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Commentary

Expert-driven methodology to assess and predict the effects of drivers of change on vulnerabilities in a food supply chain: Aquaculture of Atlantic salmon in Norway as a showcase

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ABSTRACT

Background: In the last decades, food produced by aquaculture has seen an impressive increase worldwide but maintaining high quality and safety is increasingly becoming a concern. It is apparent that changes in- and outside the aquaculture supply chain may act as driving forces for the introduction of food safety hazards. Knowledge on these drivers of change and their impact in the various steps in the food supply chain may help food producers to mitigate to potential risks and maintain high-quality food.

Scope and approach: In this study, we analysed the use of expert driven methodologies to assess and predict the effect of drivers of change on selected food/feed safety vulnerabilities in the salmon aquaculture supply chain of Norway. The presented overview is based on the findings of the “Aquarius” project, which was funded by the European Food Safety Authority (EFSA).

Key findings and conclusions: In this study, over 100 experts were involved and various expert elicitation methods were applied such as on-line questionnaires, interviews, Delphi and Failure Mode and Effect Analysis (FMEA). This approach resulted in a comprehensive overview of the Norwegian salmon supply chain. For each step in the supply chain, vulnerabilities for human and animal health were identified, which were prioritised by FMEA. For the two highest-ranked vulnerabilities in each step of the supply chain, drivers were identified and prioritised by expert elicitation in a Delphi study. Also, indicators and linked data sources were obtained for the highest-ranked drivers. The comprehensive information collected was integrated in a Bayesian Network (BN) model that links data sources for indicators and drivers of change. The applicability of the BN model was demonstrated for salmon health for four vulnerabilities and three steps in Atlantic salmon aquaculture. The accuracy of developed model was 81%.

1. Introduction

The global fish supply is expected to reach 186 million tons in 2030 of which over 60% is expected to come from aquaculture (The World Bank, 2013). The majority of the world’s salmon production is farmed (around 70%), of which more than 90% consists of Atlantic salmon (FAO, 2016). Currently, the Atlantic salmon consumed in the European Union (EU) is produced in Norway, Chile, Great Britain, Canada and Faroe Islands with Norway as the greatest producer (i.e. >80% of all Atlantic salmon) (NSC, 2016). Although the production still increases, a biological limit is approaching where biological and environmental issues need to be tackled by pursuing sustainability, low environmental impacts and biosecurity (Rabobank, 2014).

The Atlantic salmon supply chain consists of various supply chain steps such as feed, broodstock, fertilized eggs, farming, processing, retail and consumer. In each of these steps, specific food safety hazards need to be monitored because it may affect the salmon quality or production volumes. For example, feed is a major component of the costs in Atlantic salmon aquaculture. Therefore, the quality of feed is very important (Sørensen, 2012). During the salmon life cycle, the feed composition

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varies as there is different feed for freshwater (i.e. starter, grower and smolt transfer), seawater grower and broodstock. Previously, the two most relevant ingredients in fish feed have been fish oil and fishmeal (FAO, 2016). However, the composition of salmon feed produced in Norway has changed considerably since the 1990s (Ytrestøyl et al., 2015). The marine ingredients have been replaced by plant ingredients, and in 2016, marine protein sources constituted only 14.5% of the feed (Aas et al., 2019). The use of marine raw materials has been replaced by plant protein sources, such as wheat, soy, corn, sunflower, beans peas (Chile and Canada) and rapeseed oil, depending on price and availability. Soy protein concentrate, rapeseed oil, camelina oil, wheat and wheat gluten accounted for the largest amounts in Norwegian salmon feed in 2016 (Aas et al., 2019). The substitution is mainly driven by the decreased availability of fishmeal and fish oil (Tacon and Metian, 2008). This is also related to the feed costs, which is one of the most important cost factors in aquaculture production.

Change in and around the salmon supply chain may impact feed and food safety. Potential food safety hazards may enter the supply chain via feed, environment or by improper management, e.g. lack of hygiene during the various steps in the supply chain. Potentially, a wide range of microbial and chemical hazards may occur, such as viruses, bacteria, heavy metals and persistent organic pollutants (POPs).

Vulnerabilities in a certain step of the salmon supply chain may introduce or increase the level of food safety hazards. A vulnerability has been defined as a weakness in the salmon supply chain that may cause harm to humans or animals (FDA, 2012). Vulnerabilities should be identified and controlled. Potential human and animal health vulnerabilities in the salmon aquaculture have been described in the literature for various steps of the supply chain. Examples of vulnerabilities related to human health are: i) presence of chemicals & quality of feed ingredients (feed step), ii) use of antibiotics and biocides (farming in seawater step), iii) storage conditions, fraud and lack of knowledge (processing step). Examples of vulnerabilities related to animal health are: i) dietary deficiencies (feed step), ii) stress & mortality (broodstock step), and iii) water quality (fertilized eggs step & farming in seawater step). A full overview may be found in the final "Aquarius" report (Marvin et al., 2019).

Changes inside and outside the supply chain may act as driving forces for vulnerabilities or the introduction of hazards. Such driving forces are referred to as "driver of change" and has been defined by the European Food Safety Authority (EFSA) as "Issues shaping the development of a society, organisation, industry, research area, technology, etc.", which can be classified in social, technological, economic, environmental, and political (STEEP) categories. Drivers may act as modifiers of effect on the onset of emerging risks as they can either amplify or attenuate the magnitude or frequency of risks arising from various sources (EFSA, 2010). Many drivers of change in various sectors within i.e. environment, economy and society have been identified as drivers of change on vulnerabilities in the salmon supply chain.

It is apparent that the aquaculture of salmon faces many challenges that may have an impact on the quality and safety of the products it produces. Various control measures are in place in different steps of the supply chain to ensure the quality and safety of the products. In addition, new farming strategies such as integrated and off-shore farming, closed containment technologies, and land-based recirculating aquaculture systems are being developed (Lekang et al., 2016; Liu et al., 2016).

Besides these technological developments, safety and quality control of the salmon aquaculture may benefit from methodologies that are able to consider the supply chain and its surrounding, hence methodologies that enable a system approach. Recently, such system approach was realised with Bayesian Network (BN) based models and was demonstrated for the safety of dairy cows' feed, food fraud and fruit and vegetables (Bouzembrak and Marvin, 2019; Marvin et al., 2016; Marvin & Bouzembrak, 2020). These models were constructed with a combination of expert knowledge (e.g. expert elicitation and scientific literature) and machine learning using historical data (Bouzembrak & van der Fels-Klerx, 2018; Marvin et al., 2016).

The aim of this study was to develop an integrated methodology to assess and predict the influence of drivers of change on vulnerabilities and the occurrence of food safety hazards along a food supply chain. Several methods and expert elicitations techniques were integrated to link vulnerabilities to drivers of change such as Focus Group Discussion (FGD), the Failure Mode and Effect Analysis (FMEA), Delphi study, and BN approach. The developed methodology was applied to cultured Atlantic salmon in Norway as a case study, which is the most important salmon producer in the world.

2. Mapping of the supply chain, identification of vulnerabilities, drivers of change and indicators

2.1. Literature overview

A literature review of the aquaculture salmon supply chain was prepared and included the various steps in the supply chain, vulnerabilities and drivers of change that may influence the development of a food safety risk. The method applied and results obtained are not reported here but can be found in the "Aquarius" final report (Marvin et al., 2019). The overview was verified and complemented by expert elicitation using in-depth interviews, on-line questionnaires and FGDs as described below.

2.2. Expert elicitation

It is clear that the aquaculture salmon supply chain is dynamic and continuously under development and to ensure that the most updated overview was used for this study, the distinguished steps as described in the scientific literature overview (seven steps, see introduction) were discussed by in-depth interviews with five experts on Atlantic salmon aquaculture.

Experts interviewed were highly knowledgeable on this topic and came from Norway and United Kingdom. The supply chain structure as generated from the literature study was discussed and updated when indicated by at least 2 experts. In addition, two on-line questionnaires were prepared (provided in English, Norwegian and Spanish) to validate the salmon supply chain structure and to complement the literature study on potential microbiological and chemical hazards that may enter the salmon supply chain. The first part of the on-line questionnaire focused on the salmon supply chain as derived from the literature review and in-depth interviews and experts were asked to indicate missing steps and/or recycling loops. The second part of the questionnaire focused on food safety hazards in each step of the supply chain. At the end of the questionnaire, the respondents were asked to mention trends that may have an impact on the development of an emerging risk. A link to the on-line questionnaire was sent to 220 stakeholders (governmental, scientific and industrial). These experts have been selected from literature, relevant international research projects and through consultation with key organizations in the salmon aquaculture and were senior experts (Dr/Prof in academia, quality & programme managers, directors policy officers and inspectors) generally operating more than 10 years in the salmon supply chain. For more details we refer to the "Aquarius" final report (Marvin et al., 2019).

2.2.1. Human health hazards questionnaire

In total, 24 questionnaires (i.e. 10.9%) on human health hazards were completed by experts from academia (54%), farming (15%), retail (11%), consultancy (8%) and trade (8%) (Fig. 1). The experts were from Norway (42%), Chile (17%), the Netherlands (17%), Unites States (8%), Denmark (4%), Ireland (4%), Spain (4%) and United Kingdom (4%) (Fig. 1). Greater part of the experts (58%) agreed with the presented salmon supply chain structure and 42% proposed changes and recycling connections between supply chain steps. On the question "which part of

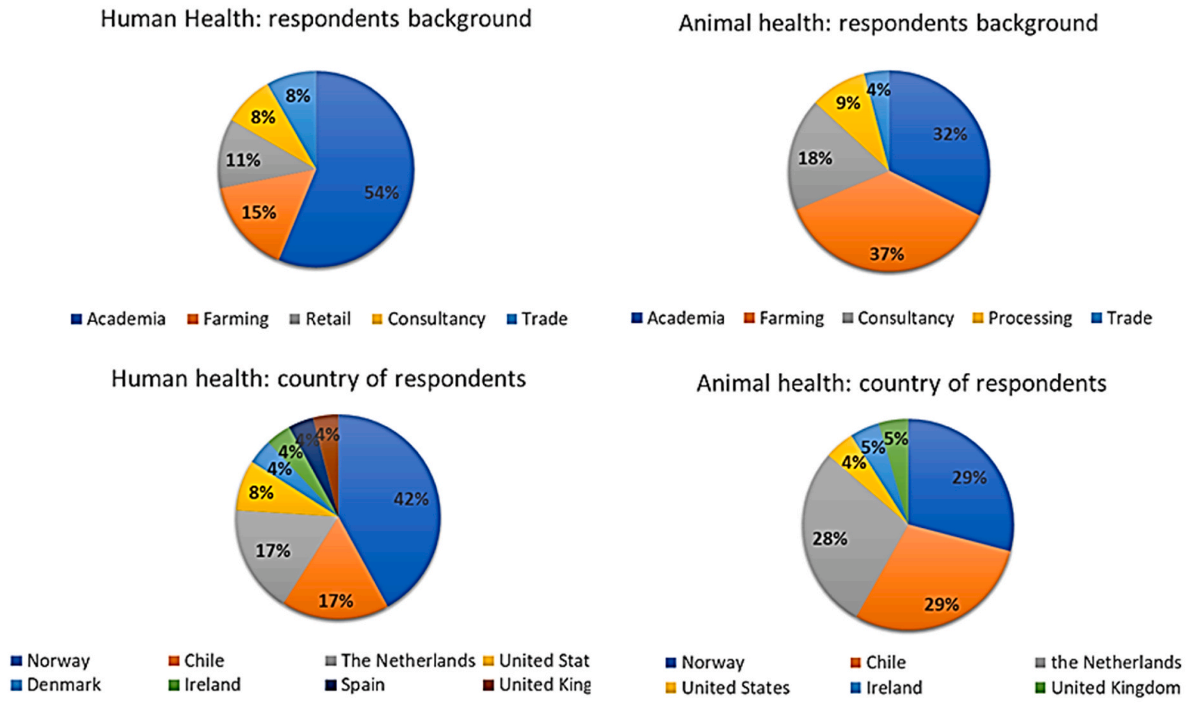

Fig. 1. Background of the respondents on the human and animal health on-line questionnaire.

the supply chain deserves most attention related to the occurrence of hazards for human health", processing was identified as most relevant, followed by retail, consumer and feed.

2.2.2. Animal health hazards questionnaire

In total 20 completed questionnaires (i.e. 9%) were received on animal health hazards. The animal health hazards questionnaire was filled in by more experts from industry than from academia (50% vs 32%) followed by farming sector (37%), consultancy (18%), processing (9%) and trade (4%) (Fig. 1). The countries of the experts were Norway (29%), Chile (29%), the Netherlands (28%), Unites States (4%), Ireland (5%) and United Kingdom (5%) (Fig. 1).

The majority (58%) agreed with the segments of the salmon supply chain as presented in the questionnaire and 42% proposed some changes. The experts were asked which part of the supply chain is most relevant in relation to the occurrence of hazards to animal health.

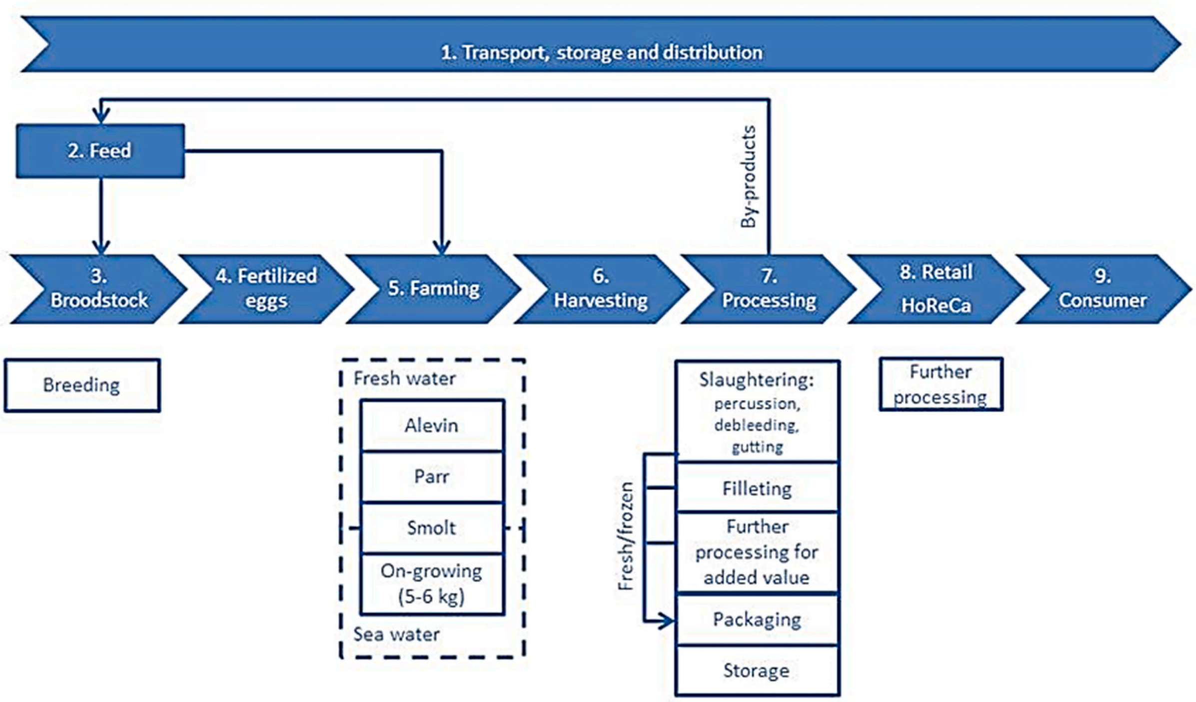

Fig. 2. Atlantic salmon aquaculture supply chain.

Table 1
FMEA results: the two highest scoring vulnerabilities per supply chain step (Table from (Marvin et al., 2019)).

Type	Supply chain step	Vulnerability
A	Feed	The use of new raw materials
		Quality/formulation of the ingredients
A	Broodstock	Presence of pathogens
		Uncontrolled breeding effects
A	Fertilized eggs	Epigenetic effects
		Presence of pathogens
A	Farming freshwater	Transport of fish
		Introduction of chemicals
A	Farming seawater	Disease transmission
		Water quality
A	Harvesting	Water quality
H		Harvesting procedures
H	Processing	Lack of knowledge
		Packaging
H	Retail/HoReCa	Hygiene
		Lack of traceability
H	Consumer	Hygiene
		Lack of knowledge

A: Animal health; H: human health.

Farming was considered most important followed by broodstock, fertilized eggs and feed.

The literature overview, feedback from the on-line questionnaires and the experts in-depth interviews were used to map the salmon supply chain (see Fig. 2).

2.3. Focus Group Discussions

Focus Group Discussions (FGDs) were organised to i) identify vulnerabilities in the salmon supply chain (i.e. human and animal health), ii) to prioritise the identified vulnerabilities, and iii) to identify the drivers acting upon it. To this end, a 1.5 days' workshop was held with 13 experts on the aquaculture salmon supply chain. Prior to the FGDs, all experts received a document describing the results of sections 2.1 and 2.2.

2.3.1. Identification of vulnerabilities

The first FGD session aimed to identify vulnerabilities for human and animal health for each step of the supply chain. The session was led by a moderator and two colours of post-it (i.e. human and animal) were used to collect the experts' opinion. To make sure that all experts agreed, the vulnerabilities noted on the post-it were read out loud and, if necessary, explanation was provided by the experts. At the end of the session, all vulnerabilities were discussed and ranked on frequency mentioned. From this preliminary list, a final list was generated in consensus with the experts.

2.3.2. Failure Mode and Effect Analysis (FMEA)

In the FGD session, an FMEA method was used to prioritise the defined food safety vulnerabilities. FMEA is a systematic approach that focuses on analysing vulnerabilities in a system, the possible causes, the potential effects, and the potential corrective and preventive actions. The prioritisation is performed by calculating a risk level for each vulnerability, which is the Vulnerability Priority Number (VPN). The VPN is the result of a multiplication of three variables (1): severity (S), occurrence (O), and detection (D). The experts give scores between 1 and 10 for each variable (Arvanitoyannis & Varzakas, 2008):

$$VPN = S \times O \times D \quad (1)$$

The session started with an explanation of the methodology and some examples. For an effective FMEA, 2 groups of 5–7 experts were formed. The first group assessed the vulnerabilities of the first steps in the salmon supply chain (i.e. feed, farming freshwater) and the second group analysed the vulnerabilities in the second part of the supply chain

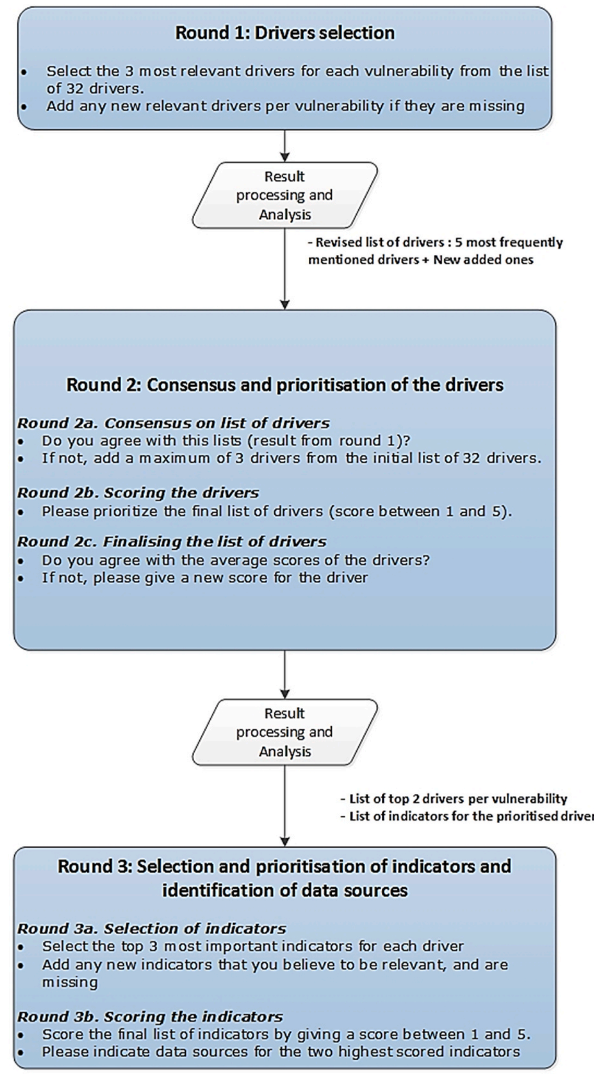

Fig. 3. The steps of the Delphi study.

(i.e. farming seawater to consumer). For each vulnerability, the experts were asked the following questions: i) what is the effect of the vulnerability on the human/animal health? ii) what are the causes? and iii) what is the current control/detection system?

For each vulnerability, the VPN was calculated automatically from equation (1). A long list of 162 vulnerabilities were assessed by experts using FMEA (data not shown). The next step was the prioritisation of the vulnerabilities per step by selecting the most frequently mentioned vulnerabilities per step and by consultation with the experts in the wrap-up session. The final list of vulnerabilities (agreed by all experts) includes 35 vulnerabilities for human health and 32 for animal health (data not shown). All vulnerabilities were scored and the two highest scoring per supply chain step are shown in Table 1.

2.3.3. Identification of drivers of change

In this session, drivers of change of the vulnerabilities with the highest VPN score (see Table 1) were determined.

A background document that contained examples of drivers and sub-drivers was given to the experts. They were asked to mention drivers of change that can have an effect on the selected vulnerabilities. In this session, 130 different sub-drivers were identified, where 52 sub-drivers had not been found in the literature. Following the FGD, the mentioned drivers were grouped into four categories; i) environment, ii) science and technology, iii) economy and iv) society and drivers as found in the

Table 2
Top two ranked drivers per vulnerabilities related to salmon health (Table from (Marvin et al., 2019)).

Chain segment	Vulnerability	Drivers
Feed	The use of new raw materials	Competition on price Price fluctuations
	Quality/formulation of the ingredients	Competition on price Quality of ingredients determined by market origin
Brood stock	Presence of pathogens	Poor quality of vaccination or lack of vaccination Large scale production/intensive farming
	Uncontrolled breeding effects	Progress in breeding science Selective breeding
Fertilized eggs	Epigenetic effects (due to poor holding conditions)	Selective breeding Mutation in salmon physiology
	Presence of pathogens (due to insufficient hygiene or contaminated water)	Changing farming practices Selective breeding
Farming in fresh water	Transport of fish, which may increase stress and mortality of the salmon.	Large-scale production/intensive farming Changing farming practices
	Introduction of chemicals	Increasing release of industrial (chemical) contaminants in the environment or the food chain Large-scale production/intensive farming Changing farming practices
Farming in seawater	Disease transmission	Shorter distances between the farms Large-scale production/intensive farming
	Water quality	Bigger farm sites Large-scale production/intensive farming
Harvesting	Water quality	Bigger farm sites Large-scale production/intensive farming

scientific literature. The full list can be found in the “Aquarius” final report (Marvin et al., 2019). Most drivers were within two categories economy (n = 44) and society (n = 39). The most frequently encountered drivers within these two categories were: price pressure, consumer behaviour, and demographic changes. The category environment contained 19 sub-drivers, which were primarily related to climate change.

3. Connecting drivers of change to vulnerabilities, identifying associated indicators and data source

3.1. Delphi study

A Delphi study was performed to identify key drivers of change linked to the two most relevant vulnerabilities per supply chain step, and to identify indicators and data sources associated with these vulnerabilities. The Delphi method uses repeated individual questionnaires to combine the judgements of several experts with the aim to reach a certain amount of consensus. In subsequent rounds, the individual experts receive the anonymous results of the previous round as feedback and can revise their answers (Keeney et al., 2001and Linstone; Turoff, 2002). Finally, remaining differences are aggregated using equally weighted pooling. The Delphi survey conducted in this study consisted of three rounds (Fig. 2). For each round, prior to sending the on-line questionnaire it was tested by 4–6 experts not involved in this study, for i) clarity of objective, ii) clarity and completeness of the questions, iii) missing information and iv) duration to complete the questionnaire. An email invitation to participate was sent to 178 experts. This email provided some background information and aims of the study. After 1 week, an email was sent with links to the on-line Delphi questionnaire. The experts could choose to fill in the questionnaire on salmon health, human health or both.

3.1.1. Drivers selection

In the first round, the experts had to select the most relevant drivers (with a maximum of three) from the provided list of drivers that they would consider significant for the identified vulnerability in the upcoming 3–5 years. They were asked to do this for the two most important vulnerabilities for each step. The list of drivers was determined from the literature study and expert elicitation. The experts were allowed to add relevant drivers that were missing (up to a maximum of three). The same list of drivers was used for every vulnerability.

3.1.2. Prioritising the drivers

The aim of the second round was to obtain consensus on the drivers mentioned in the 1st round and to prioritise them. To enable this, this round consisted of 3 sub-rounds and details are presented in Fig. 3. Upon round 2C, the 2 highest scoring drivers per segment were determined for which the indicators were sought from the literature by the project team.

3.1.3. Selection and prioritisation of indicators, and identification of data sources

The 3rd round of the Delphi was used to link indicators from the gross list established after the previous round with to the two highest ranking drivers per segment. Experts were allowed to add new indicators not present on the gross list (see Fig. 3). Finally, the experts were asked to score the indicators and to mention relevant data sources for these.

Of the experts sent the on-line questionnaires of the first round, 40 completed the questionnaires, giving a response rate of 22.5%. The majority of the completed forms were for salmon health (18), followed by human health (12) and the combined questionnaire (10). The country of origin of the respondents was Chile (30%), Norway (25%), the Netherlands (17.5%), Portugal (7.5%), Spain (5%), Belgium (2.5%), Canada (2.5%), Denmark (2.5%), France (2.5%), Italy (2.5%), and Mexico (2.5%). The respondents worked at a research organization (40%), a university (30%), in industry (15%), as advisors for the industry (5%), government (5%) and non-governmental organizations (5%). During the subsequent rounds in the Delphi, the response rate decreased. Round 1 was filled in by 40 out of 178 invitees (22.5%). Round 2A by 25 out of 40 invitees (62.5%), round 2B by 23/40 (57.5%), round 2C by 19/39 (48.7%), round 3A by 13/39 (33.7%) and round 3B by 18/39 (46.2%). Such decrease in response rate over time is generally observed in Delphi’s with multiple rounds (Keeney et al., 2001; Linstone; Turoff, 2002).

3.1.4. Selecting and prioritising the drivers

In the first round in the Delphi study, the experts were asked to link drivers to the top two vulnerabilities per segments. In the second round (2A to 2C), the drivers were prioritised. The results are shown in Table 2 (salmon health) and Table 3 (human health). The level of consensus between the experts was between 67 and 83% for Table 2 and between 89 and 100% for Table 3. Consensus levels between 51 and 80% are considered acceptable (Keeney et al., 2001and Linstone; Turoff, 2002).

Table 3
Top two ranked drivers per vulnerability related to human health in the aspect of food safety (Table from (Marvin et al., 2019)).

Chain segment	Vulnerability	Drivers
Harvesting	Harvesting procedures (damaging introducing pathogens, hygiene practices)	Competition on price More requirements towards producers (better hygiene due to scandals, more information about the product)
Processing	Change in packaging (new technology, new materials)	Changing processing techniques Increased demand for ready-to-eat and fresh products
	Lack of knowledge	Economically driven decisions by retailers and producers Competition on price
Retail /HoReCa	Poor hygiene	Increased demand for ready-to-eat and fresh products Economically driven decisions by retailers and producers Consumer hygiene knowledge and cooking practices (poor education system)
	Lack of traceability	Increased complexity of the supply chain Changing processing techniques
Consumer	Poor hygiene	Consumer hygiene knowledge and cooking practices Increased demand for ready-to-eat and fresh products
	Lack of knowledge	Consumer hygiene knowledge and cooking practices Increased demand for ready-to-eat and fresh products

3.2. Identifying and assessing the quality of data sources

In this session, the quality of the data sources provided by experts in the Delphi study, as well as the data sources collected from literature study and the internet by the project team was assessed according to Rodgers and colleagues (Rodgers et al., 2011) The first quality parameter is the relevance of the data source, which represented the main quality criterion, which means each data source had to be relevant to the topic in order to be considered in the assessment. The remaining quality parameters were timeliness, accessibility, clarity, comparability, and coherence weighted (α_j) as 25%, 20%, 12.5%, 12.5% and 10% respectively. The following formula was used to calculate the overall quality score (QS_i) of each data source *i*:

$$QS_i = \sum_{j=4}^{8} \alpha_j . S_{ij} \frac{100}{80} \quad (2)$$

The total number of data sources was 113, which were assessed for relevance. The number of data sources evaluated per supply chain step was as follows: feed (22), broodstock (10), fertilized eggs (6), farming in fresh water (17), farming in seawater (11), harvesting (18), processing (13), retail/HoReCa (14) and consumer (13). The results of the assessment showed that 40% of the data sources were relevant. The Patent Agency Norway website was the data source with the highest score (QS = 52.5) and the lowest score was given to the Fisheries and Oceans Canada website (QS = 15.8). An overall summary of the Delphi including the quality scores of the data sources can be found in the "Aquarius" final report (Marvin et al., 2019).

4. Assessment of the impact of drivers of change on vulnerabilities

4.1. Bayesian Network

A BN approach was applied to assess the effect of drivers of change on vulnerabilities. The information collected in the Delphi study were the building blocks for the BN.

The Institute of Marine Research (IMR) in Norway provided official monitoring data for the period 2010–2016, which primarily contained analytical results on the presence of chemical hazards in fish feed and farmed Atlantic salmon fillet samples. The data is part of the national monitoring program for fish feed and farmed Atlantic salmon, funded and assigned by the Norwegian Food Safety Authority. In addition, monitoring data on salmon diseases was retrieved from Brantswatch website[1] for the period 2012–2016. The diseases monitored are pancreas disease (PD) and/or infectious salmon anaemia (ISA). The hazards and diseases were linked to vulnerabilities as described previously (Marvin et al., 2019).

Linkages could be made between chemical hazards and the two vulnerabilities for animal health in the feed step of the salmon supply chain. Furthermore, a link was found with the vulnerability "Introduction of chemicals" during farming in fresh water. The disease data could be linked to the vulnerability "Disease transmission" in the segment of farming in sea water. Vulnerabilities and indicators used in the BN model are indicated in Table 4.

BN construction and validation was done as described previously (Bouzembrak and Marvin, 2019; Marvin et al., 2016). In this study, 100656 different cases (i.e. 80%) were used for BN construction and 25163 different cases (i.e. 20%) for BN validation. The validation set was randomly drawn from the entire dataset.

A BN was constructed using the collected data on indicators and vulnerabilities and was optimised for the variable/node "vulnerability' (see Fig. 4). The probability of each state is shown as green bars and as a figure and the following probabilities for the included vulnerabilities

Table 4
Vulnerabilities and indicators per step used in the BN model (Table from (Marvin et al., 2019)).

SC segment	Vulnerability	Indicator
Feed	The use of new raw materials	1.Price of feed ingredients – vegetable oils (containing omega-3 fatty acids) 2.Price of feed ingredients –marine proteins 3.Price fluctuations of feed ingredients –marine proteins 4.Price fluctuations of feed ingredients – vegetable oils (containing omega-3 fatty acids)
	Quality/formulation of the ingredients	1.Price of feed ingredients – fish oil 2.Composition of salmon feed: a.Fish meal (%) b.Vegetable meal (%) c. Fish oil (%) d. Vegetable oil (%) e. Other materials (%)
Farming FW	Introduction of chemicals	1.Level of use of antiparasitics/antibiotics 2. Stocking density (number of fish per m3) 3. Amount of chemical products used at the farm: a. Anaesthetic agents use b. Agents against intestinal worms c. Agents against surface infections d. Agents against lice e. Hydrogen peroxide
Farming SW	Disease transmission	1. Density of farms in an area

[1] www.BarentsWatch.no.

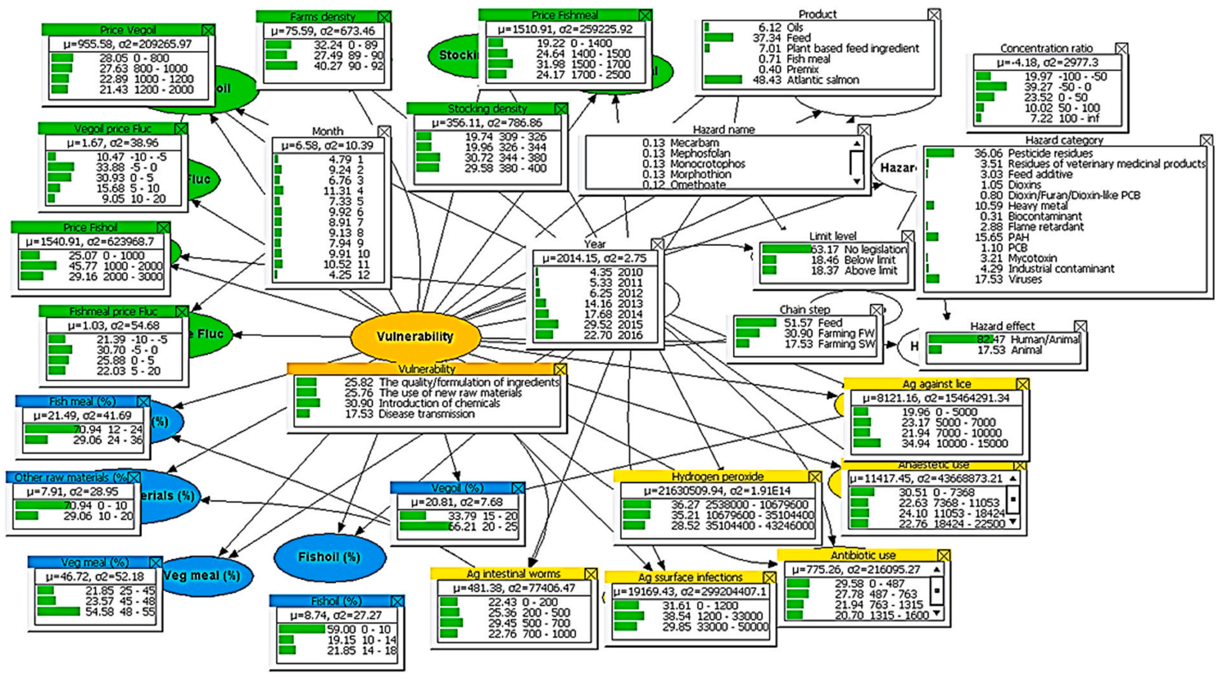

Fig. 4. BN for salmon health. The nodes (ellipses in the figure) represent the indicators. The arrows indicate linkages between these nodes. The states are depicted as squares below the nodes.

were observed: the use of new raw material (25.8%), introduction of chemicals (30.9%), the quality formulation of ingredient (25.8%) and disease transmission (17.5%). The BN validation showed an 81% accuracy of the constructed model.

A sensitivity analysis was performed to identify the most relevant indicators, which had the highest contribution to the vulnerabilities in the aquaculture chain. The sensitivity is expressed as entropy and the higher the value, the higher the contribution the variable has to probabilities of the vulnerabilities. The highest impact on vulnerability comes from the indicators i) price fluctuation of vegetable oil, 2) fish oil used in feed and 3) price of fish oil.

For this study, all concentrations of a hazard reported in the monitoring programme were used as input and linked to a vulnerability and are considered to have similar impact on the vulnerability. Obviously, this is not the case and could be accounted for by introducing a weighted impact of the concentrations in the model for each hazard. Such weights may be determined by expert elicitation but was outside the scope of the reported study. To be able to analyse the contribution of the concentration of a hazard to a vulnerability, we created the nodes “limit level” and “concentration ratio”. When the “limit level” node is opened and the state “above limit” is selected, the BN calculates the probabilities of the vulnerabilities for the conditions where the concentrations of the hazards are above the legal limit.

The BN can be used for scenario analysis by changing any indicator (e.g. farm density, etc.) and determining its effect on any other parameter in the model (e.g. vulnerability, hazard type, concentration level). An increase in the probability of a vulnerability then means that under the selected conditions, the vulnerability becomes more relevant. The presence of a year and month node allows to show trend lines of other nodes being indicator, hazard or selected combinations. Such types of analysis may be of interest for quality managers and/or risk assessors operating in the salmon supply chain in Norway. The applicability of the current model will increase by adding more data for the indicators and monitoring data at the different segments along the salmon supply chain. Currently, only data for 4 supply chain segments could be retrieved and no data on microbial contamination was available. It is apparent that the value of the model will increase when data from more segments is available and microbial contamination can be included. Finally, in this study for indicators, only publicly available data sources could be used. It is clear that a further increment of the models can be realised when also other sources (private and/or more often updated) can be used.

5. Conclusions

Based on FGDs with experts working in the salmon aquaculture in Norway, a large number of vulnerabilities and drivers of change that have an impact on these vulnerabilities were identified for each step in the aquaculture salmon supply chain. The number of vulnerabilities identified using this approach exceeded the number of vulnerabilities found through the scientific literature overview study. The FMEA showed to be effective in prioritising vulnerabilities, but the evaluation was time-consuming and the output depends on the experts present.

By means of an international Delphi study, drivers of changes were prioritised for the two most important vulnerabilities per step, indicators were linked to the prioritised drivers identified including associated data sources identified. The Delphi was effective to prioritise the drivers of change and the consensus among the experts was high. The Delphi was less effective to identify data sources for the indicators. Furthermore, the complexity of the study (focusing on drivers, indicators and data sources) most probably negatively impacted the response rate.

It was shown, by using salmon health as an example, that BN methodology can be used to develop models that predict the effects of drivers of change on vulnerabilities in a food supply chain.

The developed integrated methodology will enable the development of models that will support risk managers (industry, authority) to warn for human and animal health risks developing in the supply chain and to analyse the effect of potential mitigation actions.

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