, food safety, food supply chain management). Feedback from these experts was gathered and incorporated in the final version presented here (Fig. 1).

Resilience as a multidimensional and multidisciplinary concept can be setup with different objectives e.g. social resilience, economic resilience, environmental resilience (Kamalahmadi & Parast, 2016). In this study, we set the objective as to "ensure a safe food supply" (Fig. 1), which is aligned with our resilience definition. Building a resilient food supply chain to food safety shocks is vital for realizing the aforementioned objective. Previous studies addressed the importance to specify the context of resilience as the initial step (Oliver et al., 2018); (Meuwissen et al., 2019). Subsequently, the quantification of resilience and improvement of resilience are suggested by several authors ((Ouyang, Dueñas-Osorio, & Min, 2012); (Elleuch, Dafaoui, Elmhamedi, & Chabchoub, 2016)). We, therefore, distinguish three steps to enhance the resilience of the food supply chain, which are: 1) resilience context specification, 2) resilience measurement, and 3) resilience improvement (Fig. 1). These three steps are explained in detail in the following section, together with the methodology and data needed for realizing the three steps. The boundary for the food supply chain illustration in this research is from primary production (including plant and animal production) up to the stage of retailing. The stages of processing, wholesaling and transportation in between two stages are included as well. However, for specific cases under study, not all stages might be relevant, and fewer stages might need to be covered than the proposed ones. In addition, although managing food safety shocks from the consumption point view is important, it is often considered more difficult to manage and we only consider resilience from the point of a safe food supply.

2.1. Resilience context specification

Although the definition of resilience has been narrowed down to the context of the food supply chain and food safety, it is still necessary to further specify the research context with the targeted food supply chain and food safety shocks (Stringer & Hall, 2007). As indicated in Fig. 1, questions of 'which food supply chain' and 'what food safety shocks' should be answered in the first step of the procedure. The relevant supply chain stages, for example, are different for vegetable supply chains when compared to meat supply chains (Stringer & Hall, 2007). Meanwhile, various types of food safety hazards (e.g. microbiological, chemical) are relevant for a range of food supply chains as well (Stringer & Hall, 2007). In addition, there are fundamental differences between types of food safety hazards. Microbiological and chemical hazards, for example, are different in term of transmission dynamics throughout the food supply chain (Guo, Claassen, Oude Lansink, & Saatkamp, 2014). Take the meat chain as an example, microbiological pathogens can multiply in animals, while this is not possible for chemical hazards (van Asselt, van der Fels-Klerx, Marvin, van Bokhorst-van de Veen, & Groot, 2017). Moreover, the presence of microbiological pathogens can be eliminated or reduced after heat processing, while most often this is not the case for a chemical contamination. These differences in research context can lead to different resilience measurements and improvement options, which are investigated in the later steps of the procedure.

In order to specify the resilience context, methodologies such as trend analysis (Adamse, Van der Fels-Klerx, & de Jong, 2017), systematic literature review (Ali, Mahfouz, & Arisha, 2017; Banach, Hoek-van den Hil, & van der Fels-Klerx, 2020) and expert elicitation (Marvin et al., 2009) can be adopted to identify the most relevant food supply chain and corresponding major food safety hazards relevant to the particular chain.

2.2. Resilience measurement

The study of Pimm, Donohue, Montoya, and Loreau (2019) emphasizes the importance of measuring resilience, so that it can be operationalized (Pimm et al., 2019). Once the research context is well defined, the next step is to assess the supply chain resilience to food

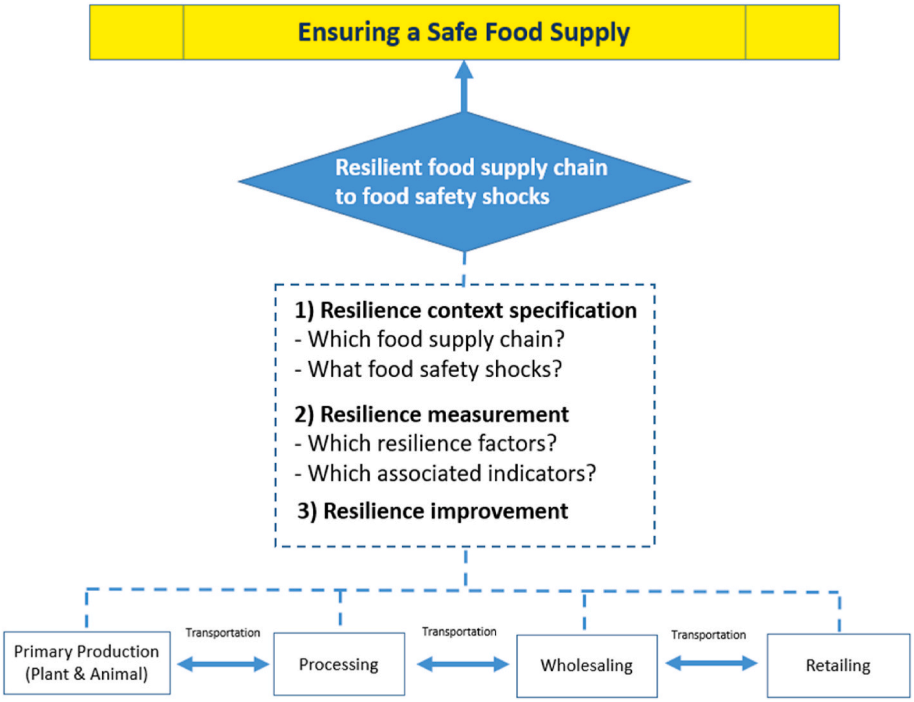

Fig. 1. Procedure for building a resilient food supply chain to food safety shocks.

safety shocks. Since resilience in the context of food safety is a rather new concept, no existing framework can be applied one-to-one for this aim. We therefore adopted the concept developed by the study of Nakov et al. (2019) on resilience of animals to diseases, because it has a close connection to the food safety domain. Three factors are derived to quantify food supply chain resilience to food safety shocks, which are: 1) time, 2) degree of impacts caused by the food safety shocks, and 3) degree of recovery.

Three aforementioned resilience factors are illustrated in Fig. 2. Time is reflected in the horizontal axis whereas the vertical axis shows the performance which can be, for example, the productivity of a farm. The study of Nakov et al. (2019) only focuses on the animal level, and for this research, we extend the concept to the supply chain level, thus when identifying relevant resilience indicators, such indicators should be searched from all three factors and be identified for each individual chain stage separately, as well as for the overall supply chain.

The first factor for measuring resilience is time. Three types of time should be considered i.e. incubation time, detection time and recovery time. *incubation time* is the time period between the emergence of the food safety shocks and the time when the impacts caused by the shocks start. At the level of animal/plant, the incubation time can be the period between infection and the moment clinical symptoms are shown. While at the level of retailing, the incubation time is the period between the arrival of unsafe products/batches at the retailer entry point and the safe supply capacity of retailers starts to drop compared to the business as usual. To be more specific, if (future) detection technology allows, resilient retailers can detect unsafe products upon their arrival at entry point and, in the ideal situation, retailers can immediately remove the unsafe products and get alternative safe products either from their supplier or from their own stock, which means the resilience of retailers

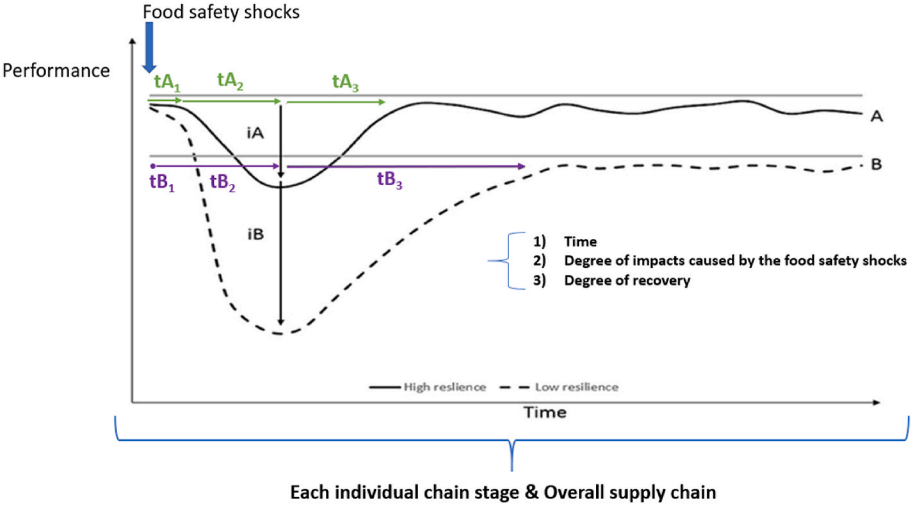

Fig. 2. Resilience factors for quantification of food supply chain resilience to food safety shocks, adapted from (Nakov et al., 2019) (*tA_1 and tB_1 represent the incubation time; tA_2 and tB_2 represent the detection time; tA_3 and tB_3 represent the recovery time; iA and iA + iB are the degree of impacts caused by the food safety shocks.*).

to food safety shocks is very high. If when the shocks happen, the retailers are unable to supply the same amount of as they usually do, their resilience performance tend to be lower as well. *Detection time* is defined as the time difference between the presence of a food safety shock and the detection of the shock. At the animal or plant level, the detection time is the time difference between the animal or plant getting infected and the animal/plant being detected with infection. An infection can be detected before the animal/plant shows clinical symptoms or much later. Therefore, the detection time can be shorter than the incubation time or longer. While at the retail level, the detection time is the difference in time between the arrival of unsafe products and the unsafe products being spotted. Last but not least, the *recovery time* is defined as the time between the presence of a food safety shock and recovery back to the pre-shock situation or to a new equilibrium. The recovery time at the animal or plant level is the time difference between the animal/plant becoming infected and being recovered. While at the retail level, the recovery time is the time difference between the shock being present and the supply capacity recovering back to business as usual.

The second factor for measuring the resilience (i.e. *degree of impacts caused by the food safety shocks*) can range from the severity of symptoms at the animal level, to the quantity of products withdrawn from the market at the retail level. The degree of impacts caused by the food safety shocks can be reduced if the system is adapted to become more resistant to the shock. For example, at the animal level, the symptoms of animals can become less severe when the animal gets infected a second time after a previous infection. Immunity after first infection can develop for certain hazards, and this immunity can be seen as the effect of the 'adaptation' of the animal. The third factor for measuring resilience (i.e. *degree of recovery*) reflects the capacity to recover back to a steady state which can be lower, equal to or even outperform the pre-shock conditions (Cimellaro, Reinhorn, & Bruneau, 2010). In the situation of small impacts being caused by the occasional food safety shocks, only small adaptations may be needed for the system to recover from the shocks and back to the pre-shock situation; while in the case of large impacts being caused by the food safety shocks or the shocks are constantly happening, the system may need to have transformation to reach to a new equilibrium that can either lower or outperform the pre-shock conditions.

In Fig. 2, two different scenarios (i.e. A and B) are presented. Scenario A represents a high resilience while scenario B represents a low resilience. The degree of impacts caused by the food safety shocks is quantified as iA for scenario A, and as iA + iB for scenario B. The incubation time is quantified as tA_1 for scenario A, and tB_1 for scenario B. In both scenarios, the food safety shock is assumed to be detected at the moment of its highest impact. The detection time can then be quantified as tA_2 for scenario A, and tB_2 for scenario B. The recovery time can be quantified as tA_3 for scenario A and tB_3 for scenario B. The degree of recovery can be reflected in the difference between pre-shock situation and after-shock situation; so for scenario A, this is approximately 0, while for scenario B, this is iA.

In order to mathematically quantify the resilience performance of food supply chains to food safety shocks, our methodology is based on the "infrastructure resilience modelling" approach (Ouyang et al., 2012). The conceptual similarity between food safety shocks and infrastructural system hazards (e.g. disruption of power grid due to hurricanes) allows us to utilize the referred methodology. The grey area (i.e. ACDB) of Fig. 3 represents the performance deviation (deviated performance × time) of the food supply due to the food safety shock. The smaller the relative size of the grey area (i.e. ACDB) to the big rectangle area (i.e. AEFB), the lower the performance deviation and the more resilient the food supply chain. Equation (1) calculates the resilience of the food supply chain with respect to a food safety shock (R). The closer R is to 1, the more resilient the system is.

$$R = \frac{\mathrm{TP} - \sum_{h=1}^{H} \nu^h \sum_{q^h} E\left[AIA^h(q^h)\right] \phi^h(q^h)}{\mathrm{TP}} \tag{1}$$

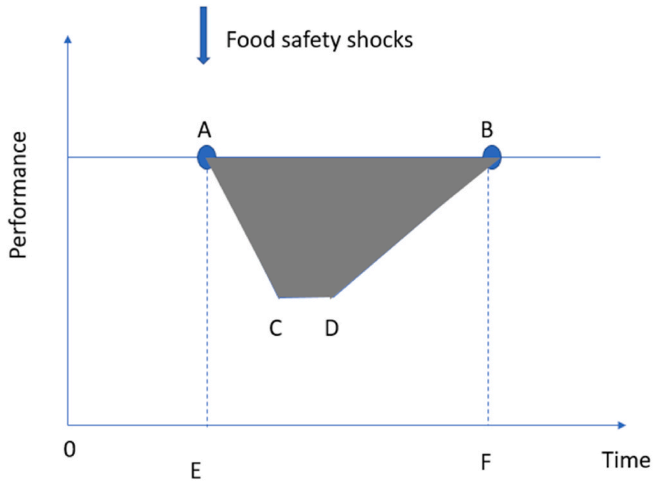

Fig. 3. Mathematical quantification of resilience performance of food supply chain to food safety shocks (The area of ACDB is the reduced performance caused by the food safety shocks, the area of AEFB indicates the normal performance without influence of the food safety shocks).

R, resilience of the food supply chain with respect to a food safety shock
TP, the target performance level at retail in the normal period
h, shock type that can range from 1 type to H type
ν^h*, the occurrence rate of shock type h*
q^h*, the intensity of hazard type h*
$E[AIA^h]$*,the expected grey area of Fig. 3 when a specific shock intensity* q^h *of shock type h occurs*
$\Phi^h(q^h)$ *, probability mass function when* q^h *is a discrete variable*

Equation (1) estimates the resilience of the food supply chain (R) with respect to a food safety shock. *TP* is the target performance level at retail in the normal period, which can be stochastic or deterministic. Here, we consider it as a deterministic variable. In practice, we can set the "mean value" of performance in the last several years as the T.

ν^h is the occurrence rate of shock type h. A shock type is determined by both the nature of the shock (e.g. carcass contamination) and the occurring supply chain stage (e.g. slaughtering, food processing or retailing).

q^h is the intensity of hazard type h. It is a stochastic variable with the probability density function $\phi(q^h)$ (If q^h is a continuous variable) or probability mass function $\Phi^h(q^h)$ (If q^h is a discrete variable).

$E[AIA^h]$ is the expected grey area of Fig. 3 when a specific shock intensity q^h of shock type h occurs. Considering a shock type named "contaminated feed introduction at farm level", the intensity of this shock type can be considered as the number of introduced batches of the contaminated feed. Two batches introduced has a higher intensity than one batch introduced because it will cause a larger grey area $E[AIA^h]$ given all other conditions are kept the same.

From function (1), we can see that obtaining the expected value of grey area in Fig. 3 is key to calculate the food safety resilience in a supply chain (R).

2.3. Resilience improvement

Resilience can be reflected by major components, namely resistance capacity, recovery capacity as well as time (Melnyk, Closs, Griffis, Zobel, & Macdonald, 2014). Resilience improvement can, therefore, be achieved by improving any of those components. A stronger resistance can be achieved by, for example, enhancing herd immunity and following food safety measurements like good manufacturing practices (GMP) as well as analyzing food safety shock patterns (Alban et al., 2017; Darnhofer, 2014). The recovery capacity can be improved by, for example, quick detection of the food safety hazards (e.g. using sensor technologies for the real-time monitoring, proactive surveillance scheme) and allowing redundancy on the production capacity (e.g. labor, raw materials, equipment) and supply chain network (e.g. alternative supplier, transporter). Flexibility can be created to make adjustments to the unexpected food safety hazards (Wang et al., 2016). In addition, at the supply chain level, enhancing efficient communication and coordination between the supply chain partners can accelerate the recovery process when the food safety shocks occur (Ouyang et al., 2012).

3. Numerical example

3.1. Case description

To further elaborate on the proposed procedure, a case study on *Salmonella* spp. In the pork supply chain was used. This case was selected based on the fact that more than one-fourth of the total protein consumed worldwide is derived from pork production, and *Salmonella* spp. Is the most studied food borne pathogen in pork and derived products in the period of 1966–2016 in Europe (VanderWaal & Deen, 2018). Resilience can be explored at different stages (e.g. stage of animal, farm, slaughter house) of the pork supply chain. Resilience in this context is defined as the capacity of the pork supply chain to recover after a high *Salmonella* prevalence in pork to reach the delivery of safe pork products over a reasonable lead time.[1] We focused the case study on resilience from the retailers' point of view. Recovery at retail is defined as the zero prevalence of *Salmonella* spp. In the final pork products supplied by retailers, which can be achieved by either recovery of the contaminated stages or by switching to an alternative safe pork supply to retail. The extreme (hypothetical), optimal situation of zero *Salmonella* spp. prevalence is assumed for the purpose of numerical illustration to provide a clear picture of how building resilience can improve the safety of food supply.

A Monte Carlo simulation study was conducted to intuitively demonstrate the process of quantifying supply chain resilience in the context of food safety, in this case from the retailers' perspective on *Salmonella* spp, in pork. It is necessary to point out that this simulation study serves as a numerical example for illustration purposes only. The results can only provide very rough indications concerning the particular case; no concrete conclusions or managerial implications for real practice can be drawn from this simulation study.

In the simulation study, we considered a hypothetical pork supply chain in which a representative pig farm delivers finished pigs to a representative slaughterhouse, and the slaughterhouse supplies the pork products (e.g. half carcasses, cuts) to a representative retailer. *Salmonella* spp. monitoring, including sampling and analyses, is conducted at the slaughtering stage. The input parameters of the model, the default parameter values used in the baseline scenario, and the reference sources are listed in Table 1. The model was run for 500 rounds to arrive at the distribution for the resilience performance.

The baseline scenario was constructed using the default parameter values in Table 1. The baseline scenario is the default situation where no extra interventions are applied when the shock happens, the recovery of the system is only linked with the recovery rates defined in Table 1. The resilient animals in this numerical example are defined as the animals that have a lower daily transmission probability and higher speed of recovery (in Table 1). Alternative scenarios (in Table 2) are explored to represent effects of potential interventions on the resilience in practice as well as for the purpose of sensitivity analysis.

Table 1
Important parameters used in the Monte Carlo simulation model.

Parameter	Parameter value in the baseline scenario[a]
Simulation horizon	365 days
Total number of animals on the farm	1000
The number of initial resilient animals out of the 1000 are generated from a normal distribution	mean = 500 and Std = 100
The time span in days between two batches of animals to the slaughterhouse	7 days
The number of animals that the farm sent to the slaughterhouse once per 7 days	240
Total number of new animals purchased by the farm once per 7 days	240
The number of the newly purchased resilient animals out of the 240 are generated from a normal distribution	mean = 120 and Std = 24
Ratio to convert pigs to pork products	80 pork product per animal
Hazard occurrence probability per day	0.007
The number of batches of infected feed to be introduced to the farm are generated from a normal distribution	mean = 3 and Std = 1
The number of initial infected animals from one batch of feed	10 animals per batch
The daily transmission parameter for the resilient and non-resilient susceptible animals	0.05 and 0.5
The daily transmission parameter for the resilient and non-resilient recovered animals	0.025 and 0.25
Sampling size in slaughterhouse for each batch of 240 animals	1 animal
The sensitivity of the test in slaughterhouse	0.9
The daily recovery rate before hazard detection for the resilient and non-resilient susceptible animals	1/60 and 1/120
The time-dependent daily incremental recovery rate after the hazard detection	1/30

[a] The parameter values are assumptions made based on the study of Van der Gaag et al. (2004) and (Alban et al., 2012).

Table 2
Scenarios investigated in the Monte Carlo simulation model.

Scenario Category	Scenarios No.	Description
Baseline	Scenario1	No extra intervention applied for the shocks
Alternative supply	Scenario2a	Alternative supplier to fill a quarter of the gap
	Scenario2b	Alternative supplier to fill the whole gap
Test sensitivity	Scenario3a	Reduce the sensitivity of the tests from 90% to 50%
	Scenario3b	Increase the sensitivity of the tests from 90% to 99%
Recovery rate	Scenario4a	Reduce the recovery rate after detection by half
	Scenario4b	Double the recovery rate after detection
Animal resilience	Scenario5a	All animals are assumed resilient
	Scenario5b	All animals are assumed non-resilient

The first group of scenarios (i.e. scenario 2a and 2b) aim to determine the effects of having an alternative supply with different abilities to fill the shortage of safe pork products in case of the food safety shock. The second group of scenarios (i.e. scenario 3a and 3b) aim to determine the effect of a lower or a higher test sensitivity for the food safety shock on the resilience performance. The third group of scenarios (i.e. scenario 4a and 4b) explores the effect of the recovery rate after detection of the shock on the resilience performance. Last but not least, animal resilience, which has a close link with the transmission rate and the recovery speed, is considered in the last group of scenarios (i.e. scenario 5a and 5b).

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[1] Lead time is a common term used in supply chain management for the latency between a customer order received and the moment the order is delivered.

3.2. Numerical example results

The result of one simulation run in the baseline scenario is presented in Fig. 4, showing that the *Salmonella* contaminated pork start to appear at the retailer stage around day 60 and is totally eliminated from the chain around day 140. The shaded area i.e. marked with oblique blue lines (Fig. 4) is the deteriorated resilience performance compared to the *Salmonella*-free situation.

The results of the entire simulation study are presented in Fig. 5. For each of the 9 scenarios, the mean and standard deviation (Std) of the resilience performance are reported. The average resilience performance under the default parameter settings of the baseline is equal to 95.4%. This means that in the baseline scenario, the number of safe pork products supplied to the retailer accounts for 95.4% of that in the *Salmonella*-free period. Scenario 2a shows that having an alternative supply to fill a quarter of the gap of safe pork products can improve the average resilience performance from 95.4% to 96.3%. The performance will increase to 98.9% when all the entire gap is filled by the alternative supply (scenario 2b). Results on effects of test sensitivity on the resilience performance show that reducing the test sensitivity from 90% to 50% does not further bring down the resilience performance much (from 95.5% to 93.8%). Meanwhile, when increasing the test sensitivity to 99%; there is hardly any change in resilience performance (from 95.4% to 95.5%). For the recovery rate after detection, we find that if we reduce the recovery rate after detection by half (scenario 4a), the resilience performance will drop from 95.4% to 92.8%, while if we double the recovery rate after detection (scenario 4b), the resilience performance will increase from 95.4% to 96.5%. Last but not least, the scenarios exploring the impact of animal resilience show that if the animal is resilient (scenario 5a), the resilience performance of the safe pork supply will increase from 95.4% to 98.5%, while if the animal is non-resilient (scenario 5b), the performance will decrease from 95.4% to 90.8%.

Based on the means and standard deviations of the resilience performance in all scenarios, having an alternative supply that can fill the shortage of safe pork supply (scenario 2b) is the most effective way of ensuring a high pork chain resilience. Making all animals resilient (98.5%) (scenario 5a) is also an effective option to improve the resilience performance of the pork supply chain.

4. Discussion and conclusion

Resilience, as an emerging concept, has shown its importance in enhancing the supply of safe food. The difference between the resilience approach compared to the conventional food risk management approach is that with resilience the key is the ability to adapt while the goal of conventional risk management approach is to resist (i.e. prevent or eliminate) food safety shocks. With increasing threats of food safety, a system that has the capacity to make adaptation and be resilient to food safety shocks is more practical than a system that focuses only on building its resistance capacity. A good example can be seen in the water management system in the Netherlands. The system has changed from increasing the height and width of the dikes to a new approach allowing the river water flood over the lands and give space to the water.

Due to the multidimensional and multidisciplinary traits of resilience, its definition can be diverse and inconsistent. The ambiguity can hamper further research and practical applications to assess and improve resilience. It is, therefore, vital to provide a clear definition of resilience given the specific context, which in this case is food safety. MacAskill and Guthrie (2014) concluded in their study that a strict consensus on the definition of resilience is not practical and perhaps not even possible, and meanwhile an acceptance on multiple and valid interpretations of resilience is encouraged (MacAskill & Guthrie, 2014). To formulate a clear and context specific definition, Oliver et al. (2018) provides a useful structure (i.e. to the resilience 'of what', 'to what', 'for whom' and 'over what timeframe'). The definition of resilience proposed in this study is from the food supply point of view. Nevertheless, when increasing the resilience of food supply chains to food safety shocks, the recovery of the supply capacity is just one side of the story, meanwhile, the recovery of consumers' trust should not be neglected in the process. Fast actions to remove unsafe products from the market and solve the food safety problem as well as good public communication can reduce unnecessary public alarm and anxiety.

The procedure for building a resilient food supply chain to food safety shocks developed in this study provides a guidance for future research on how to assess and improve resilience performance of food supply chains towards food safety shocks. The approach is developed by synthesizing resilience aspects from different fields (e.g. supply chain management, infrastructure system management) where the concept of resilience has been intensively discussed and applied. With this approach, the purpose is not to make theoretical contributions on

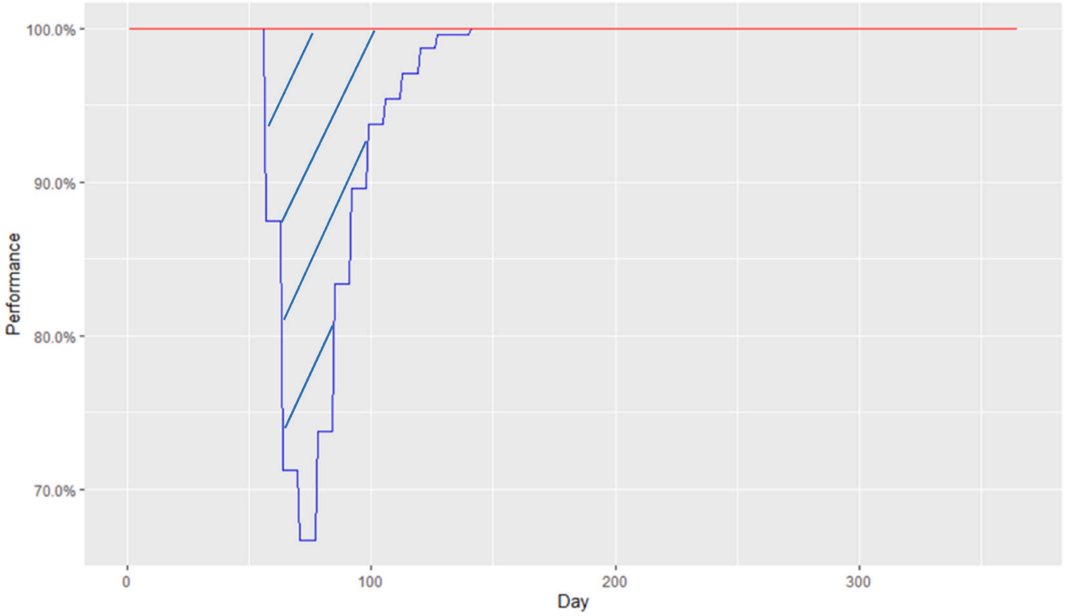

Fig. 4. An example of the result of one simulation run in the baseline scenario.

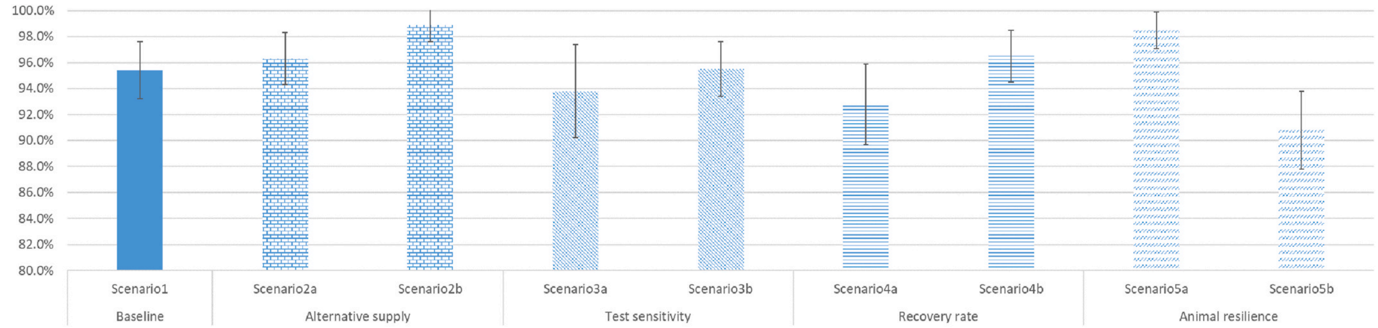

Fig. 5. The resilience performance (%) achieved in each of the tested scenarios.

further developing the concept of resilience, but rather to initiate connections between the field of food safety and supply chain resilience in order to ensure a safe food supply. The developed procedure starts with addressing the importance of specifying the resilience context before assessing the resilience performance. Methodologies, such as literature review and trend analysis, can be used to identify which food supply chain and which corresponding food safety shocks need to be addressed. Given the complex and comprehensive nature of resilience, a multidisciplinary collaboration is suggested. Meanwhile, through involving relevant stakeholders and experts into the identification process, a good link with real life practice can be achieved. Nevertheless, the proposed procedure can also serve as a more generic approach that is applicable for the emerging food safety shocks that we have limited or no experience with.

The resilience factors (i.e. time, degree of impacts caused by the food safety shocks, degree of recovery) for quantification of resilience performance of the food supply chain to food safety shocks are derived from resilience factors of pigs to diseases in the study of Nakov et al. (2019). Nevertheless, the factors we applied in this study are well connected with the broader literature on resilience. For example, the factors can be used to quantify some key capabilities of a resilient supply chain that are derived by the study of Ali et al. (2017) on a systematic literature review related to supply chain resilience. Ali et al. (2017) proposes five capabilities which are the ability to anticipate, adapt, respond, recover and learn. With our approach, the ability to anticipate, adapt, respond and recover can be quantified. To be more specific, the ability to anticipate can be for example reflected by a shorter detection time or lower degree of impacts caused by the food safety shocks. Meanwhile, a shorter detection time and lower degree of impacts often reflect a stronger ability to adapt and respond. In the case study, the adaptation ability is considered by allowing the resilient animals to have a lower infection rate and a higher recover rate and by allowing the retailer to have a flexible supply network (i.e. alternative safe supplier). The ability to recover can be reflected in the recovery time and degree of recovery. With regard to the ability to learn, it is difficult to be quantified in one shock period. With multiple shock periods simulated, the ability to learn may be reflected. Future study is suggested to incorporate learning element into the quantification process.

In addition to the supply chain resilience field, our resilience factors can also be applied in a more generic resilience framework. Take the five dimensions (i.e. resistance, absorptive resilience, adaptive resilience, adaptive preference and transformation) developed by Béné and Doyen (2018) as an example, the three proposed resilience factors can be applied to quantify the resilience of a system and help the decision makers make better decisions on which resilience dimension is more appropriate to choose for the system. Those dimensions are highly dependent on the severity and frequency of shocks. With a small and seldomly occurring shock, a resilient system may not need to change at all. But if the severity and frequency of shocks increase, a system needs a transition from absorptive resilience (i.e. temporary change in the system) to adaptive resilience (i.e. permanent change in the system), and eventually the system needs to transform in order to conquer the challenges brought along with the major shocks. Although in Fig. 2, only one shock is shown for illustration purpose, multiple shocks can occur over time.

This study is the first study that provides a quantification methodology and demonstrates its application for resilience of the food supply chain towards food safety shocks. The numerical example on the case provides a better illustration of the proposed procedure. Nevertheless, it has to be kept in mind that a simplified version of the supply chain is used and various assumptions have been made for the model parameters as the numerical example was just meant to demonstrate the proposed procedure.

In the numerical example, we only considered the scenario of back to the pre-shock supply performance. However, it is important to note that it is possible to outperform the original situation after a shock. Just to name a few examples, after the massive outbreak of avian influenza in Northern Italy, the old-fashioned poultry production facilities were replaced by new and modern facilities, due to some producers going either bankrupt or being taken over (Terregino et al., 2007). Similarly, in the context of the recent Covid-19 pandemic, it is likely that food and animal production systems will change eventually after the shock. The mink (a small brown animal that is kept for its fur) production, for example, might come to an end in countries, like Denmark and the Netherlands, in which is it not yet forbidden (Lesté-Lasserre, 2020). This is the so-called transformation of the system as introduced in Béné and Doyen (2018). When the consequences caused by the shock are irreversible, it is not possible for the system to adapt, but rather systems will transform (Béné & Doyen, 2018). In addition, it is important to realize that short-term effective coping strategies might not provide satisfying results in the long run. Meanwhile some resilience strategies such as using certain food processing treatments or changing the supply network can also bring in potential negative consequences on food quality or production cost (Béné, Headey, Haddad, & Grebmer, 2015).

The current study was a first attempt to apply the resilience concept to food safety so as to broaden the view on food safety management. Given the fact that resilience in this study is only examined from the technical aspects related to food safety shocks, future studies are suggested to further refine the proposed procedure to also incorporate other aspects of resilience (e.g. social, organizational and economic) to food safety so as to provide more comprehensive resilience insights (Ouyang et al., 2012). Potential trade-offs between different dimensions should be considered as well. Moreover, the application of the procedure on the case study should use more detailed information and data of different supply chain stages, so more realistic insights can be drawn from the case study. Meanwhile, the model should be parametrized with historical data as much as possible, so that realistic resilience performance of food supply chain to food safety shocks can be assessed and feasible improvement options can be explored. However, due to the limited knowledge on quantifying the resilience of different actors (e.g. animals, farms, processors, retailers), accurate quantification on some of the model parameters (e.g. recovery rate of the resilient actors) can be rather challenging. In addition to the microbiological hazards of the pork meat supply chain as explored in this study, other food supply chains (e.g. vegetables, dairy products) and types of hazards (e.g. chemical hazards, viral hazards) are suggested for future study because of the differences in relevant supply chain stages and transmission dynamics throughout the supply chain. Different resilience factors are expected to be derived for different supply chains and hazard types.

To conclude, this study provides a clear definition for the resilience of food supply chain towards food safety shocks. Furthermore, a procedure is developed to assess the resilience performance of food supply chains towards food safety shocks. For assessing resilience, three resilience factors (i.e. time, degree of impacts caused by the food safety shocks, degree of recovery) are suggested. This quantitative approach allows for scenario evaluations in order to improve the resilience of the food supply chain. With a numerical example on the case of *Salmonella* spp. In the pork supply chain, the mechanism and effectiveness of the proposed procedure are demonstrated. The results show that the modelling approach allows for selecting the most effective strategies (e.g. having alternative supplier, enhancing animal resilience) to improve supply chain resilience and the safe food supply capacity.

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