

A Bayesian Network as a tool to measure Supply Chain Resilience

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Abstract

Resilience frameworks and tools are generally qualitative. The Diagnostic Tool presented in this paper provides a quantitative tool in the area of supply chain resilience. It is among the first tools to quantify the complex concept of resilience. We apply the tool to a sustainable pork chain in the Netherlands. We use a Bayesian Belief Networks (BNN) approach entailing among others the composition of multiple conditional probability tables. This proved to provide necessary transparency and structure to the concept of resilience and resilience enhancing strategies in a business context.

Keywords: Supply chain resilience, Diagnostic Tool, Bayesian Belief Network, profitability, disruptions

1. Introduction

Many bio-based production systems have been designed to maximize productivity and efficiency under standard conditions, increasing their vulnerability to changes in their surrounding natural, technological and social systems (Ge et al., 2016). Agri-food companies have been optimized to produce as many goods and services as efficiently as possible under standard conditions. However, insufficient attention has been paid to resilience, adaptability and transformability (Ge et al., 2016). Resilience is the capacity to absorb disruptions and thereby retain essentially the same function. Adaptability is the capacity of actors to influence resilience. Transformability is the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.

Agri-food companies are generally linked together in an agri-food supply chain to produce a consumer good. These agri-food supply chains have become increasingly global (Gereffi et al., 2005), increasing the number of companies involved and the complexity of the relationship between companies. Disruptions can occur at each of these companies, potentially not only disrupting the agri-food company itself but also other companies in the supply chain. These disruptions can have different causes, such as geopolitics, climate change, economics, or fraudulent behaviour. For example, a Russian import ban on agricultural commodities from the EU resulted in two digit percentage declines in the EU export of some of these commodities (Kutlina-Dimitrova, 2015). Severe rain and hailstorms destroyed crops and agricultural properties in large areas in the Netherlands (Trouw, 2016)¹. A combination of low harvests and stocks, increased demand for biofuels, speculation, and cross-contamination with unauthorised varieties of genetically modified feed materials resulted in low availability and high prices of soy and of animal feed in the EU (Van Wagenberg, 2009). The use of the prohibited anti-lice agent fipronil on laying hens resulted in the culling of millions of laying hens and a recall of millions of eggs and egg products in 15 EU Member States, Switzerland and Hong Kong in 2017 (FarmingUK, December 2017)² and large financial losses.

¹ Trouw (2016). Miljoenschade landbouw door extreem grote hagel. Article in Trouw of 24 June 2016.

² https://www.farminguk.com/News/Farmers-face-bankruptcy-as-retailers-look-for-fipronil-damages_47386.html

In the Netherlands alone, losses were estimated between €65-75 million for the whole supply chain (Horne, et al, 2017). Disruptions can have major impacts on multiple stages of supply chains, even resulting in bankruptcy. Resilience thinking, through improving resilience and adaptability, could be a promising way for agri-food companies and supply chains to prepare for future disruptions.

Hohenstein et al. (2015) state that research applying quantitative metrics to supply chain resilience is limited. This study therefore aims to develop a prototype of a tool to quantify supply chain resilience and to identify strong and weak points in the supply chain. The specific focus of the study is on disruptions affecting a single company within its supply chain, where the emphasis is to look beyond the boundaries of this company and measure how well this particular company can withstand disruptions. Thus, supply chain resilience is measured from a viewpoint of 1 company within its supply chain. As such, the developed tool can be used to answer questions such as ‘how well are my company and my supply chain prepared for disruptions?’ and ‘How can I improve the resilience of my company and supply chain?’. The measure of SCR takes place at one moment in time and has a function of so called “a thermometer effect” and can be repeated within certain time intervals (e.g. monthly, quarterly or yearly). Thus, the effectiveness of measures are assessed by multiple measurements at different times. The tool developed is based on a Bayesian Network as a Diagnostic Tool to measure resilience. The tool has been developed and tested using a case study of a Dutch sustainable pork supply chain.

This paper is organised as follows: the next section provides a background of supply chain resilience and includes the description of the methodological framework used. This is followed by the description of Bayesian Network as a Diagnostic Tool to measure resilience, which includes data description and the analysis of the pork supply chain case. The discussion/implementation section together with the conclusions are finalising this study.

2. Supply Chain Resilience

2.1 Methodological Framework

This section describes the steps of the study that were undertaken for the development of the Diagnostic Tool to measure SCR. In order to be able to measure SCR there is a need to define it. The study has started, therefore, with a broad literature review on definitions of SCR (Section 2.2), and on measurement attributes that are also called resilience-building factors (Section 2.3). Furthermore, a case study on sustainable pork chain has been selected in order to test the usefulness of selected SCR attributes to measure SCR. As a starting point for our study we are focusing on a singular stage of a supply chain where we focus on one company within its supply chain as presented in Figure 1 below.

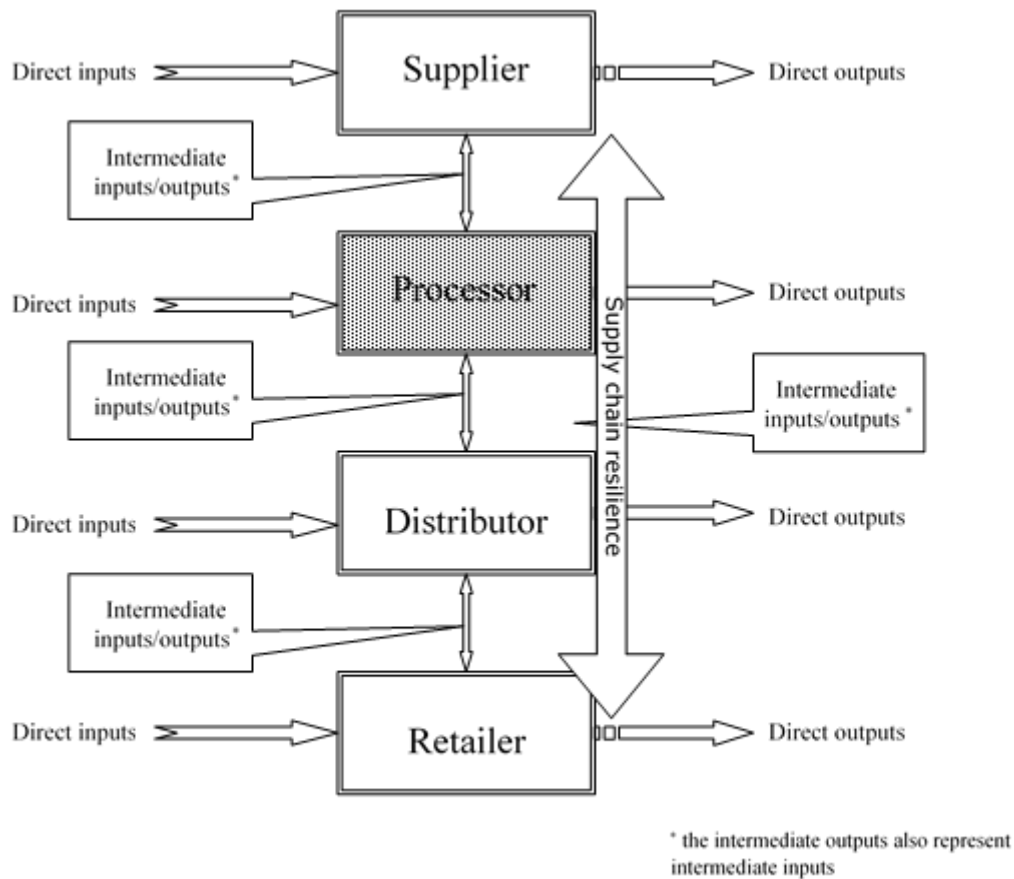


Figure 1: The illustration of the focus of the SCR measuring tool.

2.2 Definition of SCR

Several recent literature review articles provide a definition of SCR. Kamalahmadi and Parast (2016) defined SCR as “The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations”. Hohenstein *et al.* (2015) defines SCR as “the supply chain’s ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance”. Tukamuhabwa *et al.* (2015) define SCR as “The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption”. Based on these definitions, we define SCR as “*the adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations, which is preferably better than prior to the disruption, in order to maintain or increase customer service, market share and financial performance*”.

2.3 Key attributes of SCR

The key resilience attributes are the so-called resilience-building factors. Along the spectrum of robustness, adaptability and transformability they often relate to similar factors but with increasing degrees of intensity and complexity (Meuwissen et al., 2018). Kamalahmadi and Parast (2016) constructed a framework with the principles for supply chain resilience and their antecedents. The principles are based on the analysis of Christopher and Peck (2004). Supply chain *reengineering* is achievable through incorporating redundancy and/or flexibility into the supply chain. Supply chain *collaboration* is not possible unless members of a supply chain have developed channels to share information and develop trust. Supply chain *agility* is the ability to respond quickly to unpredictable changes in demand and supply and has two antecedents: visibility and velocity. Visibility, or making an informed decision on the status of a disrupted supply chain and the courses of action to be taken is only possible when the decision makers have complete knowledge of the status of their system, and they can easily navigate how their decision can affect different entities of the chain. Velocity is related to the pace of the response to disturbances. Finally, a supply chain *risk management culture* is needed to develop effective responsive actions with regard to an abnormal situation. Antecedents for supply chain risk management are innovation and leadership of the organisation being an example for risk management. Kamalahmadi and Parast (2016) stress that these principles and antecedents of each principle should not be viewed as independent attributes in the framework. For instance, a relationship exists between velocity and other attributes of the framework such as flexibility and innovation.

2.4 Disruptions

In the Cambridge dictionary, a disruption in a business context is described as an interruption in the usual way that a system, process, or event works³: In the introduction of this study we have presented several examples of disruptions (Russian import ban, fipronil affair, soy cross contamination) that have affected the agri-food supply chain in the past.

2.5 SCR and performance

Disruptions have direct impact on the performance of the company and the supply chain as a whole. Supply chain performance is the degree to which a supply chain fulfils end user requirements concerning the relevant performance indicators at any point in time and at what total supply chain cost (Van der Vorst, 2000; Aramyan, 2007). While there are many indicators of performance that can be deployed in an organization or supply chain, there is a relatively small number of critical dimensions which contribute more than proportionally to success or failure in the market, which are key performance indicators (KPIs). KPIs are quantifiable measures that are related to the strategies and goals of supply chain and reflect how well the stated goals and objectives are achieved (Aramyan et al., 2007). Thus when measuring resilience it should be compared to the performance of the chain, namely how performance indicators change after the disruption compared to the basis situation. Hohenstein et al. (2015) carried out a literature review on supply chain resilience and its effect on performance and identified three KPIs to measure supply chain resilience performance, i.e. customer service, market share, and financial performance.

These 3 performance indicators were discussed within our case study of pork supply chain (Personal communication, quality manager of the meat processing company, July 2017). After the

³ <https://dictionary.cambridge.org/dictionary/english/disruption>

discussion it has been decided to focus our prototype Diagnostic Tool on only one performance indicator, with the possibility to extend it to other performance indicators in the future. The most important performance indicator for the company currently was financial performance. Based on this, “Profit stability”, has been chosen as the key performance indicator in the tool, which refers to differences in profit before and after a disruption.

3. Bayesian Network as a tool to measure Supply Chain Resilience

Bayesian Networks or Bayesian Belief Networks (BBN) have been used extensively in areas such as pattern recognition, medical diagnosis, financial analysis, environmental research, and risk analysis (see e.g. Chen and Pollino, 2012; Willems and Vuurpijl, 2010; Trucco et al. 2008). Bayesian Belief Networks, also known as probabilistic or causal networks, are well established as a valuable representation of knowledge and uncertainty in artificial intelligence (AI, Drudzel and van der Gaag, 1995). A Bayesian Belief Network is a Directed Acyclic Graph (DAG) where each of the nodes in the graph represents a variable in the network and each edge represents a causal relation between the variables (Trucco et al. 2008). The direction of the edges is important as it defines the direction of causation, e.g. which variable (the predecessor or parent variable) *causes* an *effect* on the other variable (the child variable).

Networks contain both a qualitative part and a quantitative part. The qualitative part consists of the definition of the relevant variables in the model, the causal relations between these variables, and the definition of the different states that a variable can be in. The quantitative part consists of the formalisation of the conditional probability distribution of a variable. The probability distribution is often discretised as the states of a variable are often discrete states, even if the variable is a continuous (ordinal) variable. Other variables are non-ordinal categorical variables (i.e. that have no natural ordering, such as colour) and are discrete by their nature. As the states are discretised, the probability distribution is, therefore, often represented in a conditional probability table (CPT). The CPT can potentially be very large as a probability has to be defined for every combination of each state of the variable for each combination of states from the causal variables.

3.1 Data Requirements

As the BBN model is developed, both the qualitative and the quantitative part need to be defined. The model can be created from existing expert knowledge, by using (statistical) data as input for machine learning algorithms, and from a hybrid combination of the two. Expert elicitation (Drudzel and van der Gaag, 1995) is often used to extract and formalise expert knowledge, where (different) domain experts are interviewed by knowledge experts (having experience in the formalisation of knowledge in BBN) in several sessions. The domain experts are either people in the field that have a lot of practical knowledge (e.g. farmers), researchers/scientists, advisors, or any other who has domain expertise. Often expert knowledge may not be scientifically validated but still be very valuable for the BBN. While scientifically validated knowledge is preferred, it is often limited to very specific conditions, which will limit the usefulness of a model. On the other hand experts may be reluctant to provide conditional probabilities (Drudzel and van der Gaag, 1995).

A BBN model may also be created using machine learning algorithms together with data relevant to the model. Depending on the quantity and quality of the data this may result in very valuable models. Data is most often used to determine the conditional probabilities (such as in Willems and Vuurpijl, 2010), while the structure (the set of variables, their discretisation and the causal relations) is more often defined by expert elicitation. Structure learning can, however, use

data to determine the structure of the BBN. The advantage of using machine learning is that it dramatically limits the effort that is needed when using expert elicitation, and when the quality and quantity of the data are sufficient, the model may be more accurate as the pitfalls that come with expert expectations are circumvented. A major disadvantage is that the model is only as good as its data. Especially when using structure learning, the model may only produce reliable results as long as the inputs are within the range of the data the BBN model was trained on. If, for instance, one variable is the price (e.g. of pork) and the BBN is trained using historical data, the model will not produce reliable results when the price becomes higher (e.g. due to inflation) than the prices encountered in the training data. If structure learning was used, the discretisation of the levels of the price (i.e. the states of the variable) may not even be able to represent the higher prices. This problem is especially a concern when the model is used to predict the effects of extreme events that will probably not have occurred before and are therefore not present in the historical training data. When modelling resilience, where we want to predict the effects of exactly those events that occur very infrequently, this becomes a major problem and severely limits the use of data for training the BBN.

3.2 Sustainable pork case: An empirical illustration

The BBN tool for measuring Supply Chain Resilience models both identified disturbances and the Key Performance Indicators (KPIs) and relates the effects of the disturbance' effect on the different KPIs. In the end, this will provide us with a tool to *predict* the supply chain resilience of a supply chain, but also to *diagnose* the supply chain and determine where improvements to the chain would have the greatest effect when the goal is to increase the resilience of the supply chain (Figure 2).

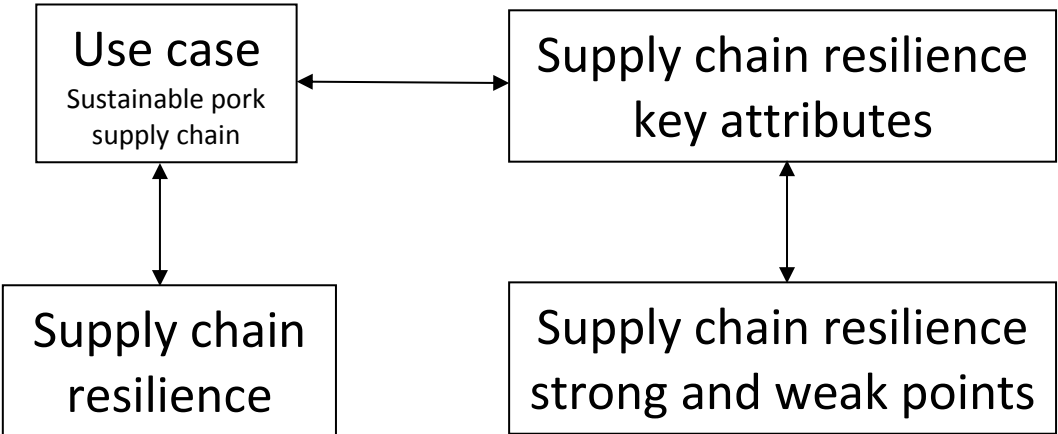


Figure 2: Framework to assess supply chain resilience of pork case.

In order to illustrate the measurement of the resilience of the pork supply chain, we introduce a hypothetical disruption for a pig slaughter company, namely the contamination in pig feed with a recall of pork meat. The contaminated feed has impact on the entire supply chain since it involves suppliers of feed, pig producers, pig slaughters, retailers and final consumers. In this situation we have tested with the case study company how such contamination and recalls affect the case study company and how it can affect the other stages of the supply chain. A Dutch sustainable pork value chain was used as a basis for the case study slaughter company. In 2016, more than 300 pig farmers participated in this chain. The meat is sold by several big retailers, quality butchers, restaurants and caterers at more than 500 locations throughout the Netherlands. Pig farmers deliver their products

to a meat processing company which has sustainable pork as one of its concepts. In this study, we used publically available data about this chain.

To model the supply chain resilience of the sustainable pork case in a BBN, we focused on the identified disruption, i.e. the contamination of feed. Using expert elicitation the most important factors (variables) for this case and their causal relations were determined. Many of the variables were economic variables such as volume and price. In this sustainable pork case with the feed contamination, profit stability was modelled as a resilience indicator for the impact of the disruption. Profit stability was defined as the difference in profit between the situation without the disruption and the situation with the disruption. The larger this difference, the higher the impact. The key resilience attributes and indicators were also modelled into the BBN. These key resilience attributes link through e.g. the number of pig farmers the supply chain can source from and the presence of risk control measures (e.g. insurance) to the case study disruption. The key resilience attributes were finally linked to the supply chain *resilience* variable, which is a general measure of the resilience of the specific supply chain (and specific chain partner, i.e. the slaughter and meat processing company). A straightforward approach was chosen here so that, for instance, *velocity* has a causal relation to *agility*, which has a causal relation to the *resilience* variable. All key resilience attribute variables have five ordinal states, *Very Good*, *Good*, *Neutral*, *Bad*, and *Very Bad*. The conditional probability tables (CPTs) for these variables were created by taking the average over the conditional variable states. For example, the conditional probability $P(\text{Collaboration} | \text{Trust}, \text{Information Sharing})$ was given the value 100% for the state '*Collaboration = Good*' for the conditions '*Trust = Very Good*' and '*Information Sharing = Bad*'. The CPTs for the key resilience attributes were, therefore, deterministic. Figure 3 gives a screenshot of the BBN. On the left side of the figure is the modelled sustainable pork chain with the feed contamination disruption. On the right side are the key resilience indicators and the supply chain resilience variable. The squares are modelled variables, the arrows show the casual relationships between the variables.

The CPTs for the variables that relate to the disruption that was modelled into the BBN, i.e. feed contamination, were determined mostly with expert elicitation with the support of economic data such as prices and volumes. These data were not used in a way that involved machine learning, but were used by the domain experts to determine the ranges of the continuous variables states.

The BBN can be used in two directions. First, by modelling a potential disruption in the supply chain it can be determined how resilient the supply chain is for that disruption. Second, by changing the values of the resilience key elements it can be determined what the strong and weak points are in the supply chain and what the most effective measures are to minimise the impact of the modelled disruption.

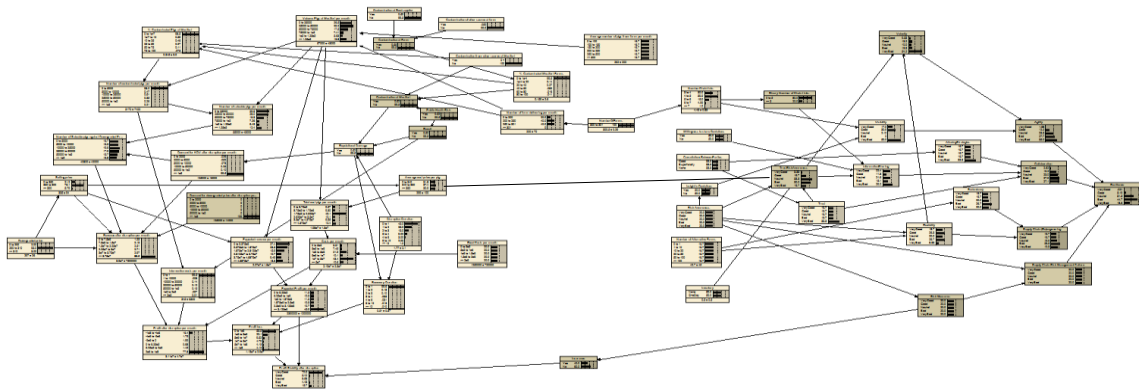


Figure 3: Screen shot of the supply chain resilience tool for the case study of the sustainable pork chain with a feed contamination disruption.

3.3 Relationship between resilience attributes and business characteristics

Before filling the conditional probability tables, we first investigated business characteristics potentially contributing to the resilience attributes, as a basis to build the BBN. Table 1 provides an overview of attributes, their proposition, the elicited score, and an explanation of the score. Elicitation was made by use case experts.

Table 1: Business characteristics in pork case linking to resilience attributes.

Attribute	Proposition	Score ¹	Business characteristics
<i>Agility: The ability to respond quickly to unpredictable changes in demand and supply.</i>			
Velocity	The SC is able to respond quickly to environmental turbulences/ disturbances (time needed for decision-making and transformation time)	2/3	It is not easy to find 'new' pig farmers and if they are found they need to be assessed first before they can be certified as a farmer in this chain. However, the processing company can offer several distinctive pork products of different suppliers.
Visibility	The ability to see through the entire supply chain (all nodes and links: supplies, planning, markets, measures), which helps to identify and foresee potential threats and to effectively respond to a disruption	2	It is not easy to foresee crises caused by the outbreak of an epidemic disease or by contamination of the feed.
<i>Collaboration: The ability to work effectively with other supply chain entities for mutual benefit, e.g. sharing information and other resources to reduce vulnerability, or for response and recovery; The extent of collaboration between SC partners.</i>			
Information sharing	The information sharing within the SC is sufficient Background questions: what kind of information is shared, how is it shared and with whom is it shared? Do the partners of the SC meet on a regular basis both within and between links of the SC? How often? Is there a report of telephone calls, cross-company teams, on-site representativeness, on site meetings and collaborative problem solving on site?	4	New year's meeting for farmers every year for information sharing and personal interaction. Cooperative relationship with suppliers by hiring a company veterinarian who visits the suppliers and discuss health and animal welfare issues with them. New criteria are tested and discussed with suppliers before introduction

Trust	There is a report of mutual trust that the partners of the SC fulfil their obligations	4	There are clear arrangements between the pig farmers and the processing company that the pig farmers receive €0,08/kg extra for their product, even if the demands decreases.
Attuning strategies	There is report of common arrangements within the SC about who will deliver what, in which quantity and in what term There is a report of common, shared goals in the SC, which are clear to all parties involved Background questions: Is there cooperation between the partners in explicitly verbalizing and discussing basic terms of the relationship, setting of common goals, devoting extra effort to sustain the relationship, proactively trying to enhance each other's business and developing a high level of trust in the relationship?	4	One board for the whole chain, including farmers and slaughterhouse. Farmers, Dutch nature and environment foundation, Solidaridad and others are involved in the advisory board and contacts with NGO's like the Dutch animal protection organisation and the Dutch government are maintained in order that food safety, human and animal health, animal welfare and societal and environmental concerns are taken into account
<i>Supply Chain (re)engineering: Extent to which the supply chain is optimised/ designed for resilience</i>			
Redundancy	The SC is able to make use of spare capacity and inventory that can be used to cope with disruptions strategically and selectively (e.g. spare stocks, multiple suppliers and extra facilities)	3/4	The processing company has one slaughtering location. However if problems within the slaughter house occur, they can change to other slaughtering locations of competitors/ colleagues.
Flexibility	The ability of a firm and supply chain to adapt products, product volumes and delivery processes to changing requirements with minimum time and effort	2/3	The processing company offers several distinctive pork products which are produced by different suppliers. It can process different distinctive pork products and is able to replace the pigs in the sustainable pig concept by regular pigs quite easily. If all pigs in the Netherlands are unavailable (e.g. outbreak of infectious disease), hardly any alternative sourcing is possible. Pig farmers fully depend on the processing for the sale of their product. The processing company depends on the pig farmers for the delivery of sustainable pork. However, sustainable pork is only one of the distinctive pork products offered by the processing company. However it is not very easy to change specific pork products. It is not easy to find 'new' pig farmers and if they are found they need to be assessed first before they can be certified as a pig farmer in this chain.
<i>SC risk management culture: Within a SC the culture should be such that all organisational members embrace supply chain risk management. This involves, e.g. top management support and firm integration/team work before and after the risk event</i>			
Risk thinking	Within the SC communication, trust and information sharing before the risk event is such that SC members are aware of risks (this limits vulnerability and can enable rapid access to resources necessary for recovery after the risk event)	3/4	The processing company has a risk manager and a team of people who are responsible for the management of risks within the company. He pays attention to ICT-related risks. In addition, the company has to fulfil all kind of regulations regarding food safety.
Risk measures	Extent to which risk measures are already taken (including financial measures)		The processing has a team of people who are responsible for the management of risks within the company.

¹Measured on a 5-point scale (1=absolutely untrue, 2=untrue, 3=neutral, 4=true, 5=absolutely true).

4. Discussion and conclusions

The Diagnostic Tool presented in this paper provides a quantitative tool in the area of supply chain resilience. It is among the first tools to quantify the complex concept of resilience. The approach of linking resilience and resilience attributes (engineering, agility, collaboration, risk management thinking) on the one hand with the stability of profitability on the other hand proves a fruitful and understandable concept. Business activities such as information sharing, preventive back-up capacity and well-organised business insurance schemes provide practical links between robustness of profit and resilience attributes.

The BBN approach including the composition of multiple conditional probability tables provides transparency to the resilience concept and gives a structure for business and researchers to unravel and discuss the details of resilience enhancing strategies. Business discussions of draft results illustrated that this holds for model inputs (definition of variables, choice of states and quantification of conditional probabilities) as well as outputs (profitability, resilience).

Further work on this Diagnostic Tool will be twofold. First, the tool will be used as a tool to initiate resilience enhancing discussions among sustainable pig chain members, among others by discussing implications of key variables and model outcomes of alternative scenarios. Next, the Diagnostic Tool will be extended towards the farm stage in order to be able to model potentially conflicting interests between chain actors, i.e. the pig farmers and the slaughterhouse. Next to the application of the tool in the sustainable pork chain, the approach will be elaborated for the actual disruption caused by fipronil in the poultry chain. For the fipronil disruption, behaviour of chain agents has been documented in great detail thereby allowing adequate validation of the model.

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