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UNIVERSITY OF NEW ZEALAND

The Application of Social Network Analysis to Study Supply Chain Resilience

A thesis presented in partial fulfillment of the requirement for the degree of Master of Supply Chain Management

At Massey University, Auckland, New Zealand

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2019

Abstract

The purpose of this research was to assess the applicability of social network analysis for studying supply chain resilience. Supply chain resilience contains various attributes related to the supply chain ability to prepare, react, recover and grow in the face of a disturbance. The study aimed at exploring which social network analysis tools and techniques can be appropriate to evaluate a range of supply chain resilience attributes.

The thesis delivers an empirical study of agricultural supply chain network in a rural area in New Zealand. Thirty-nine businesses were interviewed regarding their supply chain relationships and their organizational attributes. In addition to these 39 central actors, 283 secondary nodes were identified as their suppliers and customers, forming a supply chain network of 322 members for the research analysis. UCINET software was then used to model the network characteristics from three levels; holistic network, group level cliques and individual nodes. Visualization via graph theory and simulations were also utilized to obtain meaningful findings.

This study presents the findings of how to use social network analysis as a comprehensive approach to model supply chain resilience. Interconnectedness, network structure and actor criticality can be modelled for five resilience attributes: adaptation, robustness, agility, visibility and anticipation. For each association between network properties and resilience attributes, different analysis tools are proposed, included in three categories: graph theory, analytics and simulations.

The thesis proposes a comprehensive framework of which social network analysis tools can be appropriate to analyze which network properties and to evaluate which attributes of supply chain resilience. The work has therefore extended the study of supply chain resilience and the contexts in which social network analysis is applicable. Practically, it contributes to building a resilient supply chain which can be initiated by evaluating the current status via social network analyses. Therefore, this research is useful to various stakeholders such as academic researchers, business managers and policymakers.

Acknowledgements

Along this research journey which is really challenging but interesting for me, I would like to extend my sincere thanks to all of those who provide me with support, encouragements, care, love and comfort. First and foremost, I would like to express my gratitude to my supervisor – Prof. Paul Childerhouse, who opened my eyes to how to conduct a real academic research. It was his generous support, guidance, motivation and insightful feedback that made the research journey possible for me. He has also taught me many useful things which contribute immensely in my personal intellectual growth and life perspectives.

I am also thankful to my co-supervisor, Prof. Nigel Grigg. His valuable feedback on my very first work and my draft version were greatly important. His kind help and comment about the conference proceeding also motivated me to attempt during the journey. Special thanks to Scion and Joanne Stevenson's team for helping me in research allowance and data collection. I would like to particularly mention and thank Robert Radics for his motivations and valuable comments on my work.

I am eternally grateful to New Zealand people represented by the Ministry of Foreign Affairs for the scholarship that supported me to pursue my degree. I highly appreciate the administrative support and great care of the International student office team at Massey University, especially Mr. Jamie Hooper and Mrs. Anita Albert.

Last but not least, words cannot express how grateful I am for the love, care and encouragements from my beloved family back home and also my dear friends in both New Zealand and Vietnam. All of them have contributed to make my study journey enjoyable.

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List of Abbreviations

CAS	Complex adaptive system
GDP	Gross domestic product
RBV	Resource-based view
SCM	Supply chain management
SCN	Supply chain network
SCRes	Supply chain resilience
SCRM	Supply chain risk management
SNA	Social network analysis

CHAPTER ONE: INTRODUCTION

This research pursues the goal of discovering the methodological application of social network analysis onto supply chain resilience. The research will analyze the characteristics of agricultural supply chains within the selected context through a social network lens and investigate how these attributes impact on resilience factors. This research is supported by a larger research project, “Evaluating the Resilience of New Zealand Rural Value Chains”, led by the Scion research institute.

1.1. Research background

In recent decades, there has been a growing interest in supply chain risk management (SCRM), to the extent that it is now a crucial research area in both the academic world and in practice. SCRM is viewed as the intersection between supply chain management (SCM) and risk management, dealing with uncertainty and vulnerability in supply chains (Paulsson, 2004). Three major reasons behind the development of SCRM are: the emergence of wider and more complex supply chains as a result of globalization; the reduction of redundancy due to the application of lean philosophy; and the increase in catastrophic events (Behzadi, O'Sullivan, Olsen, & Zhang, 2018a). For the purpose of business continuity and sustainability, researchers and practitioners have recently concentrated attention on resilience as a core sub-section of SCRM (Ponomarov & Holcomb, 2009) and a novel trend in this area of management (Elleuch et al., 2016; Kamalahmadi & Parast, 2016). Resilience is one of four key elements of the enterprise competitive model, namely 4Rs: Reliability – Responsiveness – Resilience – Relationships, which has shifted from the old paradigm of the 4Ps (i.e., Product – Price – Promotion – Place) (Waters, 2010). All in all, resilience has become a critical strategy to build a sustainable competitive advantage for any system, especially given the interdependencies among organizations and individuals as demonstrated in the contemporary world.

In New Zealand, natural hazards are among the top risks and disruptions faced by all social, ecological and economic entities which are likely to be impacted negatively. The Centre for Economics and Business Research (2012) ranks New Zealand third in the most vulnerable economies to be impacted by natural disasters, in terms of percentage of gross domestic product (GDP). Such hazards have cost this country an annual average of one percent GDP, approximately NZD 1.6 billion, since 1990 (Insurance Council of

New Zealand, 2014). Although the rural economy is a crucial pillar of the New Zealand economy, with a contribution of over one-third to national GDP (New Zealand Government, 2014), it is vulnerable to natural disasters of both high- and low- frequency (Whitman, 2014). The agriculture sector, particularly, depends on natural and ecological factors; and is therefore profoundly affected by disasters such as earthquakes, floods, hurricanes, volcanic eruptions and tsunami. As agriculture and agribusiness are vitally important components of the New Zealand economy, the need to study and build the resilience of agricultural supply chains becomes critical, especially for rural areas.

Complex adaptive system (CAS) theory lens is sought-after to use for research on supply chains as it captures the complexity and capabilities of today's world supply chains in the context of a changing environment. In line with CAS theory, social network analysis (SNA) could be an appropriate approach to study supply chain thanks to its focus on the interactions and complexities of a network. SNA is the part of sociology that focuses on collections of individuals and their relationships. SNA is a powerful method which has been used widely in sociology, anthropology, politics, technology and economics (Rodriguez & Leon, 2016). It employs concepts from graph theory, statistics and algebra (Wasserman & Faust, 1994). SNA is considered a potential approach for application in many ways to supply chain research (Borgatti & Xun, 2009), but as yet there is no comprehensive SNA framework for studying risk management in general and supply chain resilience specifically.

1.2. Research questions

The main question of this research is: *"How can SNA be applied to study the resilience of supply chains?"*. This research sets out to analyze the method of using SNA to investigate supply chain network properties and resilience in a specific context. The selected area for this study is the agriculture sector of New Zealand, which provides both appropriate rationale and adequate potential input for research. By examining the characteristics of rural supply chain networks, the study aims to explore the relationships between network patterns and resilience elements. Accordingly, an appropriate research framework is recommended to illustrate how to apply SNA to study and foster the resilience of supply chains.

1.3. Scope and boundaries of the research

This research takes a social network view to enhance supply chain resilience; and is thereby not so much concerned with the individual attributes that support to the building of resilience as defined in other literature. This research concentrates on several specific useful and fundamental tools in SNA to investigate their potential application.

The study is set within the agriculture sector of New Zealand's rural areas as an empirical world for the research. However, the research can be generalized to and replicated in other industries and geographical areas with using the conceptual model and quantitative approach.

1.4. Importance of the research

As methodological research, the thesis is expected to make an important contribution to the area of risk management and sustainability development for supply chains, especially in terms of research methods to investigate resilience. By building an SNA application framework, this study demonstrates how to apply an appropriate method to assess and understand a network, even a complex system. It is expected to add value to the gaps in research as listed below:

- The thesis provides an empirical analytical to fill a gap of methodological approach in the current body of literature. Throughout the research on the development of supply chain resilience, the body of research has focused on theory building, conceptualization and qualitative case study, with little attention given to the empirical approach, especially analytical studies.
- This research advances the holistic supply chain or network as the focus of analysis, whereas the literature concentrates at firm rather than network level, probably due to the lack of network data.
- The analysis provides an opportunity to acknowledge the association between supply chain network patterns and supply chain resilience. This appears to be an area for academic research urgently required, according to several major peer-reviewed journals.
- This study also concentrates on the gap in the preparedness stage of resilience.
- The research focuses on resilience against catastrophic disruptions, rather than purely business-as-usual disturbances. In particular, it offers significant insights into agriculture supply chains in New Zealand rural areas, which are needed to build resilience strategies against future serious events.

The research contribution is appropriate for both academic and practical audiences. First, it contributes to the academic body of knowledge on how to use SNA for empirical data, and how to apply this analysis to fill the gap between network characteristics and supply chain resilience. Practitioners in this area can adapt these research findings and framework to analyze their own relational network and build business strategies to develop external relationships appropriate to their resilience. Additionally, the research provides policymakers with a tool to assess social network patterns and how they influence other observed phenomena, as well as a framework to consider possible impacts of a decision on a value chain network.

1.5. Research method overview

The researcher follows a constructivist ontological and interpretivist epistemological perspective in the methodology of quantitative approach. The choices about philosophical perspectives and methodology may at first seem incompatible; however, in essence they can be well matched. This will be explained more in chapter three.

The research design and plan were considered and developed for further implementation phases. Data was collected through semi-structured interviews by Scion's project team. Afterwards, the data was error-checked, edited, and coding steps developed to prepare for the analysis stage. Descriptive analysis and graphics visualization provide an overview of the current state of the research subjects. With the processed data, quantitative and graphical analyses of SNA have been approached for in-depth study.

1.6. Thesis outline

The thesis is divided into six chapters. The following chapter provides a thorough review of the current literature on supply chain resilience, network properties and methodologies used in resilience research. From this literature review, research gaps are defined and a general conceptual model developed as a framework for the thesis. Chapter three outlines the research methodology chosen for this study, including philosophical choices, research methods and design. In chapter four, data analysis is conducted to provide both case study descriptions and in-depth investigation on the research network using selected SNA tools. Chapter five discusses the findings from chapter four to finalize the research model and put it into the context of the current literature. The final chapter summarizes the contributions of the thesis, as well as its limitations and recommendations for future research.

CHAPTER TWO: LITERATURE REVIEW

To seek answers to the research questions, the initial need is to build a framework for the research. This requires thoroughly reviewing the existing literature related to the research topic, including supply chain resilience, supply chain network characteristics and methods used in studies on supply chain resilience. From this coherent picture, research gaps will be identified, and a research framework developed.

2.1. Introduction

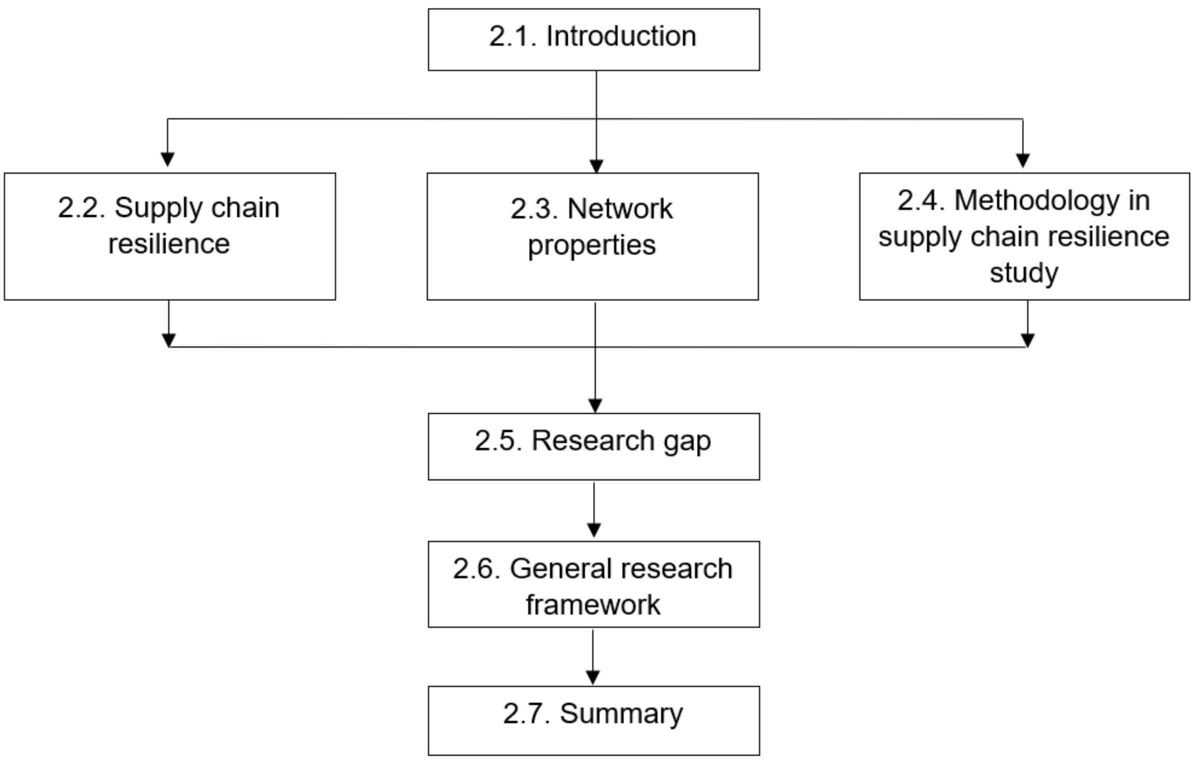


Figure 1: Summary of areas in the literature review chapter

With the main objectives of reviewing the current body of knowledge in the research area and forming a research framework, the literature review chapter discusses and synthesizes previous research as a starting foundation for the study. The topic areas to be discussed in this chapter are summarized in Figure 1. The first review section examines the current body of knowledge on resilience in supply chains. Since this topic has close links with SCRM, disruptions and vulnerability (Christopher & Peck, 2004), the review concentrates on previous research on those concepts as well as the elements of resilience. In particular, studies on the resilience of agricultural supply chains are examined, with a focus on the rural New Zealand context**.** According to Carter, Enram, and Tate (2007), the social network approach is important to understand system configurations and relational patterns, supporting cross-functional and cross-organizational decision making in supply chain development. Hence, this area of network properties is also investigated as a critical part of the foundation for further works on resilience evaluation. It is also important to review methodologies used in these research areas, focusing on social network analysis. Research gaps and a general research model are then discussed and collated from the above areas.

2.2. Supply chain resilience

This section will review the current body of knowledge on supply chain resilience (SCRes) and related concepts such as risks, disruptions and vulnerability, to give a full understanding about research to date. This will offer a synthesized picture of SCRM with those related concepts and SCRes that is considered a novel approach to SCRM, with a focus on resilience construct and resilience in the context of agricultural supply chain, particularly in New Zealand.

2.2.1. Supply chain risk management

As resilience is a core part of SCRM, it is crucial to examine the concept of risk, SCRM and other related terminologies. Risk in the supply chain is defined as “the likelihood and impact of unexpected macro and/or micro level events or conditions that adversely influence any part of a supply chain leading to operational, tactical, or strategic level failures or irregularities” (Ho, Zheng, Yildiz, & Talluri, 2015, p. 5035). Based on the contextual level, risks are categorized into three groups; namely the firm (or organization) level with process and control risks, the supply chain level with supply and demand risks, and the macro-environment level with environmental risks such as natural, political, or economic risks (Behzadi et al., 2018a; Christopher & Peck, 2004; Manuj & Mentzer, 2008). In addition to this popular classification, there are other ways to define risks; for example, categorizing risks based on supply chain flows: physical, financial and information risks (Waters, 2011).

SCRM is defined differently by different researchers focusing on either the risk management process or involving subjects or objectives or combinations of these aspects. Fan and Stevenson (2018) proposed a holistic definition of SCRM as a process of identifying, assessing, treating and monitoring supply chain risks with the efforts of internal organizations coupled with external collaboration and coordination with other supply chain members to reduce vulnerability, ensure business continuity, and enhance profitability and competitive advantage. This definition embraces all three aspects of the previous concepts, clarifying the full implementation process, classifying initiatives and emphasizing SCRM goals. Despite disagreement or lack of consensus about the concepts of risks and SCRM, the described above definitions are supposed to be the most comprehensive and widely used within the body of literature (Behzadi et al., 2018a; Fan & Stevenson, 2018). In short, SCRM is a key management strategy for the whole chain as well as for individual businesses to minimize failures and increase profit.

SCRM has a crucial relation to other concepts of disruption and vulnerability. From the above comprehensive definition, it can be seen that supply chain disruptions arise from supply chain risks (Fan & Stevenson, 2018; Handfield & McCormack, 2008), disturbing the normal flow of goods, finance and information (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007). Whereas, supply chain vulnerability is defined as a system's susceptibility or "at risk" status with exposure to disruptions (Christopher & Peck, 2004; Singh-Peterson & Lawrence, 2015). Wagner and Neshat (2010) defined the three main drivers of system vulnerability as being the supply side, the demand side and the supply chain structure. Their research has added an important theme, that is, system structure, into the construct of risk management. These risk attributes and their relationships with disruption and vulnerability are demonstrated in Figure 2.

2.2.2. Resilience as a novel approach to risk management

With the context of globalization and the widespread adoption of collaborative management concepts, such as 'just-in-time' or 'lean', the problems of supply and demand chain risks, disruptions and vulnerability tend to be more complicated (Abe & Ye, 2013; Scholten & Schilder, 2015), capturing significant attention from researchers and practitioners to develop the concept of resilience. Among the first researchers, Rice and Caniato (2003) and Christopher and Peck (2004) expressed their emphasis on researching SCRes to minimize risk and reduce vulnerability and severe disruptions. Since then, the body of research on SCRes has experienced huge growth with thousands of academic studies and more than a hundred peer-reviewed articles in academic journals, signifying the importance of this area.

Figure 2 illustrates the relationships between terminologies in the SCRM field as mentioned in the previous section. It has been adapted from studies of Christopher and

Peck (2004), Manuj and Mentzer (2008), Waters (2011) and Behzadi et al. (2018a). Accordingly, supply chain risks pose network disruptions or disturbances, and also indirectly determine system vulnerability. This vulnerability is largely influenced by three drivers, which include the demand side, the supply side and the network structure in the supply chain system. The severity of adverse results is dictated by levels of supply chain vulnerability and disruptions. To decrease these negative impacts, and to minimize risk and vulnerability, SCRes emerges as a powerful strategy within the SCRM area.

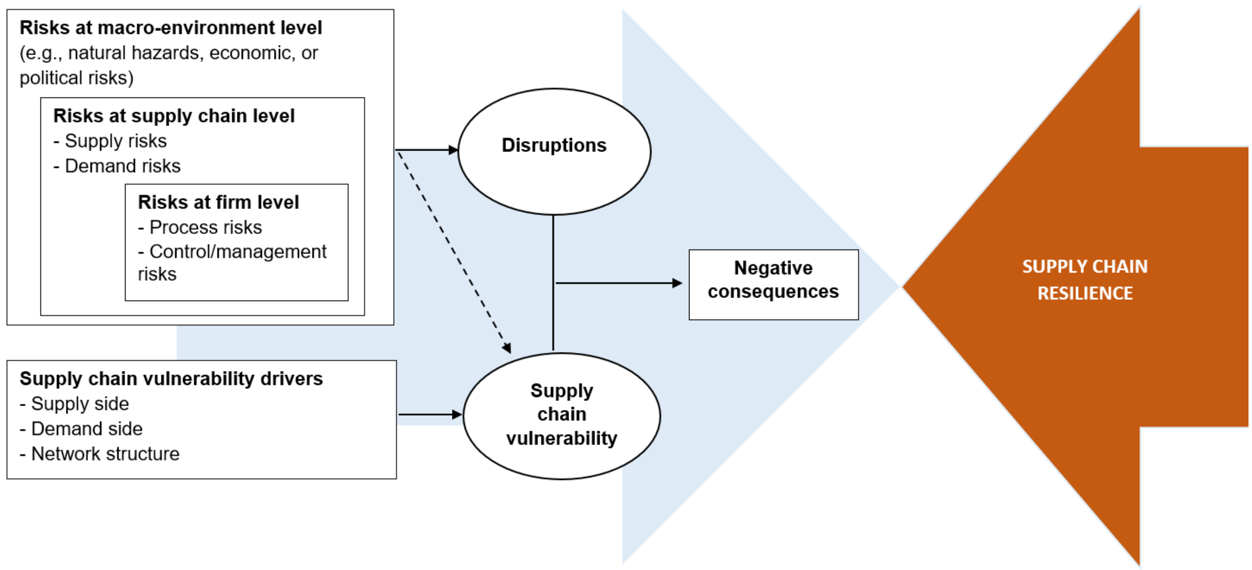


Figure 2: *Relationships between concepts of SCRM*

Although the term of "supply chain resilience" is not explicitly mentioned in many previous studies, the concept of SCRes has been developed as a critical focus within the body of research, concerning either or both the supply and demand sides of the system (Vroegindewey & Hodbod, 2018). Christopher and Peck (2004) first defined SCRes as the ability of the system to recover or move to a better state after suffering a disruption. This new and interesting concept triggered the interest of researchers and practitioners to build a resilient network for competitive edge in today's changing and turbulent world (Abe & Ye, 2013; Appleby et al., 2018; Manning & Soon, 2016; Purvis, Naim, Spall, & Spiegler, 2016). One of the most popular and comprehensive definitions of SCRes was developed by Ponomarov and Holcomb (2009), as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (p.131). This is the first definition that is holistically constructed by detailed analysis from multidisciplinary perspectives, borrowing major elements from ecological, psychological, social and economic fields (Ali, Mahfouz, & Arisha, 2017). This pattern suggests that their definition could be adapted to many other areas thanks to its wide-ranging coverage.

Recent increases in the complexity and connectivity of socio-economic systems has led to the higher vulnerability of supply chains to disruptions (Behzadi et al., 2018a), necessitating the need for enhancing SCRes. SCRes is considered a major contemporary pillar of SCRM (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009). It supplements current SCRM strategies to remove the limitations of conventional risk management approaches, which could not cope with today's global supply chain complexity and unpredictable disruptions (Pettit, Croxton, & Fiksel, 2013). As a result, resilience in supply chains helps the whole system, as well as each member, to ensure business continuity and develop competitiveness (Birkie, Trucco, & Campos, 2017; Sheffi & Rice, 2005).

2.2.3. Constructs of supply chain resilience

Extant studies on SCRes are still fragmented with inconsistencies in constructs, phases, elements and principles. The main reason is that resilience is a wide-ranging terminology with contextual characteristics, originating from several areas such as ecology (Holling, 1973), psychology (Luthar, Cicchetti, & Becker, 2000), disaster relief (Manyena, 2006) and engineering (Hollnagel, 2011). One of the most confusing themes is the usage of resilience and robustness terminologies. Sometimes these two terms are synonymous, especially in practice (Pack, Seager, & Rao, 2013), yet they have a distinct connotation in the body of research (Christopher & Peck, 2004). Several researchers (Behzadi et al., 2018a; Mangan & Lalwani, 2016; Zsidisin & Ritchie, 2008) refer to robustness and resilience as two different dimensions or approaches of SCRM, in which robustness relates to resistance or a withstanding pattern and resilience represents adaptiveness or recovery ability. Other researchers, such as Christopher and Peck (2004), Wieland and Wallenburg (2013) and Elleuch et al. (2016), however, consider robustness as one dimension or as a strategy of the broader concept of resilience. This thesis follows the latter approach, viewing resilience as a more comprehensive concept embracing robustness. Additionally, existing studies have described SCRes in different ways, regarding its stages, strategies, themes, elements and principles. These differences are summarized in Figure 3 as below.

		2003	2004	2005	2006	2009	2010	2011	2014	2015	2016	2017
Key studies		Rice & Caniato	Christopher & Peck	Sheffi & Rice	Peck	Ponomarov &Holcomb	Pettit et al.	Juttner & Maklan	Day	Hohenstein et al.	Purvis et al.	Ali et al.
Phases	Pre-disruption					●			●	●	●	●
	During-disruption	●			●	●	●	●	●	●	●	●
	Post-disruption	●	●	●	●	●	●	●	●	●	●	●
Themes	Readiness					●			●	●	●	●
	Response	●			●	●	●	●	●	●	●	●
	Recovery	●	●	●	●	●	●	●	●	●	●	●
	Growth						●		●	●		●
Strategies	Proactive					●			●	●	●	●
	Concurrent	●			●	●	●	●	●	●	●	●
	Reactive	●	●	●	●	●	●	●	●	●	●	●
Main elements/ principles	Anticipation					●			●	●	●	●
	Visibility		●			●		●	●	●	●	●
	Robustness		●		●				●	●	●	●
	Flexibility	●	●	●		●	●	●	●	●	●	●
	Redundancy	●	●	●		●	●		●	●	●	●
	Collaboration		●	●	●	●	●	●	●	●		●
	Agility		●			●		●		●	●	●
	Adaptation	●		●			●		●		●	●

Figure 3: *Summary of SCRes constructs in key research studies*

Resilience is categorized into three phases surrounding network disturbances; namely pre-disruption, during-disruption and post-disruption (Ali et al., 2017). Each phase has various themes, strategies and elements, shown color-coded in Figure 3. While previous studies focus on the responding and recovering themes, Ponomarov and Holcomb (2009) initially added another important idea for the period before a disturbance, namely readiness, preparing, avoiding or alerting theme. Later, Pettit, Fiksel, and Croxton (2010), Day (2014) and Hohenstein, Feise, Hartmann, and Giunipero (2015) supplemented the fourth theme: “Growth”. All in all, the four main themes in these phases include; readiness in the pre-disruption stage, response during disruption, recovery and growth after the disruption.

Regarding resilience strategies, they were sorted into three groups: proactive, concurrent and reactive initiatives. Proactive strategies relate to the pre-disruption of system resilience, including the actions of planning and preparing (Ali et al., 2017; Hollnagel, 2011). Concurrent strategies refer to themes such as responding, adapting or coping with changes, necessitating active thinking and responses to disturbances in the during-disruption stage (Hollnagel, 2011). The last strategy area is a central focus in the post-disruption phase, with initiatives to recover to the original state or achieve a new desired position (Christopher & Peck, 2004; Hohenstein et al., 2015; Peck, 2007; Ponomarov & Holcomb, 2009). While proactive and reactive strategies have been explicitly examined in the current research, concurrent strategies have been usually mentioned as first or immediate response and merged into the reactive category. However, concurrent and reactive strategies have a distinct difference in time and goal, necessitating the separation these strategies into two different categories. The former focuses on quick actions or responses to sustain the system, whereas the latter aims at recovering the original or targeted state after the disruption.

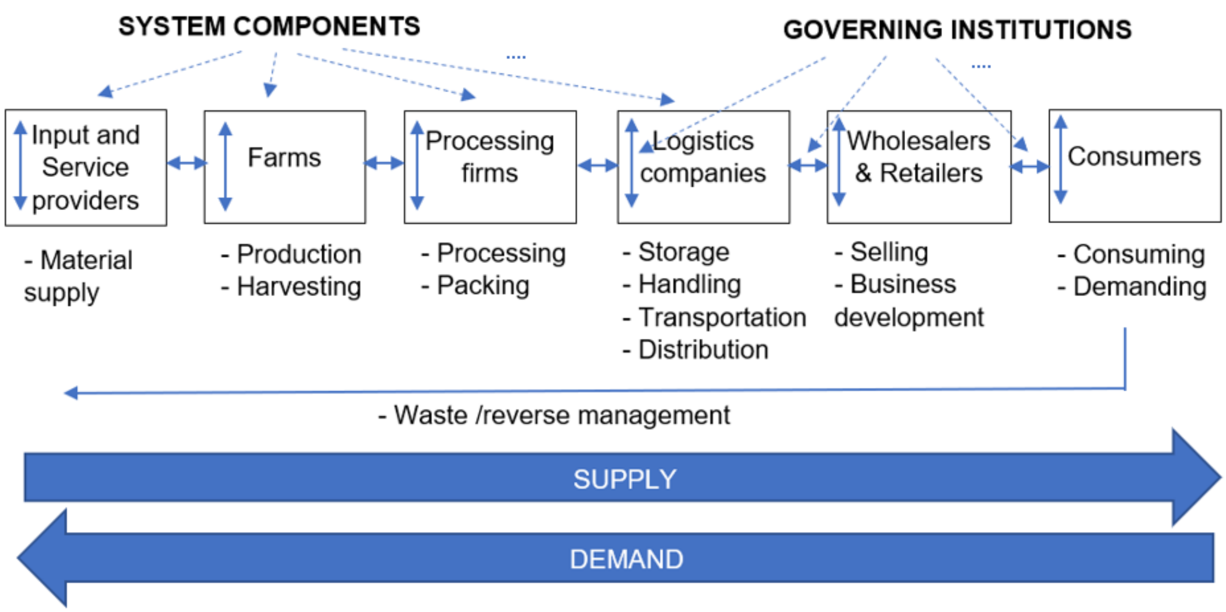
The SCRes literature defines and groups elements in resilience in diverse ways. Figure 3 summarizes the main elements or attributes of a resilient supply chain. Attributes required for proactive strategies are anticipation capability, visibility, robustness, network security and information and knowledge management. Specifically, anticipation refers to the ability to sense the risk and become aware of the situation (Datta, Christopher, & Allen, 2007), to build continuity plans (Pettit et al., 2010), to understand supply chain vulnerability (Melnyk, Closs, Griffis, Zobel, & Macdonald, 2014), and thus to control and minimize risks and consequences (Manuj & Mentzer, 2008). Visibility is necessary for all three phases, relating to supply chain transparency, information sharing and connectivity (Ali et al., 2017). Robustness depends on supply chain design or configuration and supply base strategy (Craighead et al., 2007), and therefore to continue supply chain function despite disruptions. Meanwhile, concurrent strategies require the capability to adapt and respond, in which flexibility, redundancy, adaptation and agility all play an essential role (Ali et al., 2017). Rather than merely withstanding disruptions, flexibility allows supply chains to adjust their management functions and processes in different ways (Wagner & Neshat, 2010). Redundancy refers to excess capacity to cope with sudden changes in a supply chain (Rice & Caniato, 2003), relating to supply chain design. Adaptation, in general, means the ability of the supply chain to respond to a disturbance before recovering, while agility focuses on how quickly a supply chain adapts to a disruption (Ali et al., 2017). Although many researchers define “visibility” as a sub-element of agility, many others argue it should be a separate element as visibility concentrates on the state of transparent information useful for all phases, whereas agility emphasizes the time of responding stage. Besides, the ability to learn or manage knowledge/ experience and collaboration are crucial elements on which little research is focused for reactive strategies (Jüttner et al., 2003). As some elements exist in more than one phase (e.g., collaboration or visibility), these components are not colour-coded in Figure 3.

2.2.4. Resilience in agricultural supply chains in New Zealand rural areas

The thesis has explored the concepts in research studies on SCRes. The following section will provide a picture of the context of the research, with regard to the agricultural supply chain, its resilience and New Zealand agricultural supply chains in general.

2.2.4.1. Agricultural supply chain

The agricultural supply chain is considered a comprehensive system with entities, relationships and a full “farm-to-fork” process to supply a specific product. Behzadi et al. (2018a) identified two product categories in an agricultural supply chain; namely crops and livestock. The former refers to products harvested from plants, such as rice, sugar cane and kiwifruit; while the latter product types are obtained from animals, such as meat, seafood, cattle, milk, or wool, silk. An agricultural supply chain has two layers: supply chain components and governing institutions (Vroegindewey & Hodbod, 2018). The first layer encompasses the farmers and companies who deploy available resources and capabilities to produce and trade agricultural products, such as natural resources, financial and human capital. The second layer represents horizontal and vertical coordination frames that govern the system components and interactions. Figure 4 demonstrates a general agricultural supply chain showing how these two layers are linked with activity flows. It is necessary to note that this figure is a simplification of the supply chain, especially when demonstrating the collaborative relationships between entities in one group component, e.g., among farms, denoted as two-way vertical arrows in the figure.



Note: Adopted and abridged from Vroegindewey and Hodbod (2018) and McAllister et al. (2010).

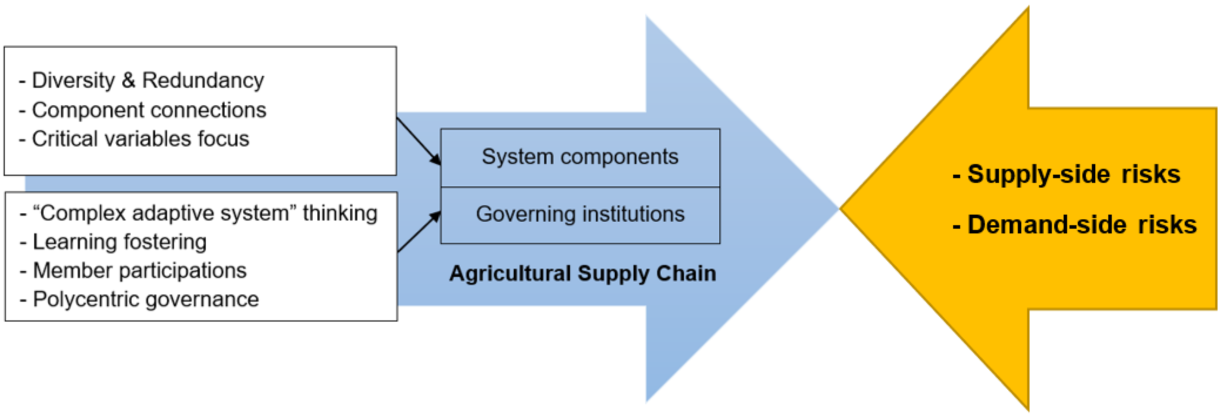
Figure 4: Structure of an agricultural supply chain

2.2.4.2. Resilience in agricultural supply chain

Researching resilience and risk management in the agricultural supply chain is essential, as agriculture is vital for society, the economy and ecosystems, and has particular attributes that need a special focus on risk management. Uncertainty and changeability are inherent in production and logistics processes for agricultural products, due to weather changes, pests, diseases, the impacts of animal welfare laws and biosafety control for trading, especially the agrarian characteristics of seasonality, perishability and long production lead-time (Behzadi, O'Sullivan, Olsen, & Zhang, 2018b; Leat & Revoredo-Giha, 2013). These challenges increase the incidence of disease and the impact of disturbances. The nature of these adverse events is usually unpredictable, emphasizing the limitations of traditional risk management, which focuses only on predicted risks (Vroegindewey & Hodbod, 2018). Requirements for understanding and enhancing the resilience of agricultural systems are arguably more urgent than other manufacturing industries (Behzadi et al., 2018a).

Despite the importance of resilience in agricultural supply chains, a limited number of studies have focused on this issue (Vroegindewey & Hodbod, 2018). Existing research regards the agrarian chain as closely linked to the food system and the socio-ecological system, which are constructed by and operate on interactions between people (i.e., relating to social aspects) and nature (i.e., pertaining to ecological character) (Ericksen, 2008). Together with the complex nature of a socio-ecological system, the agricultural supply chain is multi-level with individual, regional, national and international levels. Hence, resilience in this context is a dynamic property with ongoing development through preventive, corrective and reactive actions (Terdoo & Feola, 2016). Risks in agricultural supply chains are usually divided into two groups: the supply side and the demand side risks (see Figure 5) (Behzadi et al., 2018a). The first group refers to product diseases and recall, loss of space, capacity and yield uncertainty and shortage of input materials and labours (Behzadi et al., 2018a; Peck, 2007). The second category relates to price and market uncertainty, such as changes in food demands due to catastrophic events or customer perceptions of food quality (Behzadi et al., 2018a). These risks are critical and severely impact the whole economic network and society (Leat & Revoredo-Giha, 2013).

Researchers are interested in developing the resilience principles. The research of Vroegindewey and Hodbod (2018) is noteworthy as they propose a set of resilience principles that align with the two layers of an agricultural value chain. The system components have three principles: diversity and redundancy of system members, continuous flow and collaboration between these members, and critical variables control in system configurations. Other considerable principles are building supply chain security (Melnyk et al., 2014; Stevenson & Busby, 2015) and risk awareness and knowledge management (Pettit et al., 2010; Ponomarov & Holcomb, 2009; Rice & Caniato, 2003). Vroegindewey and Hodbod (2018) have echoed the importance of knowledge management but at the level of system relationships rather than at firm level. Other principles focus on the links among components, including fostering "complex adaptive system" thinking, increasing members' participation and promoting polycentric governance for system coordination. These principles are seen as elements to build social capital (Ali et al., 2017) or to develop inter-organizational relationships (Day, 2014) or relational competence (Wieland & Wallenburg, 2013). Figure 5 depicts some of the above-mentioned principles.



Note: Adapted from Vroegindewey and Hodbod (2018).

Figure 5: *Framework of resilience principles for agricultural supply chain*

2.2.4.3. The agricultural supply chain in New Zealand rural areas

Agriculture is the most essential sector in the New Zealand economy. It includes four sub-industries: "horticulture and fruit growing"; "sheep, beef cattle and grain farming"; "dairy cattle farming" and "poultry, deer and other livestock farming" (NZ statistics, 2018). Rural areas play a significant role in the economy, providing more than 30 percent of New Zealand's GDP (New Zealand Government, 2014). Developing these sectors is, therefore, critical for New Zealand society, the economy and the country's ecosystems.

Because New Zealand has faced remarkable natural hazards, the concept of resilience has attracted much attention, particularly in agribusiness and rural development. Throughout the nation's history, agriculture supply chains in NZ have had to face many supply-side disturbances; for instance, the Psa-V bacterial disease in kiwifruit in the early 2010s and the 2016 magnitude 7.8 earthquake in the South Island (Cradock-Henry, Wilson, & Langer, 2014), as well as demand-side risks, such as the botulism scare in 2014 in the dairy sector, which led to market concerns about the safety of associated products (Behzadi et al., 2018a). Such disruptions usually lead to negative consequences, not only for the individual business or sector involved but also for the national economy and society at large. The National Hazardscape Report in 2012 emphasized that disturbances pose a serious threat to the economic viability of New Zealand due to the country's high dependence on major-sector, land-based industries.

Thus, many studies focus on risk management and resilience in this country; for example, large projects such as Resilience to Nature's Challenges programme. However, there are still significant holes in the research body, which need to be filled to enhance resilience in New Zealand in general and more specifically in the agricultural sector. Following the above review of concepts in the SCRes field as well as in the research context, this study will review current studies on the network properties of supply chains.

2.3. Network properties

The section will explain a recent concept in SCM, which considers the supply chain as a complex adaptive network. This section will review the development of SCM from early simple concepts to a more complex and holistic view. Properties of the supply chain will then be explored drawing from the previous research.

2.3.1. Supply chain as a complex adaptive network

SCM has attracted keen interest and attention from many academic researchers and practitioners, and as such has evolved over time. The term was first used in the 1980s, focusing on managing material flow within internal business functions of an organization (Oliver & Webber, 1982). SCM was then extended beyond the boundary of the organization to encompass more holistic views, including the total flow from suppliers to end customers.

Since the early development of SCM, many perspectives on the supply chain have emerged and been discussed in many academic and practical conversations. After Oliver and Webber's (1982) original definition, the concept of SCM was broadened to include multiple firms from upstream suppliers to downstream distributors and end-users (Jones & Riley, 1985; Womack, Jones, & Roos, 1990), and was referred to as an integrative philosophy (Ellram & Cooper, 1990). Later researchers pointed out the increasing importance of supply chain relationships and collaborations (Barratt, 2004; Christopher, 2005), shifting the view from organization-centric to supply chain-centric. Cunningham (1990) and Spekman et al. (1994, 1998) emphasized that the focus should be on network competition, rather than company competition. In the same vein, Harland (1996) considered the evolution of SCM perspectives through four stages; internal supply chain, dyadic relationships, inter-business chains and inter-business networks. The evolution to the network concept, which is summarized in Table 1, received a broad agreement from researchers (Braziotis, Bourlakis, Rogers, & Tannock, 2013; Cousins, 2008).

Table 1: Summary of selected approaches to SCM evolution

Author	Evolution
Braziotis et al. (2013)	➢ Flow of materials ➢ Integrative philosophy ➢ Strategic (long-term) consideration ➢ Assistance among members ➢ Mutuality and holistic approach ➢ Links together partners
Cousins (2008)	➢ Dyadic linkages ➢ A chain of suppliers ➢ Supply network
Harland (1996)	➢ Internal organization relationships ➢ Dyadic relationships ➢ Inter-organization chain ➢ Inter-organization network

Within the body of literature on SCM, the supply network or supply chain network is considered a recent advance, thanks to its holistic view that captures the complex development of the modern supply chain. The earlier linear concept of dyadic relationships oversimplifies and misrepresents the reality of current supply chains (Hearnshaw & Wilson, 2013). It is therefore necessary to re-conceptualize the supply chain definition away from a linear conception. Seminal studies by Industrial Marketing and Purchasing Group scholars; for example, Axelsson and Easton (1992), Ford, Gadde, Hakansson, and Snehota (2003), Ford, Gadde, Hakansson, and Snehota (2006), Hakansson and Snehota (2000) and Mattsson (1997), have created a solid base for developing the concept of supply network today. In general, supply network focuses on interactions and relationships between a set of entities to form a complex adaptive system (Harland, 1996; Hearnshaw & Wilson, 2013). In many studies, the supply network is also known as the supply chain web or a set of supply chains (Harland, 1996).

The reason the supply network is considered an extension of the concept of the supply chain is that its attributes match its modern complex development. Braziotis et al. (2013) differentiated some important aspects between the traditional supply chain and the supply network as summarized in Table 2. The focal goal of the traditional supply chain is to provide final products or services to maximize profit in efficient operation modes. Members in a supply chain are configured with established power attributes to evolve in an ongoing structure, aiming at transforming resources into final products or services (Barratt, 2004; Cox, 1999). However, a supply network concentrates on the relationship web, including both direct and indirect relations between active and inactive, focal and subsidiary members (Choi, Dooley, & Rungtusanatham, 2001). These relationships are in dynamic change, especially in today's fluid environment. Clearly, a supply network has more complexity than a traditional supply chain as it focuses on capturing the relationships within the system, which are vigorous and complicated. Due to the dynamic nature, the supply chain network has evolved to develop the ability to embrace complex and adaptive phenomena in the face of changes (Braziotis et al., 2013; Tukamuhabwa, Stevenson, Busby, & Zorzini, 2015). In-depth research in this area will help shed light on how modern supply chains work and cope with uncertainties and turbulence.

Table 2: Comparison between traditional supply chain and supply network

Aspect	Traditional supply chain	Supply network
Major concept	Products/ Services	Relationships
Design and configuration	Linear and relatively stable structures	Non-linear and dynamic structures
Complexity	Low	High
Operations	Predictable and stable	Unpredictable or un-solidified
Coordination	Management concentrates on the coordination of flows (products, information and finance) and on integration	Management concentrates on the coordination of the web of inter-organization relationships
Integration	Structured	Ad hoc or unplanned

Note: Adopted and abridged from Braziotis et al. (2013).

2.3.2. Properties of supply chain network

One of the emphases in supply chain network research is on network properties, which usually play as predictor or predicted constructs. In predictor constructs, network properties are used to encapsulate the starting conditions of the research subject, aiming to predict an outcome as a result of the network attributes (Borgatti, Everett, & Johnson, 2013). Meanwhile, the latter research direction considers network properties as outcome variables, concentrating on network development and evolution (Carpenter, Li, & Jiang, 2012). Understanding network features is therefore necessary to explain how supply networks work and to develop proper network research and theories.

In the body of literature, researchers use distinct and often inconsistent ways to define and classify network properties. Figure 6 synthesizes some of the noticeable concepts in this area. One of the most comprehensive research network studies is by Carpenter et al. (2012), who divided network constructs into two categories, network application and network structure. The former refers to the attempt of a member organization, so-called “actor” or “node”, to use its network as a resource. The latter describes the structural patterns of the network’s connections, so-called “ties” (Carpenter et al., 2012). In network studies however, researchers tend to focus more on network structure constructs as they might unveil network properties and the network working mechanism. Bellamy, Ghosh, and Hora (2014) named two network properties; network accessibility, the effectiveness of an actor in accessing the network, and network interconnectedness, the degree of connectedness among network members. These two attributes are similar to network position and network cohesion as defined by Carpenter et al. (2012). It could be seen that the structure attributes are classified based on levels of analysis, including the organization level, that is, position or accessibility, and the network level on cohesion or interconnectedness. This approach is agreed by many network-theory researchers, yet they use different names for the same properties. For instance, Janssen et al. (2006) used the level of connectivity to describe network-level characteristics, and level of centrality to relate to a member’s position or criticality in its network.

Other researchers classify network properties in different ways to emphasize network characteristics. Three popular network properties under research are network density, network complexity and member’s criticality (Aguila & ElMaraghy, 2019; Craighead et al., 2007; Kim, Choi, Yan, & Dooley, 2011). Network centralization also attracts much attention from researchers. Many others study network using more technical or graphical characteristics, such as path length or small-world effect, and clustering (Day, 2014; Newman, 2018) and network typology or structure (Aguila & ElMaraghy, 2019; Day, 2014; Kim, Chen, & Linderman, 2015). Other aspects, for example, types of relations and strength or nature of relations, are considered network properties to study in several research. Researchers usually choose to study network properties in a selective way, depending on their research purpose and scale.

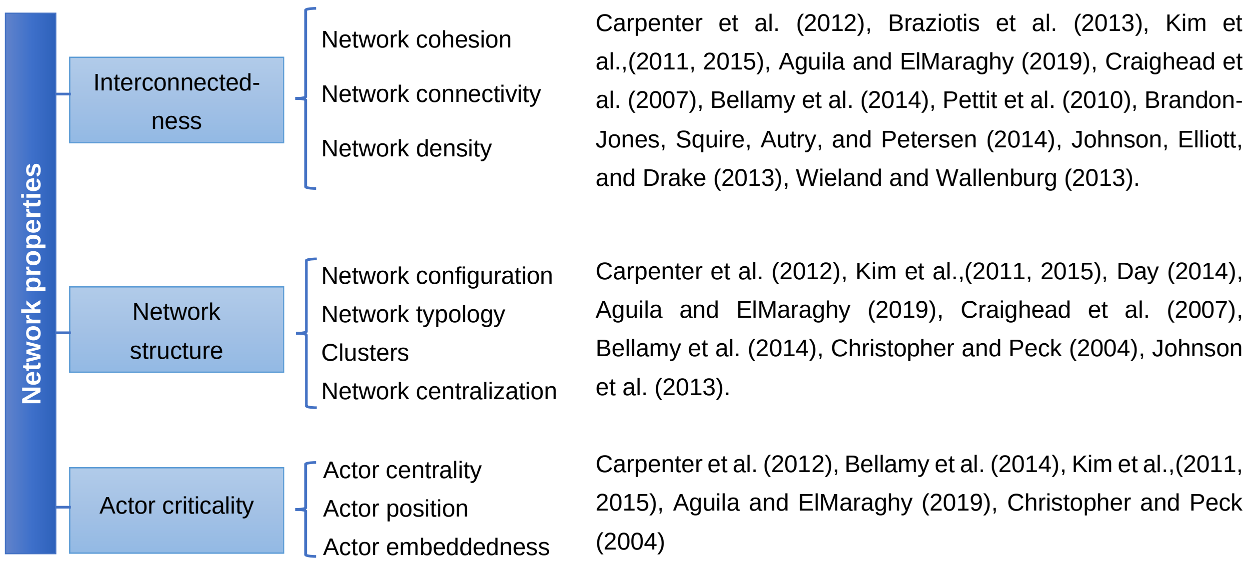


Figure 6: Summary of network properties

In a nutshell, the focus of the study of network properties is the extent to which actors are connected, how their connections are configured, and the level of centrality of actors. In this research, the first attribute is called “interconnectedness”, covering the themes of network cohesion, network connectivity and network density as found in earlier previous literature. The second property is called “network structure”, which encompasses the concepts of network configuration, typology, clusters and network centralization. The third characteristic is “actor criticality”, which refers to a member’s importance as a result of the connections and position embedded in its network. This has the same meaning as actor centrality, actor position or actor embeddedness as used in previous research. These three constructs of network properties are shown in Figure 6. Noticeably, many researchers; for example, Borgatti et al. (2013); Braziotis et al. (2013); Carpenter et al. (2012), have emphasized the interplay between network properties as a web of relationships.

Research subjects as above have been explored to understand what SCRes and the properties of the supply chain are. In the next section, the thesis will review methodologies which have been used in the literature.

2.4. Methodology in supply chain resilience study

This section will provide an overview of the approaches previous researchers have used to explore SCRes. It will contain reviews on theory lenses, methods and analysis levels in key studies. This will be followed by a general explanation of SNA, which is appropriate for exploring a CAS and to be used as the main method in this thesis.

2.4.1. Research approaches in supply chain resilience studies

Throughout the research body, many theoretical lenses have been adapted to study resilience, as in Table 3. The most common approaches are resource-based view (RBV), system theory and the dynamic capabilities model (Fan & Stevenson, 2018). RBV is considered the most popular applied theory (Tukamuhabwa et al., 2015), focusing on internal firm resources as its competitiveness sources. This theory emphasizes the importance of the organization level but ignores the system level. Other lenses applied to organization level include the dynamic capabilities model (related to RBV, viewing a company's capabilities as dynamic subjects to cope with change) and contingency theory (planning business-optimal actions based on internal and external factors) (Tukamuhabwa et al., 2015). In today's global and connected world, increasing numbers of researchers apply network-level theories to study supply or value chains, such as system, CAS or relational view theories.

System theory is an important theoretical foundation for many organizational and inter-organizational studies, especially at the supply chain level. It concentrates on the connections and interactions between elements and subjects in a system, rather than studying those subjects in isolation (Bertalanffy, 1950). Many resilience research studies using this lens were conducted both at firm level, which considered the organization as a system interacting with external elements (Blackhurst, Dunn, & Craighead, 2011), and network level to view the supply chain as a connected system (Pettit et al., 2013). Many other theory lenses based on system theory have been developed to study SCRes; these include relational view, complex system and CAS. Relational view was first proposed by Dyer and Singh (1998) as a theory that focuses on competitive advantage by developing inter-firm relations, and takes the networks of firms as units of analysis. Wieland and Wallenburg (2013) adopted this theory to understand how relational competencies could enhance resilience in terms of robustness and agility. The complex system theory, developed from complexity science, views the research subject as a system containing continuous interactions with internal and external elements, on an evolution with dynamic structure and capabilities (Allen, Datta, & Christopher, 2006). Erol, Sauser, and Mansouri (2010) applied this lens to study resilience as an inherent attribute of the extended organizational complex system. Also emerging from the complexity theory, CAS refers to a special type of complex system with the attributes of adaptation. Recently, many researchers have suggested using CAS theory as a base to study SCRes, as it requires a resilient system capable of adapting to risks and changes (Day, 2014; Tukamuhabwa et al., 2015).

Table 3: Theories applied to SCRes studies

Theory	Authors	Level of focus
Resource-based view	Ponomarov and Holcomb (2009); Blackhurst et al. (2011); Park, Hong, and Roh (2013)	Firm level
Dynamic capability	Ponomarov and Holcomb (2009)	Firm level
System theory	Spiegler, Naim, and Wikner (2012), Pettit et al. (2013), Blackhurst et al. (2011)	Firm & traditional network level
Complex system	Erol et al. (2010)	Firm & network level
Complex adaptive system (CAS)	Day (2014), Kim et al. (2015), Vroegindewey and Hodbod (2018)	Network level
Contingency theory	Park et al. (2013)	Firm level
Resource dependence	Ponomarov (2012)	Firm & network level
Relational view	Wieland and Wallenburg (2013)	Network level

Note: Abridged from Tukamuhabwa et al. (2015).

The need for research at the network level with organizational relationships is undeniable, because all firms play a specific role in at least one supply chain and cannot operate completely independently. This fact becomes much clearer in the current context of supply chain connectivity and collaboration (Sa et al., 2018). As a supply chain embraces many entities and their adaptive interactions with each other and the external environment, it is appropriate to consider the supply chain as a CAS (Day, 2014;

Tukamuhabwa et al., 2015). A CAS with the ability to capture the complexity of the reality is considered an appropriate theory lens through which to study the supply chain and its phenomenon of SCRes. In today's context of changing environments, many researchers consider the supply chain as a CAS with non-linear and dynamic traits, in which resilience emerges as an important feature to cope with disruptions. Thus, it could be said that this CAS lens is especially suitable for research in the agricultural supply chain with its multi-level and complex nature as discussed previously.

Regarding research methods in literature related to SCRes, a variety of different approaches have been applied to date. The dominant methodologies include literature review (Ali et al., 2017; Hohenstein et al., 2015), theoretical and conceptual (Christopher & Peck, 2004; Day, 2014; Pettit et al., 2010; Vroegindewey & Hodbod, 2018; Zhao, Yen, Kumar, & Harrison, 2011), simulation/modelling (Nair & Vidal, 2011; Zhao et al., 2011) and case studies (Blackhurst et al., 2011; Johnson et al., 2013; Jüttner & Maklan, 2011; Pettit et al., 2013; Vargo & Seville, 2011). Some researchers have used other approaches, including the survey and analytical approach (Brandon-Jones et al., 2014; Wieland & Wallenburg, 2013), second data analysis (Kim et al., 2015; Tang, 2006) and mixed-methods. Tukamuhabwa et al. (2015) acknowledged a lack of longitudinal and empirical studies in the body of literature. The lack of longitudinal study prevents researchers from understanding the changes and evolution of supply chains in general, and resilient natures specifically. Meanwhile, empirical research is important for academic researchers and practitioners to capture the reality in this research area. The complex and multi-dimensional nature of SCRes in the contemporary dynamic environment means it is increasingly necessary to use a combination of empirical and analytical methods in research (Ali et al., 2017).

2.4.2. Social network analysis (SNA)

2.4.2.1. Introduction about social network analysis

Social network analysis (SNA) is a fundamental approach to social and economic studies, examining social structures and analyzing the nature of links among social and economic entities (Wellman, 1983). SNA was initially based on a combination of sociometric analysis using graph theory, sociology and social anthropology (Scott, 2013). It is now widely employed in many areas from biology, history and politics to economics. This analysis method is implemented using networks with nodes and links, together with graph theory; in which, the nodes play for the individual entity, people or any actor in the system, while links or ties or edges represent their connections or relationships. The relationship among interacting entities is the key concept in this approach.

Several distinct principles help to differentiate SNA from other approaches. The first and most critical is that the relational concepts are the central focus. Accordingly, the unit of analysis is not the individual but a subject including a combination of individuals and their linkages (Borgatti et al., 2013). Rather than considering those entities as independent autonomous subjects, SNA views them and their behaviours or actions as interdependent. Among individuals, relational links play the role of channels to transfer either material or nonmaterial resources; for example, information, products, or money (Wasserman & Faust, 1994). Hence, SNA matches the perspective of researchers who consider the research subject as a system of units that depend on others through their relational ties.

2.4.2.2. Social network analysis in supply chain studies

SNA is considered a powerful methodology in supply chain studies, which require analyzing and understanding the interrelationships between members. In particular, as CAS theory is used more and more, the social network lens is an area of interest to study the supply chain with a holistic network approach (Carter et al., 2007; Childerhouse, Ahn, Lee, Luo, & Vossen, 2010). Through the social network lens, the supply chain network is configured by a set of entities that have both interdependencies with their social capital and a certain level of independence or autonomy. As discussed in the previous section, the fact that the modern supply chain is considered a network of interrelated actors has encouraged some researchers to choose SNA for supply chain studies (Carpenter et al., 2012; Childerhouse et al., 2010; Day, 2014; Kim et al., 2015; Rodriguez & Leon, 2016).

One reason is that SNA is believed to be a powerful analytical approach that can quantify the different properties of a network to study. On the one hand, SNA allows researchers to test hypotheses with a confirmatory approach quantifying the subjective character of relationships to abstract parameters, measure or probability (Hanneman, 2005). On the other hand, SNA also offers the capability to conduct exploratory research, facilitating visualization and exploration of special properties of network and individual position (Rodriguez & Leon, 2016). In line with quantitative approach, SNA's potential is emphasized based on various analysis tools with different measures and indicators to shed light on network's and its members' characteristics, such as network density, network fragmentation, centrality measures and reachability.

Some researchers previously conducted studies on SCRes using SNA or similar approaches of network analysis. The characteristics of the supply chain system were identified and examined, indicating their influences on SCRes (Craighead et al., 2007; Day, 2014; Kim et al., 2015). Some noticeable network aspects studied in the previous research were proposed to exert influence on SCRes, such as network typology or structure affecting network response to a disruption (Kim et al., 2015), and network density, complexity and individual criticality impacting on supply chain disruption severity (Craighead et al., 2007). The most critical entities in the supply network were also determined and investigated to analyze their vulnerability and to build appropriate resilience strategies (Vroegindewey & Hodbod, 2018). These network properties and their association with SCRes, however, lack in-depth and comprehensive understanding, especially with empirical study. Therefore, it is more important to highlight the need within the academic world for more research on resilience with a social network.

2.5. Research gap

From the above review of the current literature, it can be seen there is much room for further research in SCRes and supply network areas.

First, research in this area lacks empirical testing with analytical approach, especially for relationships between sectors and business entities and the linkages between supply chain concepts and resilience dimensions. The extant publications largely emphasize theoretical resilience with qualitative research and lack empirical tests and analytical methods, which are also important for validating those theories (Ali et al., 2017). Also, the scope of research is still inadequate, falling behind current fast-paced development. The literature, therefore, necessitates more studies that contribute practical values to academic and business areas; such as more appropriate tools to evaluate and build system resilience or support tools for policymakers (Tukamuhabwa et al., 2015).

Second, existing studies concentrate more at firm level (Birkie et al., 2017; Craighead et al., 2007), whereas, the vulnerability of the supply chain is a network-level phenomenon that needs to be tackled through resilience study at a holistic chain level. As SCRes and disruptions emerge from network components' interactions (Kim et al., 2015), researchers need to focus more on holistic network to investigate how supply chain members cooperate and collaborate to face disruptions. The resilience study and solutions built at firm level might be sub-optimal and incomplete since they neglect the importance of network relationships. Hence, to develop a complete solution for enhancing resilience, the research gap in network resilience should be addressed. A complex network approach is advantageous to research and management of supply chains as it allows researchers to employ multiple units of analysis (Hearnshaw & Wilson, 2013).

The pool of research lacks studies to connect SNA with SCM and to explore how this approach can help build a better supply chain, especially in the practical world (Rodriguez & Leon, 2016). While the gap between supply network study and SCRes is still significant, and SNA is a powerful approach which could be used to fill this gap, little research is being done on developing a comprehensive framework to link SCRes, the supply chain network and SNA.

The research gap is found in the resilience stages, where preparedness is not studied adequately (Ali et al., 2017). The supply chain capability to prepare and plan in the pre-disruption phase is vital for a sustainable and robust system (Hollnagel, 2011; Wieland & Wallenburg, 2013), requiring more research on resilience readiness. Current studies also neglect resilience measurements and operationalization, a vital foundation to build and implement any resilience plan. There are no consensus measures for resilience (Behzadi et al., 2018a), resulting in incomplete guidelines to build resilient supply chains. Another gap lies in researching the role or influence of mediating and moderating factors to resilience (Ali et al., 2017), which partly determines the application of resilience theory in a specific context.

Also, the extant research studies largely focus on SCRes from business-as-usual disruptions, leaving a gap to research resilience from serious and rare disturbances which may have catastrophic consequences (Behzadi, O'Sullivan, Olsen, & Zhang, 2018). Even though there is a strong interest in resilience in the body of knowledge in recent years, with notable contributions as discussed above, very few studies focus on the resilience of agricultural supply chains (Leat & Revoredo-Giha, 2013; Vroegindewey & Hodbod, 2018).

2.6. Applications of SNA to supply chain resilience study

Considering the above literature review, Table 4 illustrates how SNA could be used to resolve the lack of research scopes, empirical tests and relationships between concepts.

The goal is to understand how SCRes has been examined by different approaches in previous research, and how SNA has the potential to contribute in the future. In this framework, SCRes attributes are grouped into categories; anticipation, supply chain design (including robustness and redundancy), cooperation and information exchange (including visibility and collaboration) and disruption response (including adaptation, agility and flexibility). Anticipation category relates to "readiness" theme in the phase of pre-disruption, while disruption response refers to "responsiveness" theme in the stage of during-disruption (Ali et al., 2017). Supply chain design has an association with supply chain engineering and structure (Christopher & Peck, 2004), relating to proactive and concurrent strategies in pre and during-disruption phase, whereas the category of cooperation and information exchange relates to flows of relationship, collaboration and information necessary for all stages of SCRes (i.e., pre, during and post-disruption) (Ali et al., 2017).

Table 4: Approaches to study aspects of SCRes

Resilience category	Theoretical/ conceptual	Case study	Survey	Simulation/ modelling	SNA
Anticipation	✓	✓			✓
Supply chain design	✓	✓	✓	✓	✓
Cooperation and information exchange	✓	✓	✓		✓
Disruption response	✓	✓	✓	✓	✓

The framework shows that all SCRes attributes might be explained using SNA tools. These resilience categories have all been studied in the previous literature, using different approaches. The different methods provide distinct viewpoints to look at SCRes and can be supplementary. Many studies have conceptualized or built theories of resilience (Christopher & Peck, 2004; Day, 2014; Jüttner, Peck, & Christopher, 2003; Pettit et al., 2010; Vargo & Seville, 2011; Vroegindewey & Hodbod, 2018). These studies have developed conceptual propositions, which have been then tested mostly by case study research using a qualitative approach (Blackhurst et al., 2011; Craighead et al., 2007; Johnson et al., 2013; Jüttner & Maklan, 2011; Pettit et al., 2013). Several recent studies have been more quantitative, and analytical approaches have explored SCRes (Brandon-

Jones et al., 2014; Kim et al., 2015; Wieland & Wallenburg, 2013). However, these have not covered all aspects of resilience but have focused on specific aspects, such as robustness, agility, adaptation or visibility. This thesis proposes that SNA might be appropriate to merge a qualitative approach (in-depth analyses) with a quantitative approach (ability to visualize and quantify network characteristics), thereby studying all the resilience categories.

Figure 7 demonstrates the research's general framework to guide further steps in order to answer the main research question of "How can SNA be applied to study the resilience of supply chains?". As SNA is a method specially for network data (Borgatti & Xun, 2009; Wasserman & Faust, 1994), it might be powerful to examine properties of network interconnectedness, network structure and actor criticality. Many researchers have recognized the impacts of various network properties on SCRes through anticipation (Blackhurst et al., 2011; Pettit et al., 2013; Vargo & Seville, 2011), information exchange (Brandon-Jones et al., 2014; Jüttner & Maklan, 2011), supply chain design (Day, 2014; Wieland & Wallenburg, 2013; Zhao et al., 2011) and disruption response (Craighead et al., 2007; Kim et al., 2015; Nair & Vidal, 2011; Wieland & Wallenburg, 2013). This research framework puts forward the proposition that SNA provides an effective means to understand all four categories of SCRes via characteristics of the supply network, using different sets of techniques of graph theory, analytics and simulations. These tools are potential to discover network properties with both quantitative and qualitative approach. Quantitative techniques consists of graph theory tools, which can visualize the web of relationships using graphs, and analytical tools, which can help understand properties at network, group and individual level by quantifying these characteristics (Borgatti et al., 2013; Hanneman, 2005). Qualitative approach includes simulations to examine the network dynamics and in-depth analyses – in combination with quantitative methods – to see how network characteristics matter to SCRes performance (Scott, 2013). SNA might therefore bridge the methodological gap to fully investigate SCRes from a network perspective with empirical network data.

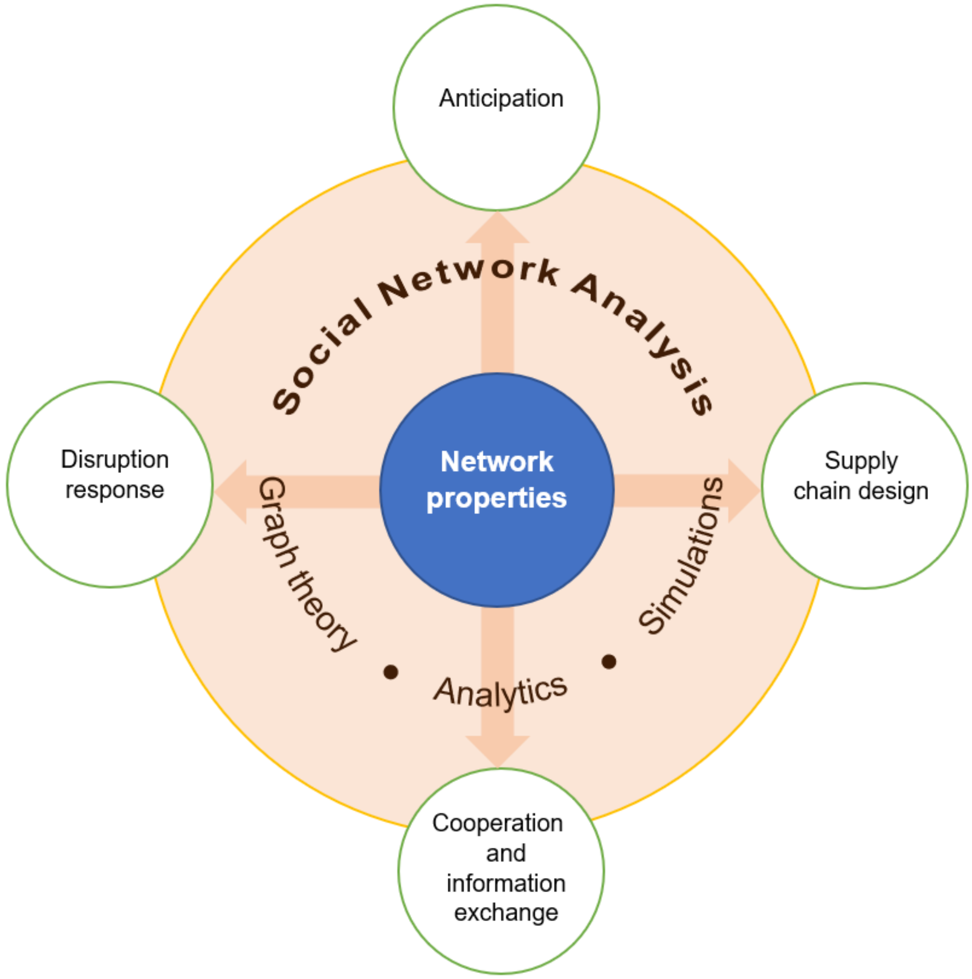


Figure 7: Potential applications of SNA to study SCRes – General framework

2.7. Chapter summary

Recent developments in supply chain research have considered the supply chain to be a network rather than a linear chain (Braziotis et al., 2013; Harland, 1996). Facing continuous change in the environment, the supply chain network is a CAS with a dynamic structure, high complexity and with the capability to cope with disturbances. In a supply network, relationships and interactions between members are the key considerations on how to capture the complexity of reality. Network properties could be classified into three categories; network interconnectedness, network structure and actor criticality. The first property notes the network connections or the degree of network connectivity (Carpenter et al., 2012) (Braziotis et al., 2013). Network structure reflects on how connections in the network are distributed and condensed into different groups (Bellamy et al., 2014; Day, 2014; Kim et al., 2015). Actor criticality refers to the positional importance of a member when embedding in the web of connections (Carpenter et al., 2012; Kim et al., 2015).

Resilience has recently emerged as a critical and interesting supply chain phenomenon (Ali et al., 2017; Christopher & Peck, 2004; Tukamuhabwa et al., 2015). Resilience is not only about actively responding and recovering after disruptions, but also developing well-prepared actions as a proactive strategy. Achieving this could protect economic communities and businesses from disasters as well as bringing prosperity. Throughout the literature, many authors have carried out research on SCRes. Table 5 summarizes major contributions of academic authors who have supported this research in building a conceptual framework.

Table 5: Summary of major contributions from previous research in SCRes area

Authors	**Research**	**Main contributions**
Christopher & Peck (2004)	Building the resilient supply chain	Putting forward the importance of resilience in supply chain. Building four resilience principles.
Ponomarov & Holcomb (2009)	Understanding the concept of SCRes	Reviewing and building interdisciplinary resilience concept from psychological, ecological, organizational views.
Day (2014)	Fostering emergent resilience: The complex adaptive supply network of disaster relief	Utilizing CAS lens to define the impact of network attributes on resilience.
Kim & Linderman (2015)	Supply network disruption and resilience: A network structural perspective	Discovering how the network structure affects supply chain disruption likelihood and resilience.
Ali, Mahfouz & Arisha (2017)	Analyzing SCRes: Integrating the constructs in a concept mapping framework via a systematic literature review	Reviewing the literature on resilience with a systematic method to give a comprehensive understanding.

Regarding the methodology in SCRes studies, CAS has been considered an appropriate theory lens to research supply chains in a changing and uncertain world (Tukamuhabwa et al., 2015; Vroegindewey & Hodbod, 2018). Taking CAS theory as a principle, SNA is a promising approach to study SCRes, concentrating on exploring how interactions and relations between actors could affect resilience (Borgatti & Xun, 2009; Rodriguez & Leon, 2016). This empirical research will, therefore, attempt to find solutions to apply SNA tools to investigate the supply chain network characteristics, assessing its resilience, and linking these two areas together into a comprehensive framework.

This chapter has reviewed key literature in research areas related to the topic, including SCRes, network properties and SNA methodology. The synthesizing work in this chapter about resilience construct is valuable to understand a comprehensive concept of SCRes, helping to build the research conceptual model. As SCRes is a relatively new and novel approach in SCRM, a large proportion of studies in this area focus on theory building and conceptualizing, literature review and qualitative case study (Ali et al., 2017). This therefore needs more studies on empirical data with analytical methods. The chapter has also indicated the potential of SNA in studying SCM problems, particularly SCRes, and in connecting two areas of network properties and SCRes attributes. With a generic research framework based on the literature review and research gaps, the study now needs to consider how to select the methodology and design research process to best answer the research questions. The next chapter discusses these issues in detail.

CHAPTER THREE: RESEARCH METHODOLOGY

This research methodology chapter will begin with the research questions that need to be addressed. This will be followed by a discussion of philosophical viewpoints with ontological and epistemological perspectives to clarify the author's position. An explanation will be given for the researcher's personal interest in quantitative research. The research design will then be developed with a general approach, data collection and management as well as an analysis procedure design. Critical and ethical considerations will be explained at the end of the chapter.

3.1. Research questions

In the context of facing changing and turbulent factors, SCM, in general, and specifically rural agribusiness in New Zealand, needs further study to analyze and build resilience plans. As stated in the previous chapter, there are research gaps in the empirical study of resilience and the applicability of methodology to SCRes research. The main question of this research is: *"How can SNA be applied to study the resilience of supply chains?"*

The detailed questions below need to be answered in this research:

Question 1: Which network properties of a supply chain can SNA investigate?

Question 2: Which tools of SNA are applicable to study which aspects of SCRes?

Question 3: How do these network properties associate with these SCRes aspects?

3.2. Ontology and epistemology perspectives

It is essential to consider the different positions of ontology and epistemology, then identify the personal interests of the researcher relevant to answering the research questions. These perspectives will strongly impact how the research will be designed and implemented to align with research purposes (Bryman & Bell, 2015).

Ontology represents the way an individual thinks about reality and how society exists and interacts with itself. This belief is considered to be a foundation for theories and concepts (Gustavsson, 2007). It frames the question as to whether actors in society affect their environment or whether those two variables are independent subjects (Grix, 2002). The two most common perspectives of ontology are objectivism and constructionism.

Objectivism views the world as an objective and independent reality with the ability to define, observe and measure (Bryman, 2015; Creswell, 2014). This means that reality is viewed as an external, tangible and static existence, functioning beyond the impact of individuals living and acting in this society. Thus, objectivist researchers assume a reality with harsh natural laws, processes and structures that individuals or objects have to adjust and follow accordingly (Bryman & Bell, 2015).

Constructivism follows a different view of reality, which is not an external and static existence but which continuously changes and develops with the constant interaction of the individuals within (Bryman & Bell, 2015; Gustavsson, 2007). This position assumes that agents are not bounded by the reality surrounding them; instead, the reality exists along with individuals interacting, to together create a distinct reality (Scotland, 2012). Contrary to objectivism, constructivists regard the rules or processes not as rigid law, but rather as a means of instruction to understand behaviour (Bryman, 2015).

The concept of epistemology generally refers to the nature of knowledge, knowledge gaining and the relationship between the known and obtained understandings (Mertens, 2010). More specifically, it focuses on how knowledge can be achieved and created to assist researchers to develop or improve theories and models. The core concern of epistemology is whether the real world can be studied following the same principles, processes and rules of the natural sciences (Bryman, 2015). Two typical epistemology perspectives that can be observed are positivism and interpretivism.

Positivism considers social reality as a natural science (Bryman & Bell, 2015), whereby the knowledge obtained from events and observations follow predefined processes, rules and ethics (Gustavsson, 2007). These observations are then associated with existent theories and laws to create new knowledge (Scotland, 2012). This understanding is derived from observable, definable and measurable events, and thus, is objective and not influenced by the observer’s values (Grix, 2002). Researchers with ontological objectivism therefore, often follow epistemological positivism in their research.

Interpretivism argues that social phenomena cannot be studied on the logic basis of natural science because their nature is different (Bryman & Bell, 2015). Interpretivist researchers assume that reality is determined by individuals living and acting in it, and thus value the pathway to observe and explain human behaviour and its meaning (Gustavsson, 2007). As opposed to positivism, interpretivism does not apply natural science rules and processes to knowledge development but uses human sense and inductive reasoning to gain new knowledge (Bryman, 2015). Hence, an interpretivism perspective is usually derived from a constructivism ontology.

Although researchers in SCM studies have followed various directions of research philosophy, constructivism ontology and interpretivism epistemology are dominant in this domain of SCM, particularly SCRes. This matches the key idea of supply chains which are largely determined by relationships, cooperation and transactions between supply chain members (Waters, 2010). In particular, conceptual and theoretical research studies, which account for a large number of the research pool in SCRes, tend to consider relationships and interactions in the supply chain as an important influencer. For example, Christopher and Peck (2004) and Scholten & Schilder (2015) prioritized the collaboration between supply chain members and SCRM culture to build a resilient supply chain. Tukamuhabwa et al. (2015) echoed the criticality of member interactions to supply chain system, which is complex and dynamic. Some authors used measures and quantified characteristics to investigate SCRes, but still adopted interpretivism perspective (Kim et al., 2015). Some others, in contrast, considered SCRes objective and used dependent elements to understand their impacts on resilience (Brandon-Jones et al., 2014). Even though SNA uses quantified metrics and graphs to represent network relationships, studies applying this method tend to follow interpretivism to respect the dynamics and importance of interactions and relationships to the network state (Pryke, 2012).

As the researcher of this thesis, I believe in the constructivism ontology perspective, and accordingly the interpretivism epistemology position, because this allows me to obtain in-depth insight and comprehension of a topic that interests me. This is appropriate especially as it relates to social network and supply chain relationships. I would like to understand the way this type of network interacts with supply chain concepts such as resilience, and how network properties impact on those resilience elements. As a supply chain embraces the complex social patterns of inter-organizational and organizational relationships, as well as independencies versus interdependencies, it is necessary to assess those characteristics from a constructivism and interpretivism standpoint. Although part of this research analyzes the SCN according to its model of structures or quantified measures of relationships, I believe its ultimate foundation should be derived from social relations and interactions to create the phenomena of the current situation.

This section has presented the research philosophy of this thesis. The next sections will deal with research method selection.

3.3. Appraisal of alternative research methodologies

There are two contrary directions for research methods; quantitative and qualitative. Each determines the role of research theories differently, and to some extent, aligns with the pre-determined perspectives of epistemology and ontology of a research (Bryman, 2015). The combination methodology approach has become more popular, especially in practice, as it incorporates aspects of both quantitative and qualitative methodologies to offer a more effective approach (Creswell, 2014).

Quantitative methodology utilizes natural science models with a deductive approach to study (Mertens, 2010). It is usually applied to test existing theories with a hypothesis and the aid of measurable methods. A quantitative approach may be experimental (i.e., randomized), quasi-experimental (i.e., non-randomized) or non-experimental (e.g., observational studies or numerical data surveys) (Bryman, 2015). With the survey, a structured questionnaire or interview, usually with closed questions, is used to collect quantifiable data on the subjects' attitudes or opinions (Creswell, 2014). Two study options in terms of survey time are cross-sectional (acquired at one point of time) and longitudinal (obtained over a period of time) in the case of repeated studies (Bryman, 2015; Creswell, 2014). Quantitative studies are designed to ensure the validity and reliability of the set of data collected (Creswell, 2014). Statistical tests differ depending on the type of data, and are used to interpret the data to answer research questions (Bryman, 2015). Quantitative methodology is usually applied by ontological objectivism and epistemological positivism.

Qualitative methodology fosters in-depth research studies and utilizes an inductive approach to propose a theoretical explanation or creation (Bryman, 2015). It usually starts with data collected from reality to explain and interpret a general theory or concept. Its methods of data collection consist of observations, interviews, focus groups and document analysis (Creswell, 2014). The data collected is in the words of the participants, the actions or phenomena observed and the words written in the documents. These are then analyzed and generalized into themes (Mertens, 2010). This methodology is usually applied when a particular subject of research is not much known or when the research requires an in-depth insight (Creswell, 2014). Qualitative methods are typically narrative research, grounded theory, phenomenology, ethnography, action research and case studies (Creswell, 2014). The last two methods could also be used in a quantitative approach (Bryman & Bell, 2015). When a study focuses on individual or specific events, narrative research and phenomenology are usually applied, while, case studies or grounded theory are typical in exploring processes, activities and events. Ethnography is adopted to research the culture and behaviour of groups or individuals (Creswell, 2014). This methodology, to a large extent, fits with ontological constructivism and epistemological interpretivism.

The mixed method represents a combination of quantitative and qualitative methodologies. It has emerged as a new approach since the late 1980s and early 1990s (Bryman & Bell, 2015; Creswell, 2014). The approach is called different names, including the quantitative-qualitative method, multi-method, integrated and mixed methods (the most popular name) (Creswell, 2014). By combining the use and advantages of quantitative and qualitative data collection and analysis in various ways, this new approach helps researchers to ensure their study is more robust. The principles and methods of qualitative and quantitative research are not new but are modern in the way they combine to avoid conflicts between the two methods and to intensify the effectiveness for the study. Creswell (2014) describes some typical types of combination research, which include convergent parallel (quantitative and qualitative research conducted at the same time), explanatory sequential (quantitative study conducted before qualitative research), exploratory sequential (qualitative study conducted before quantitative research) and embedded (either parallel or sequential but embedded within a broader design and data).

In short, each research methodology has its own strengths and weaknesses, which researchers need to consider before deciding on a suitable methodology for their studies. Quantitative methodology offers a broad insight into the research population, with the ability to replicate and generalize studies, as well as validate the qualitative findings; while qualitative approach can provide in-depth knowledge of the research subject to explain behaviours and social phenomena, as well as to improve and create theories, which quantitative methodology cannot offer. However, qualitative research is critiqued so it cannot be generalized or replicated in broader areas or topics, and can easily involve the researcher's bias. The mixed methods approach is increasingly being used because it has the advantage of combining the strengths (and minimizing the weaknesses) of the quantitative and qualitative methodologies. However, conflict when implementing this approach is a noticeable issue of this methodology.

3.4. Selection of research methodology

Throughout the history of the literature on SCRes, researchers have adopted various methodologies for different research directions and objectives. Within the broad field of SCRM, quantitative studies, with diverse methods such as simulation, mathematical programming and exploratory factor analysis, are more extensive than qualitative methodology (Ho et al., 2015). Speaking specifically of SCRes, however, the qualitative approach has been predominant, especially with theory generating and conceptual works, or case studies (Ali et al., 2017; Kamalahmadi & Parast, 2016). This could be because this area is relatively new; thus, researchers focus on developing resilience constructs, building relating concepts and generating research ideas and framework. The less popular adoption of quantitative methodology for SCRes research results a lack of consensus on the foundation concepts and resilience measurements (Kim et al., 2015). Although there is a large number of quantitative studies in separate areas of risk management and agriculture, Behzadi et al. (2018a) recognize a critical absence of adequate resilience research in agricultural supply chains.

Given the research objectives discussed previously, this study will apply quantitative methodology in a formal approach together with exploratory elements. This approach enables the research to discover the relationships between the variables of supply network and SCRes proposed in the research framework. With a key focus on the application of SNA tools, network characteristics will be quantified into measures for further assessment and mathematical analysis. SNA offers a comprehensive analysis of the network, including structural characteristics, which a qualitative approach only might overlook (Kim et al., 2011). Through this network lens, the analysis will be conducted mainly on the network structure of contractual relationships, along with a complementary analysis on materials flows with metrics at node, group and network level, resulting in a comparative and full understanding of this network. Although this quantitative approach does not follow the typical ontological and epistemological alignment, it is argued that constructivist and interpretivist perspectives may still adopt quantitative methodology (Bryman, 2015). Pryke (2012) emphasizes that SNA is a quantitative approach, which leans towards constructivism and interpretivism. It therefore has inherent features of both quantitative and qualitative approach. This thesis is based on the concept of social network, indicating that any changes in network actors' relationships and interaction might alter the social phenomena and situation.

In summary, using constructionist and interpretivist viewpoints, the quantitative method has been chosen for this research. The rationale behind this choice has been explained in the section above. The next section will present the research design for this thesis.

3.5. Research approach and process

This section considers the research design and process as a blueprint for conducting this study. Research design is a plan of data collection, measurement, investigation and analysis to achieve the appropriate answers to the research questions (Cooper & Schindler, 2008). To guide the choice of data source and type, as well as outline the research procedure, this design is built on the foundation of research questions, needed to be considered along with the appropriate rationale at the early stage of any study (Gorard, 2013). The study's research design considerations are summarized in Table 6.

Table 6: Research design considerations of this study

Category	Chosen option	Explanation
Question crystallization	Formal	Clear research questions
		Proposed research framework, tools and metrics before analysis
Data collection	Communication	Face-to-face interview
Control of variables	Experiment	Quantifying the network characteristics
Purpose	Causal	Exploring how network properties affect SCRes attributes
Time	Cross-sectional	A snapshot of the study time point
Scope	Case	Network case of agricultural supply chains in research site
Research environment	Field	Research site is a rural region
Participants perceptions	Routine	No deviations from respondents' routine

Note: Adapted from Cooper and Schindler (2008).

This research is a formal study as it aims to answer the research questions and investigate a proposed research framework. In other words, the research questions are clearly outlined at the beginning, followed by a detailed process with data specifications (Cooper & Schindler, 2008). SNA is considered a formal method as it contains mathematical and graphical techniques, which help represent network data and patterns compactly and systematically (Hanneman, 2005). In this thesis, metrics and graphs will be used, and the methods of collecting and analyzing data explained. It also has elements of exploration as the research questions tend toward loose structures to explore how SNA can be applies and which tools are appropriate, especially in order to discover some patterns and associations that have not been studied before.

The method of data collection is communication or interrogation, when respondents are asked to provide the necessary information (Cooper & Schindler, 2008). This information is obtained through a list of questions during face-to-face interviews. Details about data collection will be discussed in the next section.

Regarding the researcher's ability to control variables, the experiment design will be applied to manipulate the research variables. This influence is implemented for the purpose of quantifying network characteristics, including structural and resilience patterns, to test the conceptual model and answer the research questions.

In terms of purpose, this research is a causal study as it is concerned with “why” aspects. More specifically, the research focuses on discovering the cause-and-effect patterns of social network attributes and resilience variables. The relationships among these variables are explored by SNA tools.

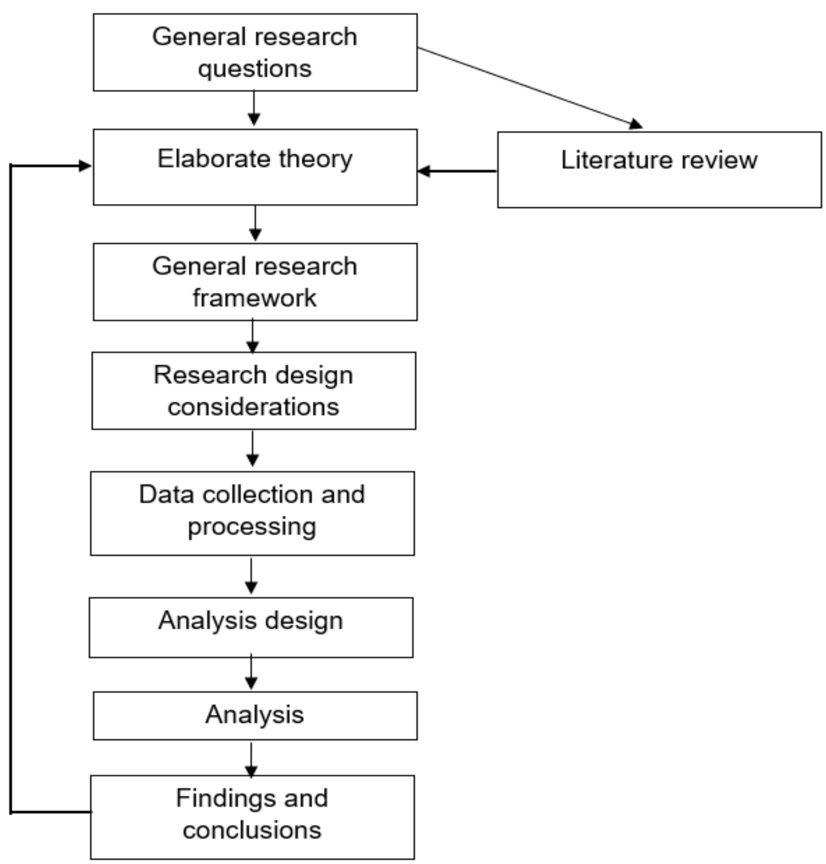
The time dimension of this research is cross-sectional, meaning that it captures the data set at one point in time. Although longitudinal studies would be more comprehensive and adequately depict the changes in variables, especially in network analysis (Pack et al., 2013), a snapshot of the study time point is more suitable given the limitation of research duration and human and finance resources.

The topical scope in this context is a case study as the research is designed to gain in-depth insights into the research network. The whole network is considered as the case under investigation via different aspects. Under this case, the thesis focuses on explore the relationships within and their impacts on output performance of the whole network. This choice is well aligned with the ontological and epistemological viewpoints.

In terms of the environment to conduct research, the field condition is selected from rural areas of New Zealand. In other words, the study is carried out within an actual environment in which the site/field of data sources will be specifically chosen by the researcher. The next section will explain more about this choice.

With regards to participant perceptions, the routine option is selected in this context. The respondents will have no deviations from their daily routine when the interview is conducted; that is to say, in order to get objective collected information, the researcher will attempt to not let the participants alter their behaviour and perceptions.

Figure 8 depicts the full research process, modified from Bryman and Bell's (2015) quantitative research strategy. This process is used as a general direction for the study. In practice, research implementation may be more complicated and less linear than this process, as some steps may be repeated several times during the study to ensure research reliability and validity (Creswell, 2014).



Note: Adopted from Bryman and Bell (2015).

Figure 8: Full research process

3.6. Data collection and processing procedure

This section will explain the data collection and processing used to measure the concept dimensions in the context of this study. As with the common principle of “garbage in, garbage out”, this stage of collecting data is important to determine reliable research results (Zikmund, Babin, Carr, & Griffin, 2010). Considerations of data sources, required data types, collecting methods and sampling will be discussed below.

3.6.1. Data collection methods

The data sources for this research are largely from primary sources supplemented by secondary data. Primary data was chosen to ensure data reliability and validity as well as to capture the reality of the research case. Primary data sources have two main categories, organizational information and relational data. The former contains general information – company name, address, title of respondent – as well as attributes about business revenue, industry, number of employees. Relational data includes information about company trading relationships with its suppliers and clients. Primary data is used for the analysis phase of this study. Secondary data is mainly from external sources, including published and commercial sources, and is used for the literature review, understanding of the research context and for comparing with research results for discussions and conclusions.

As this research relates to Scion’s Resilience project, the data collection process was professionally conducted by Scion’s data collection team. The semi-structured interview approach was selected to collect data within the deductive process. This approach is supposed to gain appropriate insight into the current situation, achieve the predetermined target for information within time and budget constraints, and minimize researcher and respondents bias (Bryman & Bell, 2015). Before conducting interviews, a detailed guideline for data collection was developed by the project team. Some pilot interviews were also conducted to test and modify the interview process, in order for the interviewers to easily follow. The interview guideline is attached as Appendix A.

The interview method was to gain initial insight into the participants’ “world” and to explore relationships in their supply chain network. Among the three types of interview, structured, semi-structured and unstructured, the semi-structured interview provides flexibility of question flow in order to obtain in-depth and interviewee perspective data within a pre-designed guideline for required factual information, achieving a balance between consistent and insightful data. Given the data requirement discussed previously, the semi-structured interview was chosen as the most appropriate for this study.

The interview technique was face-to-face and one-on-one, as this is the most effective way to acquire rich information from interviewees. The organization respondents were in management or supply chain positions, and those who clearly understood their business and its relationships within supply chains. The organizations were asked if they wanted to participate in the research and were then given a clear explanation of the study purpose from the Scion project. Participants were able to reserve their right to withdraw from the research at any time and to decide whether or not the interviewer could record the conversation. At the interview, the interviewer explained the research scope and context before discussing the main themes and insights with the respondents. Interviews ended with a summary of the interview content, the answering of any interviewees' questions and requesting future cooperation (if needed).

3.6.2. Sampling

The research area Scion chose for the research project is a rural area in the South Island of New Zealand. This choice fitted the researcher's expectation of a study field; that is, a rural area facing considerable risk of natural hazards and vulnerable to these disasters. More specifically, the chosen research site had been affected by a serious earthquake in the recent past, and has suffered impacts of this disaster both economically and socially (Cradock-Henry, Fountain, & Buelow, 2018). Agriculture is the most important sector in this area (NZ statistics, 2018).

The non-probability sampling technique was applied because the business population of North Canterbury is large and it is difficult to determine all potential subjects, coupled with the difficulty of selecting cases equally when there are critical actors as well as peripheral members in any supply chain network. At the beginning, the purposive technique was adopted to select a few key organizations from a business directory list of the research site. These subjects were interviewed and then asked to nominate others with whom they had business relationships. This technique is called snowball sampling, and is based on the social networking of the initial participants. It is self-selecting, and suitable for this research because of its ability to reflect the social network of chosen subjects (Griffiths et al., 1993). Because, however, this sampling technique relied on respondents to approach other contacts, the sample may be biased. To minimize such shortcoming, the data collection team made an effort to gain good buy-in from target respondents, and the network member list was checked with other agricultural references and rural associations or agents for any necessary supplementation. Since it is almost impossible to set a boundary for a full supply chain network (Choi et al., 2001) but highly possible to limit and research a network with key components (Carter et al., 2007), Scion's data collection stage stopped at 50 interviewees, with 456 total members in the network. As the target of this research is agricultural supply chains only, data was extracted to get an agribusiness network of 322 organizations, of which 39 businesses were involved in interviews. End-users or individual people were not included in this supply network as the study focuses on inter-organizational relationships only.

3.6.3. Data processing

A rigorous process was used to handle and analyze the data collected from the research field. First, the raw data was checked and managed through the editing step, which included both field and in-house editing (Zikmund et al., 2010). Immediately following each interview, the researcher reviewed the response and asked the respondent if there was any omission or inconsistency. The raw data was then checked any mismatches (e.g., different names of the same organizations) and examined the logicality and accuracy. The previously edited data was then coded for analyzing and computational handling. The data from closed-ended questions was assigned to numerical symbols, while open-ended question responses were coded using words to represent the dimensions of the research constructs (Creswell, 2014). Names of organizations in the network were also coded to ensure confidentiality. After the processing phases, the data was stored in an electronic file as the primary base for further analysis. The steps of error checking, data editing and coding was to ensure data integrity (Zikmund et al., 2010), as this is critical for analysis and decision making, serving the ultimate goal of the research. After data preparing processes, data analysis process will be designed in the next section.

3.7. Analysis procedure design

3.7.1. Analysis procedure overview

Analysis is a crucial part of the study, where propositions of the research framework are tested in an empirical world. In this research, a descriptive analysis and graphical visualization are first implemented to offer an overview of the agricultural supply chain network and its resilience in the selected rural area. The network properties are then investigated using SNA tools to analyze the network interconnectedness, structure and critical parts. UCINET 6, a comprehensive software for SNA, is used in this research (Carrington & Scott, 2011). Key Player 2 is also used as a supporting software in some certain analysis techniques in the thesis. Resilience attributes are then explored through the findings on network characteristics. After the analysis process, interview records and notes are erased to ensure confidentiality for respondents. The results of data analysis, then, become the foundation for theoretical, policy and managerial implications.

3.7.2. Analysis tools and key metrics proposal

Developing measures is a vital stage in quantitative research (Neuman, 2006). The abstract concepts need to be turned into observable and measurable entities, using operational definitions and measurement development (David & Sutton, 2011). This process is called “operationalization”, extending the sense of the “invisible” aspects of the social world and facilitating further works of data collection and analysis (Neuman, 2006). Developing measures is the most essential part of the deductive process for any quantitative study. As discussed in the literature review, two central concepts of this study are social network and SCRes. This section aims to clarify the designed analysis procedure, presented in Figure 9, and key metrics that will be used in the analysis chapter for the purpose of answering the research questions.

3.7.2.1. Network level analysis

General network characteristics

The initial approach is to explore the general characteristics of the research network. Several key measures are selected for this purpose; these are summarized in Table 7. A necessary starting point in SNA is using network cohesion analysis to understand general network properties. Several basic concepts of network cohesion will be introduced in this subsection, providing an overall picture of the network connections. These are categorized into two types; direct connection, called adjacent tie/ relation, and indirect connection. The latter consists of a sequence of several adjacent nodes and their ties to connect two non-adjacent nodes. SNA studies use various technical terms like walk, path, or trail, to describe types of indirect connections. Network cohesion measures consisting of average degree, network density, connectedness or fragmentation, average distance and diameter. This network cohesion analysis is based on the idea of ‘knitted-ness’ or the level of connections in the network.

Table 7: Concepts in network cohesion analysis

Measure	**Explanation**
Average degree	Mean of number of relations each actor has (i.e., average number of adjacent ties per actor)
Density	Number of ties divided by the maximum number possible
Connectedness	Proportion of pairs of actors that are reachable ("reachable" means being connected by either direct or indirect connection)
Fragmentation	Proportion of pairs of actors that are unreachable (1 minus the connectedness)
Average distance	Mean of shortest distance (distance means number of connection steps) between reachable pairs of actors
Diameter	The distance between the farthest pair of actors

Note: Adopted and abridged from Borgatti et al. (2013); Freeman (1979); Wasserman and Faust (1994).

The first measure, average degree, presents the average number of adjacent ties per actor. This measure is calculated based on actors and their relations which are only present in the underlying network. Density index quantifies how dense the connection is in a network. It depicts the probability that any random pair of nodes in the underlying network have a connection (Borgatti et al., 2013).

The connectedness and fragmentation indices indicate the extent to which the underlying network is connected as a whole (Borgatti et al., 2013). They capture the network cohesion via the aspects of the possibility of two random nodes that could be connected either directly or indirectly. This concept of connection is called reachability in SNA, which will be explained in more detail latter in this section.

Average distance and diameter measure how far two random nodes are in the network. The distance between a pair of nodes is calculated on the number of connection steps linking them. In SNA, the minimum number of connection steps required to link two nodes is called geodesic distance, or simply distance. Average distance, thus, refers to the mean of the distance of all pairs in the network. Diameter means the longest distance, in other words, the distance of the farthest pair of nodes.

Network shape

Network centralization is a useful measure to study network shape or configuration. Centralization measures were developed by Freeman (1979), and refer to the level of a single node to dominate the whole network. There are many options for constructing centralization measures, but the most popular is degree-based centralization. Degree centralization measures the variability between the degree centrality (number of ties per actor) of the most central actor and of other members, ranging from 0 to 1. The maximally centralized network has a centralization index of 1, and a star-like shape. Another type of network shape with high centralization is called centralized or core-peripheral structure, a few nodes of which have high central position while others have significantly low connections. There are several other types of network shape; for example, scale-free, circle-shaped or block-diagonal structure (Borgatti et al., 2013; Rivkin & Siggelkow, 2007). The typology of the network structure has the potential to impact on the ability of the underlying network to solve problems (Borgatti et al., 2013) and its resilience (Kim et al., 2015).

Network separation

Component analysis is a top-down approach to examine how the network is separated in general. A component of a network refers to a maximal connected group (Wasserman & Faust, 1994). In this definition, ‘connected’ group is a set of nodes in which each actor could reach every other in any way, meaning that the connectedness index of the group equals 1. ‘Maximal’ means it is impossible to extend the group size without abolishing the underlying feature. If a network has only one component, this network is connected as a whole; otherwise, it is disconnected. Examining components could help to assess the reachability of a network and see how the network is separated into disconnected regions.

Connectivity analysis

Connectivity analysis proposes to examine how the network retains its connectedness when removing nodes or lines. It, then, includes two direction of analysis: node connectivity and line connectivity. These tools use the idea of connectedness in the graph to define a set of actors or edges that are critical for the network’s connectivity (Wasserman & Faust, 1994).

Node connectivity is applied to analyze network connectivity based on the removal of nodes. It usually focuses on two levels, nodal and network. At nodal level, SNA aims to calculate the number of nodes needed to be deleted to disconnect any pair of nodes (Hanneman, 2005). Results of this analysis will show a matrix in which the numbers of removed nodes are displayed for all pairs. This eventually indicates the strength of linkages between any two nodes in the graph. At network level, the purpose of the analysis is to find the minimum number of nodes, called k-node cut, whose removal can leave the network disconnected (Harary, 1969).

Similar to node connectivity, line connectivity analysis consists of two different levels: node and network, focusing more on indirect connections (i.e., paths). The node-level analysis examines the minimum number of edges to be removed between two nodes to disconnect them, using tools such as k-local bridge and line connectivity or maximum flow. The maximum flow is the base for line-robust group analysis, which will be explained in the next sub-section. The network-level analysis for line connectivity focuses on the set of lines whose removal disconnects nodes, called "l-line cut" (Wasserman & Faust, 1994). This analysis aims to explore robustness and vulnerability of the network in the face of a disruption to relationships.

Fragmentation analysis

Fragmentation analysis aims to examine the connectedness of the underlying network, calculated on the concept of reachability. Thus, this type of analysis relates to connectedness measure, component analysis and reachability analysis. Fragmentation examination is applied at both node and network levels. The latter is the foundation for measuring the former. Specifically, the fragmentation index of a network is defined as the proportion of node pairs that could not reach each other in any way (Borgatti, 2006). It refers to the number of nodes located in different components, calculated on 1 minus connectedness (Krackhardt, 1994). Based on this index at network level, the fragmentation measure of a node is defined as the difference in the network's fragmentation score before and after the removal of the underlying node (Borgatti et al., 2013).

3.7.2.2. Group-level analysis

The study uses a set of analysis techniques at group level to explore different cohesive and robust sub-structures. Using both bottom-up and top-down approaches, these tools aim at finding special groups of actors that have relatively high density, special patterns of connections and robust feature in the face of node or line removal. Some special actors which position in overlaps between these groups are also a focus of the group-level analysis. The analysis contains different types of groups; clique, k-plex, k-core and line-robust groups.

Investigating cliques is a bottom-up approach to understand the sub-structure of the network in terms of highly intense, connected groups. A clique refers to “a maximal complete subgraph” (Luce & Perry, 1949). A “complete subgraph” is defined as a sub-group in which every actor has a direct relation to every other actor. “Maximal” has the similar meaning as explained previously; that is, if we add any other actor into this subgroup, the complete feature will be eradicated. Clique examination is a worthwhile starting point for cohesive subgroup analysis (Wasserman & Faust, 1994).

K-plex is another type of cohesive group based on a more relaxed criterion than the clique. A k-plex is a group with n actors, in which each node has direct connections with at least $n - k$ other actors (Seidman & Foster, 1978). In other words, k is the maximum number of ties that could be absent from each actor in a k-plex. Thus, a clique is a special case of k-plex when $k = 1$, meaning that each node has $n - 1$ ties with others and miss only the reflexive tie. Deciding a meaningful group size (n) and a value for k to analyze is important in this technique. For an interesting and interpretable result, the k-plex size should be restricted so that it is not too small relative to the value of k (Wasserman & Faust, 1994). After using clique analysis, the k-plex tool is useful to investigate the cohesive and robust substructure of the research network from a more flexible and relaxed approach.

K-core analysis is applied to investigate the connection distribution, dividing the network into different core or peripheral layers. “A k-core is a subgraph in which each point is adjacent to at least k other nodes in the subgraph” (Seidman, 1983, p. 272). This approach is more relaxed than the k-plex as it allows actors to join if they have enough connections to other members, regardless of how many members there are with whom they do not have ties. Thus, k-cores are usually larger than cliques or k-plexes, and therefore could be seen as “seedbeds” for those cohesive groups.

Line-robust group analysis is a top-down approach to investigate cohesive subgroups in terms of line connectivity. In this technique, a key concept is the level of lambda: the minimum number of ties needed to be removed to cut all the paths between any two nodes of the subset. Thus, the higher the level of lambda, the more robust the subgroup (Wasserman & Faust, 1994). It is worth noting that each member of a lambda set may not have direct relations to others, meaning that the connections in concern could be direct (adjacent) or indirect (connected via other nodes). This is a type of the line connectivity analysis mentioned previously.

3.7.2.3. Node-level analysis

Two common SNA techniques to investigate how individuals embedded in a network are centrality and reachability. Centrality measures in SNA could describe the importance of each actor via its position in its network structure. In this way, the most crucial and notable measures are degree centrality, closeness and betweenness (Wasserman & Faust, 1994). Actors with high rank in terms of these measures are considered powerful members, influencers, prominent, gatekeepers, prestigious or leaders in their network (Borgatti et al., 2013).

Centrality concepts are summarized in Table 8. Degree centrality is the number of adjacent nodes, or directly connected nodes, an actor has for a given type of relation (Borgatti et al., 2013). For the directed graph, an actor's degree centrality is considered through two aspects, in-degree and out-degree, which refer to quantity of ties with which this actor plays as a receiver and a sender, respectively. Closeness centrality focuses on how close a node is to other nodes in a network, calculated on the distance between actors (Hanneman, 2005). Related to degree and closeness centrality measures, eigenvector centrality is also a crucial indicator, representing the power of an actor when it links to other powerful actors. Betweenness centrality refers to the frequency of an actor to lie on the shortest path between two other nodes (Freeman, 1979).

Reachability analysis investigates the possibility of connections between actors in a network, considering both direct and indirect linkages. Two nodes are reachable if there is a path tracing from one to the another of the pair, regardless of how many other nodes and ties lie on this path (Wasserman & Faust, 1994). In this study, the ties on a path connecting two nodes are called the steps of their connection. If there is an un-reachable pair of nodes, it is said that these two nodes are disconnected, indicating that their network is divided into more than one sub-population (Hanneman, 2005). It is noticeable that the reachability of one certain pair could be different if the direction of ties is taken into account, or not. For the directional graph, the chance of each node to reach all others is usually lower than in the non-directional graph, except in the case of complete reciprocity; that is, two-way relations. Reachability is an important concept in SNA, acting as a foundation for many other analysis tools in this study.

Table 8: Summary of centrality measure concepts for individuals

Measure	**Explanation**
Degree centrality	Number of ties each actor has with other actors
Closeness centrality	How close an actor is to others, in terms of connection steps
Eigenvector centrality	How central an actor is as it links with well-connected actors
Betweenness centrality	Frequency of an actor positioned on the shortest connections between two other actors
Reachability	Power of an actor to transfer something to others

Note: Adopted and abridged from Borgatti et al. (2013); Freeman (1979); Wasserman and Faust (1994).

3.7.2.4. Simulations

Importantly, SNA allows researchers to conduct several simulations for different scenarios. These simulations offer researchers options to investigate a network facing a certain situation, as well as to see its changes in terms of network properties, internal dynamics, structural transformations, or re-configuration (Scott, 2013). Simulations are based on different assumptions and standards, depending on the purpose of the study. Because of limitation in time, length and resources, this research will explore only two types of simulations, diffusion and disruption. Diffusion simulation is based on the idea of reachability, consisting of two steps: finding the optimal set of nodes to spread something (e.g., a message), then, visualizing the way it is transferred within the network. Disruption analysis will be conducted in two steps; first identifying a set of nodes whose removal will leave the most serious consequence for the network, and then, visualizing this consequence in a diagram.

Figure 9 summarizes the flow of analyses which is conducted in the analysis chapter. First, an overall picture of the network properties is uncovered to capture the general understanding of this research network. Next, levels of analyses are carried out, moving from macro to micro levels. At each level, specific tools are chosen a pool of SNA tools, in order to examine network resilience. Simulations for different what-if scenarios are then conducted to explore the mechanism of flows running through the research network, and to ascertain how the network reacts to disruptions.

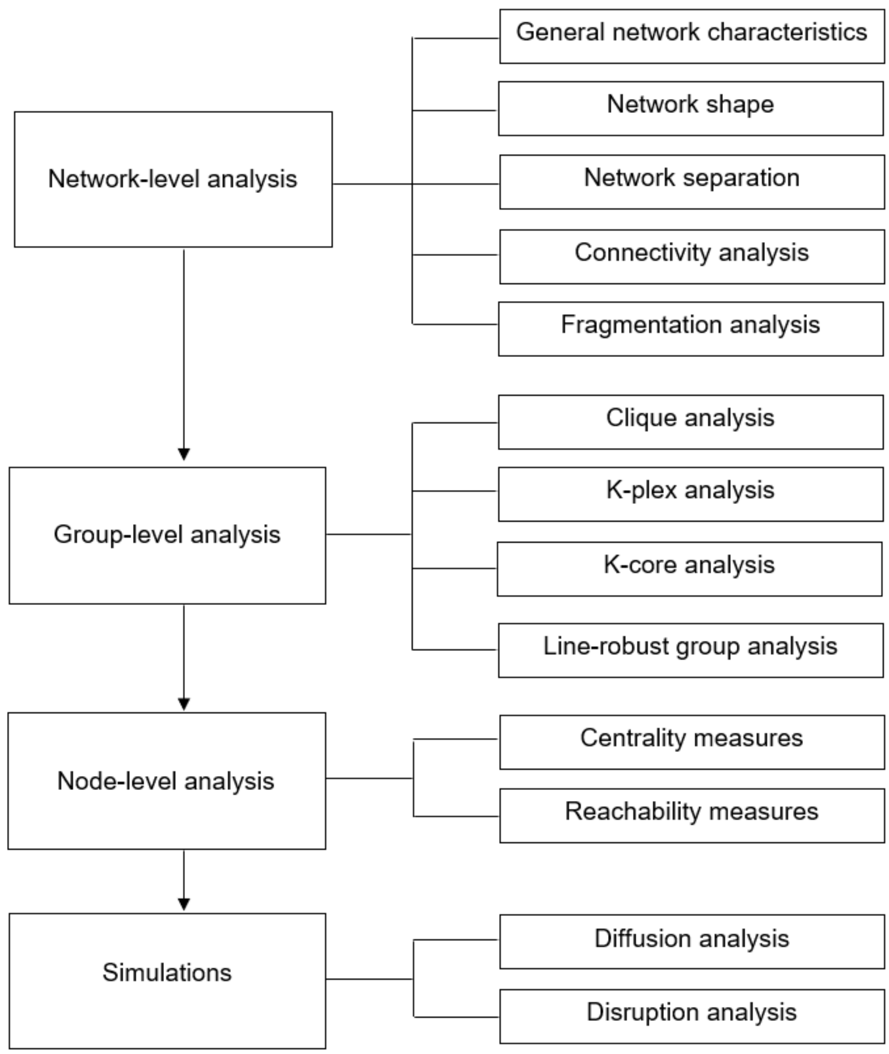


Figure 9: Analysis process in this research

The methodological agenda of this research has been explained in this section, providing details of analysis techniques using for the dataset. The next section will consider the quality and strength of the research design.

3.8. Critical review of research methodology

To ensure the research findings are credible, truthful and believable, the study strives for the reliability and validity of its selected methodology and measurement. Reliability refers to measure consistency or dependability, whereas validity relates to its truthfulness as indicated by the 'fit' of research constructs and actual reality (Neuman, 2006). Accordingly, measuring in a consistent manner and striving for a tight fit between theoretical ideas and empirical world are major concerns of this research. In particular, the study uses a triangulation of measurement and fully considered design to increase the confidence of its findings (Bryman & Bell, 2015).

The reliability of this research could be achieved by virtue of the research design and alignment. To achieve stable outcomes, the research utilized a strict research protocol for the procedures of data collecting, processing and analyzing, coupled with multiple measures. It is notable that the research seeks consistency in the research process, yet respects the variance in subject matter over the time as an inevitable change and even metamorphosis of social network reality. Noticeably, the data collection process was designed and conducted by the Scion project team in a professional manner, thus ensuring quality data and minimum individual bias. With representative reliability that refers to the dependability across a subgroup of the population, a triangulation of analysis tools is applied to the study at each level of analysis in order to archive reliable final findings.

To ensure that research measures correspond to the conceptual definitions, several techniques are applied in this study. Two validity types are used; face validity, which relates to judgement by the academic community, and content validity, which refers to the comprehensiveness of measures in capturing constructs (Neuman, 2006). To obtain the highest level of validity possible, the research reviewed thoroughly the body of literature to investigate and critique existing concepts and judgement of different authors. Notably, literature review articles were examined closely to aggregate materials and ideas for selecting appropriate tools from SNA to investigate the SCRes. In addition, pilot interviews were conducted to ensure the questions were well designed to gather the appropriate data for the designed analysis procedure.

In addition, the research attempts to archive the transferability of the data and analysis which refers to the ability of the research findings to be generalized and applied to other research settings (Bryman & Bell, 2015). To increase the transferability of this research, several measures are taken. A full description is provided of the research case and its context in New Zealand agricultural supply chains. Also, the study aims develop a detailed research model which explains how SNA could be applied to SCRes investigation; whereby archive the theoretical generalization.

3.9. Ethical considerations

As a social research, this study involves interactions with and participation of individuals and organizations, who need to be protected from potential harm or adverse consequences from the research activity. This calls for ethical behaviour, which is a set of standards or norms guiding moral choices in dealing with others (Cooper & Schindler, 2008). Ethical treatment is considered for all parties, including respondents, companies, the researcher, institutions and other involved organizations. It is guided by the Massey University Code of Ethical Conduct for Research, Teaching and Evaluations Involving Human Participants (Massey University, 2017), consisting of several key principles as considerations.

Respect for persons: This study enables all participants to freely decide to join the research or not. The target organizations and individuals are invited to participate with a clear explanation about the research objectives and methods. They will reserve the right of withdrawing from the process at any time.

Minimization of harm: Harm could be physical or psychological, or damage to one's dignity, reputation or relationship with others (Massey University, 2017). Since interviewing and surveying about on academic topic may lead to potential stress for respondents, especially farmers, the research strives to minimize harm by consulting with the researchers' supervisors and appropriate agricultural associations or agencies about question design and interview tactics. A great deal of effort was put into the pilot interview to test question suitability and clearness of expression for further modification if needed. A rigorous research protocol was applied to ensure safeguards for participants and researchers during the research process.

Informed and voluntary consent: Research objectives and methods were explained to participants before their decision to participate, or not. All the necessary information on which to base their decision would also be provided at the participants request. Participants were able to give informed consent afterwards.

Respect for privacy and confidentiality: All respondent responses and opinions gathered during the data collection phase are non-attributable. In other words, participants and their responses were coded so their personal nature and information cannot be identified. All interview records and notes were erased after data analysis to guarantee privacy and confidentiality.

Avoidance of unnecessary deception: All information about the research is available to open for the participants, without deception or concealment.

Avoidance of conflict of interest: There is no potential conflict of interest between the researcher and research participants. If any potential interest conflict emerges among research participants, the researcher seriously attempts to avoid.

Social and cultural sensitivity: The research focuses on rural areas so, there is the potential to interact with Māori, the indigenous people of New Zealand. To respect their culture and values, the research considered thoroughly these aspects when collecting data, and with the support of and consultancy from Ngāi Tahu, the Māori partner of Scion's Resiliency project. The manner with which to communicate with farmers in the research site was also seriously considered as they are still sensitive to the topic of natural disasters and resilience.

Justice: The distribution of benefits from the research is likely to be fair for all participants as it aims to build the resilience of the whole network and participants can seek practical value from it. The harm to or burden on any participant has been minimized as much as possible to ensure no one suffers adverse consequences.

3.10. Chapter summary

The chapter has explained the research methodology for this research for the purpose of answering the proposed research questions of how SNA is applied to study SCRes. The philosophical choices are constructivism ontology and interpretivism epistemology, viewing the supply chain is a dynamic system, of which its performance depends on interactions between its elements, members and environment. SNA is the approach chosen to assess the study, and quantitative has been selected to match this approach in quantifying network properties.

As the subject to be analyzed is a supply network, this study has chosen a cross-sectional case study with data collected through face-to-face interviews. The data was collected by the Scion's data collection team, aiming at grasping both attribute and relational data from key businesses in the research region. As the business community in the research site is relatively small, the research network of 322 organizations with 39 primary businesses is rich and can capture a large number of trading relationships in the region. It is therefore appropriate and valid to use analysis tools for both global and local level to investigate the network characteristics.

This chapter has detailed the procedure developed to provide a clear and consistent analysis process. The proposed analysis set contains two categories; tools for understanding the state of the network characteristics and modelling approach to simulate the network mechanisms. The former investigates the network at three levels; network, group and individual. The SNA method in the analysis stage will start with exploring general characteristics of the network, expected to provide an understanding of overall network connectedness with network average degree, density, fragmentation, average distance and diameter. Some other network-level tools will then be carried out to investigate network configuration, separation, connectivity and detailed fragmentation, which might help shed light on network interconnectedness and structure. The network sub-structure will also be explored using group-level tools, such as clique, k-plex, k-core and lambda set, expected to help understand special cohesive and robust groups in the network. This chapter has also proposed using node-level analysis tools of centrality and reachability to identify key players in terms of influencing other network members and being well-connected and power to reach others. Simulation tool is expected a useful approach to explore how network connections impact on the way something flows in the network and the way the network responds to a disruption. A critical review on research design has also been outlined to understand the research reliability and validity, followed by ethical considerations. The following chapter will deal with analysis of the results and potential findings.

CHAPTER FOUR: ANALYSIS AND RESULTS

This chapter will present an important part of the study; an introduction to the case study network and results from the proposed analysis tools. It will first give an overview of the case study, including the business demography and a visualization of the research network, followed by, the analysis process of network properties at three levels: network, group and individual. Simulations will also be carried out to model the network mechanism in some certain cases. The analyzed results will then be interpreted in order to link the network properties with resilience attributes, following the guideline of the proposed research framework.

4.1. Overview of case study

The collection and processing of the empirical data used in this case study has been explained in the previous chapter. The dataset consists of organizational attributes and relational data. This section will provide an overview of the case study based on the collected dataset. The first section will provide descriptions of the sample; that is, the demographics of the businesses interviewed. The information on the organizations in the sample is attached as Appendix B. A visualization of the network in this case study will then be presented with general information on the relational data.

4.1.1. Business demography

The final dataset for analysis contains a total sample of 322 organizations. Within this dataset, 39 businesses were interviewed while the remaining 283 organizations were referred to by respondents as their suppliers or clients. As stated in data collection section, the organizational attributes data is about the 39 interviewed businesses only. Table 9 presents the organizational attributes of the industry sector and business size in terms of employee numbers. The industry sector is categorized according to the official Business Industry Classification Code in New Zealand. The research follows the common practice of statistics in New Zealand, which is to classify business size based on the number of employees. It needs to note that a few data points are missing due to some respondents' refusal to supply information on, for example, business revenue or number of employees.

Table 9: Descriptive statistics of the case study

Title	Number of business	Percentage (%)
Industry sector		
Agriculture, Forestry and Fishing	24	61.5
Construction	1	2.6
Wholesale trade	1	2.6
Retail trade	3	7.7
Accommodation and Food services	5	12.8
Transport, Postal and Warehousing	1	2.6
Financial and Insurance services	1	2.6
Education and Training	1	2.6
Arts and Recreation Services	2	5.1
Number of employees		
0 – 5	16	50.0
6 – 19	8	25.0
20 – 49	5	15.6
50 or more	3	9.4

The table shows that 61.5 percent of the sample operates in the agriculture sector, while nearly 18 percent is related to the tourism industry, including accommodation, food services, entertainment and recreation services. About 10 percent of businesses operate downstream in supply chains; for example, wholesalers or retailers, whereas the remaining 10 percent provide general services such as construction, logistics, transportation, finance or education. Most (90%) the interviewed sample are small businesses with fewer than 50 employees. This spread reflects the reality of the New Zealand economy, which is mainly small-and-medium-sized enterprises, especially in rural areas (New Zealand Government, 2018). Half the sample organizations have less than six employees (micro-businesses). All of these enterprises are local businesses, in which most are farms and a few are self-employed retail businesses or service providers.

A small proportion (9.4%) of the sample is midsize or large companies with nationwide or even international operations.

Data on business revenue was also collected and is described in Figure 10 and Table 10. Annual revenue as reported by respondents contributed at least 80 percent of their income flow. Table 10 provides an overview of the descriptive statistics of this revenue variable. The mean annual revenue is approximately NZD 99 million, while the standard deviation is significantly higher, and the median is NZD 950 thousand only. This indicates a large gap in business income among interviewed companies, ranging from the lowest, nearly NZD 20,000/year, to the highest at NZD 2.7 billion/year.

Table 10: Descriptive statistics of annual revenue of interviewed companies

Title	**Statistics result**
Mean	98,796,423
Standard Deviation	454,664,424
Median	950,000
Minimum	19,668
Maximum	2,700,000,000
Sum	3,655,467,650
Count	37

This large spectrum of annual turnover in the sample is shown graphically in Figure 10. This demonstrates that more than 50 percent of the sample earns less than NZD 1 million/year, of which, about 25 percent receives an annual revenue of less than NZD 500,000/year. While approximately 70 percent of the total sample earns less than NZD 3 million/year, the largest annual revenue accounts for nearly 74 percent of the total revenue of all interviewed businesses. This illustrates the huge gap in revenue, which can be explained by the difference in market coverage of these businesses. Specifically, many local businesses serve local or regional markets only, whereas a few companies provide goods or services to larger nation or overseas markets.

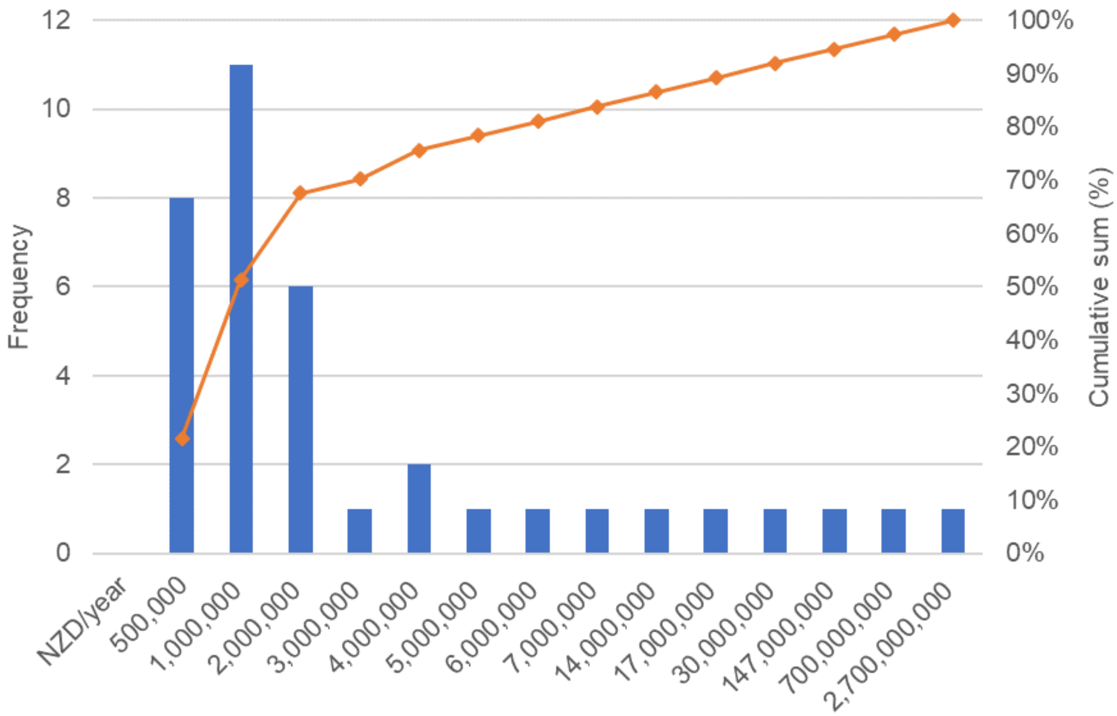


Figure 10: Distribution of annual revenue of interviewed companies

4.1.2. Inter-organizational network in this research

Figure 11 demonstrates the research network in the case study in a New Zealand rural region. This network data is the result of completing the data collection and management processes explained in the previous chapter. The network contains 322 organizations, including 39 interviewed businesses, so-called "primary organizations", and 283 organizations that were mentioned as their trading partners, so-called "secondary organizations". These 322 organizations are indicated by coloured nodes Figure 11; green nodes refer to primary organizations and blue nodes represent secondary organizations. The business relationships between these organizations were recorded by the interviewers, based on at least 80 percent of expenditure or sales that they have with their suppliers or clients. More specifically, if the interviewed companies had bought or sold products and services from or to their partners, these trading relations were recorded and depicted as arrowed lines in Figure 11. The research network contains 546 business relationships; this excludes the ties to unknown general customers or end-users. The method used to locate these organizations in the diagram is based on the graph theoretic layout of the UCINET software, whereby close actors (in terms of direct connections) are located near to each other, and nodes with large numbers of business relationships are sited more centrally.

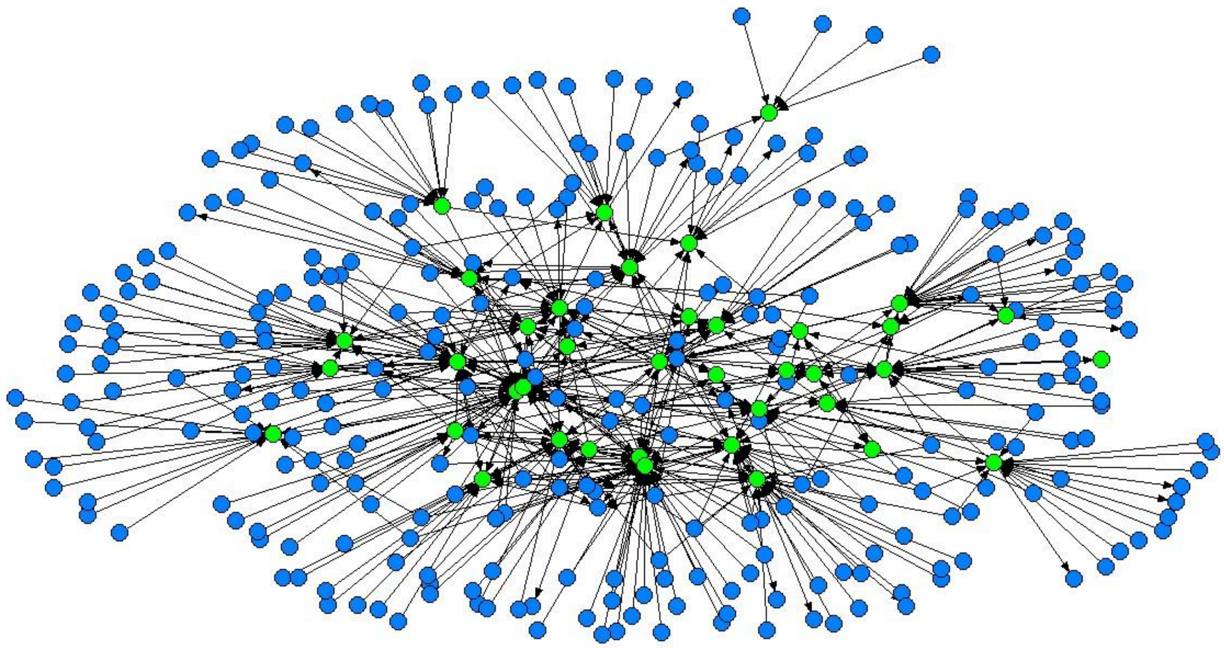


Figure 11: Visualization of the research network

In SNA, the direction of ties can be taken into account or not, depending on the analysis tools and research purposes. For this analysis, the main focus is on the web of business relationships, which are reciprocal (mutual dyad), except for some special cases where direction of ties is also considered; for example a case of product flows in the network (most ties are one-way). Thus, the direction of ties will generally be ignored, unless otherwise noted, and the research network regarded as undirected. Accordingly, the dataset analysis is symmetrized.

An overview of the network has been provided in this subsection. The following sections will look at analyzing the key parts of relational data to explore network properties, addressing this objective at the three levels of network, group and node.

4.2. Network-level analysis

SNA is especially useful for investigating network properties. Network-level analysis is important to study underlying network configuration and structure. One of the basic approaches is network cohesion, which provides an understanding of overall network characteristics. Several other analysis tools at network level can be applied for the purposes of this study. Some useful tools will be also discovered, including network shape study, component analysis, connectivity examination and fragmentation analysis. Findings from these analyses will be explained at the end of this section.

4.2.1. General network characteristics

Network cohesion analysis will be applied in this subsection to explore overall characteristics of the research network. The results will then be interpreted in order to see how these characteristics relate to SCRes attributes.

4.2.1.1. Analysis of general network characteristics

Table 11 shows the results from the network cohesion function in UCINET, running for both the whole research network and the primary subset of 39 interviewed businesses. The rationale is that some measures are only meaningful when relational data from all members are fully available. This will be explained more specifically later. The whole network and the primary subset have 322 and 39 members, respectively.

Table 11: Network cohesion measures of the whole network and the primary subset

Measure	The whole network	The primary subset
Average degree	3.317	3.385
Density	0.010	0.089
Connectedness	1	0.899
Fragmentation	0	0.101
Average distance	3.717	2.947
Diameter	6	7

Regarding the average degree measure which is based on number of ties each actor has, it is more meaningful to take into account the score of the primary subset rather than the whole network. The reason is that the whole network has 283 organizations (out of the total 322), which were not enquired to list their business partners, whereas the relationships of all members in the primary subset were captured at the interview stage. The average degree index of the primary subset is 3.385, indicating that each member has approximately three adjacent relationships with others within the 39 members of the subset. This result is similar to the whole network score of 3.317. However, it is worth noticing one additional index of the mean of the primary organizations' degree scores calculated on their relationships in the whole network, rather than in the small primary subset only. This average number of their ties is 15.385, meaning that each primary member has approximately 15 adjacent actors in the whole network.

The network density measure will only reflect the actual meaning of a case, if the network dataset contains all the existing relationships of all members. Thus, it is more appropriate to use the index from the primary subset where all members are asked about their relationships. According to Table 11, there is an 0.089 probability that a tie exists between two random primary members, but only 0.01 for the whole network. It is clear that the primary subset is much denser than the whole network.

The connectedness measure score of one for the whole network means that each organization in the network can reach all other members. In other words, there are no isolated nodes in this research network, resulting in the fragmentation index of zero. It is necessary to note, however, that the primary subset has two isolated nodes – those which have no direct connection with any other interviewee, but are their tier-2 supplier or client. Secondary actors who are intermediaries between the two isolators and other primary actors are omitted in the subset, which explains why the subset's connectedness measure is only 0.899.

According to Table 11, it takes an average of about three steps to connect primary nodes, but nearly four steps to connect nodes in the whole network. It can be said that the primary actors are, in general, closer together than the actors in the whole network. Interestingly, the diameter of the primary subset, that is, seven steps, is higher than the whole network score of six steps. Thus, the farthest two nodes in the whole network are closer together than in the primary subset. It is worth noting that because the primary subset has two isolators, the algorithm calculating these two measures dismisses them and focuses only on the largest connected group (Wasserman & Faust, 1994).

4.2.1.2. Findings about general network characteristics

The average degree results indicate that each organization has, on average, three business partners. It is noticeable that the average degree index reflects only the number of each organization's partners who are also members of the underlying network. Thus, the richness of a firm's business relationships, which is captured by average degree, focuses only on the scope of the underlying network and ignores relationships with nonmember organizations. That is why this study also considers the average degree of interviewed businesses in the context of the whole network. Considering business-transaction relationships in this study, the additional index shows that, generally, one organization has around 15 trading partners. This means that members of the network have excellent opportunities to exchange economic benefits, information and other resources with other organizations. However, only some of these opportunities originate from the research network.

Network density is one of the simplest measures of cohesion, characterizing probability that a business relationship exists in the underlying network. It gives an overall understanding about network connectedness (Carrington & Scott, 2011). It cannot be concluded that the whole network is less dense than the primary subset, as the whole network lacks relational data from secondary organizations. In other words, interpreting the one percent density of the whole network is meaningless. The result of 8.9 percent density in the primary subset might indicate that the subset is dense or spare, depending on the type of relationships and the size of the underlying network (Borgatti et al., 2013). Hence, it is difficult to conclude how dense the subset is. Kim et al.'s (2011) SNA study on contractual relationship networks in the automotive industry might be a useful benchmark. They discovered that networks with 27 and 34 members have density indices of 7.4 percent and 6.6 percent, respectively. Compared to these examples, the 39-member primary subset of this study is relatively dense.

With regard to connectedness and fragmentation, the analysis result above indicates that the research network has a wholeness feature; that all ties are interlinked and form a connected community. Thanks to this feature, information and other resources can be disseminated within the entire network, from any one organization to all others.

Average distance and diameter relate to flows of information or resources within the network in terms of time or quality (Borgatti et al., 2013). The results indicate that it takes around three to four steps, on average, to pass a message from one organization to another, whereas the maximum time is six steps. The speed of passing on information is interpreted on the assumption that a resource will be disseminated the shortest way possible. In addition, the relatively low number of steps suggests that the information might not be too distorted during the communication transaction between organizations.

4.2.2. Network shape: Centralization measure

In this research, degree centralization is applied to investigate the typology of network structure. This index reaches 1 when one organization dominates all others as a central point in the network and equals 0 when all actors are equally important in terms of degree centrality. According to UCINET results, the degree centralization metrics of the whole network and the primary subset are respectively 0.102 and 0.267. This shows that centrality is neither too extreme to any one organization, nor equally distributed. Within the range of 0 to 1, both scores are closer to 0, which indicates that the difference in actor connections is small. In other words, overall connections are distributed fairly equally, although centralization is, to some extent, still concentrated in some specific organizations more than others. It is also noted that the primary subset has a much higher degree centralization index than the whole network, demonstrating that connections among primary actors are more concentrated than in the whole network.

4.2.3. Network separation: Component analysis

Component analysis shows that the research network is one large component; that is the global cohesion of the network is not separated but consolidated into one large body. This result matches the measure of network connectedness, indicating that this network is connected as a whole.

4.2.4. Network connectivity: Connectivity analysis

This section explores the two directions of connectivity analysis; that is, node and line connectivity. The analysis investigates how connections between nodes are affected when removing other nodes or lines.

4.2.4.1. Node connectivity

As mentioned in chapter three, node connectivity analysis has two levels; network-level with cut-set examination, and node-level, which is similar to line-robust group analysis carried out in the next section. This section will focus more on the network level to examine the k-node cut or cut-set of the network. The most popular approach for this tool is cut-point analysis. Cut-point is defined as one point or node that if deleted it will result in a generation of one or several components (Wasserman & Faust, 1994). The parts into which the cut-points separate a network are called blocks or bi-components (Hanneman, 2005). Cut-set or k-node cut is precisely the extension of the cut-point concept, referring to the set of actors needed to maintain the state of connectedness for the graph. A cut-point is a cut-set with the size being 1, named 1-node cut.

Applying this analysis to the research dataset shows that the network has 29 cut-points with 216 bi-components. This is shown in Figure 12 in which the 29 green nodes are the cut-points. Instead of using the graph theoretic layout in UCINET software, the positions of the nodes in this diagram are re-arranged to illustrate how the bi-components are linked together by the cut-points. Noticeably, 16 of the 29 cut-points are farms that produce main products in this supply chain network.

Among the 216 bi-components are 215 groups each with only two members, which have one cut-point and one other node (shown in blue in Figure 12). These 215 blue nodes are considered peripheral because the removal of cut-points will leave them as isolated nodes. They are tied to the whole network by only one edge which connects them with one other cut-point.

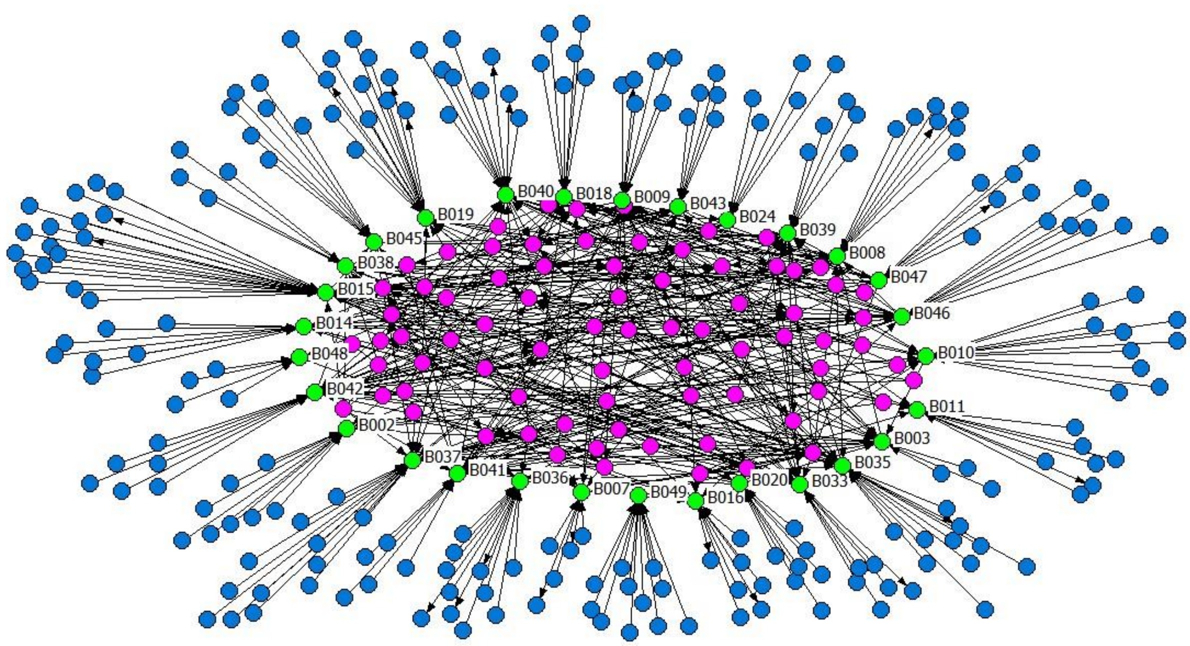


Figure 12: Cut-points and bi-components of the research network

The group with magenta nodes and green cut-points is the only central bi-component. This is the critical bi-component of the network where connections and important actors are embedded. This bi-component is where the network’s connections are most condensed.

4.2.4.2. Line connectivity

Line connectivity analysis is conducted in the same manner as node connectivity, aiming to investigate how robust and vulnerable the network is when coping with line removals. The analysis can also be conducted at two levels; node and network. The node-level connectivity analysis is the core idea of line-robust group analysis, which will be analyzed in the next section. The network-level analysis focuses on l-line cut, in which value of *l* indicates number of lines required to remove in order to disconnect nodes. It is most popular to analyze with *l = 1*, using a concept similar to cut-point, named “bridge”. A bridge is an edge that must be deleted to leave the network more disconnected, so-called 1-line cut. In Figure 12, the lines connecting cut-points and the 215 peripheral nodes are the 215 network’s bridges.

4.2.5. Network fragmentation: Fragmentation analysis

Fragmentation analysis is conducted to examine how separate the network is, quantifying the network separation explored by component analysis, with a more sensitive measure. It is worth noting that the fragmentation scores of directional and non-directional graphs are different due to the distinction in their reachability measures. Fragmentation analysis for the research network is run for both directional and non-directional datasets. The results from the UCINET software show that the fragmentation scores of non-directional and directional network are 0.00 and 0.86, respectively. This confirms the wholeness characteristics of the research network in terms of two-way relationships. However, the network directional flow is separated at 86 percent, meaning that only 14 percent of cases that organizations could reach other actors.

Fragmentation analysis is also conducted for each node in the network. This analysis focuses on the non-directional network only, aiming to investigate the nodal importance in information exchange or resources mobilization among the network. The results from the UCINET software indicate that 29 organizations have direct impacts on network fragmentation. The removal of any of them leaves the network fragmented within a range of 1.9 percent to 10.3 percent.

Table 12 presents the top nine organizations that are the most critical in terms of contributing to network connectedness. The farm B015 is considered the most fragile cut-point, whose removal will result in the highest fragmentation of the network at 10.3 percent. Five farms out of nine organizations are in this top list, indicating the importance of farms as focal businesses in this research network. It is interesting that a café turns out to be highly critical in this sense, yet small in terms of business size and functional role in the supply chain network.

Table 12: Top nine organizations with the highest node-level fragmentation score

ID	Type	Node-level Fragmentation
B015	Farm	10.3%
B019	Café	7.3%
B037	Farm	7.3%
B036	Farm	6.7%
B049	Retailer	6.7%
B010	Construction company	6.1%
B035	Processer and wholesaler/retailer	6.1%
B040	Farm	5.5%
B002	Farm, nurseries and retailer	4.9%

4.2.6. Findings from network-level analysis results

Beside the general characteristics findings discussed previously, analyses at network level have provided many insights into network properties. First, network centralization shows that the connection distribution within the network is unequal, but only to a minor extent. The bias in degree centrality to primary organizations suggests that the primary subset is more significant to interpret. Its centralization index implies that several organizations are more central with large numbers of connections. These organizations will take a leading role in coordinating SCM practices, controlling flows, problem solving or managing disruptions (Borgatti et al., 2013). This feature will be investigated and confirmed in latter sections by using nodal centrality analysis and tools of cohesive groups.

The component analysis provides an insight into how the network is separated. The result, once again, confirms the wholeness characteristics of the research network. An obvious advantage of this feature is that information or resource can be dispersed through the members regardless of how long this takes and how unchanged the information or resource is when it reaches the last member. The wholeness of the network means the situation is favourable for the development of joint resilience plans and cooperation strategies against risks, ensuring the organizations receive the necessary information or resources in case of emergencies. Being just one component, however, could also disadvantage the network, because a disruption at one point of could influence the whole. These positive and negative sides need to be carefully considered in building resilience for the network.

Regarding connectivity analysis, one valuable finding is that the network has 29 vulnerable points. These 29 organizations, due to their special positions, are important to network connectedness, playing brokerage roles among otherwise disconnected groups or separate components. In other words, if any of them is disrupted, a part will be separated from the network. These cut-points are therefore critical 'weak' spots in the network. It is not surprising that many of the vulnerable points are focal farms, as they possess a large number of connections and have important functions in the supply network.

Another finding from the connectivity analysis is that one-third of the network is gathered together in a hard-to-disconnect cluster, leaving two-thirds of the population peripheral and vulnerable. The closing down at any cut-point will not separate this hard-to-disconnect cluster from the main network, but could isolate a few peripheral organizations. In comparison with the whole graph, therefore, this central cluster is more robust. The peripheral organizations have relatively weak links to the whole community. They are easily separated from all other organizations if their only tie is disrupted. They find it more difficult to exchange economic benefits and information or resources as their bridge is their only link. These bridges are fragile ties, whose existence is critically important to peripheral organizations, and for the wholeness of network connection. The vulnerability mentioned here refers to how the fragility of the whole network connection depends on the existence of some organizations or relationships, and does not indicate the internal capability or attribute of the actors or ties themselves.

Network-level fragmentation analysis results verify the wholeness of the network, demonstrating that all organizations have the potential to exchange information or resources via certain means. This fragmentation result matches findings from connectedness measure and component analysis. However, from the viewpoint of material flow, the network is separated. In this case, separation means that a number of organizations cannot deliver materials to some specific others. This is understandable as it is reasonable that while a material product flow from supplier to buyer is possible, a material product flow from a buyer to its supplier is absent. Note that reverse logistics flow is not counted in this network.

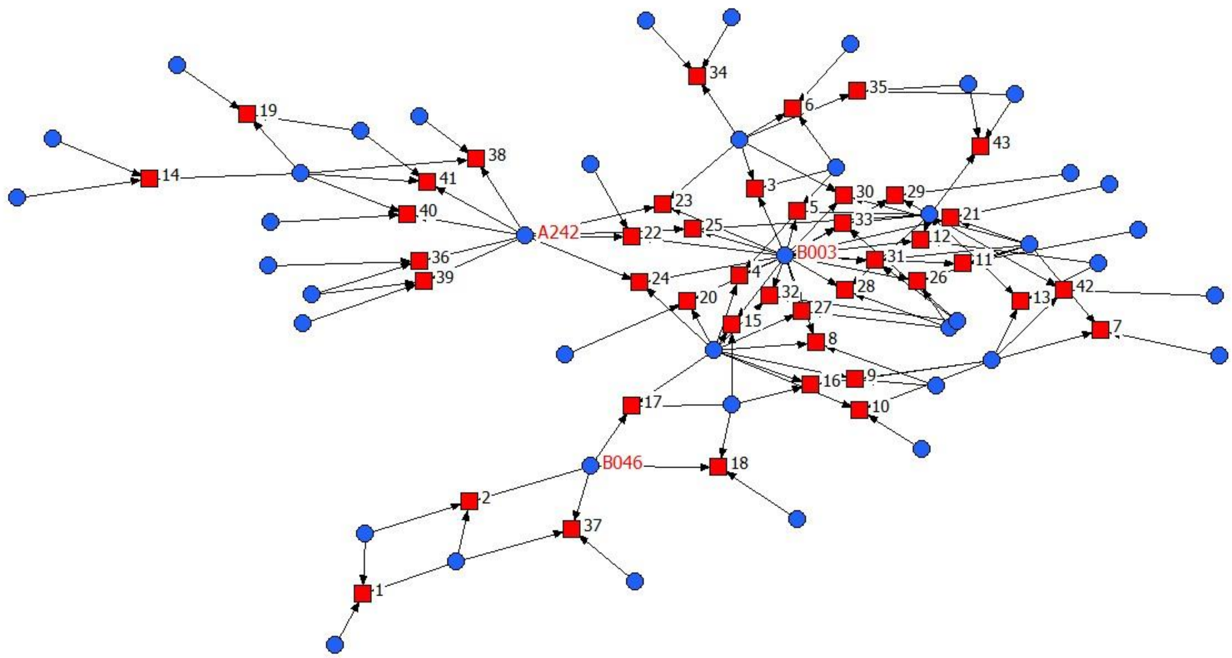
Node-level fragmentation depicts the importance of the actor's presence to network connectedness. The result reveals that there are 29 organizations in this position, along with the importance level of each to the network. This clarifies the results from the connectivity analysis in which 29 cut-points were identified. It can also be seen that focal farms play a critical role in keeping the network connected as a whole. Focal farms are also considered vulnerable points in the network, as discussed previously. Interestingly, a café is at the top of the fragmentation index, despite its small size. This will be explained in the later section of node-level analysis.

4.3. Group-level analysis

As stated in chapter three, group-level analysis is critical to unveil the network structure that provides understanding about how network connections are distributed. This section will delve into the analysis of cohesive and robust groups that possess intense connections. The robustness of the structure will be explored to see the capabilities needed to sustain against node removal, using the analyses of clique, k-plex and k-core, and against line removal via the lambda set or so-called "line-robust group". Both bottom-up and top-down approaches will be applied in line with each analysis tool.

4.3.1. Complete connected groups: Clique analysis

Regarding the strictest analysis of group connections, results from UCINET software show that this research network has 43 cliques as shown in Figure 13. The 43 red squares represent the 43 cliques, which are pointed to from their members, represented by the 42 blue circles. Within each of these cliques, members are connected tightly, forming intense connected groups. However, each of the 43 cliques has three members only, the minimum size of a clique for meaningful for analysis. Analyzing these cliques, therefore, is also a part of triad analysis in SNA.



Note: Red square: Clique name

Blue circle: Clique member

Figure 13: Cliques in the research network

It is interesting that the 43 cliques together form one large cluster with a total of 42 nodes. This cluster accounts for approximately 13 percent of the network population. Figure 14 shows how these 42 members of the 43 cliques are embedded in the network with the graph theoretic layout. It can be seen that this cluster has a central position in the network with a large number of connections. This is confirmed by its density index of 16 percent, double that of the primary subset.

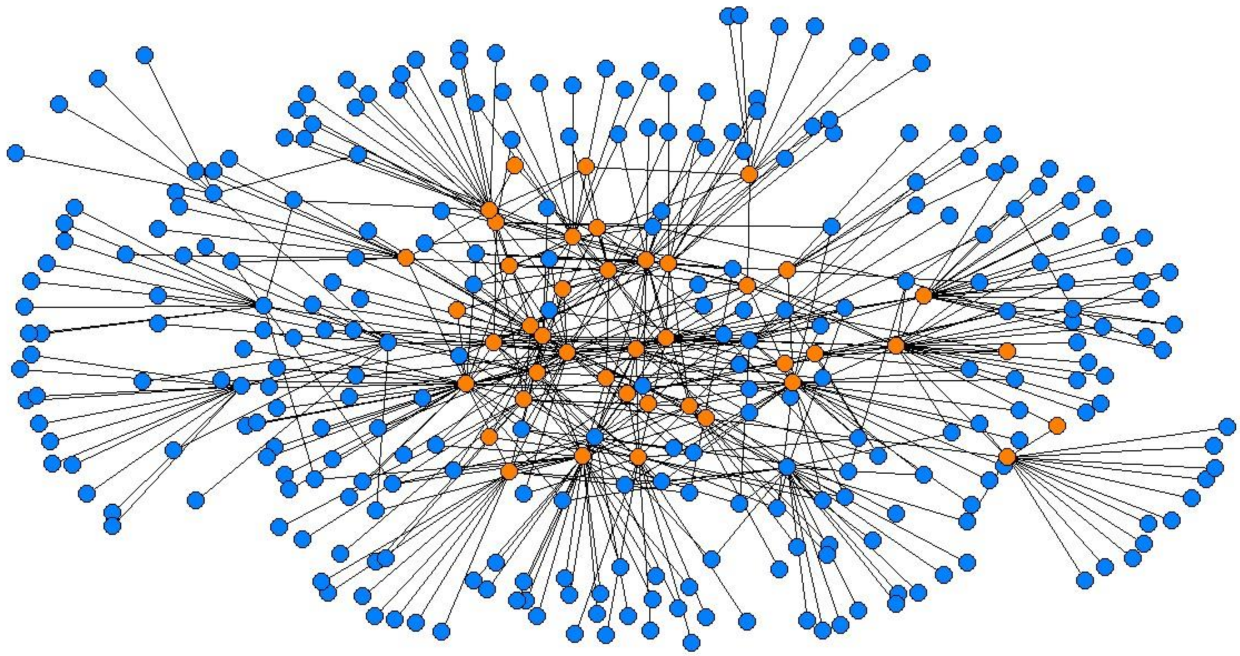


Figure 14: 42 clique members in the research network

Investigating the roles of individuals, especially co-membership, is also a crucial part of this technique.

Table 13 shows 21 organizations which are embedded in at least two cliques each. Noticeably, B003, a farm service provider, presents in haft of the cliques, taking a central position. This can be also seen in Figure 13. The farm B041 is second in the co-membership position, being in 11 cliques. From the UCINET result file of clique overlap, these two actors are mutual members of the most cliques (7 cliques), and thus have the strongest relationship with each other in terms of sharing clique membership. Accordingly, {B003, B042 – farm}, {B003, B010 – construction company} and {B003, A242 – local government agent} are also close pairs, sharing six, five and four respectively of the same cliques. Figure 13 also shows two special individuals, A242 and B046, which have brokerage positions. Specifically, the local agent A242 has a special role as a bridge between a group of cliques (number 14, 19, 36, 38, 39, 40, 41) and the remaining cliques. Similarly, the veterinary clinic B046 acts as a broker linking three cliques (1, 2, 37) with the remaining clique cluster.

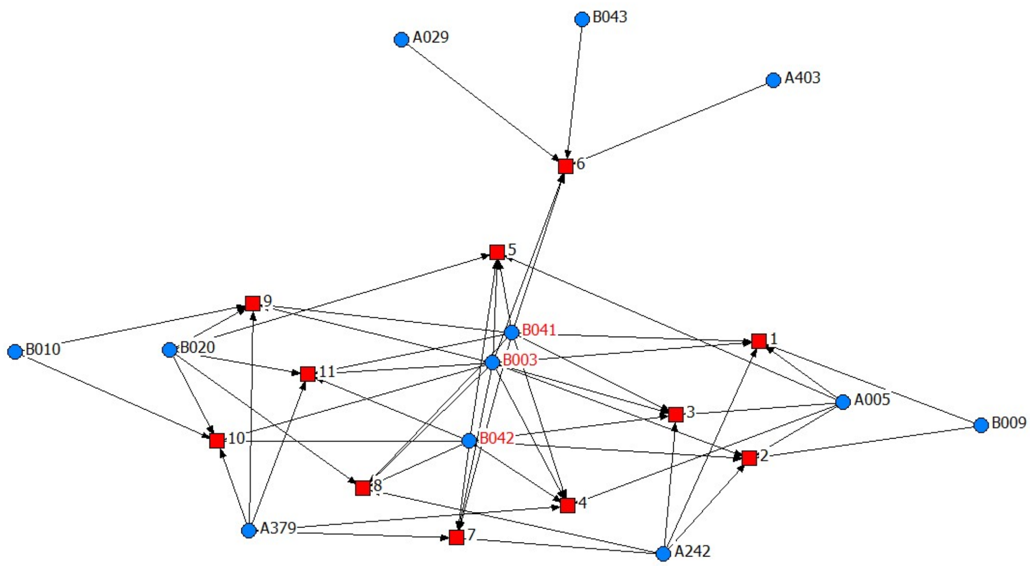
Table 13: Clique's co-members in the research network

ID	Type	No. of Cliques	ID	Type	No. of Cliques
B003	Farm service provider	21	A156	Energy company	3
B041	Farm	11	A379	Vehicle business	3
A242	Local government agent	9	B020	Hardware business	3
B042	Farm	9	A029	Internet service provider	2
B009	Farm	6	A329	Agency	2
B010	Construction company	6	A343	Farm supply business	2
B043	Transportation company	6	B015	Farm	2
B035	Processer and wholesaler/retailer	5	B024	Accounting service provider	2
A005	Insurance company	4	B032	Accommodation business	2
A403	Telecommunication company	4	B044	Processer and wholesaler	2
B046	Veterinary practice	4			

4.3.2. Intensely connected groups: K-plex analysis

As a clique itself is strict with complete mutuality, cliques in this study have a minimum size of 3 only; thus, k-plex is used as a more relaxing and flexible approach to analyze cohesive groups. In this research data, k-plex is run with several options; group size (n) and k value, to find the most meaningful set to analyze. This indicates the most worthwhile option for investigation is $n \geq 5$ and $k = 2$. UCINET software results show this network has 11 groups, each with five members, and each of which has at least three ties to others within its group.

Figure 15 demonstrates how these 11 k-plexes connect. From the diagram, 12 members of the 11 k-plexes form a robust substructure of the network with no isolated group. On closer scrutiny, it is clear that B003 is an important node because this actor presents in all 11 groups, highlighting that this farm service provider plays a bridging role among these cohesive groups. In this sense, the farms B041 and B042 are also central as they respectively join nine and eight out of total 11 k-plexes. It is noteworthy that only three out of 12 k-plex members are farms; those remaining are a local government agent (A242), a farm service provider (B003), a retailer and six associated services provider.



Note: Red square: K-plex name

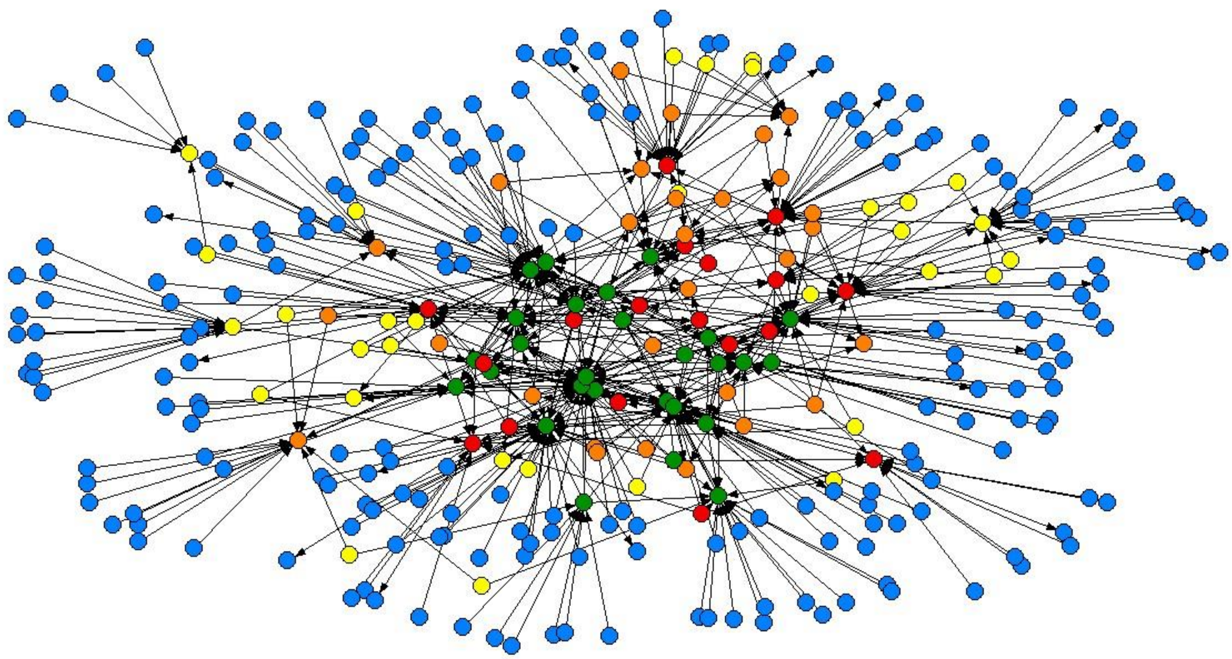
Blue circle: K-plex member

Figure 15: The 11 k-plexes with five members and k = 2

4.3.3. Core-peripheral layers: K-core analysis

K-core analysis is now carried out to investigate cohesive groups based on nodal degree, which is more relaxing than k-plex. When analyzing k-core, the procedure is usually to start at $k = 1$ to obtain a large group, then gradually increase the value of k to scale down the group size. The whole network symmetrized dataset is entered into UCINET to run this analysis.

Figure 16 shows that the network has five inclusive k-core groups, with k being one to five. When k is increased from one to two, the 215 blue nodes are removed from the group. This means that these actors form the peripheral layer of the network, having weak relationships to the network as a whole. The higher the value of *k*, the more condensed the k-core group and the stronger the relationships its members have with their groups. Twenty-seven organizations lie in the most inner core with high cohesion – *k = 5*. Noticeably, all of the k-plex co-members and 15 of the 21 clique co-members belong to this most inner group.



Note: Blue nodes: k = 1 Yellow nodes: k = 2 Orange nodes: k = 3

Red nodes: k = 4 Green nodes: k = 5

Figure 16: K-core groups in the research network

4.3.4. Line-robust groups: Lambda set analysis

In previous sections, robust groups have been identified by their direct connections. This section investigates robust structure based on indirect connections through the concept of line connectivity, as introduced in chapter three.

Results from the lambda set function in UCINET show that the research network has 18 levels of line connectivity, ranging from 1 to 22. These 18 groups are inclusive of each other; that is, the lower groups encompass the higher groups. Table 14 presents the nine highest groups of line robustness, ranging from level 11 to level 22. The highest group includes two farms, B041 and B042, with line connectivity levels of 22. This means there are 22 different ways to connect B041 with B042, even though these two organizations are not directly connected in the network. When analyzing a decreased level of line connectivity, this subgroup will become larger and, clearly, still contain all the actors in the higher level groups.

Table 14: Line-robust groups of the research network

Line connectivity level	22	19	18	16	15	14	13	12	11
	B041	B041	B041	B041	B041	B041	B041	B041	B041
	B042	B042	B042	B042	B042	B042	B042	B042	B042
		A242	A242	A242	A242	A242	A242	A242	A242
		B009	B009	B009	B009	B009	B009	B009	B009
		B015	B015	B015	B015	B015	B015	B015	B015
		B033	B033	B033	B033	B033	B033	B033	B033
			B037	B037	B037	B037	B037	B037	B037
				B003	B003	B003	B003	B003	B003
				B039	B039	B039	B039	B039	B039
					B035	B035	B035	B035	B035
					B040	B040	B040	B040	B040
						B018	B018	B018	B018
							A193	A193	A193
								A343	A343
								B008	B008
								B038	B038
									B014
									B043

4.3.5. Findings from group-level analysis results

Group-level analysis has been conducted using several different tools to examine the robust structure of the network in terms of cohesiveness and line connectivity. Different types of cohesive groups have been investigated to study how connections are distributed and concentrated into special groups. These groups include cliques, k-plexes and k-cores. Line-robust groups have been then put forward to study levels of robustness against the removal of ties.

The analysis illustrates how network connections are concentrated into a cluster of 43 cliques with 42 members. The connection of each organization to its group is difficult to break if any relationship or other node is removed. As connections are distributed densely in the clique cluster, it is highly likely that a large amount of information and resources is frequently passed across the group. This cluster, therefore, is a robust and cohesive group in which the flows that run through organizations are faster and more efficient than for the remaining part of the network. The cluster might therefore be a solid foundation on which to develop a strategic alliance in the network.

Many researchers have confirmed that actors who mutually join in more cliques will have stronger relationships and be more central in their clique cluster (Borgatti et al., 2013; Hanneman, 2005; Wasserman & Faust, 1994). The clique analysis shows that certain organizations have special positions in the clique cluster. In this research network, the most remarkable organization is farm service provider B003, which joins the highest number of cliques and thus plays a central role in transferring information and resources between cliques. The district government agent A242 and farms B041 and B042 are also important in this sense. The agent A242 and veterinary clinic B046 play a special bridging role, as without them several cliques will be separated from their large cluster. Considering the clique cluster alone, these two organizations are fragile spots for flows running through clique members. It is interesting to note that organizations that present in cliques are almost always not aware of their positions in the most dense groups of the network.

Like the clique, the k-plex is a type of cohesive group that can withstand disruption. The analysis shows a k-plex cluster of 12 organizations. If a disruption happens to any specific node or relation, the k-plex cluster will sustain connections to all of the remaining members. K-plex co-members are important organizations with high potential to influence other groups' members, to disseminate information and knowledge and to coordinate joint management practices; for example, a risk management plan. Hence, they could strengthen the relationship within this cluster by homogenizing mutual understanding, knowledge and management practices among members.

Regarding k-core analysis, the results show that the research network is divided into five clear, core-peripheral layers. These subsets are inclusive of each other, where connections are condensed in the most inner group. The result of 215 nodes with the lowest *k* value is comparable to the results from the network connectivity analysis with 215 peripheral nodes (i.e., blue nodes in Figure 12); while actors whose core-ness from two to five are the 107 members of the bi-component. The most inner group with 27 members plays a foundation role for important actors to embed in. This group contains a majority of the clique and k-plex co-members.

Another focus of group-level analysis is line-robust groups in which members have strong relationships against disruptions. The strong relationship between two organizations in this analysis is not necessary a direct connection but rather its durability when lines or nodes on paths between them are destroyed. The analysis shows that two farms, B041 and B042, have the strongest link in this sense. Hence, information and resources flows between them are robust and resilient. It is remarkable that several collections of organizations in these high line-connectivity groups operate the same functions in the supply chain. So, even though they are competitors in supplying products or services, they can also be substitute options for maintaining information or material flows in case of disruption.

4.4. Node-level analysis

Node-level analysis will discover the positional importance of each member that embeds in the network. The aim of this analysis is to identify the key players of the network as opposed to, for example, potential influencers or information controllers. This section will include two categories of measures; centrality and reachability.

4.4.1. Centrality measures

This section will explore an appropriate way to use centrality measures (i.e., degree, eigenvector, closeness and betweenness centrality) to assess an actor's importance in the research network. Considering the significance of these measures for the network, it is most appropriate to use eigenvector, closeness and betweenness centrality for this research dataset. As only around 15 percent of the network population was interviewed, degree centrality seems to bias to actual interviewees rather than those who were only mentioned by interviewees. It is noticeable that even though degree centrality is not used to assess the importance of individuals in the network, it is still useful as a foundation or supplement indicator for other analysis tools (e.g., network shape analysis).

In this analysis, eigenvector centrality is considered as the main criterion to rank actor importance. The reason is that the eigenvector measure defines an actor's power by investigating the power of the actor and its partners, paying more attention to structural patterns of the whole network rather than looking only at local characteristics, such as degree. Closeness centrality is used to characterize distance of each actor to the remaining actors, which is helpful to determine the important actors in terms of efficient communication. Finally, betweenness shows how much an actor is involved in the linkage between any pair of nodes. This section focuses on the top 10 actors in each measure to determine the key players in the network.

Table 15 presents the top 10 actors with regard to the eigenvector metric. It can be seen from here that five out of the 10 actors are farms that raise animals or grow plants to produce agricultural products. Notably, the third highest organization is a government agent, which offers a wide range of supporting services for companies in the region. These actors are the most central nodes in the overall structure of the network as they are well connected to other well-connected nodes. Also, B003, a farm service provider, as well as A193 and A343, which are farm supply businesses, are also popular in the sense of linking to powerful actors.

Table 15: Top 10 organizations with the highest eigenvector score

ID	Type	Eigenvector
B042	Farm	0.280
B041	Farm	0.247
A242	Local government agent	0.244
B015	Farm	0.239
B046	Veterinary clinic	0.234

B009	Farm	0.214
B037	Farm	0.201
B003	Farm service provider	0.196
A193	Farm supply business	0.192
A343	Farm supply business	0.187

The closeness centrality is calculated on a "farness" index, which is the distances between one actor and all other network members. Remarkably, the government organization A242 has the lowest farness score, meaning it is the most central in terms of distances from all other members. Table 16 shows that a relatively significant gap between the two highest-closeness actors and the remaining nodes. These eight nodes have quite similar farness scores. It is interesting that the 10 organizations with the lowest farness scores are also in the top 10 organizations with the highest eigenvector score. While farms have higher score in the top 10 of eigenvector score, they are in lower ranks in the top 10 of closeness measure.

*Table 16**:** Top 10 organizations with the highest closeness score*

ID	**Type**	**Farness**
A242	Local government agent	748
B046	Veterinary clinic	769
A193	Farm supply business	823
A343	Farm supply business	836
B042	Farm	843
B015	Farm	845
B041	Farm	847
B009	Farm	859
B003	Farm service provider	869
B037	Farm	870

Table 17 presents the 10 organizations with the highest betweenness centrality. It shows that five of the 10 highest betweenness actors are also in top 10 of eigenvector and closeness centralities. This means that the five actors, A343, B037, B009, B015 and A242, have outstanding power over the network. It is notable that a café and a vet clinic also lie in high betweenness positions. In this top 10 group, the supply chain partners of the farms generally have higher betweenness than the focal farms.

Table 17: Top 10 organizations with the highest Betweenness centrality

ID	**Type**	**Betweenness**
B035	Processer and wholesaler/retailer	4889
A343	Farm supply business	4744
B038	Farm	4147
B019	Café	3865
B046	Veterinary clinic	2863
B037	Farm	2444
B009	Farm	2208
B015	Farm	2126
B050	Processer and wholesaler/retailer	1834
A242	Local government agent	1814

4.4.2. Reachability measures

This analysis at node level includes two types of tools: reachability and reach centrality. The reachability analysis shows a result in matrix type, indicating whether or not each node can reach each other in the underlying network. In the reachability matrix, the first row and column list all the nodes in the network, while the remaining cells display values of 1 or 0, meaning 'could reach' or 'could not reach', respectively. The reach centrality focuses on the power of each node to reach others in the underlying network, counting the proportion of the underlying network an actor could reach in *k* steps or less (Borgatti et al., 2013).

According to the UCINET results, all the numeric cells in the reachability matrix have "1" value, indicating that all organizations are reachable. Results from the reach centrality analysis show that all nodes can reach the whole network within six steps. This result is analogous to the 6-score diameter of the network.

Table 18 presents the 10 most powerful actors in the sense of reaching many nodes in a few steps. The criterion to rank these nodes is distance-weighted reach centrality, which is calculated on the sum of node quantities an actor can reach in *k* steps divided by *k* (Borgatti et al., 2013). All top 10 actors can reach a significantly large proportion of the network after three steps and the whole network after four steps. Remarkably, the local government agent, A242, has the most powerful position, reaching two-thirds of the network in only two steps and 95 percent of the network after the third step. Five of this top 10 are farming organizations. The remaining actors are farm suppliers, that is, A193 and A343, and services providers, B046 and B003.

Table 18: Top 10 organizations with the highest reach centrality

Unit: %

ID	Type	1 step	2 steps	3 steps	4 steps	5 steps	6 steps
A242	Local government agent	6	66	95	100	100	100
B046	Veterinary	7	62	92	100	100	100
B015	Farm	11	30	95	100	100	100
B042	Farm	10	32	95	100	100	100
A193	Farm Supply	4	55	84	100	100	100
A343	Farm Supply	4	50	86	100	100	100
B041	Farm	8	29	99	100	100	100
B009	Farm	8	31	93	100	100	100
B037	Farm	9	25	94	100	100	100
B003	Farm service provider	6	35	88	100	100	100

4.4.3. Findings from nodal analysis results

According to eigenvector centrality, the top 10 organizations are considered – five farms, one local government agent, two farm service providers and two farm supply businesses

– have the most popularity and influencing potential. The analysis results show that these key players also have the highest scores of closeness centrality. This, once again, confirms the importance of these organizations in terms of their potential to influence (i.e., high eigenvector index), and to quickly communicate and exchange resources with the remaining parts of the network (i.e., high closeness index). It is interesting to note that among these top actors, focal farms tend to have higher eigenvector scores but lower closeness index scores than the local government agent and farm suppliers.

With regard to betweenness centrality, the top 10, which includes two processers/ wholesalers/ retailers, one farm supply business, four focal farms, one café, one vet clinic and one local government agent, have high potential to control flows between organizations. Thus, they play the roles of gatekeeper or broker of information and resource flows that run through them at a relatively high frequency. It is notable that despite the small size, café B019 has a central position of controlling flows among the network. That the café lies on many important paths connecting pairs of organizations is the reason of its high fragmentation score, which has been examined previously. The fact that farm trading partners seem to have relatively higher betweenness scores indicates that the clients and vendors of these farms have considerable potential to control the flows through the network, as gatekeepers or mediators for the efficient flow of materials, information, finances and relationship.

In this analysis, five organizations present in all three top 10 ranks of centrality measures. These organizations – A343 (farm supply business), B037, B009, B015 (three farms) and A242 (local government agent) – are essential to the whole network in several aspects. Their importance has been explored in the previous analyses of fragmentation and co-membership of cohesive groups. For example, they present in those groups with high levels of line connectivity. Noticeably, the most inner group in k-core analysis consists of all 10 organizations in the top 10 ranks of eigenvector and closeness centrality, a large number of the top 10 in betweenness centrality.

Reachability analysis is able to provide understanding about characteristics at both individual and network level. For this study, reachability analysis focuses on the ability to transmit information or resources between organizations. The reachability result matches the connectedness measure in the network cohesion analysis, emphasizing that the research network is connected as a whole. This also matches the findings from network-level tools of fragmentation and component analysis. Regarding reach centrality, it is noteworthy that a large proportion of the top powerful organizations in this measure perform a focal farm function in the supply chain. They possess significant capability to pass information or resources effectively throughout the network. In addition, the local government agent A242 has a powerful position in reaching other parts of the network, which supports their functions in the region.

4.5. Simulations

In previous sections, the characteristics of the research network have been investigated to provide an in-depth understanding of the state of the network. This section will offer a modelling approach, presenting the dynamics or mechanism of the network in alternative scenarios. The simulations will demonstrate how relationships or information flows diffuse within the network, and how the network changes in the case of a disruption. Using the UCINET software, this analysis is carried out with the support of Key Player software, whose provider is that of UCINET.

4.5.1. Diffusion simulation

This section conducts diffusion simulation to demonstrate how non-material and material flows are transferred within the underlying network. Key Player software offers diffusion analysis to identify the optimal set of nodes to start diffusion; for example, disseminating a message, within a pre-determined number of steps. In this analysis, the number of sending nodes and diffusion steps are pre-defined options and depend on the intention and intuition of the researcher. The first step is finding the optimal set of nodes as a starting group to reach the largest part of the underlying network after a certain number of steps. The netdraw function in UCINET is then used to visualize how diffusion works within the network.

Table 19 summarizes the results of diffusion analysis using several different choices of sending group size and number of transmitting steps. As the analysis focuses on information flow, which is two-way exchange, it is conducted on the non-directional network. If one percent of the network (i.e., three organizations) start passing information, it takes only two steps to reach most of the network (87%), and three steps to reach the entire network. Starting with five percent of the network (i.e., 16 organizations), nearly four-fifths of the network can be reached after one step, and the whole network after the second step. The optimal number to reach the whole network after one step of disseminating information is 31 organizations, which is nearly 10 percent of the network population. It is noteworthy that the members of these optimal sets belong mainly to the top list in the reach centrality measure, but not always the highest ones. This is because the most powerful organizations in this sense might have a redundancy in terms of their influencing target. Thus, diffusion analysis focuses on the joint influence of a set of actors, instead of individual concentration as does the reach centrality analysis.

Table 19: Diffusion analysis for information exchange in the research network

Sending group size	**Number of steps**	**Proportion of network reached**	**Optimal set of nodes**
3	1	26.7%	B015 (farm), B035 (processer and wholesaler/retailer), B037 (farm)
3	2	87%	A193 (farm supply), A242 (local government agent), B042 (farm)
3	3	100%	A193 (farm supply), A242 (local government agent), B046 (veterinary) or B042 (farm) *(many sets found)*
5	1	38.2%	B015, B019, B033, B035, B037 *(many sets found)*
5	2	98.8%	A193, A242, A364, A438, B042 *(many sets found)*
16	1	77.3%	*See Appendix C*
16	2	100%	*Many sets found: see Appendix C*
31	1	100%	*Many sets found: see Appendix C*

Figure 17 simulates the way information is transmitted among the network. The chosen option is three sending nodes to reach the whole network in the shortest time; that is, three steps. The rationale behind this choice is that for other options one can quite clearly imagine how information is transferred as they only have one or two steps. The three starting organizations are farm supply business A193, local government agent A242 and farm B042, which are depicted as magenta nodes in the diagram. Although Key Player shows several optimal sets for this option, {A193, A242, B042} is chosen for simulation because this is also the optimal set in the option for two-step diffusion. The figure shows organizations that receive information from previous possessors step by step. The receivers are denoted by red nodes and organizations that have not received information are represented by blue nodes. It can be seen that after one step, not many in the network obtained the information. After the second step, however, the information reaches almost all of the network.

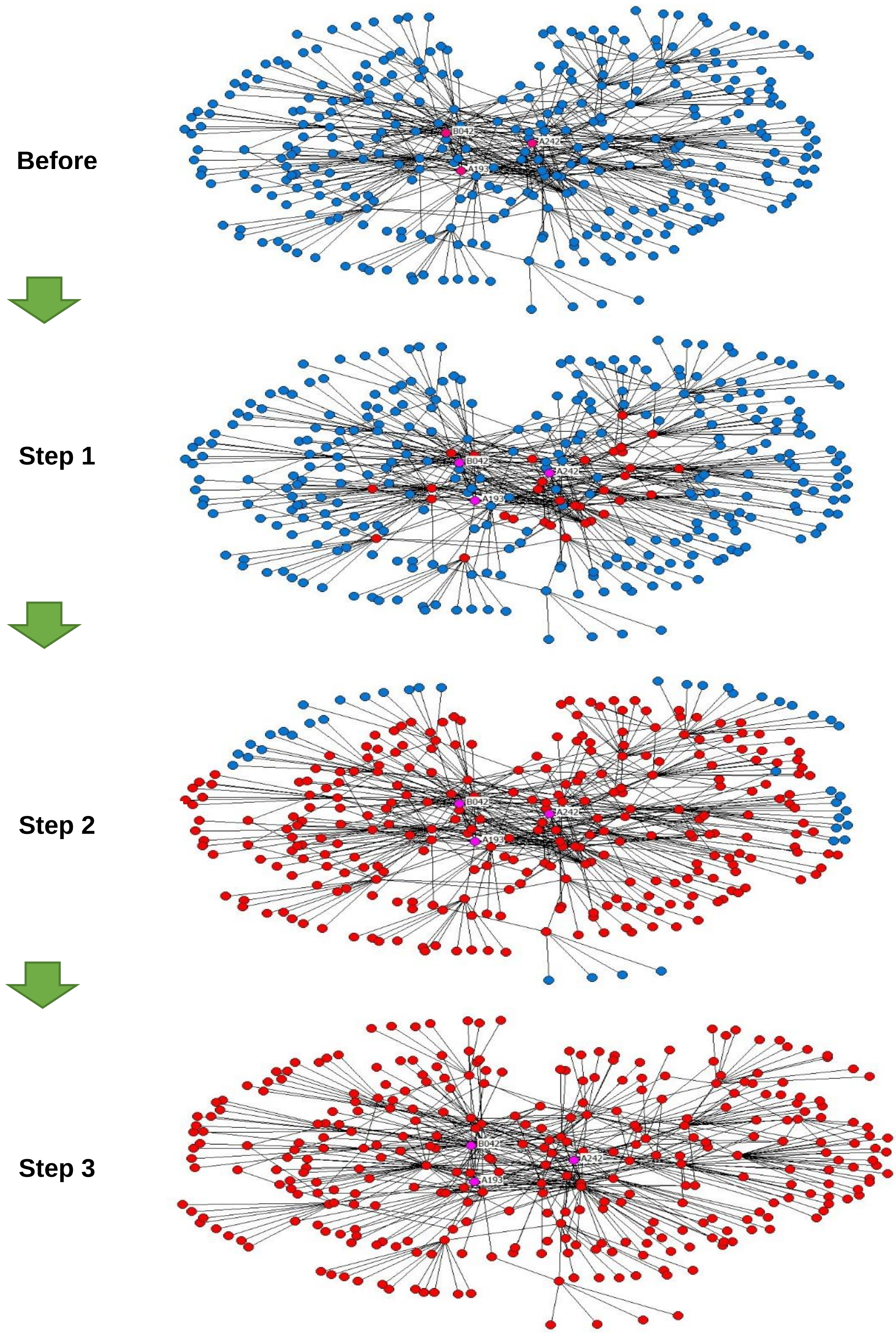


Figure 17: Simulation of information diffusion in the research network

4.5.2. Disruption simulation

The simulation is conducted to investigate changes in the underlying network when specific nodes are removed. The purpose of the analysis is to determine an optimal set of nodes whose removal will have the most serious consequences for the network. Similar to diffusion analysis, the disruption analysis function in Key Player software with the optimization algorithm is used to find the optimal group. This software provides three options to choose from for assessing the seriousness of the consequences; ‘maximize component count’, ‘maximize reciprocal distance’ and ‘maximize fragmentation’. The researcher can also choose the optimal group size.

In this study, Key Player is used to identify several optimal sets of organizations with differing pre-determined sizes. The criterion chosen to assess disruption consequence is fragmentation. As discussed in previous section, fragmentation is more sensitive than component measure in assessing a network’s connection and cohesion. Borgatti et al. (2013) emphasized that fragmentation is the typical option to use in what-if simulations to ascertain changes in the underlying network. This matches the purpose of the thesis in examining how the network is impacted by a disruption from the broad viewpoint of SCM. Netdraw in UCINET software is then used to visualize changes in the research network in response to disruptions.

Table 20 provides results extracted from disruption analysis in Key Player. The optimal set includes farm B015, café B019 and farm B037. If these organizations are removed, the network will be fragmented by one-quarter, even though they collectively account not quite one percent of the total network population. It is significant that if five percent of the network, that is, 16 organizations, are removed this community will be fragmented by nearly 90 percent. Moreover, a disruption on 10 percent of the network will break the whole network into almost independent organizations with very few connections left.

Table 20: Disruption analysis results in the research network

Group size	Network fragmentation change	Optimal set of nodes
3	25.5%	B015 (farm), B019 (café), B037 (farm)
5	37.8%	B015 (farm), B019 (café), B035 (processer and wholesaler/retailer), B036 (farm), B037 (farm) Other set also found (*See Appendix D)*
10	63.6%	*See Appendix D*
16	86.4%	*See Appendix D*
20	94.5%	*See Appendix D*
32	99.9%	*See Appendix D*

Figure 18 illustrates how the research network will change after a disruption on a targeted five percent of this network. This selected five percent is the result of running the optimization algorithm of Key Player’s disruption analysis. The 16 players involved are denoted as magenta nodes in the top diagram of Figure 18. The bottom diagram presents the network after deleting those organizations. It can be seen that the network is seriously damaged and a large number of connections lost.

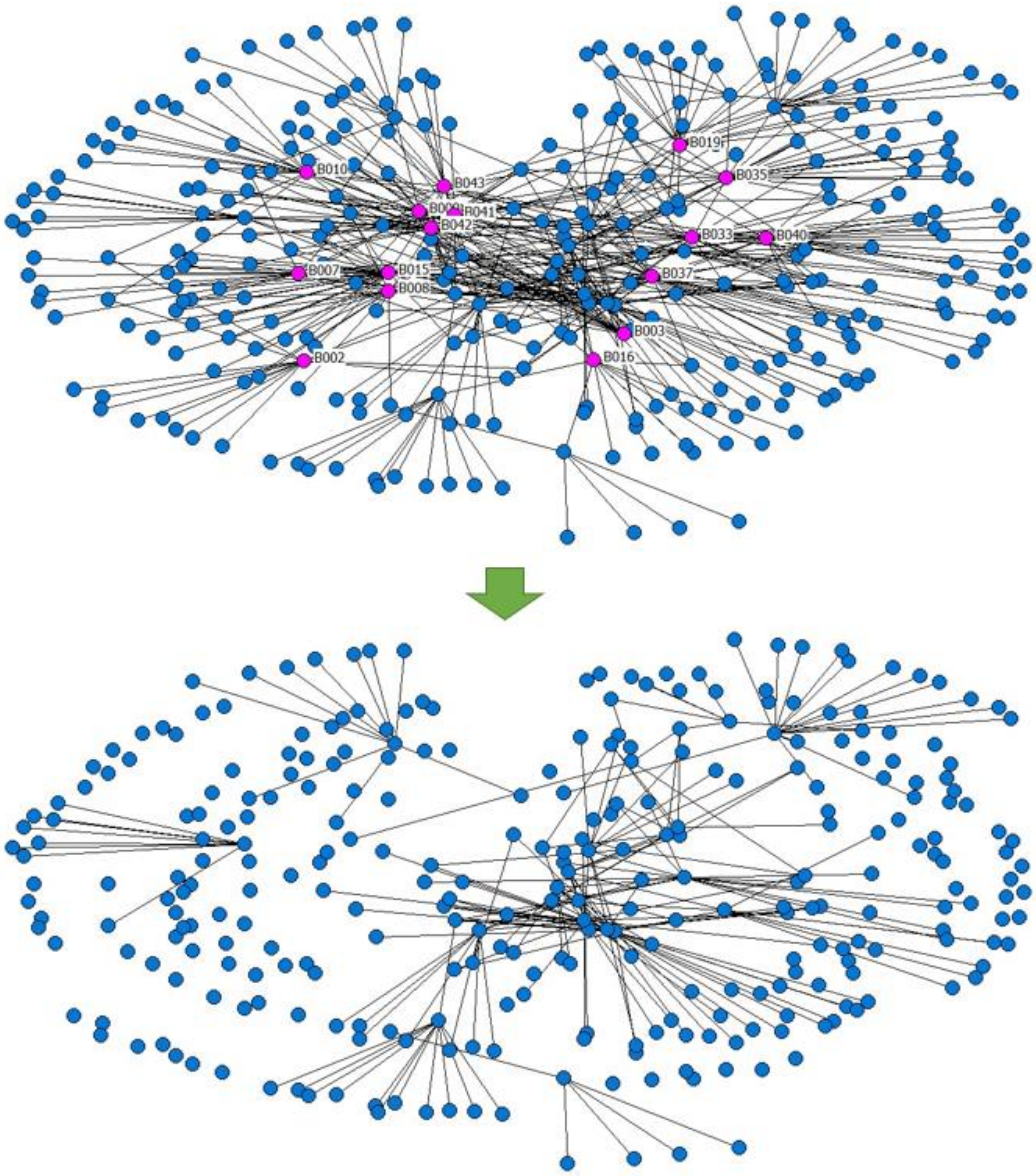


Figure 18: Simulation of disruption on five percent of the research network

4.5.3. Findings from simulations

Simulations in this research have provided worthwhile results for understanding the mechanism of the research network in information diffusion and disruption response. The diffusion analysis has visualized how information is transmitted among the network. The results demonstrate that the information flow is smooth and effective. This tool also helps to identify the optimal combinations of organizations to transfer information within the shortest time. This is the power of diffusion analysis compared to reachability analysis, even though diffusion is based on the concept of reachability.

A second useful technique is disruption analysis, which is a what-if simulation, based on a scenario where a disruption occurs, leading to a closing down of some organizations. The result indicates the importance of specific nodes, which might lead to a serious separation in the network if they shut down. If the most vulnerable one percent of this network closed down, the network would be impacted by one-fourth. These three organizations are also the three cut-points with the highest node-level fragmentation indices as has been previously analyzed. The analysis has also discovered that closing down a certain 10 percent of the network will ruin the connectedness of the whole network. This significantly serious consequence indicates that network connectedness depends hugely on a small specific part of it. This matches the previous findings that network connections are not equally distributed, but more concentrated and depend on certain organizations more than others.

4.6. Summary of findings

This section will attempt to interpret findings, relating them to aspects of resilience. Using different ways to slice the data for analysis, SNA tools indicate interdependencies, information or resource flows, cooperation between organizations and the problem-solving ability of the network. A systematic review of the analyses will be conducted to see how different SNA tools are applied to investigate network properties, as well as to find an association between those properties and elements of resilience.

4.6.1. Network-level analysis findings

The tool of network cohesion analysis is a helpful starting point to explore network properties thanks to its ability to capture important general characteristics. Network cohesion analysis includes many different measures, of which selected key metrics are summarized in Table 21 as linked to resilience attributes.

The analysis demonstrated that average degree index can imply the richness of an organization's business relationships in the network. In this sense, the mean of degree centrality score of the primary organizations is a complementary measure of how many relationships an entity has. As an inter-organizational relationship is the channel for a firm to exchange information, knowledge or other resources with another organization, the more opportunities to connect with other members the more likely is supply chain visibility. As average degree measure is calculated on actors and their relations present in the underlying network, the index might not reflect the actual richness of an organization's relationships if the underlying network does not involve either all the relationships of each actor or all the actors with which each node has relationships. In other words, average degree focuses only on the richness of relationships per organization, which presented in the underlying network.

This research confirmed the importance of density index in providing an overview of the level of connections in the underlying network. This is usually used as a complementary metric for average degree. The relatively high density result in this research suggests that the research network is complex and might contribute to the severity of disruptions (Craighead et al., 2007). This is truly justified here through analysis results at group and network level, which also confirm the network's complexity and vulnerability to disruptions. At this point, density can assist to partly understand disruption adaptation in resilience. On the other hand, the relatively dense feature indicates a good chance that organizations can cooperate with others for information and resource exchange and thus speed up the information flow. This could improve the visibility of the network. Density is also typically used for comparing characteristics between different networks. However, although density is a simple index used to characterize network connections in general, it cannot unveil anything about connection distribution.

The measures of connectedness and fragmentation are, then, useful to explore the connections distribution in the network; that is, the actors link together as a whole or separate into disconnected groups. Visibility is more likely to be improved if the network has high connectedness, a feature that might be a positive signal for a network in disruption response because the necessary information, knowledge and resources can be favourably transmitted throughout the network.

Average distance and diameter imply arrival time (Borgatti et al., 2013) and quality of information or resource flows. These are considered complementary measures to the above connectedness index. While connectedness depicts the proportion of the network to be reached, average distance and diameter show how long and how distorted knowledge or resources move within the network. When the information is transferred over a short distance, the arrival time will be shortened and the quality of information better. Considering SCRes, these measures could, therefore, examine the flows of knowledge or necessary resources related to risk management and disturbance response; whereby contribute to visibility and agility.

Table 21: Interpretations of network cohesion measures

Measure	Interpretation	Related SCRes element
Average degree	Richness of relationship of members	Visibility
Density	Level of connections or cooperation among the network	Visibility; Adaptation
Connectedness	Reachability of information or resources flows	Visibility; Adaptation
Fragmentation	Same interpretation as the connectedness	Visibility; Adaptation
Average distance	Speed and quality of information or resource flows in the network	Visibility; Agility
Diameter	The longest time for information or resources to reach the whole network	Agility

After exploring general network characteristics, it is necessary to investigate network shape or configuration. Degree centralization is one of the common approaches for this purpose. It captures how the network is concentrated into one single member, as well as the extent to which the underlying network resembles a star-shaped typology. Degree centralization provides a broad feature of organizational connections equality in the network. Many researchers have concluded that network typology has a significant impact on network resilience and its problem-solving ability which relates to adaptation in resilience (Borgatti et al., 2013; Day, 2014). It should be noted that an absolute figure of the degree centralization metric is quite difficult to assess as it depends on the network size.

Component analysis is simple and clear in this research. It provides an overview of the network structure, that is how the network is separated into disconnected areas. The level of network separation clearly impacts the information flow and thus the visibility of the supply chain. Component analysis is also important from which to develop plans to spread information or mobilize resources for the purpose of resilience building and disruptions response.

This research demonstrated that connectivity analysis is an interesting approach, offering several different ways to explore how actors are connected via other nodes or lines. This analysis could be used to investigate how robust the whole network is, as well as to identify vulnerable parts of the network. Another helpful way is line-robust group analysis, which will be discussed in the summary of group-level analysis. The network-level analysis is about identifying cut-points or bridges that are the weak “spots” of the network. This analysis suggests ideas on the vulnerability and dependency of the network for certain members or relationships. The findings from these analyses help in the construction of a supply chain vulnerability map and emergency plans to ensure the wholeness of the underlying network when disruptions happen, accordingly related to anticipation in SCRes.

Fragmentation analysis is also a powerful tool at both node and network level, as well as a foundation for other analysis tools. Node-level fragmentation depicts the importance of the actor’s presence to network connectedness. Thus, it is useful to enhance anticipation with the knowledge of organization importance, and to explore the changes in network interconnectedness against disruptions in each organization. At network level, in terms of evaluating network connectedness and cohesion, the fragmentation index is more sensitive than measures of network density or component, especially for large networks (Borgatti et al., 2013). While the component analysis unveils how many separated parts the network has and how they position in the network map, fragmentation analysis provides a complementary approach to understand the level of separation between pairs of actors. Another typical application of this measure is to investigate how a network changes in reality, in longitudinal studies or in what-if simulations.

4.6.2. Group-level analysis findings

The set of group-level tools is helpful in determining the different sub-structures of the network that are cohesive with intense business relations or robust to withstand disturbances. In other words, group-level analysis tools can offer insights into how relationships in the supply network are distributed through distinct and complementary viewpoints. This is summarized in Table 22.

Cliques are cohesive groups where connections are dense compared to the overall distribution of the network. The purpose of this approach is to evaluate structure and zoom in on intensely dense areas. These areas could be more robust in the case of disruptions in some organizations or relationships (Christopher & Peck, 2004). The robustness of subgroups is an important feature of resilience. Also, robustness can be extended to larger clusters in which several cliques are connected via co-members. As business relationships between members of a cluster are relatively intense with a high level of relational mutuality, material and non-material flows are potentially exchanged and transferred within the cluster effectively and efficiently. Such a cluster may therefore be a good base on which to develop a core strategic network alliance against disaster. For resilience strategies, this advantage might support the two attributes of anticipation and adaptation. The former is enhanced by constructing a joint risk management plan, continuity planning or developing situation awareness for such a potential alliance. Adaptation here relates to the benefits from quickly passing emergency information or knowledge, effective collaboration against disruption or sharing risk management practices.

Clique co-membership plays a notable role in network resilience. Organizations that lie in the overlapping area of these cohesive subgroups usually have a huge potential to influence other clique members. In the pre-disruption and post-disruption phases, these co-members are important points in the network for sharing knowledge and building joint risk management plans and a risk management culture. In the case of a disruption, requiring fast information dissemination and quick responses, these actors may be vital for passing on information or knowledge, and also as coordinators in disruption response plans.

Besides clique analysis, k-plex is an alternative and complementary tool to ascertain the structure of robust groups in the network. Because the criterion to define a clique is too strict, a clique size is usually small, as seen from the clique analysis of this research where the network cliques have three members only. This three-member clique itself is difficult to interpret for a valuable insight. K-plex analysis can therefore offer a different picture of the robust sub-structure of a network, which is larger than a clique size yet still has high potential for cohesiveness. K-plexes might possess good capability to identify and deal with problems (Hanneman, 2005). This is because k-plex members tend to have more ties and stronger connections with members than outsiders. Also, the connection distribution within a k-plex is relatively equal, which has the advantage of homogenizing mutual understanding, knowledge and management practices among members, helping to strengthen k-plex internal relationships for a robust group.

K-core analysis allows researchers to investigate the network's connections distribution according to a core-peripheral range. This analysis can provide an insight into peripheral layers as well as the core group, offering ideas of where to put more efforts to develop SCRes. K-core analysis could be used to eliminate peripheral layers, supporting further study on network attributes. Thus, its results can help in developing plans for resilience enhancement in the preparation phase. The most core group with the highest value of *k* is usually larger than a clique or k-plex; and also offer an alternative way to determine an intensely connected community of organizations, which might work in its favour for fast communication and response in the case of an adverse event.

Regarding line-robust group analysis, the robustness feature of a subgroup is seen through the ability of the group to retain connections between its members in the case of line removal. This is an important feature to demonstrate the robustness of a network structure. The findings here help to not only reveal the robustness of the structure in terms of relationship disruption (Wasserman & Faust, 1994), but also to identify substitute organizations and back-up relationship flows to transfer information or resources. This is important for maintaining linkages between organizations in responding to disruptions.

Table 22: Interpretations by group-level analysis tools

<table>
<tr><th>Tool</th><th>Potential interpretation of results</th><th>Related SCRes element</th></tr>
<tr><td>Clique analysis</td><td rowspan="3">- Different ways to investigate distribution of business relations
- Robust groups with intense connections
- Potential collaborative alliance
- Special “brokerage” organizations</td><td rowspan="3">Anticipation; Visibility; Agility; Robustness; Adaptation</td></tr>
<tr><td>K-plex analysis</td></tr>
<tr><td>K-core analysis</td></tr>
<tr><td>Line-robust group analysis</td><td>- Robustness in relationships flow
- Substitute organizations</td><td>Robustness; Adaptation</td></tr>
</table>

4.6.3. Node-level analysis findings

Centrality measures analysis is a useful tool for actor-level research to identify key players of the underlying network from different viewpoints. Several measures have been proposed by authors in this area. This research explores some fundamental measures for the purpose of identifying important organizations. They are eigenvector, closeness and betweenness centrality. Degree centrality was also investigated, but used as a supporting metric for other analysis tools.

Eigenvector centrality can be interpreted as a measure for popular and powerful influencers in the research network. It is one of only a few nodal metrics that can capture nodal position in the network structure globally rather than locally. Some researchers argue that this measure indicates a node’s popularity only and propose another measure, namely beta centrality, to capture the potential influence of actors (Borgatti et al., 2013). The problem, however, is that beta centrality is a combined measure of eigenvector and degree centrality which is relatively biased in this case study. Also, beta value is usually arbitrary. Eigenvector centrality considers a node powerful if it has good connections with other powerful actors. Thus, this research proposes to use eigenvector for both popularity and influencing power, supporting building anticipation strategies, agility and adaptability. One limitation of this measure is that, because of its formulation, it could be misleading when applied to a disconnected network.

Closeness centrality is a supplementary metric for the eigenvector measure in terms of influencing power. It measures how fast something can be transferred, such as information, to all other organizations in the network. Note that this metric is problematic in disconnected graphs as distance cannot be calculated for unreachable pairs of actors. Together with eigenvector centrality, closeness centrality can uncover popular and powerful influencers, contributing to visibility, agility, anticipation and adaptation in resilience. The first two aspects are beneficial thanks to the way powerful influencers transfer information and impact on other organizations’ responses to change. The last two elements might be impacted as critical actors have great opportunities to exert their risk management practices and knowledge on others.

Betweenness centrality explores critical members in the network in a different sense. This deals with the role of “controller” or “filter” situated on the paths that connect other organizations (Wasserman & Faust, 1994). Key organizations in this favourable position require considerations as they can impact positively or negatively on information or resources flows within the network. In other words, they have the power to filter information to make flows either more effective or more distorted, depending on their capability and intention. Thus, betweenness centrality can support increased visibility and agility.

Examining the reachability of actors in a network is beneficial to studying the ability of information exchanged or resources mobilized in the network. This analysis offers a natural metric for examining key individuals in terms of supplying materials or transmitting information or resources. It should be noted that the direction of the ties will impact on analysis results, and taking the direction into account or not depends on the research questions and purpose of the study. To examine the information and relationship flows in the network, this research considers the ties to be non-directional. The findings correspond with other analysis results on the ability of any organization to reach the whole network. One valuable application of this tool is determining how much each organization can diffuse information to others at a certain time. It, hence, refers to the visibility and agility aspects of resilience.

4.6.4. Simulation findings

As well as providing tools for understanding network characteristics, SNA is a useful method because of its ability to allow researchers to conduct simulations. The what-if simulation is one of the most powerful tools for insights into the research network mechanism. Two types of simulations in this research contain diffusion analysis; one to illustrate flows within the network, and a disruption analysis to evaluate network changes in response to shocks.

The diffusion simulation helps examine how the network transmits information or knowledge for the purpose of developing resilience. Understanding how different flows are disseminated within the network could be advantageous to enhance situation awareness, and control information and knowledge management. Importantly, this tool also supports the identification of optimal sets of actors in information spreading and influence management practices in their community. Being aware of which groups of organizations are powerful influencers and transmitters is beneficial for effectiveness and efficiency of knowledge management. For a better understanding of these issues, this tool could be used in combination with other techniques, such as connectivity analysis, co-memberships of robust groups or centrality and reachability measures. In general, the potential insights from this analysis are valuable for planning effective business continuity strategies and risk management projects, developing SCRM culture and synchronized SCRes practices, as well as understanding how visible and responsive the network is.

Disruption simulation is carried out to illustrate how the network structure responds to a crisis. Such simulation helps researchers to understand the network change in the case of disruptions, and to build strategies and emergency plans to deal with this. It is also helpful in determining the set of members who will be the most vulnerable part of the network when facing disruption. Importantly, this understanding will enable the development of SCRes strategies with the most appropriate solutions to protect network connections when disruptions happens, and to build a resilient network as a whole. This suggests it is necessary to focus on these optimal sets to develop joint risk management plans and prioritize resources to protect these organizations in such emergencies. Disruption simulation also supports knowledge management for supply chains by providing a valuable material for education and training. This modeling tool, therefore, helps to examine robustness and adaptation, as well as to develop knowledge management in anticipation of SCRes.

In summary, this chapter illustrates how essential SNA tools are for evaluating the resilience of a network. General information about the case study has been provided at the beginning of the chapter for a mutual understanding of the research network. An analysis of network cohesion has been then applied to provide an overall picture of network characteristics. Next, more in-depth analyses have been explored, moving from network level to group level and individual level, followed by a powerful simulation analysis. This demonstrates that SNA can be used at any level of analysis to investigate the connections between organizations, structural properties, position and roles of organizations and network dynamics. Through these analyses, characteristics of network interconnectedness, such as network density, separation degree and connectivity, have been investigated using various tools at network level. The network robustness and vulnerability have been examined using analyses on network configuration, special sub-structures and cohesive groups. Key players in the network have also been identified based on differing criteria. Importantly, simulations have investigated changes in the network given various scenarios relating to resilience. Various analysis tools play different role to investigate the network properties and resilience, with unique and complementary functions. Further discussions and critique on the applicability of SNA will be considered in the next chapter.

CHAPTER FIVE: DISCUSSIONS

This chapter will discuss the findings from the previous chapter on analysis and results. The main purpose of this chapter is to finalize the research model and fit it into the current body of research. The research model will be developed from the findings in chapter four, summarizing the applicability of SNA in examining SCRes. These research findings, according to each SCRes attribute, will then be compared with previous studies.

5.1. Final framework of SNA applications to SCRes

The final research model on applications of SNA to SCRes assessment will be explained in this section. The model is based on the analysis findings, and is a more detailed version of the research framework proposed in chapter two. It is summarized in Figure 19 as below.

SCRes Elements / Network properties	Anticipation	Visibility	Agility	Robustness	Adaptation
Interconnectedness	Connectivity analysis Simulations	Network cohesion Simulations Fragmentati-on analysis	Network cohesion Simulations	Connectivity analysis Simulations	Network cohesion Simulations
Network structure	Group-level analysis set	Group-level analysis set Component analysis	Group-level analysis set	Group-level analysis set Connectivity analysis	Group-level analysis set Network shape
Actor criticality	Centrality measures Fragmentati-on analysis	Centrality measures Reachability measures	Centrality measures Reachability measures		Centrality measures Fragmentati-on analysis

Figure 19: Applications of SNA tools to SCRes investigation

The figure illustrates how SNA tools can bridge the gaps between network properties (left-hand column) and SCRes attributes (top row). The coloured boxes within the body of the figure present the different tools. Generally, the green boxes refer to network-level analysis tools, the pink boxes the group-level tools, the yellow boxes the analysis tools at individual level and the orange the simulation method. It is noted that the fragmentation tool can be applied at both network and node level, as stated in the previous chapter.

Figure 19 shows that SNA can be used to ascertain all three categories of network properties (i.e., interconnectedness, network structure and actor criticality), and relate them to various SCRes elements, including anticipation, visibility, agility, robustness and adaptation. First, the interconnectedness of a network refers to the level of connections and how they form a whole connected population. This property impacts all five afore-mentioned aspects of SCRes, which can be explained using SNA tools at network level; that is, network cohesion, connectivity analysis, fragmentation analysis and simulations. Second, network structure, which means typology, configuration and sub-structure, can also influence the anticipation, visibility, agility, robustness and adaptation of resilience. At this point, analysis both at network and group levels can examine the relationship of these attributes. The network-level tools, such as component and network shape analyses, help to explore network typology and configuration, while group-level tools are useful to explore network sub-structures. Finally, the importance of actors based on their position and connection characteristics can be examined using centrality, reachability and fragmentation measures, helping to develop aspects of anticipation, visibility, agility and adaptation. This section has synthesized different appropriate SNA tools used in this study to investigate SCRes. The next section will discuss the findings of individual aspects of resilience in the context of the current literature.

5.2. SNA of anticipation

This study demonstrates how SNA can be applied to the attribute of anticipation in SCRes. The importance of the ability of the supply chain to anticipate risks, potential changes and unforeseen events has been confirmed by many previous researchers (Ali et al., 2017). They have considered anticipation using different concepts; including situation awareness (Vargo & Seville, 2011), continuity and preparedness planning and forecasting (Pettit et al., 2013), supply chain risk management planning (Blackhurst et al., 2011) and warning strategies (Craighead et al., 2007). This thesis has systematically reviewed the SCRes research and uses a comprehensive concept of anticipation drawn from previous concepts. Relatively few studies focus on how anticipation of resilience might be influenced or determined by connections within the supply network. Filling this gap, this research contributes to the limited pool of research on the relationship between network properties and anticipation in SCRes.

In this study, SNA has been applied to investigate the network property of interconnectedness and how it impacts on the anticipation aspect of SCRes. Many researchers have emphasized interconnectedness as an important factor in supply chain performance (Bellamy et al., 2014; Braziotis et al., 2013). According to the thesis findings, the link between connectedness of a network and anticipation can be investigated using the tools of connectivity analysis and simulations. These SNA tools assist in supply chain vulnerability mapping and emergencies planning, and shed light on the mechanism of supply chain flows, helping to build joint risk management plans. The studies of Pettit et al. (2010) and Pettit et al. (2013) are two of a few research studies that explore the association between supply chain connectivity, vulnerability and firm's resilience using system theory. This thesis extends their work on SCRes from firm level to network level, considering the supply chain as a CAS.

The applicability of SNA in evaluating network structure characteristics has been also illustrated to increase the anticipation capability of SCRes. Through the analysis of cohesive groups, the findings offer an understanding of how trading relationships are distributed throughout the network and which areas have potential for supply chain alliance and cooperation development, to help build a joint SCRes plan. The finding of the criticality of network structure corroborates the ideas of Christopher and Peck (2004), who emphasized supply chain engineering as a key factor in building a resilient supply chain. This thesis continues their theoretical study with a quantitative approach to explore empirically how important the network structure is to SCRes. In line with their proposition on responsibility and leadership in supply chain risk management, this thesis also studied the property of actor criticality using SNA to identify key players, potential influencers, leaders or fragile 'spots' for business continuity plans or joint risk management strategies.

In this study, SNA is used to study anticipation in terms of mapping of supply chain vulnerabilities, building joint risk management plans, providing knowledge of the network characteristics for education and training, as well as developing warning and emergency strategies. However, this analysis neglects some elements of anticipation, such as, sensing and interpreting events and building security in the supply chain, which are also important to enhance the ability to anticipate in preparedness stage of SCRes (Ali et al., 2017; Manuj & Mentzer, 2008; Melnyk et al., 2014). In addition, the argument of favourable groups for planning joint risk management and alliance is based on the current transactional relationships between organizations, yet does not consider their willingness to collaborate or the capability of each entity.

In short, this study offers a different approach from previous research to the study of anticipation and its related network characteristics. The thesis argues that SNA is a quantitative method applicable to empirical data. It complements the pool of other methods for studying anticipation in SCRes, alongside approaches such as conceptual or theoretical study (Christopher & Peck, 2004; Pettit et al., 2010), case studies with systems theory and the resource-based view (Blackhurst et al., 2011) and the qualitative multiple case study (Vargo & Seville, 2011).

5.3. SNA of visibility

Study findings indicate that SNA is also a powerful method to evaluate visibility. Visibility in the supply chain has been recognized as a fundamental element of resilience in many research studies from the early development of the concept of SCRes (Christopher & Peck, 2004). Visibility might consist of various concepts; for example, information sharing (Jüttner et al., 2003; Vroegindewey & Hodbod, 2018), supply chain transparency through integrated systems (Christopher & Peck, 2004) and information exchange and information technology (Pettit et al., 2010). This study adopts the broader concept from Brandon-Jones et al. (2014), who suggested that visibility is a capability at supply chain level to capture information flows. Despite the importance of this factor, little attention has been paid to explaining how network properties influence resilience via visibility. This study answers this question using SNA, concluding that all three aspects of network properties, network connectedness, structure and actor critical, impact on the visibility of SCRes.

This research has demonstrated the method of using SNA to explain how the characteristics of network connections impacts on visibility. The analysis tools of network cohesion and fragmentation can be applied to understand the extent to which information and knowledge can flow smoothly and without interruption across the supply chain network. Then, using diffusion simulation, the research demonstrates how information flows, and therefore, which parts of the supply chain, potentially have high visibility or considerable power to disseminate information. In the previous literature, only a few studies have attempted to research the relationship between network connectedness and visibility in SCRes. Blackhurst et al. (2011) also noted this gap for future research in their case study. One noticeable study, developed by Brandon-Jones et al. (2014), focused on the influences of supply chain connectivity and information sharing to visibility, and visibility to SCRes. They undertook confirmatory factor analysis with a RBV and quantitative approach to study the supply chain visibility of manufacturing plants and their suppliers. Also an empirical study, this thesis has addressed the limitations on the lack of network data and extended Brandon-Jones et al.'s (2014) firm-level perspective of the RBV to the broad, network-level approach of the CAS lens.

This research suggests a supplementary approach to how network structure affects resilience with respect to visibility. Christopher and Peck (2004) pointed out that internal organization structure is an influencing factor for visibility in a resilient supply chain. Extending this to the inter-organizational level, Johnson et al. (2013) confirmed the importance of structural dimensions such as network ties and configuration to the visibility aspect of resilience. This qualitative study of Johnson et al. (2013) is in line with this thesis regarding the social constructionist approach and case study methodology, offering an in-depth knowledge of studied network cases and emphasizing the determinative feature of reality and relationships within a network. Compared to their studies, this thesis provides a complementary method using quantitative SNA to explore the associations between network structure and visibility. It shows that SNA can allow researchers to study network structure in different ways (e.g., components, cliques, k-plexes) and thus understand more about its complexity and impacts on visibility.

The thesis also suggests that SNA could be appropriate to explain the influence of organization criticality to visibility in the resilience of a supply network, an area that has been not clearly addressed in previous literature. From the literature review, no research that focuses on this question has been found. This thesis, then, offers an exploratory study on how the positional importance of actors in a supply network can impact on the visibility of SCRes. It shows the value of SNA analyses of centrality and reachability in addressing this question.

In summary, this thesis illustrates an appropriate approach which is quantitative and empirical, to study visibility in SCRes, extending the existing pool of the literature; for instance, the theoretical approach (Christopher & Peck, 2004; Pettit et al., 2010) and the empirical case study (Blackhurst et al., 2011; Johnson et al., 2013).

5.4. SNA of agility

The applicability of SNA to analyze agility is illustrated using all three network properties in this study. The concept of agility has been used inconsistently in previous studies. Some authors have included visibility (Christopher & Peck, 2004; Wieland & Wallenburg, 2013) whereas others have separated them in two concepts (Johnson et al., 2013; Jüttner & Maklan, 2011; Vroegindewey & Hodbod, 2018). In this research, agility is considered to be responsiveness, speed of reaction time or velocity against events, and separated from visibility.

The research presents the impact of network connectedness on agility in SCRes. This can be explored by using the SNA tools of network cohesion analysis or diffusion simulation. These powerful tools can provide interesting insights into how information, resources or reaction responses are diffused throughout the network in terms of time and mechanisms. Although the association between network connectedness and agility has similarly been confirmed by some researchers (e.g., Hohenstein et al. (2015); Johnson et al. (2013)), it has been rejected by others, such as Wieland and Wallenburg (2013) in their quantitative, empirical study with a relational view. Interestingly, this thesis shows that SNA can offer a different viewpoint, assessing agility via network connectedness.

SNA has demonstrated its ability to explore two other properties, network structure and actor criticality, as influencing factors of agility. The findings of this thesis of the impact of network structure on agility was also confirmed by Johnson et al. (2013) in their qualitative case study. This thesis, thus, contributes a quantitative approach to the set of appropriate methods of studying this issue using different ways to examine special sub-structures. The question of how organization criticality affects agility has been not studied in much detail in the past. This thesis presents the SNA method with a CAS lens to identify how powerful organizations transfer and filter information, disseminate resources, control response time and accordingly exert influence on velocity or responsiveness. The study is based on special positions and connections of organizations to interpret how network structure and actor criticality impact on agility. This, however, is just an element of agility, requiring more research on the organization capability to response quickly and to cooperate effectively with others in the case of a disruption.

It is interesting that CAS view has been also applied in a conceptual study of Vroegindewey and Hodbod (2018), who confirmed velocity as an important principle of resilience development. This thesis extends this point with an empirical study with large network data and more in-depth analyses. In general, the SNA offered here might be an appropriate method to be added to the pool of other approaches on the study of agility in SCRes, such as the conceptual and theoretical method (Christopher & Peck, 2004; Hohenstein et al., 2015; Vroegindewey & Hodbod, 2018), the qualitative case study (Johnson et al., 2013; Jüttner & Maklan, 2011) and the empirical quantitative study (Wieland & Wallenburg, 2013).

5.5. SNA of robustness

Robustness is a popular and fundamental element in previous studies on resilience, although most studies have seen robustness as separate from resilience or as a distinct aspect of SCM. This thesis uses SNA tools to examine robustness, following concept of Christopher and Peck (2004) who viewed resilience as a broader concept than robustness. The thesis shows robustness, impacted by network connectedness and structure, can be used to investigate resilience.

In this research, network connectedness is investigated through SNA, implying that it can impact on robustness. The use of disruption simulation further contributes to exploring how the supply chain copes with the shock of closing down certain organizations, and therefore robustness. The simulation approach is similar to Zhao et al.'s (2011) study, which aimed at node robustness. The thesis supplements another approach to the study of line robustness using connectivity analysis, which can assist in mapping robust groups to help withstand disruptions in business relationships. Yet the link between robustness and business connections was unable to be confirmed by Wieland and Wallenburg's (2013) quantitative empirical study, which adopted the RBV. In all, the relationship between network connectedness and robustness seems to depend on individual (real or actual) cases and on the different viewpoints of researchers**.** This thesis offers a more complete set of metrics at network level to study the association between network connectedness and robustness, extending the previous agent-based modelling works at firm-level analysis of Nair and Vidal (2011).

The thesis also shows how applicable SNA tools are for understanding the impacts of network structure on robustness. Using group-level analyses, such as cliques or k-plexes, robust areas in the supply chain network can be identified as potential groups to develop strategic alliances in terms of robustness. This finding is useful as it continues the conceptual study of Tang (2006) who emphasized the importance of supply alliance network in developing robust strategies.

5.6. SNA of adaptation

The resilience attribute of adaptation can be analyzed by SNA using all three network properties: network connectedness, network structure and actor criticality. Craighead et al.'s (2007) empirical study suggested that the characteristics of network connections, such as density or complexity, can influence on the severity of disruptions in the supply chain. This thesis continues their work by testing these associations with a large-scale dataset and extending to a simulation-based study.

The adaptability of a network against disruptions is also explained by the property of network structure. This thesis demonstrates how to use SNA to explore the structural characteristics of connection distribution and network shape. This approach is similar to the work of Kim et al. (2015), who offered a useful analytical approach based on network structural perspective and graph theory to assess how different supply network structures affect adaptation in SCRes. The thesis uses Kim et al.'s (2015) findings as a foundation to argue the influence of network shape or typology on resilience, as well as to add another approach – the set of group-level analyses. This addition offers a more in-depth understanding about network structure and how connections are distributed into cohesive groups with high adaptability.

The thesis demonstrates how important organization criticality is to network adaptation against disturbances. Using centrality measures, SNA can identify critical actors who have the power to implement risk management practices and control knowledge or information flows of the supply network in responding to disruptions. The association between actor criticality and disruption severity was studied by Craighead et al. (2007), using a multiple-method and multiple-source empirical research design. However, their study was conducted on small-scale data and with the purpose of theory building. This thesis expands their work into a large-scale network case, testing their propositions with empirical data to provide deeper insight into this issue.

Many studies focus on how adaptability supports resilience in general, rather than delving into the factors behind adaptation attribute. Studies have been conducted using different approaches, such as systems theory (Pettit et al., 2013), the resource-based view (Blackhurst et al., 2011) and CAS theory (Vroegindewey & Hodbod, 2018). As most of these studies are qualitative, this thesis offers a useful quantitative approach but still with in-depth analyses of the network. This thesis has discovered that fragmentation analysis is also a useful tool for understanding how fragile the network is in response to disruptions at certain points, which further contributes to explaining the relationship between actor criticality and adaptation.

However, the thesis does not take any data or information about actual response or changes of the research sample into consideration. The severity of supply chain disruption is assumed using simulations and fragmentation indices only. The real data about disruption severity and how a network responds to a disruption are necessary to be captured in further research, in order to complete this analysis on the association between network characteristics and adaptation.

5.7. Chapter summary

In summary, one of the most meaningful contributions of this thesis is its methodology. Within the current body of literature, which lacks much empirical study on resilience and its related network attributes, the thesis provides a useful and powerful analytical approach to this research area. While a considerable number of studies have focused on conceptualization and theory building (Ali et al., 2017; Christopher & Peck, 2004; Hohenstein et al., 2015; Tang, 2006), it is also necessary to study resilience and related issues using empirical approach. Empirical research on SCRes has been carried out in the past (Blackhurst et al., 2011; Craighead et al., 2007; Johnson et al., 2013; Jüttner & Maklan, 2011), but many of the studies are qualitative case studies, which leave a gap in the quantitative approach. The analytical approach to studying resilience is similarly limited, with a few exceptions; for example, Brandon-Jones et al. (2014); Kim et al. (2015) and Wieland and Wallenburg (2013). This thesis demonstrates how to use SNA as a quantitative method with an analytical approach, graph theory and simulations to explore SCRes, providing in-depth insights into an important subject.

The SNA approach in this thesis allows researchers to conduct study at different levels of analysis, from individual to group to network level. A large part of the extant pool of research has focused on resilience at firm level and its ego-network (Blackhurst et al., 2011; Johnson et al., 2013; Pettit et al., 2013; Wieland & Wallenburg, 2013). A plausible explanation is that organizational resilience has been considered a foundation upon which to build SCRes, and collecting and mapping network data is limited in many research studies. This thesis continues the recommended research direction of the previous literature, proposing research on an empirical network dataset. The data is sliced in different ways and analyzed at both micro and macro levels. As resilience and its related issues are network-level phenomenon, it is appropriate and more meaningful to focus on evaluating SCRes at network level. To support this focus, the lens of CAS is applied, to consider the supply chain as a complex and dynamic system, depending on the organizations themselves, inter-organizational relationships and environmental changes.

Compared to previous research, this thesis offers a more comprehensive framework to evaluate resilience attributes by exploring network properties. Other studies have confirmed various associations between resilience and network properties, such as network connectedness and anticipation, visibility and agility (Brandon-Jones et al., 2014; Hohenstein et al., 2015; Pettit et al., 2010) and network structure and visibility, agility and adaptation (Johnson et al., 2013; Kim et al., 2015). Using a CAS view, this thesis develops a framework to test these previous propositions as well as to explore new insights into associations have not yet been discovered.

The thesis focuses largely on the readiness phase of SCRes, with its related attributes of anticipation, visibility and robustness. This phase is one of the issues academic researchers have called for further study (Ali et al., 2017), as is type of disruptions another gap to which this study potentially contributes. Generally speaking, much of the current research has focused on business-as-usual disturbances, such as demand fluctuations or demand-supply mismatches, while resilience against catastrophic events has received inadequate attentions. This thesis helps filling this gap by focusing on natural disasters and closing-down disruptions.

Some weaknesses in this study analysis have been also acknowledged in this chapter. They are about the lack of considering some important elements (e.g., sensing future disturbances and supply chain security) in anticipation analysis, the need to study further the organization capabilities of responding quickly and cooperating effectively to boost the agility. Noticeably, the disruption severity and the way a network responds to a disruption in the real-world setting, which the thesis has neglected, are necessary to be studied for more understanding of the adaptation aspect. The final chapter will provide a brief conclusion and contributions of the thesis, as well as propose some directions for future research.

CHAPTER SIX: CONCLUSIONS

This final chapter will begin with a review on how the research archives its proposed objectives. Theoretical, policy and managerial implications will then be discussed in this chapter to see how this research contributes to the academic body and to the practical world. The chapter will also present the limitations of the study and propose directions for future research.

6.1. Review on research questions

The research aims at exploring how SNA is applied to the study of SCRes. Due to the shortage of existing literature on resilience from a network view, this study has strived to fill this gap, focusing on an empirical study on how network attributes affect different aspects of resilience in the agriculture sector in New Zealand. It seeks answers to key questions of how the supply chain network is structured and characterized, which SNA tools are applicable to study SCRes, and how network properties impact on SCRes.

The most valuable result from this study is the research framework, which can be used as a guideline for the application of SNA to resilience studies. The key question of *“How can SNA be applied to study the resilience of supply chains?”* has been answered in this detailed framework. It indicates that SNA is a powerful method to study SCRes regarding different elements of resilience with different levels of analysis from macro to micro. With this framework, the thesis contributes to bridge the gap between network properties and network resilience using various types of analysis tool from quantitative methods (i.e., graph theory and analytics) to qualitative elements (i.e., simulations and interpretation to synthesize the findings).

The final framework provides the answers to all the detailed research questions previously formulated. Regarding sub-question 1 of *“Which network properties of a supply chain can SNA investigate?”*, various characteristics of network interconnectedness, network structure and actor criticality have been examined by different SNA tools. The findings provide understanding of the network connections; how dense they are, which areas are considerably cohesive, how connections are distributed in the network and which members are important and have special positions

Concerning the second sub-question (i.e., *“Which tools of SNA are applicable to study which aspects of SCRes?”*), it can be said that SNA has many tools useful for studying SCRes at network, group and individual level. Remarkable tools at network level include network cohesion, network centralization, component analysis, connectivity analysis and fragmentation examination. At group level, tools include clique analysis, k-plex analysis, k-core analysis and line-robust group analysis. At individual level, SNA offers centrality and reachability measures. Additionally, simulation is a powerful tool to model mechanisms and disruption response of the network. These analytical and simulations tools are supported by graph theory to visualize the supply chain relationships and member positions.

With regard to the third sub-question of *"How do these network properties associate with these SCRes aspects?"*, three network properties have been found to impact on the SCRes aspects of anticipation, visibility, agility, robustness and adaptation. The final framework demonstrates that network interconnectedness and structure exert influence on all these five attributes of resilience, while actor criticality directly associates with four elements of anticipation, visibility, agility and adaptation. It is worth noting that network characteristics are connected and interrelated because they are all based on the inter-organizational relationships. Understanding these network properties can help build a resilient supply chain.

6.2. Research implications

This section seeks to deliver some implications and contributions of this research to the body of literature on the research topic. The most important contribution is the methodology the research has assessed. This study is beneficial to researchers who want to use SNA tools in a systematic way. It provides guidance on how to take advantage of SNA at all levels, from micro to macro, along with some fundamental metrics and techniques.

By using SNA, the research assesses the resilience of the supply network in general and the agricultural supply chain in particular. Although it does not incorporate all the useful SNA tools, it is more comprehensive than previous studies and includes some fundamental approaches to the research area of resilience.

The research also explores how network properties impact on resilience in an empirical world. Thus it helps to fill the gap between network properties and resilience attributes. With real-case data collected from a rural region, the study offers a practical view of network resilience and how to use empirical data for analysis.

This study has some policy implications. It confirms the importance of relationships between entities in a network and how relationships impact on network performance, even if those entities are not aware of this. This research could attract the attention of policymakers to consider including elements of network properties in their decision-making processes. As the framework provides a guide for investigating network characteristics and resilience, policymakers could use it to understand more about their own regional network and the mechanisms of its internal, as well as external, relationships.

Findings could be used to build SCRes plans and develop supply chain relationships from a managerial approach. Understanding the structure and characteristics of supply chain relationships, as well as how those attributes impact the SCRes, will support supply chain managers to develop appropriate strategies for a more resilient supply chain and improve supply chain performance through the development of strong relationships.

6.3. Limitations and future research

One of the limitations of this research is that it ignores several interesting SNA tools, due to constraints of time, length and scale. This leaves a gap for future studies to work on many other useful tools in the pool of SNA, such as structural hole and equivalence, not to mention other measures that fall under the tools researched in this study.

Thanks to support from the Scion project, the data source for this research is really rich. This study has not, however, exploited the full wealth of the data, which might lead to meaningful research findings in the future. One such valuable group of data are relationships that are secondary to or subsets of the transactional network; for example, communication, personal relationships and supporting willingness. Another gap in the research is the network of directional material flows. This research has focused on relationships and information flows, which are two-way, but product flow receives only a brief mention. Such promising data and information could be investigated more in the future.

The research provides a picture of the network using fixed ‘snapshots’ with cross-sectional data. However, the supply chain network is dynamic and its internal and external relationships ever-changing. This has prevented more in-depth study of the network. Hence, a longitudinal study would be helpful and appropriate for further insights into the research area.

This research has focused on the topic of resilience in SCM using SNA, which could be expanded to other potential application areas in future research. Through the power and usefulness of SNA applied in this thesis to investigate different aspects of SCRes, it is promising that SNA could be applied more broadly to study other supply chain problems, such as supply chain agility, supply chain collaboration or inter-organizational trust. Different tools of SNA may therefore be useful to a wide range of other applications to ensure value creation along the supply chain.

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Appendix A: Interview guideline

Appendix A.1: Questionnaire (a part of semi-structure interview)

Questions to be completed by the management team for the business unit.

QUESTION 1

Assume your business unit has to close down for one year due to unforeseen circumstances, how likely are the following outcomes as a result of your closure?
(Select 1 for highly unlikely and 10 for almost definitely)

Our products will be replaced by imports from another country:
1–2–3–4–5–6–7–8–9–10

Our products will be replaced by imports from another region inside NZ:
1–2–3–4–5–6–7–8–9–10

Our competition will take our market share:
1–2–3–4–5–6–7–8–9–10

The entire supply chain will shut down without us:
1–2–3–4–5–6–7–8–9–10

We are very small and our absence will not significantly affect the larger economy and supply chains in the region:
1–2–3–4–5–6–7–8–9–10

Our suppliers and customers will compensate for us and try to “help us out” as far as possible:
1–2–3–4–5–6–7–8–9–10

It will be almost impossible for us to re-initiate our business after some time of closure:
1–2–3–4–5–6–7–8–9–10

QUESTION 2

In terms of preparing for large natural unforeseen events such as earthquakes, volcanic activity, flooding, drought, heatwave etc. To what extent is your business in a state of readiness?
(Select 1 for unprepared and 10 if you feel you have done everything possible to prepare the business)

We carry additional stock and equipment to help us cope with eventualities:
1–2–3–4–5–6–7–8–9–10

We have a pot of reserved savings to help us deal with eventualities:
1–2–3–4–5–6–7–8–9–10

We have spoken to our supply chain partners about our limitations and capabilities in the case of an event:
1–2–3–4–5–6–7–8–9–10

We have comprehensive insurance:
1–2–3–4–5–6–7–8–9–10

We have developed joint risk management with our supply chain partners:
1–2–3–4–5–6–7–8–9–10

For redundancy purposes, we deliberately maintain business links with more than one service provider, especially for the critical components of the business:
1–2–3–4–5–6–7–8–9–10

We can easily obtain additional cash (or loans) from external sources, if necessary:
1–2–3–4–5–6–7–8–9–10

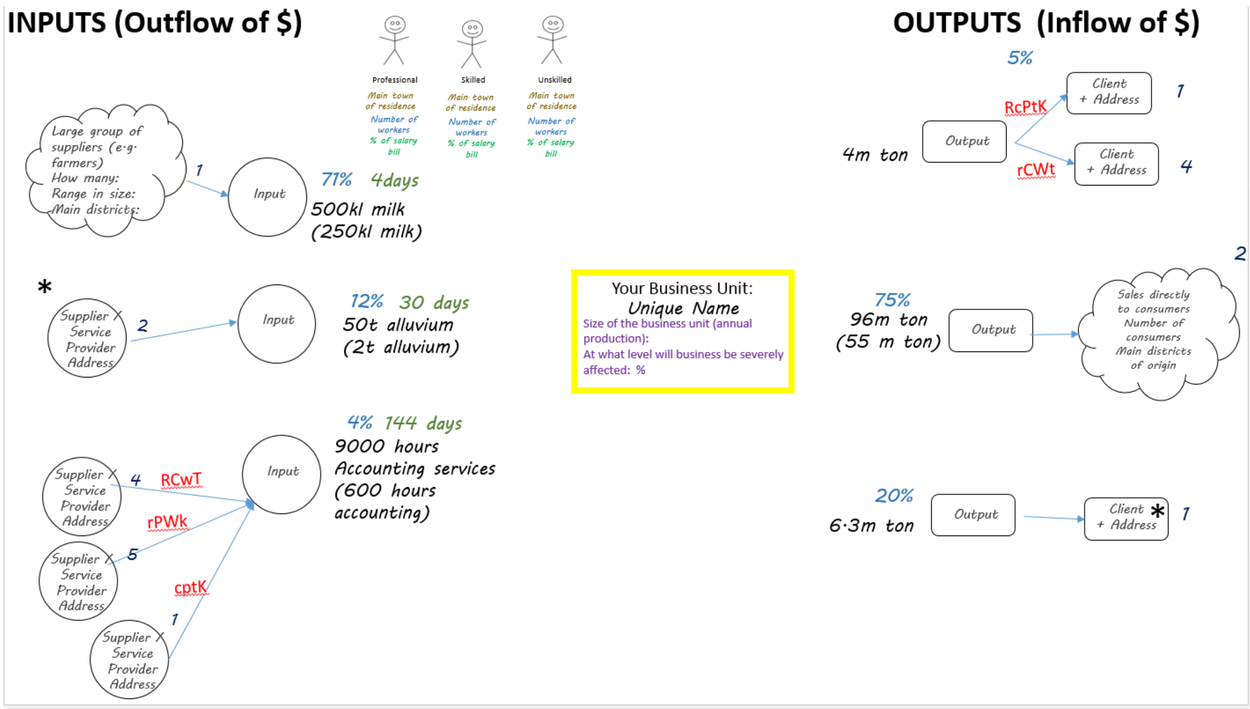
We have sufficient staff and they are are trained to do work of others who may not make it to work:
1–2–3–4–5–6–7–8–9–10

MAP OF BUSINESS CONNECTIVITY

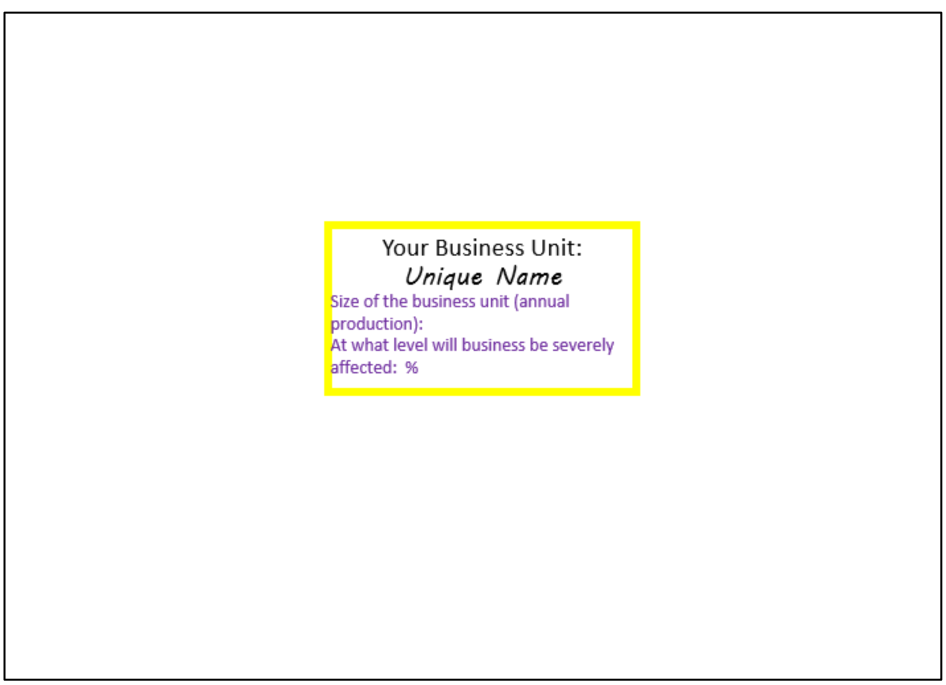
Develop a map of business connections, following the instruction of the interviewer

Appendix A.2: Guideline to develop a map of business connectivity

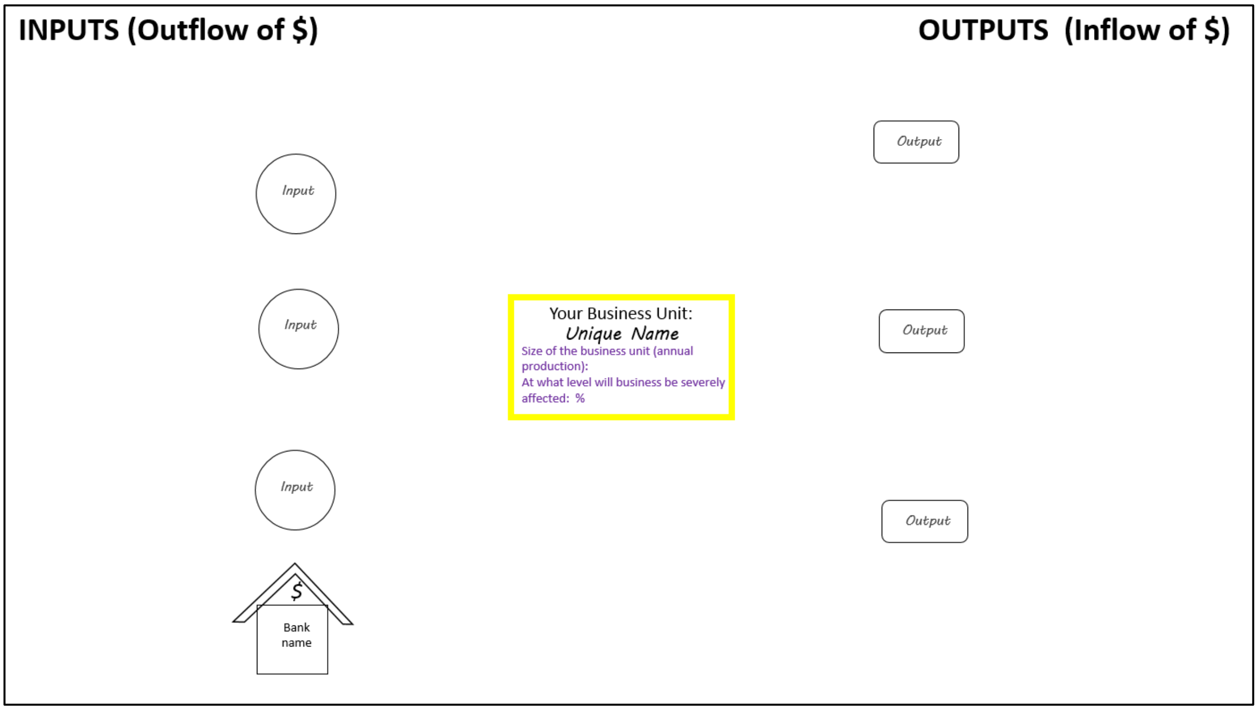
Example of the map:



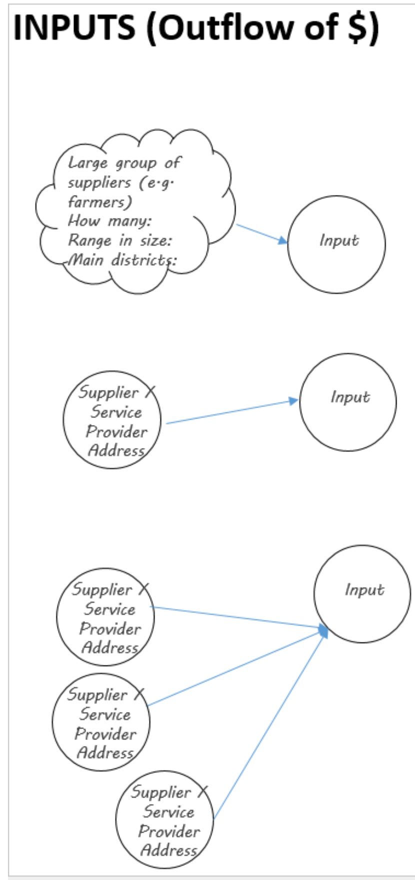
1. In the middle of a blank piece of paper place your business unit name, annual production and the minimum % of annual production at which the business could operate as normal, without being severely affected.

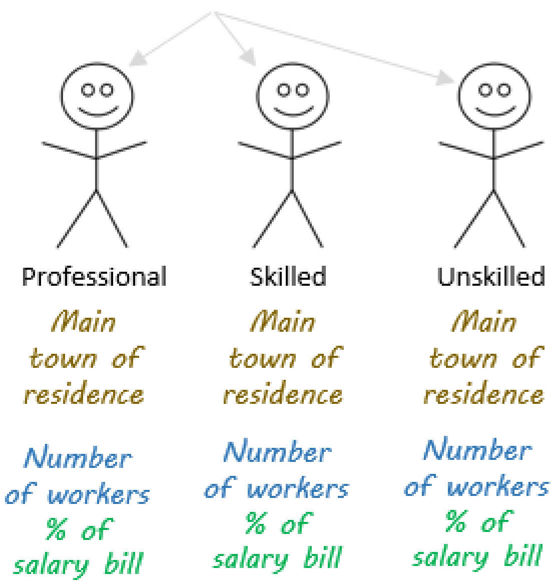


2. To the left list the major inputs to the business. To the right of your business list the major outputs of your business



3. For each of the inputs, identify to the left the major suppliers who provide this service or product to your business and their location details. If there are a large group of suppliers they can be identified as a cloud, if a cloud is used please describe the number of suppliers it represents, the range in size of those suppliers and the main districts that they are based

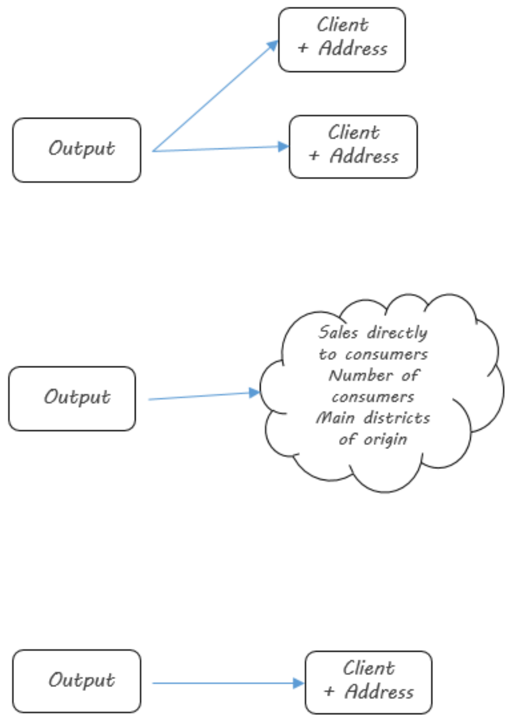




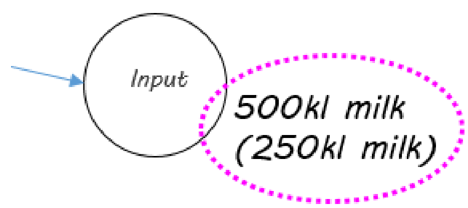
4. Include labour on the input side of the paper. Please indicate how many employees your business has categorising them as professional, skilled and unskilled workers. For each of the 3 categories indicate the % of the salary bill attributed to that group and the main area of residence of the employees

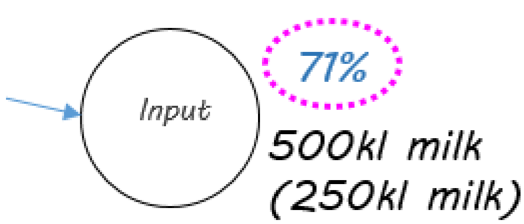
5. For each of the outputs, identify to the left the major customers who purchase this service or product from your business and their location details. If there are a large number of customers they can also be represented by a cloud, for each cloud please indicate the number of customers and the main districts where sales occur.

OUTPUTS (Inflow of $)



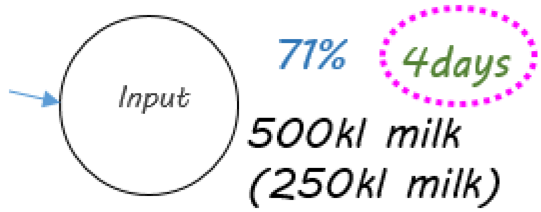
6. For each input identify to the right of the input in black the amount of that product or service that is used by your business. In brackets, if this input were to be restricted identify the minimum amount of product required before your business would be severely disrupted.



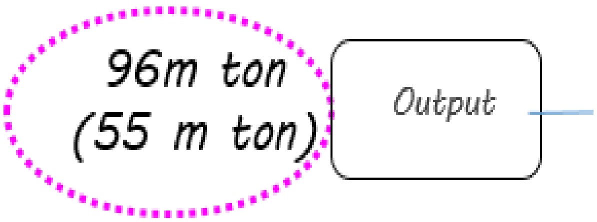


7. In BLUE pen, identify the approximate % of your operating expenditure that is spent on this input.

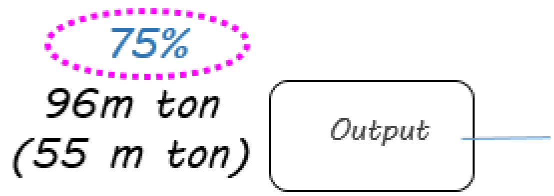
8. In GREEN pen, identify the approximate number of days the business could operate without access to this input during your peak demand period, assuming there is no access to any new suppliers.

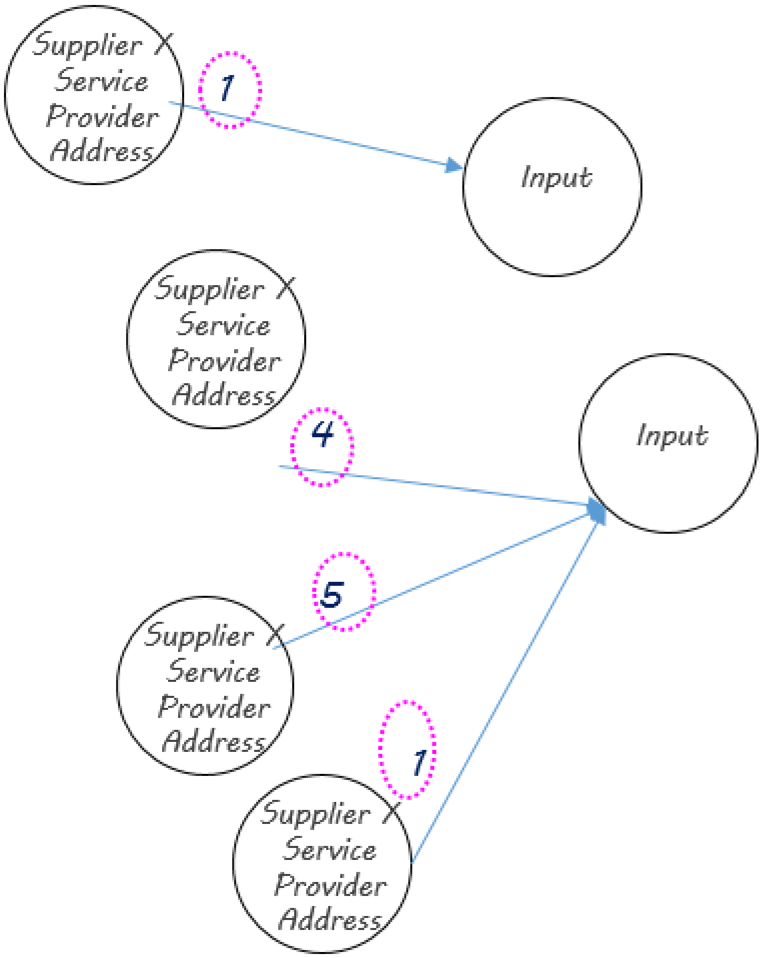


9. For each output identify to the left of the output in black the amount of that product or service that is produced by the business. In brackets, if this output were to be restricted identify the minimum amount required of this product that needs to be sold before the business would be severely disrupted.

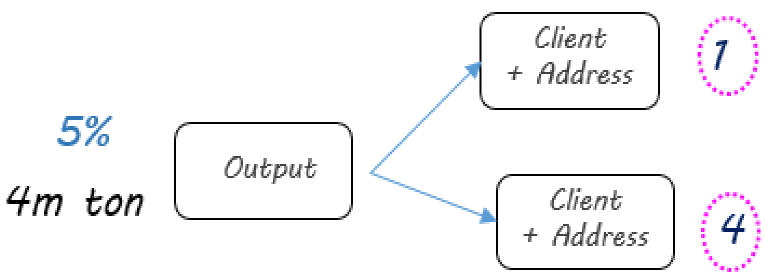


10. In BLUE pen, identify the % of your revenue that is generated from this output.



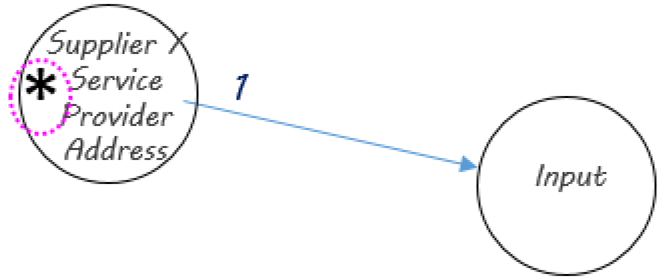


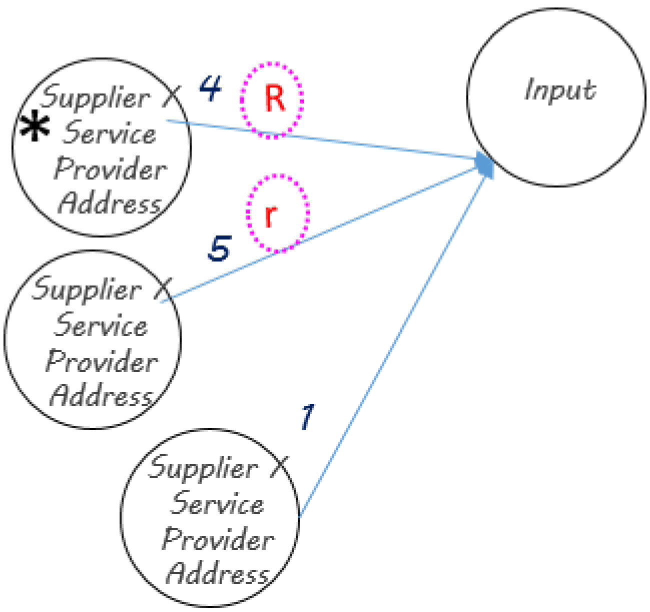
11. For each supplier (or cloud of), place a number next to them which represents how easily you could do business without this supplier. 1 = almost impossible, 5= very easily.



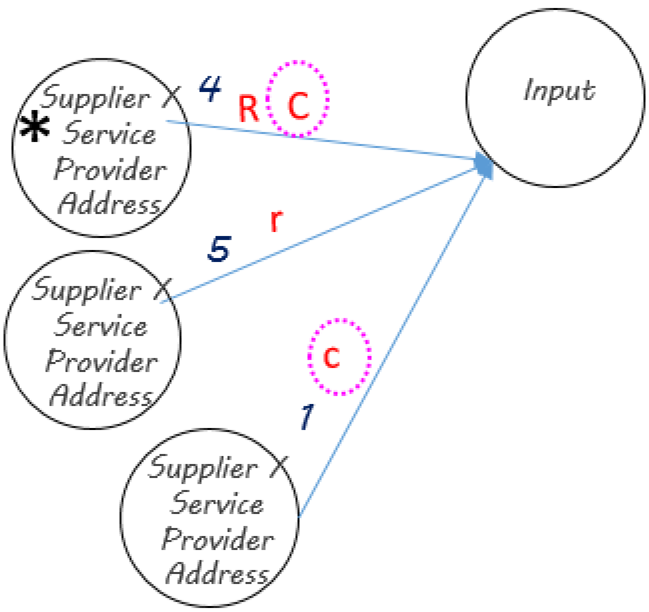
12. For each customer (or cloud of), place a number next to them which represents how easily you could do business without this customer. 1 = almost impossible, 5= very easily.

13. Place a star next to any supplier who you perceive to generally be more powerful in the relationship than your business (e.g. they set the price and the requirements).



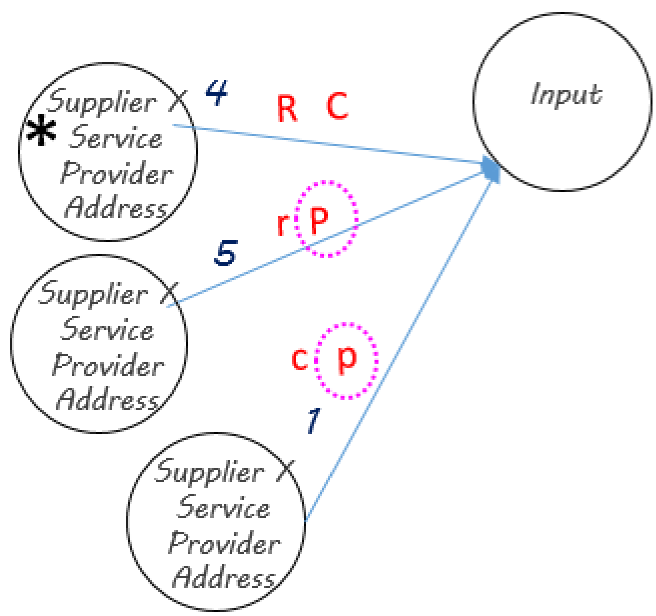


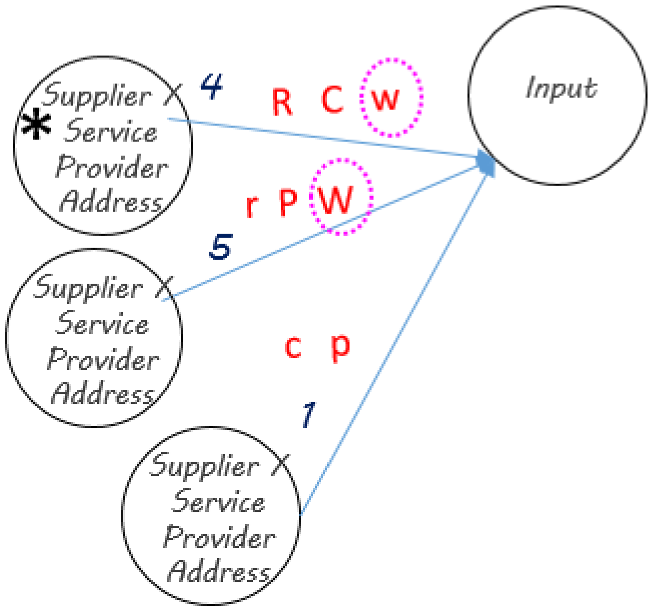
14. Using a RED pen, for each supplier (or cloud of), indicate how reliable you consider this supplier to be. Use a capital R for a very reliable supplier, a lower case r for a moderately reliable supplier, or leave it blank if this supplier is not considered to be reliable at all.



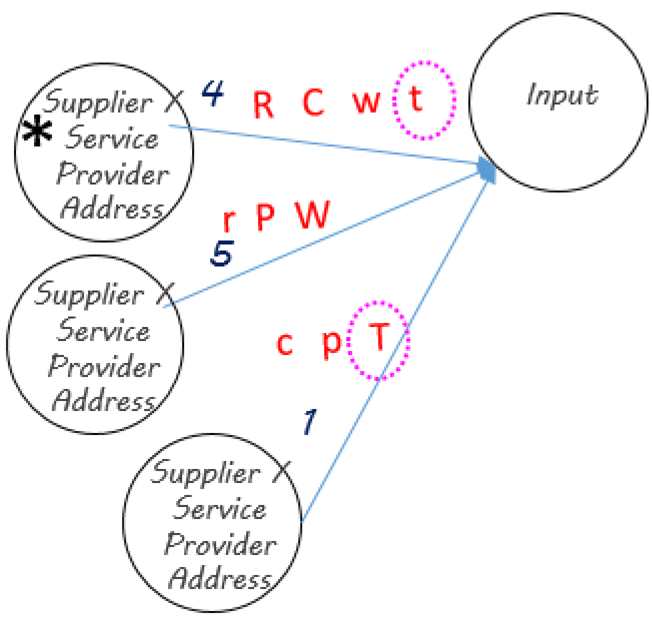
15. Using a RED pen, in a similar fashion indicate how frequently you communicate with this supplier. Use a capital C for very frequent communication, a lower case to represent a moderate level of communication and leave it blank if there is none, or very irregular, direct communication between your business and this supplier.

16. Using a RED pen, in a similar fashion indicate if there are personal professional relationships between staff at your business and staff at this supplier. Use a capital P for close personal relationship, a lower case p to represent a loose personal relationship and leave it blank if there is no personal relationship between your business and this supplier.



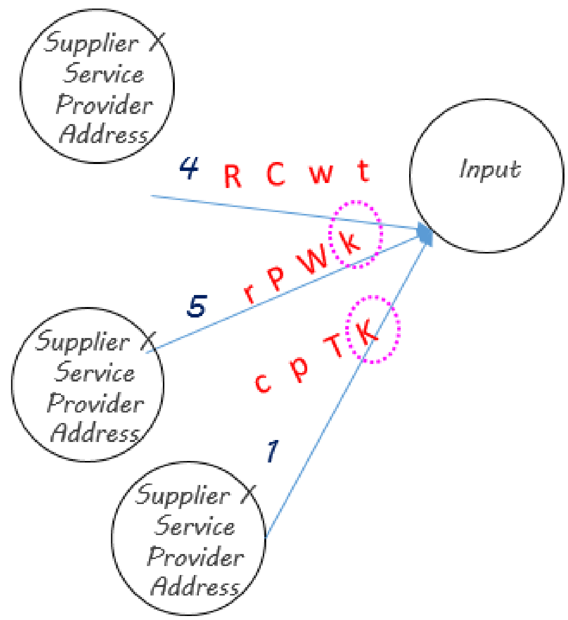


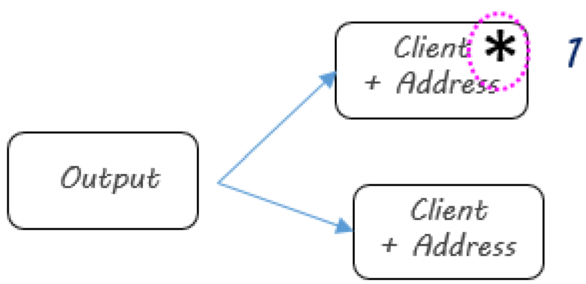
17. Using a RED pen, in a similar fashion indicate to what degree the supplier would be willing to compensate to help your business during a difficult time. Use a capital W for those with a high willingness to compensate, a lower case w to represent those with a moderate willingness to compensate and leave it blank if this supplier will not be willing to compensate for you in an emergency.



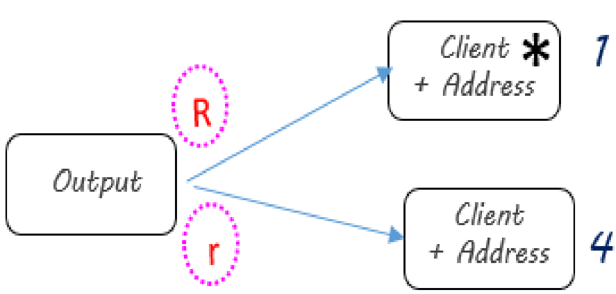
18. Using a RED pen, in a similar fashion indicate if the level of transparency you have up and down this supplier's supply chain, ie are you well aware of whom their suppliers and customers are. Use a capital T for those with a high transparency, a lower case t to represent those with a moderate transparency and leave it blank if this supplier is not transparent at all.

19. Using a RED pen in a similar fashion indicate the extent that the business relationships with this supplier are maintained through cultural connections e.g. Iwi, Chinese community etc. Use a capital K where there are strong cultural connections between your business and this supplier, a lowercase k where there are moderate cultural connections and leave blank if there are no cultural connections between your business and this supplier.



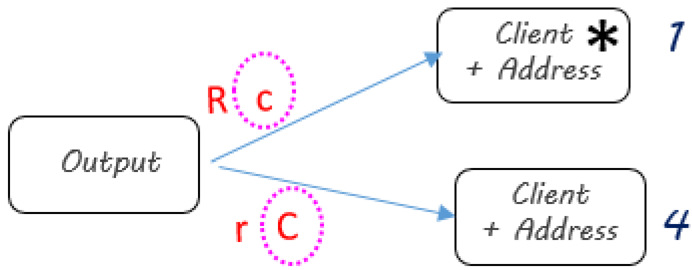


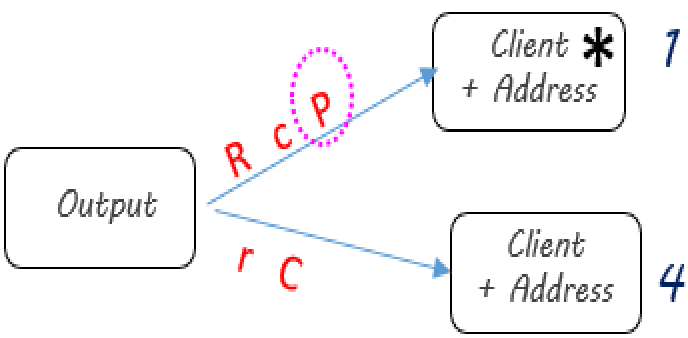
20. Place a star next to any customer who you perceive to generally be more powerful in the relationship than your business



21. Using a RED pen, for each customer (or cloud of), indicate how reliable this party is considered by you. Use a capital R for a very reliable customer, a lower case r for a moderately reliable customer, or leave it blank if this customer is not reliable at all.

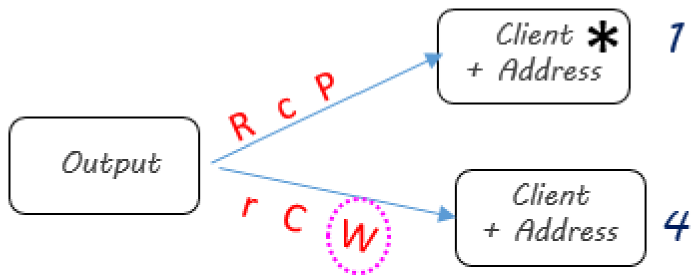
22. Using a RED pen, in a similar fashion indicate how frequently you communicate with this customer. Use a capital C for very frequent communication, a lower case to represent a moderate level of communication and leave it blank if there is no direct communication between your business and this customer.

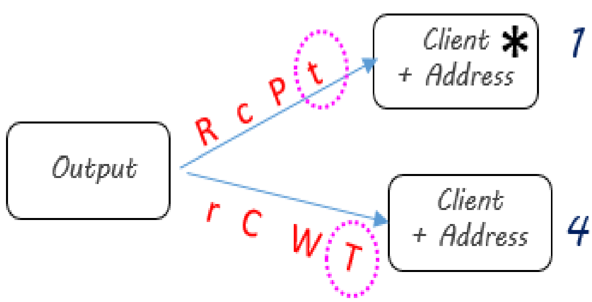




23. Using a RED pen, in a similar fashion indicate if you have a personal relationship with this customer. Use a capital P for close personal relationship, a lower case p to represent a loose personal relationship and leave it blank if there is no personal relationship between your business and this customer.

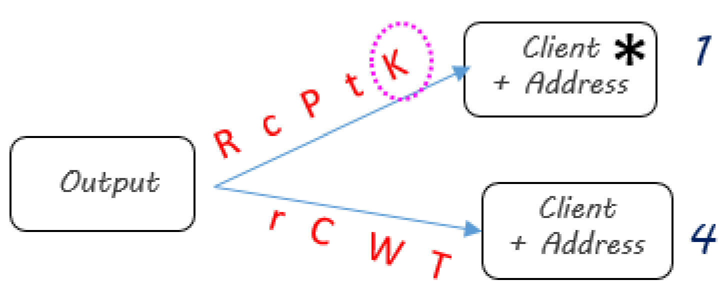
24. Using a RED pen, indicate if the level of willingness this customer will have to compensate for you if you were unable to meet you usual order to them. Use a capital W for those with a high willingness to compensate, a lower case p to represent those with a moderate willingness to compensate and leave it blank if this customer will not be willing to compensate for you in an emergency.





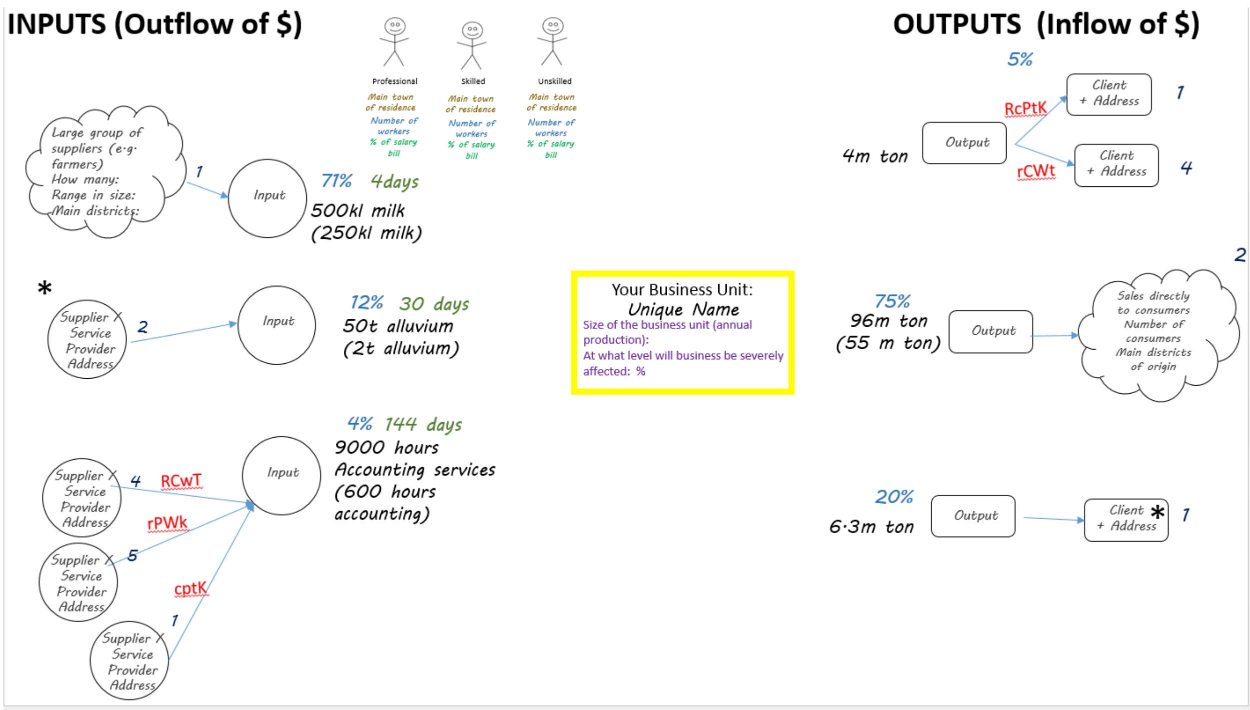
25. Using a RED pen, in a similar fashion indicate if the level of transparency you have up and down this customer's supply chain, e.g. are you able to see whom their suppliers and customers are clearly. Use a capital T for those with a high transparency, a lower case t to represent those with a moderate transparency and leave it blank if this customer is not transparent at all.

26. Using a RED pen in a similar fashion indicate the extent that the business relationships with this customer are maintained through cultural connections e.g. Iwi, Chinese community etc. Use a capital K where there are strong cultural connections between your



business and this customer, a lowercase k where there are moderate cultural connections and leave blank if there are no cultural connections between your business and this customer.

27. Your map at this stage should look similar to this



Appendix B: Information of the research sample

Coded business	Industry	Number of employees	Business revenue
B002	Agriculture, Forestry, and Fishing	2	187,043
B003	Agriculture, Forestry, and Fishing	48	1,671,794
B004	Education and Training		30,000
B005	Retail trade	3	1,070,000
B006	Accommodation and Food services	4	600,000
B007	Agriculture, Forestry, and Fishing	3	330,000
B008	Agriculture, Forestry, and Fishing	2	385,000
B009	Agriculture, Forestry, and Fishing	3	710,000
B010	Construction	3	195,000
B011	Agriculture, Forestry, and Fishing	4	625,000
B012	Accommodation and Food services	7	556,500
B014	Agriculture, Forestry, and Fishing	4	580,000
B015	Agriculture, Forestry, and Fishing	3	928,800
B016	Agriculture, Forestry, and Fishing	4	19,668
B017	Arts and Recreation Services		7,490,000

B018	Agriculture, Forestry, and Fishing	2	5,500,000
B019	Accommodation and Food services	11	698,750
B020	Retail trade	1	750,000
B024	Financial and Insurance services	9	1,000,000
B026	Accommodation and Food services	9	1,600,000
B029	Arts and Recreation Services		540,000
B032	Accommodation and Food services	45	4,000,000
B033	Agriculture, Forestry, and Fishing	7	3,400,000
B035	Agriculture, Forestry, and Fishing	45	17,300,000
B036	Agriculture, Forestry, and Fishing	69	30,000,000
B037	Agriculture, Forestry, and Fishing	1	644,000
B038	Agriculture, Forestry, and Fishing		415,595
B039	Agriculture, Forestry, and Fishing	4	410,500
B040	Agriculture, Forestry, and Fishing	6	1,710,000
B041	Agriculture, Forestry, and Fishing	2	950,000
B042	Agriculture, Forestry, and Fishing	6	1,672,000

B043	Transport, Postal, and Warehousing	26	5,000,000
B044	Wholesale trade		146,598,000
B045	Agriculture, Forestry, and Fishing	7000	2,700,000,000
B046	Agriculture, Forestry, and Fishing	45	13,900,000
B047	Agriculture, Forestry, and Fishing	700	700,000,000
B048	Agriculture, Forestry, and Fishing	9	4,000,000
B049	Retail trade		
B050	Agriculture, Forestry, and Fishing		

Appendix C: Result of diffusion analysis

Sending group size	Number of steps	Proportion of network reached	Optimal set of nodes
3	1	26.708%	"B015" "B035" "B037"
3	2	86.957%	"A193" "A242" "B042"
3	3	100%	Set 1: "A193" "A242" "B046"
			Set 2: "A193" "A242" "B042"
			And many sets found
5	1	38.199%	Set 1: "B015" "B019" "B033" "B035" "B037"
			Set 2: "B015" "B019" "B035" "B037" "B040"
5	2	98.758%	Set 1: "A193" "A242" "A364" "A438" "B042"
			Set 2: "A193" "A242" "A364" "B009" "B041"
			Set 3: "A193" "A242" "A364" "B009" "B042"
16	1	77.329%	"B002" "B008" "B009" "B010" "B014" "B015" "B016" "B018" "B019" "B033" "B035" "B036" "B037" "B040" "B045" "B049"
16	2	100%	Set 1: "A042" "A193" "A242" "A343" "B003" "B009" "B015" "B033" "B035" "B037" "B039" "B040" "B042" "B043" "B046" "B047"
			Set 2: "A042" "A193" "A242" "A343" "B003" "B009" "B015" "B033" "B035" "B037" "B039" "B041" "B042" "B043" "B046" "B047"

			Set 3: "A146" "A193" "A242" "A343" "B009" "B015" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046" "B047"
			Set 4: "A146" "A193" "A343" "B003" "B009" "B015" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046" "B047"
			Set 5: "A193" "A242" "A343" "B003" "B009" "B015" "B016" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B046" "B047"
			Set 6: "A193" "A242" "A343" "B003" "B009" "B015" "B033" "B035" "B037" "B039" "B041" "B042" "B043" "B046" "B047" "B048"
			Set 7: "A193" "A343" "B003" "B009" "B015" "B016" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046" "B047"
			Set 8: "A193" "A343" "B003" "B009" "B015" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046" "B047" "B048"
			Set 9: "A242" "A343" "B003" "B009" "B015" "B016" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046" "B047"
31	1	100%	Set 1: "A208" "B002" "B003" "B007" "B008" "B009" "B010" "B011" "B014" "B015" "B016" "B017" "B018" "B019" "B020" "B024" "B033" "B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B048" "B049"
			Set 2: "A242" "A403" "B002" "B003" "B007" "B008" "B009" "B010" "B011" "B014" "B015" "B016" "B018" "B019" "B020" "B024" "B033"

	"B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B048" "B049"
	Set 3: "A242" "B002" "B003" "B007" "B008" "B009" "B010" "B011" "B014" "B015" "B016" "B018" "B019" "B020" "B024" "B029" "B033" "B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B048" "B049"
	Set 4: "A242" "B002" "B003" "B007" "B008" "B009" "B010" "B011" "B014" "B015" "B016" "B018" "B019" "B020" "B024" "B032" "B033" "B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B048" "B049"

Appendix D: Result of disruption analysis

Group size	Network fragmentation change	Optimal set of nodes
3	25.499%	"B015" "B019" "B037"
5	37.828%	Set 1: "B015" "B019" "B035" "B036" "B037"
		Set 2: "B015" "B019" "B036" "B037" "B049"
10	63.619%	"A193" "B008" "B010" "B015" "B016" "B019" "B035" "B036" "B037" "B040"
16	86.432%	"B002" "B003" "B007" "B008" "B009" "B010" "B015" "B016" "B019" "B033" "B035" "B037" "B040" "B041" "B042" "B043"
20	94.524%	"A111" "A193" "A242" "A343" "B003" "B008" "B009" "B010" "B014" "B015" "B019" "B033" "B035" "B037" "B039" "B040" "B041" "B042" "B043" "B046"
32	99.901%	Set 1: "A242" "B002" "B003" "B006" "B007" "B008" "B009" "B010" "B011" "B012" "B014" "B015" "B016" "B017" "B018" "B019" "B020" "B024" "B033" "B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B049"
		Set 2: "A242" "B002" "B003" "B006" "B007" "B008" "B009" "B010" "B011" "B012" "B014" "B015" "B016" "B018" "B019" "B020" "B024" "B032" "B033" "B035" "B036" "B037" "B038" "B039" "B040" "B041" "B042" "B043" "B045" "B046" "B047" "B049"