MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Modelling Supply Chain Sustainability: A Case Study in New Zealand Forestry

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Supply Chain Management

at Massey University, Palmerston North, New Zealand

Bui, Viet Ha

2020

Abstract

Supply chains play a key role in business nowadays, as they are facilitating about 80% of the world trade. Supply chain operations are making great impacts not only on the economy, but also on the society and the environment through all their activities along the chain. In supply chain management, supply chain network design is the backbone because it determines on a strategic level the quantity, location, capacity, and flows for all supply chain facilities.

Businesses have been gradually shifting toward sustainability, but unpredictable happenings like the ongoing global COVID 19 disease are forcing enterprises to adapt more sufficiently to survive and grow. It is recently observed that there are some fundamental changes in a number of supply chain networks when many physical stores are replaced by online shopping websites due to the pandemic. An efficient tool is in real need in supporting the change in supply chain network.

In making decision for a supply chain network redesign, several studies have documented that there is still a lack of holistic assessment when most published papers in the field only focused on the economic or environment aspect and very few addressed all three sustainability aspects including the social one, the quantifiable justification to support decision making is still inadequate, and the integrity of the decision making processed is challenged by the possibility of manipulation. On the other hand, some approaches like the Triple Bottom Line, the Discrete Event Simulation and the Multi-criteria Decision Making method are not utilised fully.

This study set out to examine a modelling method, which is the combination of Triple Bottom Line, Discrete Event Simulation and Multi-criteria Decision Making, for the sustainability assessment of a supply chain network redesign, to evaluate the influences of the method on the holistic approach, quantifiable justification and integrity of the results. The research was designed as a formal ex post facto longitudinal simulation case study of a forestry supply chain redesign in New Zealand.

The principal findings of this study are that the modelling method of Triple Bottom Line, Discrete Event Simulation and Multi-criteria Decision Making could provide a holistic assessment by addressing all three sustainability aspects. The method could demonstrate a quantifiable justification to support decision making by the showing the results in numerical form which could be ranked. The method could also secure the integrity of the decision making processed by the participation of stakeholders. In addition, the findings indicate that the Discrete Event Simulation could also be utilised in strategic decision making, not only in operational and tactical levels as reported by previous research. Therefore, this study should be of value for practitioners wishing to improve their daily supply chain operations, for managers plaining new strategy and investing new supply chain network design, for policy makers considering recommendation and/or requirement in assessment of publicly funded projects.

Preface

After a period of time working in supply chain management and sustainable business consulting, I decided to take a further study to deepen my knowledge in the fields. This study also helped to build my research foundation to develop myself further when pursuing a green life and career. With that in mind, this thesis was written by the Ecofont which could reduce up to 49.5% of the printing ink (as claimed by Econfont.com). The low contrast of the font could also reduce eyestrain in an extended reading. The print setting was in a duplex mode which could save 50% of the paper.

As this study can never be perfect, if you have any idea to make it better please email me to h@livegreen.vn and I will be happy to discuss with you. Thanks in advance for your kind interest and all the best!

Acknowledgements

To complete this study, I received a great deal of valuable support. I would like to express my deepest gratitude to my lead supervisor, Professor Paul Childerhouse, who guided me tirelessly through the long and winding road in researching, inspired me with the beauty of knowledge, and enlighten me the core essence of social science. I wish to give a very special thanks to my co-supervisor, Dr Carel Bezuidenhout, for his great advices and prompt feedbacks. I would like to extend my thanks to Mr Tim Barnard and the management at Scion for giving me an opportunity to join the “Optimising Forestry Supply Chain – Harvesting Automation” project team at Scion, and to all the team members for the excellent collaboration and support in data collection and analysis: Dr Karen Bayne and Dr Melissa Welsh (Scion), Dr Robert Radics (Lincoln University, NZ), Mr Keith Raymond (Forest Growers Research Ltd), Mr Don Scott (Awdon Technologies Ltd), and Dr Michael Wang (Auckland University of Technology). It was a great pleasure working with you. I am also very grateful to Dr Linh Nguyen Khanh Duong (University of Lincoln, UK), Mr Mohammed Zuhair Hassan Alaqqad (Orange), Mr Peter (Imagine That Inc.) for your invaluable shares of time and experience in building the ExtendSim simulation models. I must thank Mr Keith Raymond (Forest Growers Research Ltd) and Mr Don Carson (New Zealand Forest Owners Association) for the material usage permission. A very deep thank you to Ms Susie Brown (Hopper Home Ltd) and Ms Shelley Dixon (Write Right Ltd) for your valuable time and kind support in proofreading. Many thanks also to all staff in the administration teams at Massey University for providing me great supports during my study. I owe a debt of gratitude to the ones who encouraged me in post graduate study and provided me the needed supports: Professor Shuo Ma (World Maritime University), Associate Professor Truong Thi Nam Thang (National Economics University, VN), Associate Professor Vinh Thai (RMIT University, AU), Mr Nguyen Quang Vinh and Mr Pham Hoang Hai (Vietnam Chamber of Commerce and Industry), Ms Tran Thi Hong Gam (British Council, VN), Mr Mikko Kuiri (WWF, FI). Last but not least, I am forever grateful to my family for the endless love and care, and I sincerely dedicate this work to you!

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List of Abbreviations

AGB	Automated Ground-based
AH1	Automated Hauler
AH1-2	Automated Hauler with 2 stage
AH2	Automated Hauler 2
CGB	Conventional Ground-based
CH1	Conventional Hauler
CH1-2	Conventional Hauler with 2 stage
CH2	Mechanised Hauler
DES(s)	Discrete Event Simulation(s)
DM	Decision Making
DSS(s)	Decision Support System(s)
EMAS	EU Eco-Management and Audit Scheme EMAS
EMS	Environment Management System
FGR	Forest Growers Research
FOA	(New Zealand) Forest Owners Association
FWMA	Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age
GDP	Gross Domestic Product
HPMV	High Productivity Motor Vehicles
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LTI	Lost Time Injury
MADM	Multi-attribute Decision Making
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-criteria Decision Making
MDDM	Multi-dimensions Decision Making
MODM	Multi-objective Decision Making
NEFD	National Exotic Forest Description
NPV(s)	Net Present Value(s)
OHS	Occupational Health and Safety System
OHSAS	Occupational Health and Safety Assessment Series
PMH	Productive Machine Hour
PGP	Primary Growth Partnership
QMS	Quality Management System
SBSC	Sustainability Balanced Scorecard
SA	Social Accountability
SCM	Supply Chain Management
SCN(s)	Supply Chain Network(s)
SCND(s)	Supply Chain Network Design(s)
SCNR(s)	Supply Chain Network Redesign(s)
SCOR	Supply Chain Operations Reference
SD	Sustainable Development
SDM	Strategic Decision Making
SDS(s)	Simulation-based Decision Support(s)
SMS	Social Management System
SSCM	Sustainable Supply Chain Management
SY	Sort Yard
TBL(s)	Triple Bottom Line(s)
UN	United Nations
UNCED	UN Conference on the Environment and Development
VIS	Visual Interactive Simulation
WCED	World Commission on Environment and Development
WPM	Weighted Product Model

Chapter 1. Introduction

1.1. Research topic

Facilitating approximately 80% of global trade, Supply Chain Management (SCM) plays a crucial role in business nowadays (Sisco et al., 2015). For enterprises, SCM has become strategically important because the overall competition between companies has focused on the competition between supply chains (Andersen & Skjoett-Larsen, 2009; Childerhouse et al., 2015; Lummus & Vokurka, 1999). In order to be more competitive, companies are advised to extend supply chain strategies and objectives to a broader level, and adopt more comprehensive assessment approaches to measure performance accordingly (Lummus & Vokurka, 1999).

Supply Chain Network Design (SCND), a “discipline used to determine the optimal location and size of facilities and the flow through the facilities” in a Supply chain (Autry et al., 2013), is considered as the foundation of SCM (Nagurney, 2010), and a strategic decision level in SCM (Blanco & Sheffi, 2017; Eskandarpour et al., 2015; Melo et al., 2009). Developing a SCND not only associates with heavy investment, but also makes significantly impact to the environment and society (You & Wang, 2011; Wu & Dunn, 1995). Sustainable Supply Chain Management (SSCM) is formed when sustainability is integrated into SCM (Seuring & Müller, 2008).

It is observed that SCND is changing constantly (Booth & Philip, 1998; Choi et al., 2001; Sinrat & Atthirawong, 2018; Stevens & Johnson, 2016; Tummala & Schoenherr, 2011), as the world is becoming increasingly turbulent (Christopher & Holweg, 2011) and the business environment become even more unpredictable (Bennett & Lemoine, 2014), and the raising concerns in environmental and social issues (Kremer et al., 2009; Stevens & Johnson, 2016). A good example for this phenomenon is that a number of physical shops were replaced by online shopping during COVID 19 pandemic (Li et al., 2020). The change in SCND consequently requires the redesign of the SCN.

Supply Chain Network Redesign (SCNR) is a special branch in SCND which could be defined as a process in which a current SCND is changed into a new SCND (Jahani et al., 2018). SCNR is recognised as an area which has potential research opportunities to improve SCM practice (Lambert & Cooper, 2000). In details, SCNR could help to reach sustainability goals, to reduce the costs, to improve the product quality and customer service, and to manage growth in a business (Ravet, 2013).

When evaluating a SCND, a single economic performance assessment is normally the main focus (Klibi et al., 2010; Martins et al., 2019). However, the awareness on environmental and social issues is increasing (Andersen & Skjoett-Larsen, 2009; Genovese et al., 2017; Seuring & Müller, 2008), and it would require environmental and social issues to be included into the overall assessment for SCND optimisation (Varsei et al., 2014). Therefore, SCNR should also adopt a holistic sustainability assessment when making decision on a new SCND.

In sustainability assessment, the Triple Bottom Line (TBL) approach, with three main impact areas: the society, the economy, and the ecosystem (Elkington, 1997), has been widely adopted by businesses, policy makers and economic development practitioners (Seuring, 2013; Slaper & Hall, 2011). However, most study on sustainability assessment only focus one of the three TBL aspects (Ashby et al., 2012; Hassini et al., 2012; Seuring & Müller, 2008; Singh et al., 2009). Therefore, a more balance approach in SCM sustainability assessment including all three impact areas should be addressed in future research.

Among many tools and methods in Decision Making (DM), Decision Support System (DSS) is one of the most supportive tools in assisting decision makers to solve the main issues in supply chain (Teniwut & Hasyim, 2020), and Multi-criteria Decision Making (MCDM) is the natural method required to address multidimensional character of real world problems involving multiple conflicting viewpoints (Zopounidis & Pardalos, 2010). In DSS, Simulation-based Decision Support (SDS) is the most used approach in supply chain (Teniwut & Hasyim, 2020), as it could model and simulate real systems using different approaches, multiple times, in order to support optimal decision making (Hilletofth et al., 2016). Discrete Event Simulation (DES) is also a widely used type of SDS which has been the backbone in simulation and modelling research for a long time (Siebers et al., 2010).

In SCNR, it is argued that there is a real need for innovative DSS which could efficiently support decision makers in the change process (Allaoui et al., 2019; Lenny Koh et al., 2013). This is because management teams may not satisfied with decision making practices based on trust, experiences, and estimated benefits (Yingling & Detty, 2000). These demanding decision making tasks would then require strong justification based on quantifiable benefits to prompt investment in SCNR (Stank et al., 2001). In addition, DSS is also not utilised totally in supporting decision making as the majority of the DSS only tackles individual aspects, either the environmental, or social, or economic ones (Bai & Sarkis, 2010). Similar findings also suggest that DSS should be utilised from a full TBL approach (Taticchi et al., 2015). There is still a shortage of research on SDS at the industrial level and also on an individual business level (Hilletofth et al., 2016), and DES still has more capability to be utilised in SSCM (Van Der Vorst et al., 2009) even when it could handle complex systems (Kogler & Rauch, 2018), like the complicated SSCM. Therefore, more study on the usability of DSS/SDS/DES should be focused for a better quantifiable justification in supporting decision making.

MCDM implementation still has some unclear issues in practice. While many scholars noted that MCDM provides a systematic, transparent approach that enhances objectivity and generates results which could be trusted with reasonable satisfaction (Janssen, 2001), other researchers still argued that MCDM has a high risk of manipulation which may lead to a false sense of accuracy (Zardari et al., 2015), and then badly affect the integrity of a decision making process. In order to have a better knowledge on how to utilise MCDM properly, future research should explore how MCDM could affect the integrity.

It is observed that MCDM has been typically combined with TBL for sustainability assessment studies in many papers (Cruz, 2009; Govindan et al., 2013; Erol et al., 2011; Nagurney & Nagurney, 2010). However, actually the modelling method combining TBL, DES and MCDM is rarely used in (Celestino et al., 2011). These suggest that the modelling method combining TBL, DES and MCDM should be studied further in future research.

There are some other uneven distribution of subjects and contexts in SCM research. Some common tools in SCM sustainability assessment are tied into the product, rather than to the place where the impacts may occur (Ness et al., 2007). Many studies are conducted on theoretical subjects (Taticchi et al., 2015), and the few ones conducted on empirical issues are primarily focus on a selected range of manufacturing sectors like automotive or electronics (Hassini et al., 2012). Additionally, other paper argued that the main focus in research cases is on North American and Europe (Taticchi et al., 2013). Those gaps could be filled up by more practical SSCM studies at industry or site levels and from Asia-Pacific, Africa, South America.

Forestry is a key economic factor in New Zealand because it is the third largest export industry which contributes $6 billion annually to New Zealand's economy and provides employment to approximately 35,000 employees in production, processing and trading (Forestry New Zealand, 2019). On the other hand, the logging sector has the highest rates of work related injury and mortality incidents of employees in New Zealand (Bentley et al., 2002).

New Zealand forestry supply chain are facing some challenges which are the higher cost in forest harvesting due to the increase of forest harvest in steep terrain areas, the decrease in future market prices, the limited overall harvesting productivity, the shortage of labour in the harvesting and transport sector, the poor safety records, and the increasing demand for sustainable forestry, especially in regard to creating more positive social and environmental impacts (Forest Value Chain Consortium, 2018). There is a need for a redesign of New Zealand forestry supply chain to generate more added value and profit and to improve sustainability through innovation.

The broad topic of this research is to explore how to enhance the sustainability assessment to support decision making in a SCNR case of New Zealand forestry industry.

1.2. Research question

This study focuses on a specific area which is the cross section of three main aspects: SCM, Sustainability Assessment, and DM. In particular, SCNR, TBL, DES and MCDM are the sub-topics explored. This study aimed to provide a recommendation for a sustainability assessment method to sufficiently support decision makers in SCM. The objectives of this study are to examine the utilisation of a modelling method which combines TBL, DES and MCDM for the sustainability assessment of a SCNR case. This examination is expected to reveal the influences of the modelling method on the outcomes of the holistic approach, quantifiable justification and integrity. Therefore, the research question is formed, which is “how could utilising a modelling method of combining TBL, DES and MCDM influence the sustainability assessment of a SCNR case?”.

1.3. Research method overview

To tackle the research question, this study utilised a quantitative method with the view of objectivism and positivism. It is designed as a formal ex post facto longitudinal simulation case study to examine the actual implementation of the modelling method of TBL, DES and MCDM in sustainability assessment and decision making on a forestry SCNR project in New Zealand.

1.4. Potential contribution to knowledge

It is hypothesised that this study will address some gaps in the literature, to provide recommendations for future research, and implementation suggestions for practitioners and policy makers.

This study is intended to provide more knowledge on SCM performance measurement in general by studying a comprehensive measurement. Applying TBL approach with all three sustainability aspects equally in a SCNR case are expected to contribute a more holistic sustainability assessment to support decision making. The examination of a modelling method combining TBL, DES and MCDM is supposed to explore the possibility of a DES in producing quantifiable justification for supporting decision making, to test the usability of the combination of TBL, DES and MCDM in a specific case, and to understand the influences of MCDM on the decision making process integrity. By studying a case from New Zealand forest supply chain, some gaps of the uneven distribution of subjects and contexts in SCM research relating to geographical region, industry and business may be filled up.

For future research, this study wishes to inspire more research to explore the same combination modelling method of TBL, DES and MCDM in other places or industries, or to inspire the trial of different combinations of tools and methods for the same objective on how to sufficiently support decision-makers in improving sustainability assessments in SCM. This study may also form the basis for future research which considers the process of change and a broader assessment area in a SCNR.

In practice, this study recommends a modelling method for sustainability assessment to help forest owners, harvesting and transport contractors in testing alternatives and making decisions on long term projects, resource mobilisation, and investments based on the results from sustainability assessment of SCND alternatives. The basic set-up of this method could also be implemented in different industries with corresponding SCND, and for various groups of criteria. Using the modelling method built in this study should be able to help harvesting operation and transport managers in improving daily performance as well. Elements where improvements could be made include identifying bottlenecks, and testing corrective action before adopting suggested changes. The utilisation of MCDM could also be useful in encouraging the active participation of all stakeholders in contributing to common sustainable goals.

Using this study's approach on a regional or national level could help policy makers gain an overview for long-term development on key areas such as investment and finance, manufacturing, transportation, safety, labour, export, and port development. Furthermore, the effectiveness of the modelling method in sustainability assessment could provide suggestions for policy-makers to work on recommendations and/or legal requirements in feasibility study of public investment projects.

1.5. Limitations of the study

This study has some limitations in terms of the topic, and the research design. The first limitation relates to the combination of tools and methods examined in order to find a sufficient sustainability assessment method to support for decision-makers in SCNR. This study examines the combination of TBL, DES and MCDM only, while other combinations of tools and methods are not considered. The second limitation relates to the TBL approach. This study addresses three main dimensions which are the social, economic and environmental ones, while the other joint dimensions such as eco-efficiency, environmental justice, and business ethics are not mentioned. In addition, only one criterion of each dimension is discussed: Lost Time Injury (LTI) for social dimension, Net Present Value (NPV) for economic dimension, and CO_2 emission for environmental dimension, while other criteria are not addressed. The third limitation is the qualifiable result of the study. While the study should exhibit the effectiveness of the modelling method in delivering the expected results, it does not show how well the method performs. The fourth limitation is the process of change. This study assesses the sustainability of a SCNR at two static conditions: current and new SCND, and does not take the process of change (the transition period) into consideration.

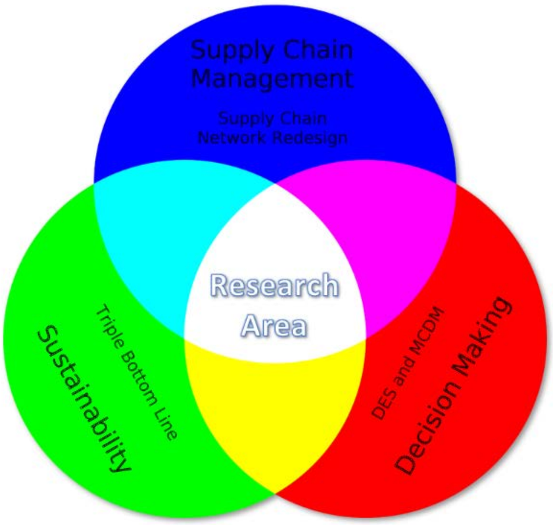
1.6. Flow and contents of remaining chapters

This study is organised in six chapters as follows. Chapter One (this chapter) briefly introduces the whole study content and its structure. In this chapter, the motivation and focal topic, the research question/objective, research method overview, the potential contribution to knowledge, and the limitations of the study are summarised. Chapter Two discusses the literature review. This chapter at first presents significant literature and definitions of concepts involved in the topic, including SCM, SCND, SCNR, Sustainability and Sustainable Development, SSCM, Sustainability Assessment, TBL, DM, DSS, SDS, DES, and MCDM. This chapter then identifies the research gap and develops the conceptual model for the study. Chapter Three outlines the research methodology of the study. This chapter starts by defining the research questions and hypothesis. The next sections of the chapter analyse the epistemological and ontological perspectives, appraising and adopting the research methodology. The chapter then discusses the selection and justification of the research design and data collection, and presents the measurement and analysis techniques. The chapter concludes with discussion of the ethical considerations, validity and reliability. Chapter Four describes the conduction of data analysis and the results of the study. The chapter provides an overview of the case study at first, then it presents the simulation set up, at the end the chapter describes multi criteria processing. The chapter concludes with the presentation of direct results from the case study. Chapter Five discusses the study results in relation with the conceptual model, and correlates study findings with previous literature. This chapter also discusses the implications in managerial/policy areas, critiques the study and makes suggestions for future research. Chapter Six concludes the study by presenting succinct answers to the research question and the original contributions.

Chapter 2. Literature review

This chapter provides the foundation of the study, based on the presentation of significant contributions to the research area which is the cross section of three main aspects: SCM, Sustainability Assessment, and DM. In order to focus on the researching aim which seeks a better tool and method to support decision making in sustainability assessment of a supply chain configuration change, four sub-topics are also identified: SCNR, TBL, DES, and MCDM, as illustrated in Figure 1.

Figure 1 – Research Area

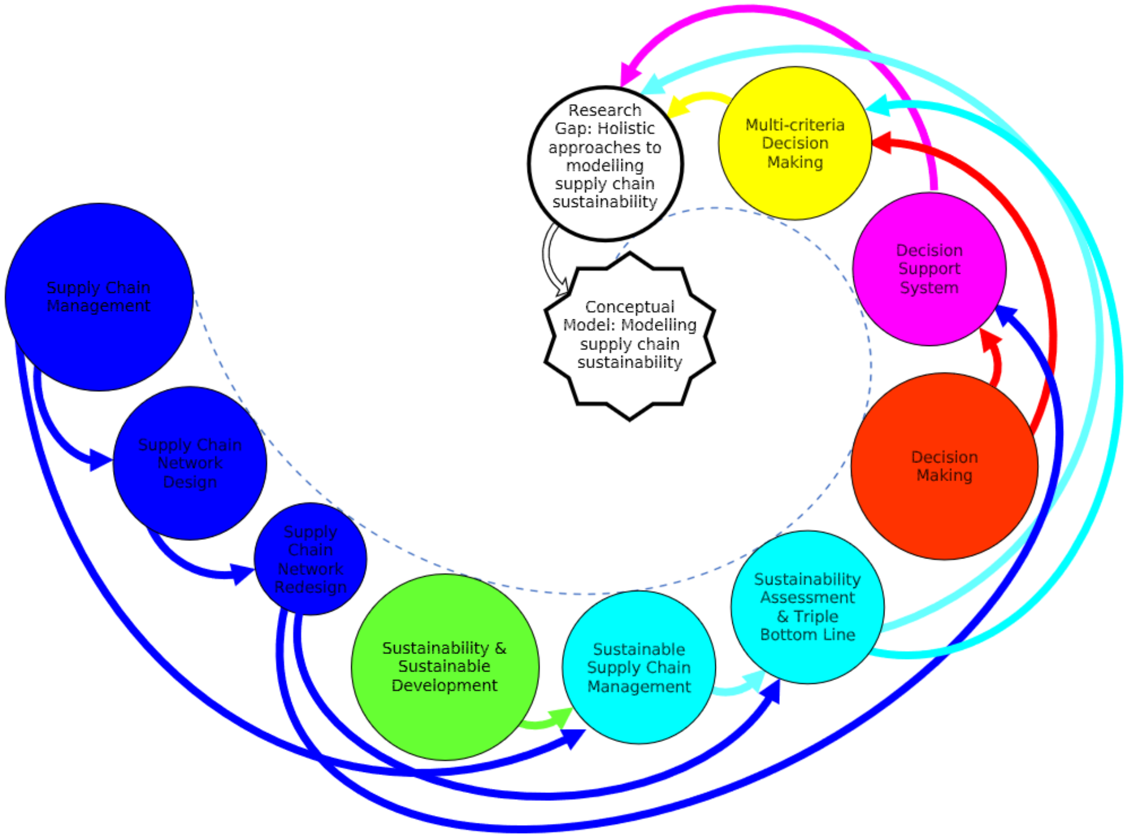


Note. DES: Discrete-event Simulation; MCDM: Multi-criteria Decision Making.

In the following parts of the chapter, the literature flow is presented in an inward spiral: more general at the beginning and more focal at the end, and this flow is structured by five main sections and eleven subsections, as shown in Figure 2. The same colour codes of different research areas from Figure 1 are repeated in Figure 2 for the subsections according to their corresponding focuses: Blue for SCM related areas, green for sustainability, red for DM, magenta for SCM and DM, cyan for SCM-Sustainability, yellow for Sustainability-DM, white for the mix of all three main areas. The coloured arrows indicate the connection between sections.

In Figure 2, the first section introduces the SCM, SCND and SCNR. Then Sustainability and Sustainable Development, Sustainability Assessment and TBL were linked in and addressed in the second section. The third section connects the literature on DM, DSS, SDS, DES and MCDM. Then the research gaps are identified in the fourth section. The conceptual model is developed in the eighth section, and the summary is presented at the end.

Figure 2 – Literature Structure and Flow



2.1. Supply Chain Management

SCM is an important business activity which is facilitating approximately 80% of global trade (Sisco et al., 2015). This section presents the findings from literature about the development of SCM, its relation with logistics, the definitions, current SCM business practices, SCND and SCNR.

From the development view, SCM is still a young concept. It was initiated from the significant strategy changes in competition and partner relations during the 1980s. In the past, companies were competing from within their own organisational boundaries (Lummus & Vokurka, 1999). Since there were many unsolved problems originating from the traditional approach among different partners in the chain of procurement, manufacture, distribution and sales, a new management approach for all partners in the chain as a whole was suggested, and the term SCM was first proposed by a consulting firm in 1982 (Oliver & Webber, 1982). Since then, this term and concept has drawn much attention and discussion (Chen & Paulraj, 2004; Christopher, 2016).

SCM has been innovatively developed and extended from logistics by integrating the management of co-operations, material and information flows (Ashby et al., 2012; Chen & Paulraj, 2004). Logistics gained much attention during the world wars when a significant amount of military equipment was mobilised. Logistics is commonly understood to relate to the movement of physical goods from one location to another, including storage, transport and distribution (Lummus et al., 2001). The most common definition of logistics could be the one firstly developed by the Council of Logistics Management which states that logistics management is “the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods, and related information flow from point of origin to point of consumption for the purpose of conforming to customer requirements” (Lambert & Cooper, 2000; Mentzer et al., 1992).

At the beginning, SCM was defined as the planning and control of materials and information flows, as well as internal and external logistics activities (Ahi & Searcy, 2013). Over time, the definition of SCM has evolved from describing internal and external flows of materials only, to including risk, performance and integration, which has led to many varying definitions of the term (Ahi & Searcy, 2013; I. J. Chen & Paulraj, 2004; Lummus & Vokurka, 1999). In this research, SCM was considered as the management of a supply chain which is,

> all the activities involved in delivering a product from raw material through to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, delivery to the customer, and the information systems necessary to monitor all of these activities. (Lummus & Vokurka, 1999)

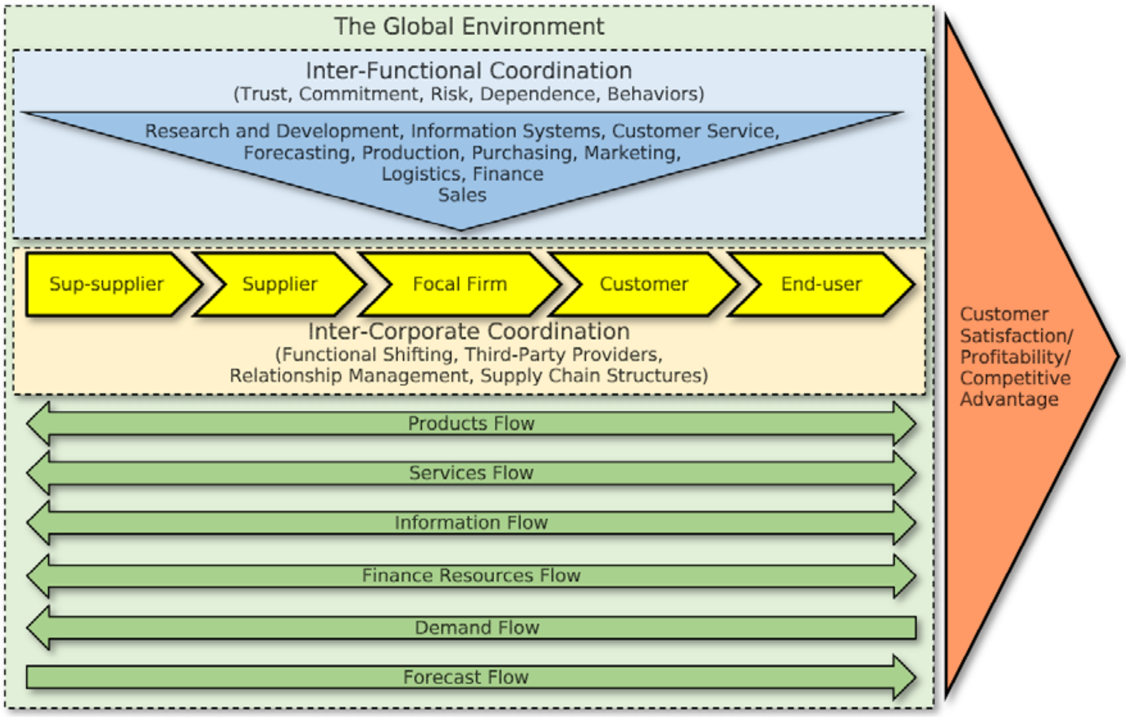
Therefore, SCM could be defined as

> the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole. (Mentzer et al., 2001)

In order to visually describe the concept, the current supply chain model is illustrated in Figure 3 (next page) (Mentzer et al., 2001). A supply chain on the right column of the figure shows the flows of products, services, financial resources, information, demand and forecasts. The business functions of marketing, sales, research and development, forecasting, production, procurement, logistics, information technology, finance, and customer service in the centre of the figure accomplish the flows to bring in customer satisfaction, value, profitability and competitive advantage (which are placed on the far right of the figure). Inter-functional coordination including trust, commitment, risk, dependence and behaviours, and inter-corporate coordination (including functional shifting, third-party providers, relationship management and supply chain structures), are placed under the global environment.

In business, SCM has become strategically important because the competition between companies has shifted to the competition between supply chains and establishing good relationships with all partners in a supply chain is essential for making competitive advantages (Andersen & Skjoett-Larsen, 2009; Childerhouse et al., 2015; Lummus & Vokurka, 1999). In order to achieve these competitive advantages, companies are advised to link supply chain strategies and objectives to the overall company, and adopt more holistic assessment approaches to measure performance (Lummus & Vokurka, 1999). Therefore, it is important to have more study in these areas.

Figure 3 – A Model of Supply Chain Management (Mentzer et al., 2001)



In SCM, SCND could be considered as the foundation (Nagurney, 2010). The next subsection explores more about SCND.

2.1.1. *Supply Chain Network Design*

In this part, the definition, configuration, and practical implementation of SCND are discussed.

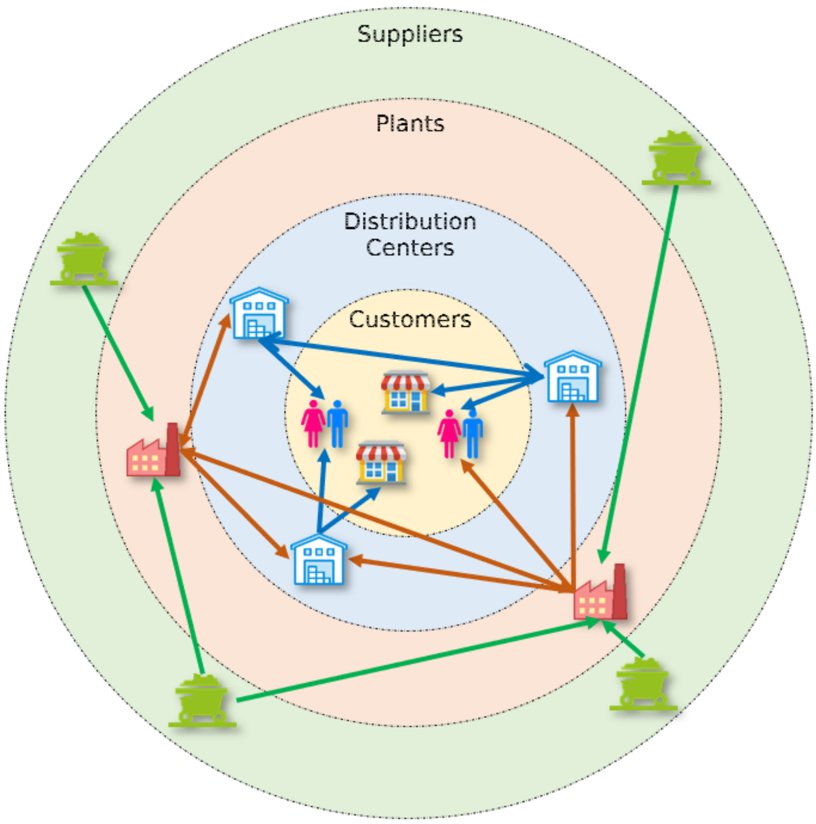
From a traditional view, SCND could be defined as "the discipline used to determine the optimal location and size of facilities and the flow through the facilities" (Autry et al., 2013). In details, this discipline answers questions about the quantity, location, capacity, and transport routes for facilities. In more complex supply chains, SCND decisions could be extended to include inventory, procurement, production, and transportation modes (Melo et al., 2009). This study adopted the traditional definition of SCND with the extension on production which relates to the manufacturing of goods, and on transportation modes which selects different options of transportation means.

Basically there are two main configuration elements in a SCND, which are the nodes and the arcs (Magnanti & Wong, 1984). Researchers shared the same understanding of the nodes and the arcs: nodes represent the facilities, while arcs represent the transport links between the nodes (Bloemhof-Ruwaard et al., 2004; Eskandarpour et al., 2015). In an example of a supply chain network shown in Figure 4 (next page), the nodes are suppliers, plants, distribution centres, and customers, and the arcs are the transport channels connecting those nodes (Melo et al., 2006). Thus, configuring a SCND could consist of two main tasks: the first task is the discrete-choice arrangement about which nodes and arcs should be included; the second task is the arrangement about the flow from supply to demand nodes along the network (Magnanti & Wong, 1984). The most important decision of SCND could probably be locating of facilities, as reported by a recent review paper on SCND (Asgharizadeh et al., 2019), and as supported by the fact that decisions on facility location is one of the main subjects for study in SCND research (Melo et al., 2009).

In SCND practical implementation, special nodes named hubs are widely used in a hub-spoke design to serve multiple flows between origins and destinations (Kelly, 1998; O'Kelly & Miller, 1994). Hubs locate in, and serve specific geographical areas to bring benefits for those regions (Kelly, 1998). Thus, this configuration could reduce the number of arcs, simplify setup costs, centralise handling and sorting, and allow the economy of scale in transport (O'Kelly & Miller, 1994). In Figure 4, the distribution centres could be considered as the hubs. In order to best utilise this design, important decisions should be made on the location of the hub, and on the flow of traffic over the network (Blanco & Sheffi, 2017).

Developing a SCND not only associates with heavy investment, but also makes significantly impact to the environment and society (You & Wang, 2011; Wu & Dunn, 1995). Thus researchers agree that SCND is a strategic decision level in SCM (Blanco & Sheffi, 2017; Eskandarpour et al., 2015; Melo et al., 2009). Developing a SCND may also utilise mathematical models and optimisation techniques in to identify the best solution (Autry et al., 2013). Strategic decision making and modelling techniques will be discussed in separate sections.

Figure 4 – Example of a Supply Chain Network (Melo et al., 2006)



As the environment is always changing, a SCND would also be altered to adapt with the change. The next subsection discusses SCNR, a special SCND branch focusing on the transforming process. SCNR also helped to build the context for this study.

2.1.2. *Supply Chain Network Redesign*

In reality, many SCNDs changes when the world supply chains are changing constantly, as observed by many previous studies (Booth & Philip, 1998; Choi et al., 2001; Sinrat & Atthirawong, 2018; Stevens & Johnson, 2016; Tummala & Schoenherr, 2011). These trending changes rise up because the world is becoming increasingly more complex and turbulent (Christopher & Holweg, 2011), and the business environment become even more evaporative, unpredictable, complicated, and ambiguous (Bennett & Lemoine, 2014). Additionally, the competition among companies is now led by the competition among supply chains, a crucial factor in the global economy (Christopher, 2011; Xiao et al., 2012). Moreover, SCM has become a driving force for business performance, due to the development of new business models and strategies which are supported by advanced technologies, tools and techniques, and by the raising concerns in environmental and social issues (Stevens & Johnson, 2016). Thus, the change of SCND may require the redesign of the SCN.

SCNR is a part of SCND, which could be defined as a process in which a current SCND is changed into a new design (Jahani et al., 2018). SCNR is recognised as an area which has potential research opportunities to improve SCM practice (Lambert & Cooper, 2000). In details, SCNR could help to reach sustainability goals, to reduce the costs, to improve the product quality and customer service, and to manage growth in a business (Ravet, 2013).

There are different SCNR strategies which could be divided into four groups: configuration, control structure, information system, and organisation structure (Van Der Vorst & Beulens, 2002). The configuration strategy is the most difficult one, as it changes the location, facilities, means, the roles and the parties involved in the supply chain, which may require significant investment. Within the context of this study, the configuration strategy was the main focus.

In the past decades, SCND has been studied more by both academia and industry (Varsei & Polyakovskiy, 2017). While a single economic performance assessment is normally focused by researchers (Klibi et al., 2010; Martins et al., 2019), the raising concerns on sustainability challenges would require to be included into the assessment in order to optimise SCND (Varsei et al., 2014), though it may add more complexity in the modelling and approaches (Tang & Zhou, 2012). Therefore, SCNR has the same challenges in integrating sustainability into the performance assessment and this area should be focused more in future research. The next section discusses more details on the sustainability and relevant issues.

2.2. Sustainability and Sustainable Development

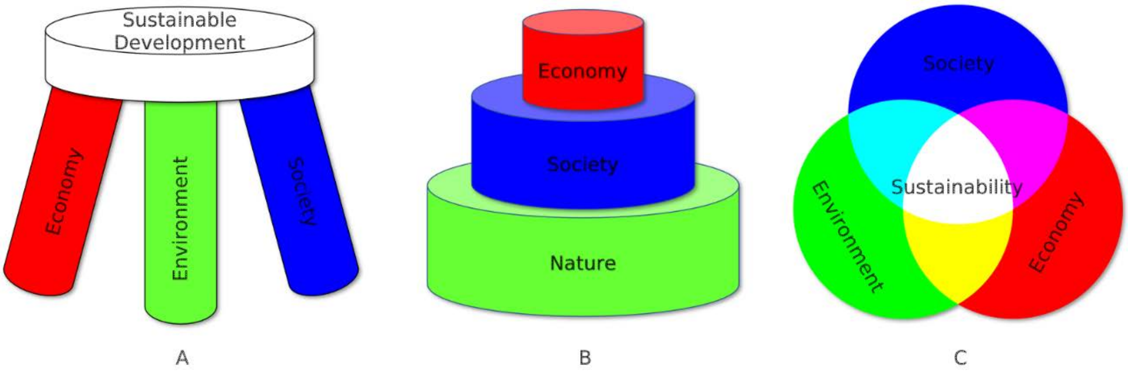
In this study, the term “sustainable development” refers to a process or a method to achieve a sustainable status, and the term “sustainability” refers to a condition in which humans live in harmony with each other and with the nature, which could be the result of the sustainable development process (Diesendorf, 2000; Mebratu, 1998). This section discusses the sustainability and sustainable development terms in relation to business activities. First the evolution over time and the depiction of the concepts is presented, then the relation of business activities and sustainability is portrayed.

The terms “sustainable development” and “sustainability” represent ideas that have been discussed for a long time, and may be viewed as a series of milestones. The first milestone was the early awareness about the environmental impacts of human activities described in the fifth century BC by Plato, in the first century BC by Strabo and Columella, and in the first century AD by Pliny the Elder (Du Pisani, 2006). The second milestone was the significant increase of concerns about population growth and the impact of human beings on the resources of the earth in the 18th century (McKenzie, 2004; Paul, 2008). This milestone was emphasised by the introduction of a German term meaning “sustainability” and its wide support in the forestry industry due to the high wood consumption and the serious timber shortage (Caradonna, 2014; Du Pisani, 2006). This milestone was also highlighted by the initiation of the “limits to growth” concept about the lack of food production for the growing population (Paul, 2008), which was considered as the most famous work in the area and was adapted by classical economists in the 18th and 19th (Bardi, 2011; Du Pisani, 2006; Mebratu, 1998; Sandbach, 1978). The third milestone was the warnings about the damage caused to the environment by human activities in the 20th century (Bardi, 2011; Caradonna, 2014; Carson, 1962; Du Pisani, 2006; Hardin, 1968; Lutts, 1985), followed by pessimistic predictions in the collapse of the global economic system if there is no change in the contemporary society conditions (Bardi, 2011; Caradonna, 2014; Forrester, 1971; Goldsmith et al., 1972; Meadows et al., 1972).

The “sustainability” term was globally recognised at the first UN Conference on the Environment (United Nations, 1972). The full definition of “sustainable development” was first introduced at the World Commission on Environment and Development (WCED) in 1987, which stated that “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland et al., 1987). The concept of sustainability in development was further defined at the UN Conference on the Environment and Development (UNCED) in 1992 with detailed recommendations and advices on how to pursue sustainable development in environmental and development areas: life quality, natural resources utilisation, commons protection, living area management, and sustainable economic growth (United Nations, 1992). These concepts have been widely accepted and primarily used since then (Du Pisani, 2006; Mebratu, 1998).

While agreeing on the main components, researchers still proposed different ways to illustrate the complexity of the sustainability concept. There could be three main depictions of sustainable development (Elliott, 2012), as illustrated in Figure 5 (next page). The first one is by showing three pillars: social, ecological and economic (part A of the figure), in which there is little interconnections between the pillars. The second way is by stacking circles where ecology is the base at the bottom to hold the society and then the economy on top (part B of the figure), which presents how all human activities, including human existence, depend on nature. The third one is by creating the intersection of interlocking circles (part C of the figure). This depiction way emphasises the trade-offs across the different spheres in the clearest way.

Figure 5 - Depictions of Sustainable Development (Elliott, 2012)



The relation between business activities and sustainability has been a long and slow development. Although business and industry sectors had significant capacity to impact economic, social and environmental issues (Barkemeyer et al., 2014), historically, they have largely ignored their involvement in environmental problems: it is only more recently that they have realised their responsibility (Elkington, 1994). The crucial role of the private sector in social and economic development was recognised for the first time in the *Agenda 21* where there is a separate part in one whole section emphasising for the promotion of cleaner production and responsible entrepreneurship (Barkemeyer et al., 2014; United Nations, 1992). This was also repeated in the *United Nations Millennium Declaration* (United Nations, 2000) and *Transforming our world: The 2030 agenda for sustainable development* (United Nations, 2015). Over time, business has changed from a passive attitude about sustainable development, to more positive action in promoting sustainability (Kremer et al., 2009).

In connection with the previous section on SCM, the next subsection explains more on the development of SCM towards sustainability.

2.2.1. *Sustainable Supply Chain Management*

In this part, the research development and definitions of SSCM are reviewed, SSCM benefits are presented and the relevant issues to improve SSCM research are discussed.

SSCM is a recent integration of sustainability into SCM, because of the importance of SCM and the trend in sustainable development. The concern about social and environmental impacts of supply chains has been raised relatively recently (Andersen & Skjoett-Larsen, 2009; Genovese et al., 2017; Seuring & Müller, 2008). This led to the SSCM discipline, a rapidly developing concept with a wider approach to SCM (Ashby et al., 2012). Thus, SSCM has become a key component in promoting sustainability in business.

At first, SSCM studies began by researching separately relevant areas, and later developed more comprehensive approaches. Early SSCM research scattered among stand-alone topics such as philanthropy, human rights, community, safety, and environment (Carter & Easton, 2011; Carter & Jennings, 2002; Murphy & Poist, 2002). Later on, SSCM theoretical frameworks were synthesised from previous literature (Carter & Rogers, 2008).

While SSCM could be approached in many different ways, there are some common SSCM categories. SSCM could be defined either as a management philosophy, or as a set of management processes (Dubey et al., 2017). This research adopted the SSCM definition of the second category, the more relevant one, which is,

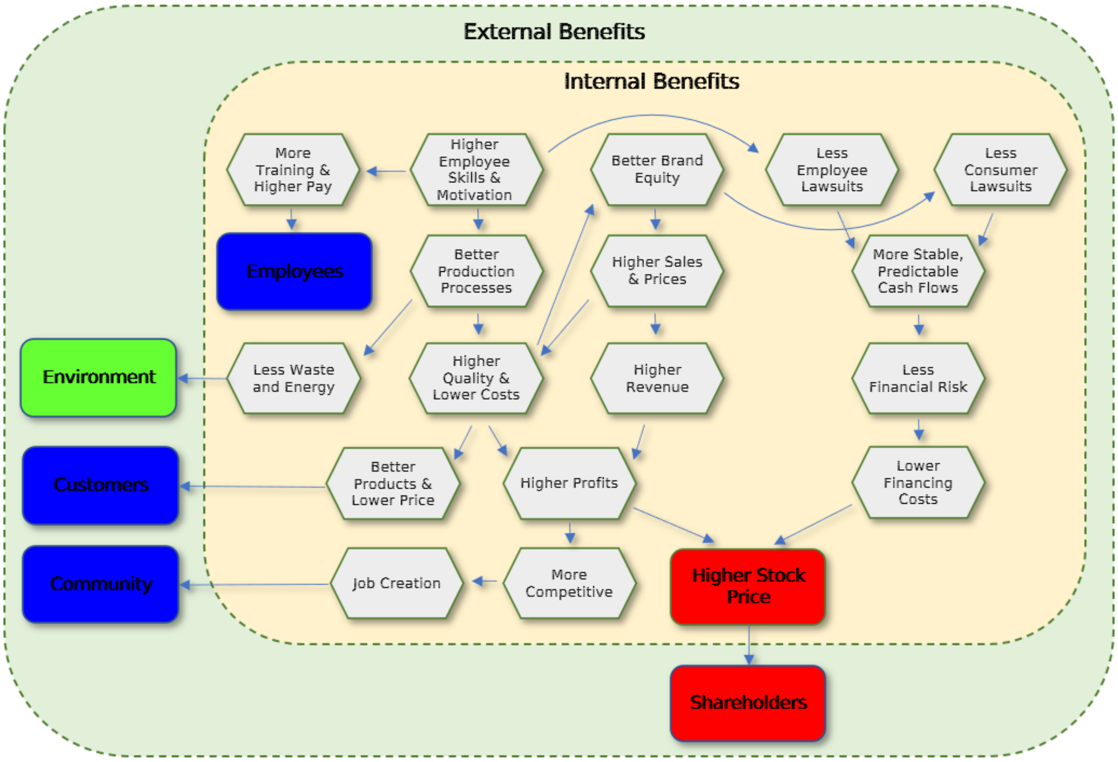
> the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements. (Seuring & Müller, 2008)

From a business point of view, good SSCM practices bring many benefits to companies. Consumers prefer to buy products from ethical companies (Auger et al., 2003), because sustainability practices enhance brand equity, and thus positively influence consumer purchase decisions (Davis et al., 2011). SSCM practices also reduce lower long-term production costs through improving efficiency and quality, which result from improved employee motivation and skills (Mefford, 2011). Some investors perceive good sustainability practices as a sign of good management which would also make the company's shares less risky (Roberts, 1992). All the above factors may logically lead to higher profits and increased stock valuation (Mefford, 2011), though there were still contradictory results about the correlation between good sustainability practices and financial performance (Orlitzky et al., 2003; Roman et al., 1999).

SSCM practices could bring four basic internal benefits for a company: better brand equity, higher employee’s skills and motivation, less employee lawsuits and less consumer lawsuits (Mefford, 2011). Better brand equity could lead to higher sales and prices, then to higher revenue, profits and stock price sequentially. Higher employee’s skills and motivation could improve production processes which could then lead to better quality and lower costs so that higher profits and then higher stock price could be achieved. Less employee lawsuits and less consumer lawsuits could both bring in, in order, more stable and predictable cash flows, less financial risk, lower financing costs, and higher stock price. Better brand equity could also result in less consumer lawsuits and higher employee’s skills and motivation could lead to less employee lawsuits, while higher sales and prices could also support higher quality and lower cost, which in turn could enhance brand equity.

SSCM could also contribute external benefits. The communities in which firms operate and employees will enjoy more jobs being created and higher pay rates, customers will experience better products and prices, and the environment will suffer less pollution and waste (Mefford, 2011). In details, more training and higher pay could make employees be happier. Better productions from SSCM practices could lead to less waste and energy, which could improve the environment. Higher quality and lower costs could bring better products and lower prices which satisfy more customers. Higher profits could make the company be more competitive and therefore could create more job for the community. Higher stock price could please more shareholders. The internal and external benefits of a sustainable supply chain are summarised in Figure 6 (next page).

Figure 6 – Internal and External Benefits of a Sustainable Supply Chain (Mefford, 2011)



In research, although SSCM is becoming a significant area for study, arguably there is further opportunity for more study on SSCM as a discipline, because SSCM is still considered as a separate stream of SCM research and the majority of research remains focused on non-sustainable SCM (Pagell & Shevchenko, 2014; Seuring & Müller, 2008). Specifically, the SSCM research identified specific issues to improve in order to develop truly sustainable supply chains: norms, measurement, methods, and research questions (Pagell & Shevchenko, 2014). There is also a need for more comprehensive research in SSCM, because only the environmental dimension is emphasised when initially integrating sustainability into SCM, and the number of these types of study has been growing continuously over time (Ahi & Searcy, 2013). Similarly, this argument was shared among other studies, which showed that most research on SSCM still focus on environmental issues, although a more holistic view of sustainability has been increasingly considered (Ahi & Searcy, 2013; Ashby et al., 2012; Seuring & Müller, 2008).

In studies of a SCM branch like SCND, previous papers shared the common finding most papers could be divided into two approaches which are on costs and profits, and on environmental impact (Neto et al., 2008; Melo et al., 2009). However, there were a limited number of studies focusing on the later, or integrating both approaches (Bloemhof-Ruwaard et al., 2004; Elhedhli & Merrick, 2012; Eskandarpour et al., 2015). These findings suggest that research having more holistic approach should be conducted to fully integrate the sustainability into SCND. Future research into new factors influencing sustainable SCND, optimisation and operation were also recommended (Tognetti et al., 2015).

Furthermore in research, there are still numerous opportunities for more theoretical and practical studies, even when the concepts and methodologies in SSCM research have been developed (Carter & Easton, 2011). From a methodology aspect, a review of more than 300 SSCM studies in 15 years showed that only 36 studies used quantitative modelling, while the remaining were solely qualitative (Seuring, 2013). Arguably, more quantitative method in SSCM research should be considered.

To understand if a supply chain is sustainable, it is important to know how sustainability is assessed in SSCM. This subject is discussed in the following subsection.

2.2.2. *Sustainability Assessment and Triple Bottom Line in SSCM*

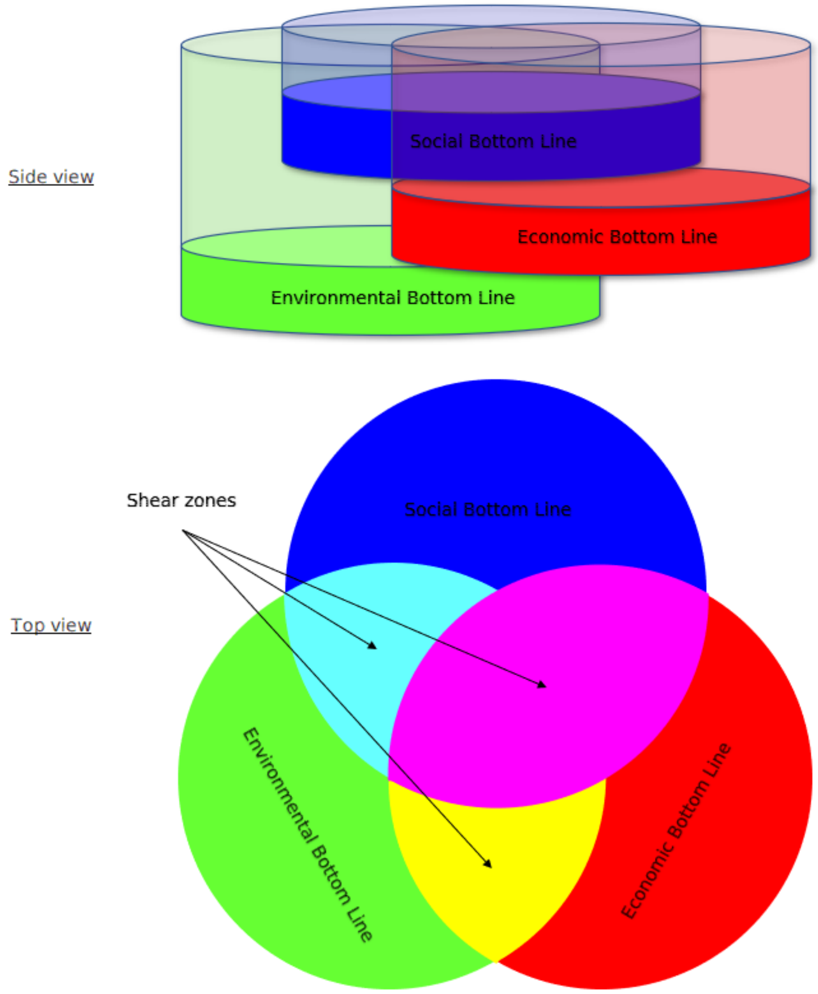
Sustainability assessment plays a supporting role in decision making process by evaluating the performance of integrated social-ecological systems so that proper actions could be taken to maintain development in long term (Kates et al., 2001). This section discusses the framework, the implementation, and the research topics of sustainability assessment in SSCM.

In general, sustainability assessment in SSCM is still a developing subject. Several studies shared the same view that measuring supply chain impact is not an easy task (Beske-Janssen et al., 2015; Hassini et al., 2012; Pagell & Shevchenko, 2014). The typical difficulties in sustainable supply chain assessment are: the selection of indicators, the choosing of metrics and data, the incompatibility of internal management and external integration, the lack of overall regulating bodies, the lack of trust and the risk of data leaking, the strategy alignment among supply chain players, the competence coordination, the streamlining of supply chain partners, and the constant changes of supply chain (Hassini et al., 2012). More knowledge certainly needs to be acquired to contribute to the building up of this research area.

Regarding the framework, sustainability assessment schemes began to emerge over the last few decades. One of the main recommendations of *Agenda 21* was to pursue a better assessment for sustainability (United Nations, 1992), because there was no workable method available (Caradonna, 2014). In an effort to measure sustainability, the term TBL was then introduced (Elkington, 1997). TBL has three main impact areas: the society depends on the economy, and the economy depends on the ecosystem being the ultimate bottom line, as presented in Figure 7 (next page). The TBLs are not stable as they constantly shift due to social, economic and environmental changes. These movements create shear zones between the social, economic, and ecological forces, which can be seen from the top view of the figure.

The TBL approach has a distinguished feature to assess more holistically, because its measuring is not only based on individual sustainability impact areas, but also on emerging shear zones (Elkington, 1997). The importance of considering complicated interlinkages and the dynamics among all three dimensions (social, economic, and ecological) was comparably recognised in other studies, because although, arguably, three dimensions could serve supplementarily to each other, sustainability is not solely the sum of all these factors (Seuring, 2013; Singh et al., 2009). Consequently, the shear zones in the TBL also bring in three joint dimensions which are eco-efficiency, environmental justice, and business ethics, besides the three basic dimensions (Elkington, 1997).

Figure 7 – The Triple Bottom Line of Sustainable Development (Elkington, 1997)



In implementation, many businesses, policy makers and economic development practitioners have widely adopted TBL in performance assessment (Seuring, 2013; Slaper & Hall, 2011). In this study, TBL was utilised as a method for sustainability performance assessment. To measure a performance, indicators are the key factors (Beske-Janssen et al., 2015). In answering what and how to assess sustainability, the indicators and management tools used in sustainability assessment are presented next.

In terms of sustainability assessment methodologies, physical indicator methods used by scientists and researchers, and monetary aggregation methods used by mainstream economists, are the two main distinct groups (Singh et al., 2009). While monetary valuation has been criticised as severely limiting analytical capability in the sustainable development field (Spangenberg, 2005), indicators and indices are considered as one of the three foundations for sustainability assessment which are indicators/indices, product related assessment, and integrated assessment tools (Ness et al., 2007). Similarly, indicators are recognised as fundamental for performance measuring and benchmarking in the TBL principle (Elkington, 1997). Therefore, measuring sustainability could be carried out effectively by three main groups of indicators which are environmental, economic, and social.

Indicators in environmental category may have different indicators, presenting challenges in how to utilise them. However, the emissions and disposal of hazardous wastes are identified as the major indicators in several studies (Ahi & Searcy, 2015; Finnveden et al., 2009; Hervani et al., 2005). Other researchers shared identical findings that, among those major indicators, carbon emissions are the most important contributing factor in the supply chain, as this is an element that is created throughout the whole supply chain (Bloemhof-Ruwaard et al., 1995; Eskandarpour et al., 2015; Seuring, 2013). However, managing the carbon emissions across a supply chain is challenging (Sundarakani et al., 2010). Because of the globalisation of supply chains, this significant expansion of the distribution network has led to increasing carbon emissions during transportation, and to the consequent need to improve the design of the supply chain to lessen environmental impacts (Elhedhli & Merrick, 2012).

There are also many indicators in the social category. Among different themes and sub-themes in the measures of social sustainability in supply chains, health and safety are proposed as two representative indicators because of their importance (Hutchins & Sutherland, 2008). However, previous research focused on the existing behaviour and practices of companies in relation to the treatment of their labour force (Wang & Lin, 2007). Therefore, there could be a lack of attention paid to health/safety concerns, which suggests the need for more research.

Economic indicators could generally be classified in five main categories of cost, time, quality, flexibility, and innovation (Tajbakhsh & Hassini, 2015). While many SCM studies consider the cost, profit and service level as the most important economic objectives (Varsei et al., 2014), only the total cost and net revenue are normally taken as economic indicators in SSCM assessment (Seuring, 2013). Among those two indicators, revenue could make more impact on business performance, while cost has less influence, although both revenue and cost are the most significant economic factors (Rust et al., 2002). Therefore, in this study the revenue indicator remained the focus.

Sustainability management tools are the integral parts of SSCM as they are the instrumental response to operationalise sustainability strategies (Beske-Janssen et al., 2015). They have three main focal aspects: lowering negative impacts, integrating all stages in the product value chain, and embracing multi-disciplinary perspectives throughout the product life cycle (Taticchi et al., 2013). There are also various ways to categorise sustainability management tools: by their nature as an instrument, a concept, a system, or a standard; or by a specific performance objective such as environmental, economic, social, or integrative (Beske-Janssen et al., 2015), as detailed in Table 1. The 35 different tools in Table 1 show the complexity of sustainability management tools and the challenges faced by decision makers in selecting appropriate indicators. This study focused on an integrative instrument to lower negative impacts.

Regarding research topics, there is a scarcity of SCM research on general performance measurement (Gunasekaran et al., 2004). There is also a lack of study on SCM sustainability assessment in particular (Taticchi et al., 2013). Even a significant SCM research paper on major performance metrics does not identify sustainability measurement (Gunasekaran & Kobu, 2007). This shows the need for more holistic measurement study as well as more sustainability assessment research in SCM.

Table 1 – Sustainability Management Tools (Beske-Janssen et al., 2015)

	Environmental	Economic	Social	Integrative
Instrument	Life cycle assessment (LCA)	Cost-benefit analysis	Social LCA	Sustainability audit
	Eco-audit	Economic input-output analysis	Social audit	Sustainability benchmarking
	Environmental benchmarking	Financial reporting	Social benchmarking	Sustainability reporting
	Environmental reporting	Risk analysis	Stakeholder dialogue	
			Social reporting	
Concept	Design for the environment	SCOR framework	Corporate citizenship	Sustainability balanced scorecard (SBSC)
System	Environmental management system (EMS)	Quality management system (QMS)	Social management system (SMS)	Integrated management system
			Occupational health & safety system (OHS)	
Standard	ISO 14001	ISO 9001 (QMS)	SA 8000 (SMS)	Global reporting initiative (Report)
	(EMS) EMAS		OHSAS 18001 (OHS)	UN Global Compact
	(EMS) ISO			
	14040 (LCA)			
	ISO 14064			

Moreover, several previous researches find out some notable issues in sustainability assessment in SSCM. Firstly, only few studies completely address TBL, and in most cases the focus is on only one of the three aspects (Hassini et al., 2012; Singh et al., 2009). Most papers spend much more effort on explaining related environmental issues, while the social dimension is almost entirely ignored (Seuring, 2013). Especially in SCND, most of the studies address economic performance and only some focus on environmental issue (Devika et al., 2014). Another recent review also shows very unequal coverages in TBL, where the percentages of the articles focusing on economic, environmental and social issues are 47%, 45% and 8% respectively (Asgharizadeh et al., 2019). These findings suggest a need for further research on not only sustainable assessment in general, but also a more balanced TBL approach in details.

It was also found that there are only a few major methodologies utilised in previous research. The life cycle method, for example, is used primarily for assessing the environmental dimension; the cost and revenue method is mostly applied to the economic dimension, and the majority of the research approaches are qualitative (Seuring, 2013). This finding supports more diversity in the methods and approaches in assessment of SSCM, including the quantitative ones.

Other research reported that some common tools like the life cycle assessment are tied into the product, rather than to the place where the impacts may occur (Ness et al., 2007). Moreover, many studies are conducted on theoretical subjects (Taticchi et al., 2015), and the ones conducted on empirical issues are primarily focus on a select range of manufacturing sectors like automotive or electronics (Hassini et al., 2012). Additionally, the main focus in research cases is on North American and Europe (Taticchi et al., 2013). More sustainability assessment studies from Asia-Pacific, Africa, South America, and at industry or site levels would be beneficial.

The previous sections have discussed SCM and Sustainability, two of the three main aspects which form the research area in this study. The next section explores the last main aspect: DM and its practical implementation.

2.3. Decision Making

DM is an important process in all businesses and management areas. In SCNR, good decisions could improve the efficiency and effectiveness of the whole supply chain (Lambert & Cooper, 2000). Among many tools and methods in DM, this study focused only on DSS and MCDM, because DSS is among the most supportive tools in assisting decision makers to solve the main issues in supply chain (Teniwut & Hasyim, 2020), and MCDM is the natural method required to address multidimensional character of real world problems involving multiple conflicting viewpoints (Zopounidis & Pardalos, 2010). This section presents the literature of DSS, MCDM, in relation with SCNR and SSCM.

2.3.1. *Decision Support System and the Implementation in SCNR and SSCM*

This subsection presents the literature on DSS, SDS - the most used tool in supply chain DSS (Teniwut & Hasyim, 2020), and DES – the backbone in simulation research (Siebers et al., 2010).

Regarding definition, it has been argued that DSS is “a content-free expression” which “means different things to different people” (Turban et al., 2007). It could be more specifically defined as a computer-based system which is designed to provide integrated support in managing business and making rational decisions (Power, 2007). The latter understanding was adopted in this research because it provides a clear and relevant description for the subject.

DSS plays a crucial role in decision making process in SCNR and SSCM, as DSS could support the major development and selection phases of strategic decision making (Asemi et al., 2011), and then produce significantly better decisions (Sharda et al., 1988). Sophisticated DSS enables the design, reconfiguration, and implementation of strategies which are the keys to delivery integrated systems, especially in the business context in which supply chains are changing from traditionally optimising functional activities to designing and implementing integrated systems and processes in the contemporary era (Chandra & Kumar, 2000; Tako & Robinson, 2012). DSS could also facilitate the change process, including the SCNR and other selection of materials, products and processes in SSCM (Gladwin et al., 1995).

In SCNR, it is argued that there is a real need for innovative decision support systems which could efficiently support decision makers in the change process (Allaoui et al., 2019; Lenny Koh et al., 2013). This is because management teams may not satisfied with decision making practices based on trust, experiences, and estimated benefits (Yingling & Detty, 2000). The occasional change in competitive business strategy and technology may also bring more challenges as the assessment in supply chain would need to change accordingly (Gunasekaran & Kobu, 2007). The change of approach from the old trade-off to a new mutually beneficial thinking in dealing with the TBL issues in SSCM may add even more to the existing difficulties (Seuring, 2013). These demanding decision making tasks would then require strong justification based on quantifiable benefits to prompt investment in SCNR (Stank et al., 2001).

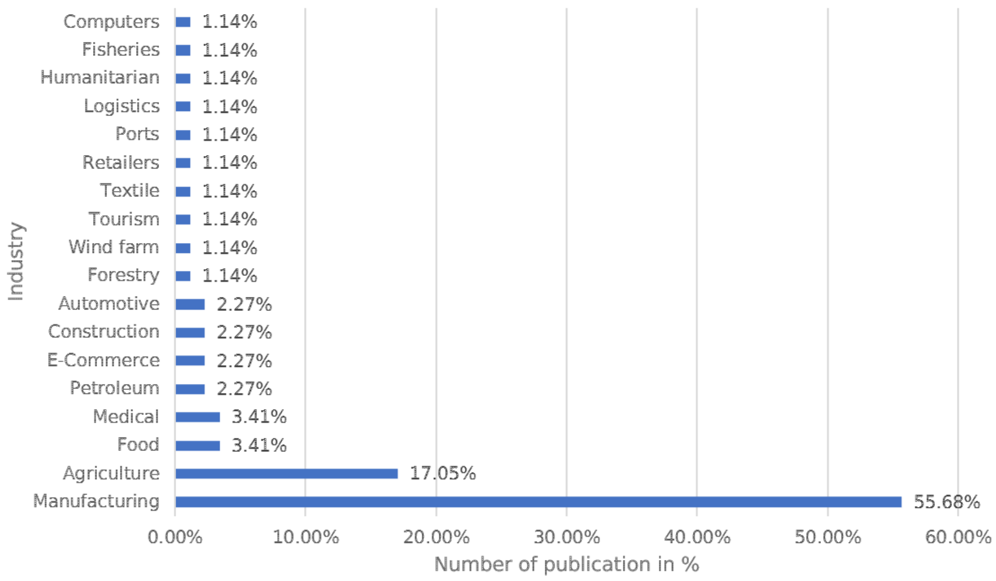
In spite of the need for DSS in SCNR as discussed above, previous studies reveal some interesting findings about the use of DSS in supply chains. Firstly, DSS in the supply chain is mostly used in activities relating to suppliers (Teniwut & Hasyim, 2020). This may be a significant waste of resource because a supply chain covers a much wider range of activities, and suppliers are just a single chain. This narrow focus on DSS use to address the supplier portion of the supply chain suggests a need for new research and applications of DSS in other supply chain activities.

Secondly, although several studies focus on analytical models to implement sustainability, only few study DSS in close association to SSCM indicators (Taticchi et al., 2015). As previously discussed, indicators are the key factors in measuring performance (Elkington, 1997). Therefore, lack of study on performance measurement may lead to insufficient understanding of SSCM assessment, suggesting the need for more research in this area.

Thirdly, a recent review reveals that DSS is utilised more in certain industries, and much less in others. More than 50% of the DSS studies are in manufacturing, while less than 50% of them are in all other industries (Teniwut & Hasyim, 2020), as shown in Figure 8 (next page). As DSS could help business leaders to make optimal decisions, it seems sensible to suggest that more study on DSS implementation is needed in other industries with low usage of DSS, including forestry industry.

Lastly, the majority of the DSS studies on SSCM tackle individual issues in the supply chains, either the environmental or social aspects of supply chains, along with economic aspects (Bai & Sarkis, 2010). This narrow focus shows a lack of attention to a more holistic point of view in SSCM research. There is, therefore, a need for more studies in this particular area. Similar findings also suggest that DSS should be utilised in solving complex SSCM problems from a TBL approach at inter-organisational and industry levels (Taticchi et al., 2015).

Figure 8 – Industry cover by DSS in SCM Research (Teniwut & Hasyim, 2020)



Regarding SDS, this is the most used approach in supply chain DSS (Teniwut & Hasyim, 2020), as it could model and simulate real systems using different approaches, multiple times, in order to support optimal decision making (Hilletofth et al., 2016). Simulation also has the capability to capture uncertainty, and this is well suited for supply chain analysis (Jain et al., 2001). Simulation modelling could also provide a strong support for not only analysing and testing various scenarios, but also comparing different alternatives for the best decision making (Smew et al., 2013). Moreover, the simulation approach could be deployed and mostly used in complex supply chain designs, when other approaches are less useful (Jain et al., 2001; Huang et al., 2003).

Recent SDS papers indicate a lack of research on SDS at the industrial level, and also on an individual business level, despite the popularity of SDS in SCM. This is due to the studies of SDS are focusing mainly on theory and concept, even though they have increased recently (Hilletofth et al., 2016). Therefore, arguably, more studies of SDS for specific business groups and cases are needed, for example in the wood supply chain (Kogler & Rauch, 2018).

DES is a widely used type of SDS which has been the backbone in simulation research for a long time (Siebers et al., 2010), due to a number of useful features. First, DES could model systems as a network of queues and activities where state changes occur at discrete points of time (Tako & Robinson, 2012), which best describes a supply chain scenario. Second, DES imitates complex supply chains in a simple and direct way to explore the supply chain and facilitate communication between stakeholders (Kogler & Rauch, 2018). Third, DES could include dynamics for system analysis in SCM (Persson & Araldi, 2009). Fourth, DES also has, for a long time, allowed users to interact conveniently with the running simulation by using animation and visual interactive tools which produce a dynamic display of the system model (Bell & O'Keefe, 1987).

DES development has a long history starting with the initial analogue simulation during the 1950s (Nance, 1993). Robinson (2005) explores the development of DES in which Visual Interactive Simulation (VIS) was introduced in the 1970s. Since then, VIS software has encouraged clients to get more experience. From the 1990s, the remarkable evolution in computer technology and the worldwide web has significantly enabled simulation to perform on a larger scale and for a longer time, and to provide more access and convenience for users. The development of visual interaction and virtual reality, optimisation, integration and application in the service sectors are the most outstanding changes in this period.

Some SCM studies argue that DES is more suitable in solving issues at an operational and tactical level, rather than on a strategic level as systems are not typically represented at an aggregate level (Baines & Harrison, 1999; Kelton & Law, 1991; Oyarbide et al., 2003). DES, for example, was used in a number of studies on aspects of lean manufacturing (Yingling & Detty, 2000). In contrast, other researchers claim that the difference between the approaches may not be so visible (Tako & Robinson, 2012). This suggests a need for more research examining the use of DES in strategic decision making.

DES is a natural approach in SCNR (Van Der Vorst et al., 2009), thanks to its useful features mentioned previously, and therefore has been used in a number of papers (Huang et al., 2003). Some typical DES application in SCNR are optimising an internal automotive logistics setup (Kurkin & Šimon, 2011), analysing a wood supply chain (Kogler & Rauch, 2018), and investigating a forest biomass logistics system (Mobini et al., 2011). Though DES is utilised widely in SCNR, it seems not having much use in SSCM (Van Der Vorst et al., 2009). Knowing that DES could handle complex systems (Kogler & Rauch, 2018), this lack in the available research suggests a need to further explore the DES application in SSCM, in which all social, economic and environmental aspects are assessed throughout the whole network of connected activities.

Having discussed DSS as the first of the two focal points of DM in this research, the next subsection presents the second focal point: MCDM in relation with SCNR and SSCM.

2.3.2. *Multi-criteria Decision Making and the Implementation in SCNR and SSCM*

This part of the study discusses the definition and utilisation of MCDM, the usage of weighting method as the main factor in MCDM, and the findings in research relating to its practical implementation.

MCDM could be defined as a method to search for an optimal decision or solution from a set of alternatives and a set of decision criteria (Triantaphyllou, 2000). MCDM is categorised into two main theoretical streams which are Multi-objective Decision Making (MODM) which deals with continuous decision spaces, and Multi-attribute Decision Making (MADM) which focuses on problems with discrete decision spaces (Zimmermann, 1996). As the terms MADM and MCDM usually mean the same as MCDM (Triantaphyllou, 2000), in this study MCDM could be understood as MADM. There are also other terms which have been used as MCDM in literature, such as Multi-criteria Decision Analysis (MCDA) and Multi-dimensions Decision Making (MDDM) (Zardari et al., 2015).

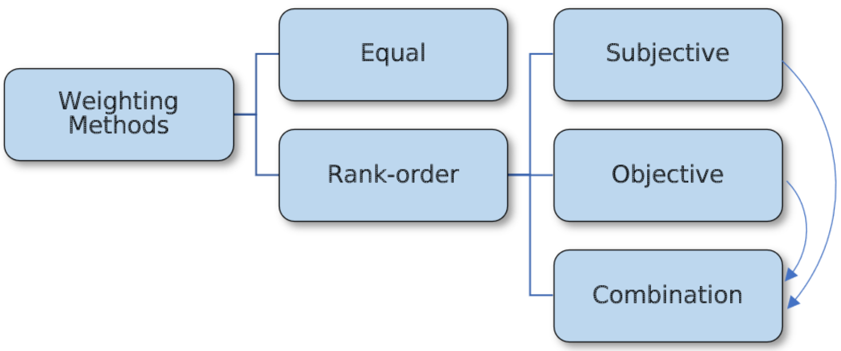
There are some common concepts and deployment steps in MCDM. The two common concepts are “alternatives” which represent the different choices available to the decision makers, and “attributes” or “criteria” which represent the different dimensions from which the alternatives could be viewed (Chen & Hwang, 1992). The first common deploying step is to determine relevant criteria and alternatives; the second is to weight the importance of the criteria and the impacts of the alternatives on these criteria (these weights are normalised to add up to one); and the third is to define the ranking of each alternative (Triantaphyllou, 2000). As the sum of all the weights is always one, the weighting value change of one criterion definitely leads to corresponding changes of the weight value of others. Thus, the balance and trade-off among the criteria is established.

The weighting of criteria plays a crucial role for measuring overall preferences of alternatives, because using different weighting methods in MCDM aggregation processes may lead to different results for the same scenario (Zardari et al., 2015). Therefore, it is crucial that the true meaning and method of the criteria weights is be understood and utilised properly (Choo et al., 1999). General understanding of two major criteria weighting methods in MCDM is explained next.

The first weighting method is equal weights: as its name suggests, all criteria are simply assigned the same value (Jia et al., 1998). Although this method was popularised and applied in many decision making problems, it has also been criticised because the relative importance among criteria could be ignored (Wang et al., 2009).

The second weighting method is the rank-order weights, which is again classified into three categories: subjective weighting method, objective weighting method, and combination weighting method (Jia et al., 1998). While the subjective method determining criteria weights may cause more unavoidable errors as it is based on the preferences of the decision makers, the objective method defines criteria weights by mathematical methods based on the analysis of initial data with less defined procedures (Zardari et al., 2015). To minimise the aforementioned shortcomings, the combination weighting method, which is the hybrid of the two previous methods, was used in this study to determine the criteria weights (Wang et al., 2009). Figure 9 illustrates these two methods.

Figure 9 - Weighting Methods

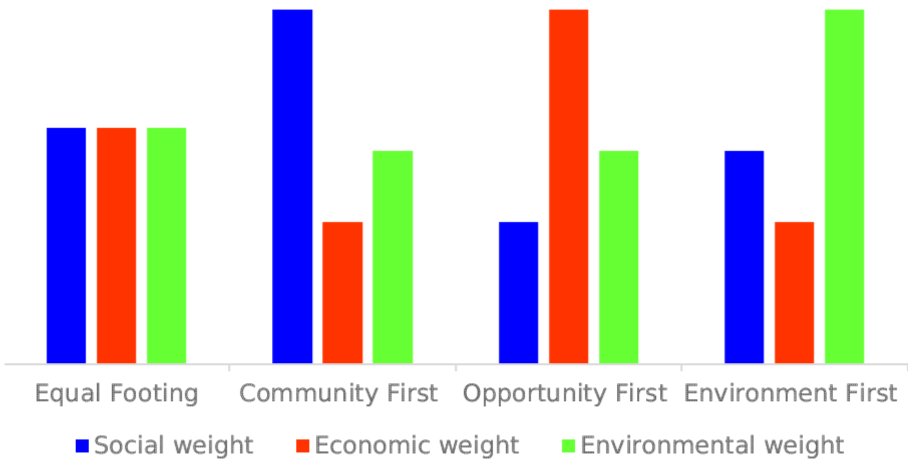


In practical implementation, MCDM methods have been both criticised and supported. Many researchers argue that MCDM has a high risk of manipulation which may lead to a false sense of accuracy (Zardari et al., 2015). On the other hand, other scholars note that MCDM provides a systematic, transparent approach that enhances objectivity and generates results which could be trusted with reasonable satisfaction (Janssen, 2001). As discussed earlier, MCDM should be utilised with understanding of the method and caution of the advantages and disadvantages, and future research should address the contrast areas in MCDM.

Despite the difficulties in determining weight, MCDM is still widely used in DM (Teniwut & Hasyim, 2020). Besides, MCDM is also the main method among modelling approaches in SSCM (Liu et al., 2011; Seuring, 2013). MCDM has been used increasingly because of its ability to handle and balance the multi-dimensional sustainability goal and the complexity of social, economic, and ecological systems, to be flexible according to the situation, and to encourage stakeholders' participation (Cinelli et al., 2014; Eskandarpour et al., 2015; Seuring, 2013; Wang et al., 2009).

Looking at more details of the weighting methods in SSCM, three aspects of TBL may be weighted differently: economic, environmental and social issues. It was suggested that companies may follow one of the four common postures: the Equal Footing which emphasises all aspects equally, the Community First which emphasises the social aspect, the Opportunity First which emphasises the economic aspect, and the Environment First which emphasises the environmental aspect (Wu & Pagell, 2011). The selection of the weighting method should be based on specific business natures and different focuses of business evaluation and decision making. Examples of these four common postures are illustrated in Figure 10, in which the Equal Footing has all the weights equally, the Community First has the highest weight on social aspect, the Opportunity First has the highest weight on the economic aspect, and the Environment First has the highest weight on environmental aspect.

Figure 10 – Examples of Four Common Weighting Postures



In SSCM research, MCDM is normally utilised in combination with other approaches. MCDM is typically combined with TBL in studies on sustainability assessment, for example measuring sustainability performance of a supplier (Govindan et al., 2013), measuring sustainability performance of a grocery retailer supply chain (Erol et al., 2011), modelling and analysing corporate social responsibility of a supply chain network (Cruz, 2009), and environmental evaluation of a SCND (Nagurney & Nagurney, 2010). Other combinations could be worth exploring in future.

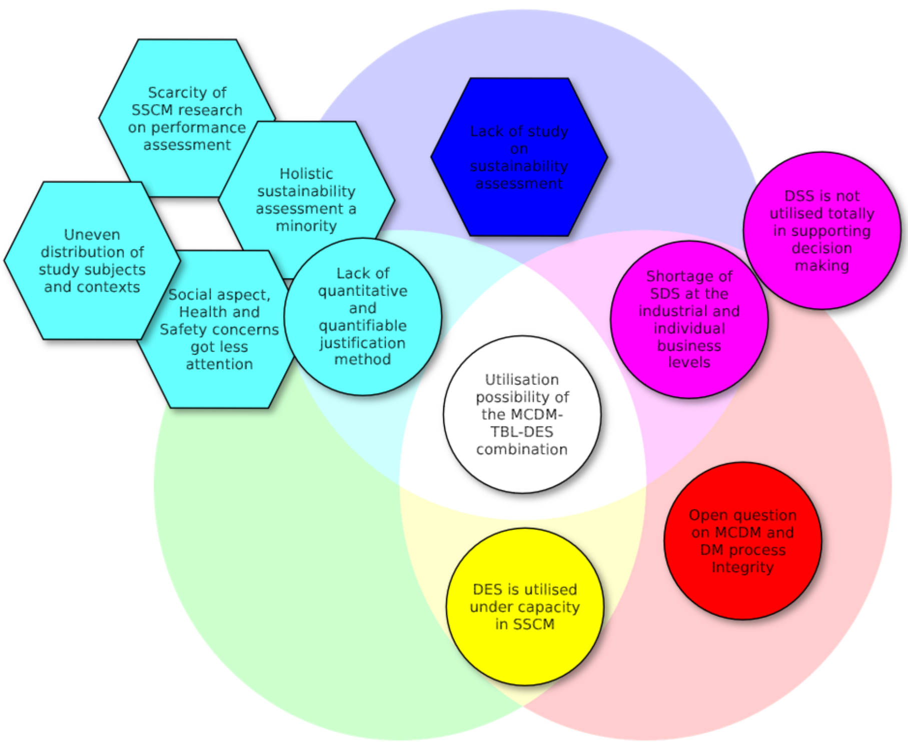
There is a rarely used combination of MCDM, TBL and DES, as only a few research using this method, such as logistics planning for a steel plant (Celestino et al., 2011). In another paper using DES in modelling a food SCNR for integration of DM on quality and sustainability, MCDM is proposed as an important analysing step leading to the final decision (Van Der Vorst et al., 2009). These findings suggest that the combination of MCDM, TBL and DES should be studied further in future research.

By reviewing the previous sections on literature, the research gap is synthesised in the next section.

2.4. Research gaps

The research gaps are illustrated based on in Figure 11 and they are grouped into two shapes/categories. The hexagon boxes represent the approach gaps in sustainable SC, and the round boxes represent the methods and tools gaps in supporting DM of sustainable SC. The gaps are also coloured and placed in accordance with the three main aspects of this study.

Figure 11 - Research gaps



2.4.1. *Gaps in the approach*

From the literature, it could be concluded that the main gap from approaching viewpoint in SSCM research is the lack of a holistic approach on multiple levels, where all sustainability aspects are assessed adequately and different in different business areas are also covered properly. This is explained in details below.

In SCM, there is still a scarcity of research on performance assessment (Gunasekaran et al., 2004). On the other hand, most of the SCND studies address economic performance (Devika et al., 2014), thus companies are advised to adopt more holistic approaches to measure SCM performance in order to achieve competitive advantages (Lummus & Vokurka, 1999). This shows the need for more holistic performance assessment study in SCM.

Looking closer at SCM performance assessment, there is also a lack of study on sustainability assessment (Taticchi et al., 2013). This argument was responded by other reviews in SCND which argued that the raising concerns on sustainability for operation optimisation also require sustainability assessment to be included (Tognetti et al., 2015; Varsei et al., 2014). It could be concluded by the common findings from previous papers that most articles focus on economic issues, and limited ones focus on environmental impacts (Bloemhof-Ruwaard et al., 2004; Elhedhli & Merrick, 2012; Eskandarpour et al., 2015), and that a single economic performance assessment is normally focused by researchers in SCND (Klibi et al., 2010; Martins et al., 2019). These findings suggest that more research on sustainability assessment should be conducted.

In SCM sustainability assessment, only the environmental dimension was emphasised during the early time when sustainability was first integrated into SCM (Ahi & Searcy, 2013). Although a more holistic view of sustainability has been increasingly considered (Ashby et al., 2012; Seuring & Müller, 2008), the number of holistic studies is still a minority. This was showed in a number of reviews arguing that only few studies completely address TBL, and in most cases the focus is on only one of the three aspects (Hassini et al., 2012; Singh et al., 2009), and that most research on SSCM still focuses on environmental issues (Ashby et al., 2012; Seuring & Müller, 2008). Therefore, more balance approach in SCM sustainability assessment research still needs to be encouraged in future.

Among the three sustainability aspects in TBL, the social aspect is paid least attention in SSCM research. It was revealed that most papers spend much more effort on environmental issues, while the social dimension is almost ignored (Seuring, 2013). Another recent review showed the percentages of the articles focusing on economic, environmental and social issues are 47%, 45% and 8% respectively (Asgharizadeh et al., 2019). In social aspect alone, though health and safety are proposed as two representative indicators because of their importance (Hutchins & Sutherland, 2008), previous research only focused on the existing corporate practices relating to the labour treatment (Wang & Lin, 2007). Therefore, social aspect in general, and health and safety concerns in particular, should need more focus in future SSCM research.

In SSCM research, there are uneven distribution of study subjects and contexts. It was noted that some common tools in SCM sustainability assessment are tied into the product, rather than to the place where the impacts may occur (Ness et al., 2007). Recent reviews reported that many studies are conducted on theoretical subjects (Taticchi et al., 2015), and the few ones conducted on empirical issues are primarily focus on a selected range of manufacturing sectors like automotive or electronics (Hassini et al., 2012). Additionally, other paper argued that the main focus in research cases is on North American and Europe (Taticchi et al., 2013). Those gaps could be filled up by more practical SSCM studies at industry or site levels and from Asia-Pacific, Africa, South America in future.

2.4.2. *Gaps in the methods and tools*

Reviewing the previous literature, the main gap from method and tool in supporting SSCM decision making are the lack of quantitative and quantifiable justification methods, the under capacity utilisation of DSS/SDS/DES, the open question on MCDM and DM process integrity, and the utilisation possibility of the MCDM-TBL-DES combination.

The qualitative method outnumbers the quantitative one in SSCM. This is discovered by a review of more than 300 papers in 15 years showing that only 11.7% of the studies used quantitative method (Seuring, 2013). However, qualitative method could not always provide sufficient support in decision making. Management teams may not satisfied with decision making practices based on qualitative judgements such as trust, experiences, and estimated benefits (Yingling & Detty, 2000). Especially SCNR, it is also argued that there is a real need for innovative DSS which could efficiently support decision makers in the change process (Allaoui et al., 2019; Lenny Koh et al., 2013), and that demanding decision making tasks would then require strong quantifiable justification methods (Stank et al., 2001). Thus, DSS which can provide quantifiable justification should be studied more in SCNR.

Though DSS is among the most supportive tools in assisting decision makers to solve the main issues in supply chain (Teniwut & Hasyim, 2020), DSS is also not utilised totally in supporting decision making in SSCM. Previous research found that the majority of the DSS studies on SSCM tackle individual aspects, either the environmental, or social, or economic ones (Bai & Sarkis, 2010). Similar findings also suggest that DSS should be utilised in solving complex SSCM problems from a full TBL approach (Taticchi et al., 2015).

In SCM, SDS is considered as the most DSS approach (Teniwut & Hasyim, 2020). However, there is still a shortage of research on SDS at the industrial level and also on an individual business level (Hilletofth et al., 2016). This research gap should be covered in future research, as also proposed in another paper that more studies of SDS for specific business groups and cases are needed, for example in the wood supply chain (Kogler & Rauch, 2018).

Though DES is the backbone in simulation research (Siebers et al., 2010), DES still has more capability to be utilised in SSCM. DES is a natural approach in SCNR (Van Der Vorst et al., 2009), and it has been used widely (Huang et al., 2003; Kogler & Rauch, 2018; Kurkin & Šimon, 2011; Mobini et al., 2011). Despite the usefulness of DES in SCNR, it seems not having much application in SSCM (Van Der Vorst et al., 2009). Knowing that DES could handle complex systems (Kogler & Rauch, 2018), these suggest a need to further explore the DES application in the complicated SSCM.

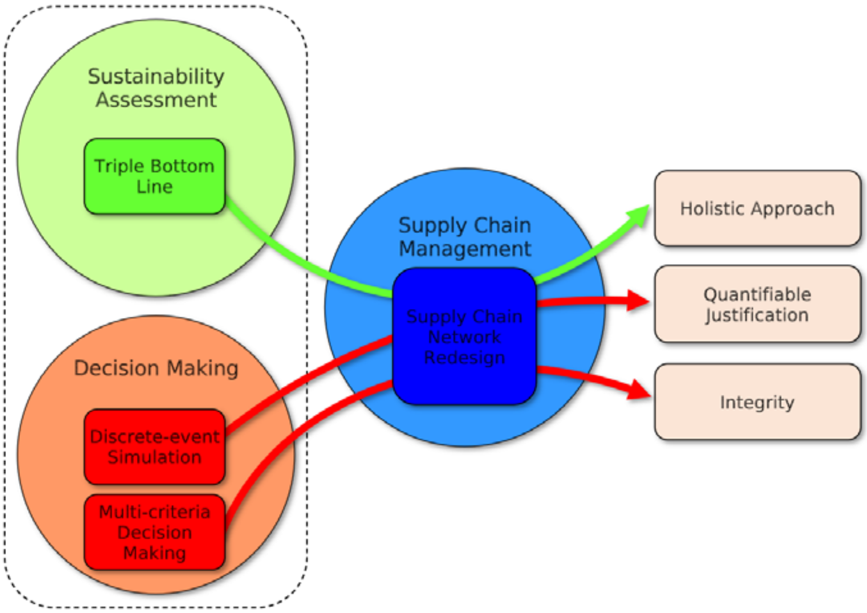
MCDM is the natural method required to address multidimensional character of real world problems involving multiple conflicting viewpoints (Zopounidis & Pardalos, 2010). However, its practical implementation still has some unclear issues. While many scholars noted that MCDM provides a systematic, transparent approach that enhances objectivity and generates results which could be trusted with reasonable satisfaction (Janssen, 2001), other researchers still argued that MCDM has a high risk of manipulation which may lead to a false sense of accuracy (Zardari et al., 2015), and then badly affect the integrity of a decision making process. In order to have a better knowledge on how to utilise MCDM properly, future research should have more exploration on how MCDM could affect the integrity.

In SSCM, it is observed that MCDM has been typically combined with TBL for sustainability assessment studies in many papers (Cruz, 2009; Govindan et al., 2013; Erol et al., 2011; Nagurney & Nagurney, 2010). Though MCDM was proposed as an important analysing step leading to the final decision in a study using DES to model a SCNR for integration of DM on quality and sustainability (Van Der Vorst et al., 2009), actually the modelling method combining TBL, DES and MCDM is rarely used in SSCM, as only one paper using this method in logistics for a plant could be found (Celestino et al., 2011). These findings suggest that the modelling method combining TBL, DES and MCDM should be studied further in future research.

2.5. Conceptual model

From the research gaps in the previous section and the research topic of this study, three main research foci were identified for this study: the lack of a holistic approach in performance assessment; the scarcity of quantifiable justification; and the integrity question in MCDM implementation. Based on the research topic and the main issues identified above, the conceptual model for this research is proposed and illustrated in Figure 12.

Figure 12 - Conceptual Model: Modelling Supply Chain Sustainability



This model consists of three main groups. The first group is the proposed modelling method for supply chain sustainability assessment to be examined in the study (the combination of TBL, DES and MCDM - the dotted rectangular on the left of the figure). The second group is the subject of the study on which the modelling method is examined, which can also be considered as the context of the study (the SCM and SCNR - the blue round in the middle of the figure). The third group is the possible outcomes from the utilisation of the modelling method in the process (the holistic approach, quantifiable justification and integrity - the three boxes on the right of the figure). The arrows are to represent the interaction between the modelling method and the subject, as well as to show the causal relationship between the modelling method and the outcomes.

This conceptual model set up a theoretical framework of a modelling method for supply chain sustainability assessment and illustrate how the different components of the study are linked and interacted. The logic of the model will be the base for further study in the next chapters.

2.6. Summary

The previous sections have reviewed the literature on three main aspects of this study: SCM, Sustainability, and DM. In summary, supply chain operations, being considered as important business activities which are facilitating approximately 80% of global trade (Sisco et al., 2015), are constantly changing (Booth & Philip, 1998; Choi et al., 2001; Sinrat & Atthirawong, 2018; Stevens & Johnson, 2016; Tummala & Schoenherr, 2011), due to the more unpredictable business environment (Bennett & Lemoine, 2014), the leading role of SCM in the business competition (Christopher, 2011; Xiao et al., 2012), and the raising concerns in environmental and social issues (Stevens & Johnson, 2016). Particularly, more and more enterprises are interested in a sustainable supply chain (Seuring & Müller, 2008). SCND, being considered as the foundation of SCM (Nagurney, 2010), is also changing accordingly, leading to SCNR.

In SCNR, DM is an important process as good decisions could improve the efficiency and effectiveness of the whole supply chain (Lambert & Cooper, 2000). However, there are still many gaps found from the literature in SCM and SSCM which may affect to the decision making in SCNR. This study focused on some significant gaps which are the lack of a holistic approach in performance assessment (Devika et al., 2014; Gunasekaran et al., 2004; Lummus & Vokurka, 1999) and sustainability assessment (Ashby et al., 2012; Hassini et al., 2012; Singh et al., 2009; Seuring & Müller, 2008), the scarcity of quantifiable justification of DSS (Stank et al., 2001), and the integrity question in MCDM implementation (Janssen, 2001; Zardari et al., 2015). From these gaps, a conceptual model was built to proposed an examination of a modelling method for sustainability assessment which combines TBL, DES and MCDM to evaluate the possible outcomes on a SNCR. The details of the examination are discussed in the next chapter.

Chapter 3. Research methodology

This chapter presents a description and justification for how the study was conducted, in order to address the aforementioned problems. First, the research questions and hypotheses are explained based on the research topic and the literature review. Second, ontological and epistemological perspectives are discussed in order to build the research fundamentals on what is regarded as the social world and how the knowledge about the social world could be obtained. Third, research methodology is appraised so that the most suitable one is selected for this study. Fourth, research design and data collection are established in order to identify the research plan in detail. Fifth, measurement and analysis are presented to operationalise the concepts. Sixth, ethical issues are considered. Lastly, validity and reliability are discussed to evaluate the chosen method.

3.1. Research questions and hypotheses

When tackling the issues in SCM identified in the previous chapter, which are the lack of a holistic approach in performance assessment and sustainability assessment, the scarcity of quantifiable justification of DSS, and the integrity question in MCDM implementation, this study aimed to provide a recommendation for a sustainability assessment method to sufficiently support decision makers in SSCM. The objectives of this study are to examine the utilisation of a modelling method which combines TBL, DES and MCDM for the sustainability assessment of a SCNR case. This examination was expected to reveal the influences of the modelling method on the outcomes of the holistic approach, quantifiable justification and integrity. Therefore, the research question was formed, which is “how could utilising a modelling method of combining TBL, DES and MCDM influence the sustainability assessment of a SCNR case?”.

Considering the conceptual model proposed in the previous chapter, three hypotheses for this question were built up:

- the integration of TBL could bring a holistic approach for the assessment
- the implementation of DES could provide quantifiable results for justification
- the utilisation of MCDM could ensure the integrity of the decision making process.

The actual sustainability assessment for the case will be presented in Chapter 4 - Data analysis, and the answers for these research questions will be examined in Chapter 5 - Discussion.

3.2. Ontological and epistemological perspectives

Ontology defines what the nature of the world is and epistemology reveals how knowledge could be acquired (Saunders et al., 2016). Ontology and epistemology are also among the main factors used to develop a research strategy (Bell et al., 2018). This section presents the different categories in ontology, epistemology, and the adopted position of this study.

To categorise different ontological viewpoints, there are two main groups which are objectivism and constructionism (Bell et al., 2018). Objectivism considers the reality as an external factor to observers, whereas constructionism believes in the world constructed by observers' activities and meaning-making. Their differences could be highlighted when reflecting on social science studies, especially on organisation and culture. Table 2 provides some distinguished views of objectivism and constructionism on the organisation and culture.

Table 2 – Objectivism and Constructionism (Bell et al., 2018)

Viewpoint	Objectivism	Constructionism
Organisation	A tangible object, external to individuals who inhabit it, which has fixed rules, regulations, procedures, hierarchy, and mission statements	A social construct raised from the interaction of individuals, in which social order is continually being terminated, established, renewed, reviewed, revoked, revised, etc.
Culture	A repository of shared values and customs in which people could function as full participants	An emergent reality in a continuous state of construction and reconstruction

The ontological viewpoint of this study was selected as an objectivism one, because the relationship between the utilisation of TBL, DES and MCDM, and the respective outcomes on holisticness, quantifiable justification, and integrity should be observed objectively. Notably, the author also had no control over behavioural events in the examination of the study.

Turning to epistemology, it could be divided into two most typical contrasting types, which are positivism and interpretivism (Bell et al., 2018). While positivism assumes that knowledge should be accepted when it is observable and measurable (which is advocated by the methods of natural sciences) and that theory will guide the research (deductive); interpretivism suggests that the study of social science should be totally different from natural science, the latter of which approaches the social world from the social interaction between humans and their behaviours, and research will construct a theory (inductive). Table 3 (next page) shows these differences in details.

The position of epistemology for this study was adopted as positivism, as a large amount of data will be collected, processed and analysed when examining the utilisation of TBL, DES and MCDM in sustainability assessment to support decision making in a SCNR. This epistemology position is also in line with the author's background in physics and engineering.

Table 3 - Positivism and Interpretivism (Bell et al., 2018)

Category	Positivism	Interpretivism
Basis	Natural sciences	Human interactions
Approach to social science	Explanation and generalisation of human behaviour, objectivity required	Causal explanation and interpretive understanding of human behaviour, subjectivity accepted
Subject matter	Nature	Social reality
Subject action	Inanimate and unmotivated	Meaningful and engaged
Data collection	Observation, measurement, mostly quantitative	Comprehend the perspective of the human subjects, mostly qualitative
Theory relation	Mostly deductive	Mostly inductive

3.3. Appraisal and selection of research methodology

Research methodology is the strategy that governs the general orientation of research (Bell et al., 2018). There are two main research methodologies: quantitative and qualitative. The following sections present these methodologies, comparison them, and describe the selected research method for this study.

Quantitative research could be considered as a research strategy focusing on quantification in the collection and analysis of data (Bell et al., 2018). This strategy involves a deductive approach for a research to test theories. It integrates the practices and standards of the natural scientific model, and more specifically, of positivism (Arghode, 2012; Bryman, 1984; Firestone, 1987; Mackenzie & Knipe, 2006). In addition, it contains a view of social reality as an external, objective reality.

In contrast to quantitative, qualitative research could be considered as a research strategy focusing on words rather than quantification in the collection and analysis of data (Bell et al., 2018). This strategy involves an inductive approach for research to generate theories. It does not include practices and standards of the natural scientific model or positivism, but supports the individual interpretation of the social world. The qualitative strategy is usually used in interpretivism (Sale et al., 2002; Saunders et al., 2016; Yilmaz, K., 2013.). Moreover, it contains a view of social reality as a constantly shifting emergent property of individuals' creation. Table 4 presents the fundamental differences between quantitative and qualitative research strategies, and their relationship to epistemological and ontological viewpoints.

Table 4 - Quantitative and Qualitative Methods (Bell et al., 2018)

Category	Quantitative	Qualitative
Reasoning	Deductive	Inductive
Epistemology	Positivism	Interpretivism
Ontology	Objectivism	Constructionism
Data type	Numbers	Words
Data attribute	Hard and reliable	Rich and deep
Driving viewpoint	Researcher	Participant
Researcher involvement	Distant	Close
Relation with theory	Theory testing	Theory emergent
Reality depiction	Static	Process
Organisation	Structured	Unstructured
Finding type	Generalisation	Contextual understanding
Research scale	Macro	Micro
Research concern	Behaviour	Meaning
Research setting	Artificial settings	Natural settings

Despite the differences, there are also similarities in quantitative and qualitative research (Hardy & Bryman, 2009). Both methods are concerned with data distillation, research questions, data analysis and research literature, variation, frequency, distortion, transparency, error, and appropriateness to the research questions. Although these similarities are quite general, this finding demonstrates that quantitative and qualitative research are not completely different.

This study utilises the quantitative method, because this method collects numerical data, which could help researchers with an objectivism/positivism view in order to gain a better understanding by the clear and unique value, in comparison with the complex meaning and value of word/image data in the qualitative case (Bell et al., 2018). The selection of the quantitative method was also made in response to the call for more quantitative method in SSCM research, since the qualitative method has been dominant in SSCM research (Benjaafar et al., 2012; Seuring, 2013).

It is important to note the limitations of the quantitative method in general and in this specific study. Although the quantitative research is expected to be accurate in general, the measurement tools and processes are artificial and the samples may not reflect the whole complex reality (Bell et al., 2018). Due to the use of advanced simulation software, which is presented later in Section 3.6.2. Analysis, the limitations mentioned above are minimised in this study.

3.4. Research design and data collection

3.4.1. *Research design*

A research design is “the blueprint for fulfilling objectives and answering questions” (Neuman, 2014). It is an important element in undertaking quality research as it provides a framework for the whole study. There are different research designs and their essentials are summarised in Table 5 (Cooper & Schindler, 2014; Neuman, 2014), in which the essentials of the research design incorporated into this study are emphasised in italics.

The design of this research is a formal ex post facto longitudinal simulation case study, as also explained in detail in Table 5. There are various reasons for this choice. Firstly, a case study is a standard research design in various empirical studies, especially in answering how or why questions for a contemporary phenomenon in which the researcher has virtually no control over the subject’s events (Yin, 2018). Secondly, quantitative case studies are popular in hypothesis testing (McCutcheon & Meredith, 1993), such as in this study. Thirdly, a similar case study utilising DES combined with MCDA in maritime transport system concludes that the combination is an efficient way to help decision making on complex systems (Celestino et al., 2011). This case study examines the same combination of DES and MCDA, but in an SSCM context, to provide opportunity to see if the results correspond. Lastly, simulation is a useful method in hypothesis testing when it is difficult for the researcher to collect real data (Cooksey, 2020).

It is worth highlighting two important notes about case studies. First, when applying case study research to the evaluation of new methods and tools, as in this study, unlike other research designs, it is not necessary to fully define current methods and tools used as comparisons (Kitchenham & Pickard, 1998), as these definitions could be derived from the literature (Bitektine, 2008). Second, case studies are often misunderstood as purely qualitative, and considered as having little generalising ability compared to survey and other quantitative methods. In fact, case studies are generalising analytically to theoretical propositions, rather than generalised statistically to populations or probabilities, thanks to the (Yin, 2018).

Table 5 – Research Design (Cooper & Schindler, 2014; Neuman, 2014)

Essential	Options	Meaning
Research question	Exploratory study	For discovering the research questions
	Formal study	*For answering the research questions*
User and audience	Basic	Scientific community
	Applied	*Practitioners*
Data collection	Communication	By interaction with the subjects
	Monitoring	*By observation of the subjects*
Control of variables	Experimental	Variables could be manipulated
	Ex post facto	*Variables cannot be controlled, only reported*
Purpose	Reporting	To provide a summation of data
	Descriptive	To find who, what, where, when, how much
	Causal - Explanatory	To explain variables' relationship
	Causal – Predictive	*To predict variables' relationship*
Time dimension	Cross-sectional	To represent a snap shot of one point in time
	Longitudinal	*To track changes over a period of time*
Topical scope	Statistical study	To study in breadth for a large population
	Case	*To study in depth of a specific context*
Research environment	Field setting	Actual conditions
	Laboratory	Manipulated conditions
	Simulation	*Replicated conditions*
Participants' perception awareness	Modified routine	With deviations from normal routines
	Actual routine	*Without deviations from normal routines*

Note. The essentials of the research design of this study are emphasised in italics.

3.4.2. *Data collection and generation*

This section presents the data collection within a selected context for the study. The context is explained first, then the data collection follows.

A business case within New Zealand forestry industry was selected as a suitable industrial case for this study. This was an endeavour to fill some gaps from the literature, which suggested that more SSCM research is needed in areas and countries outside North American and Europe (Taticchi et al., 2013). Additionally, further study on DSS/SDS implementation should also be conducted on an industry level for industries with low usage of DSS including forestry industry, and on individual business levels (Kogler & Rauch, 2018; Teniwut & Hasyim, 2020).

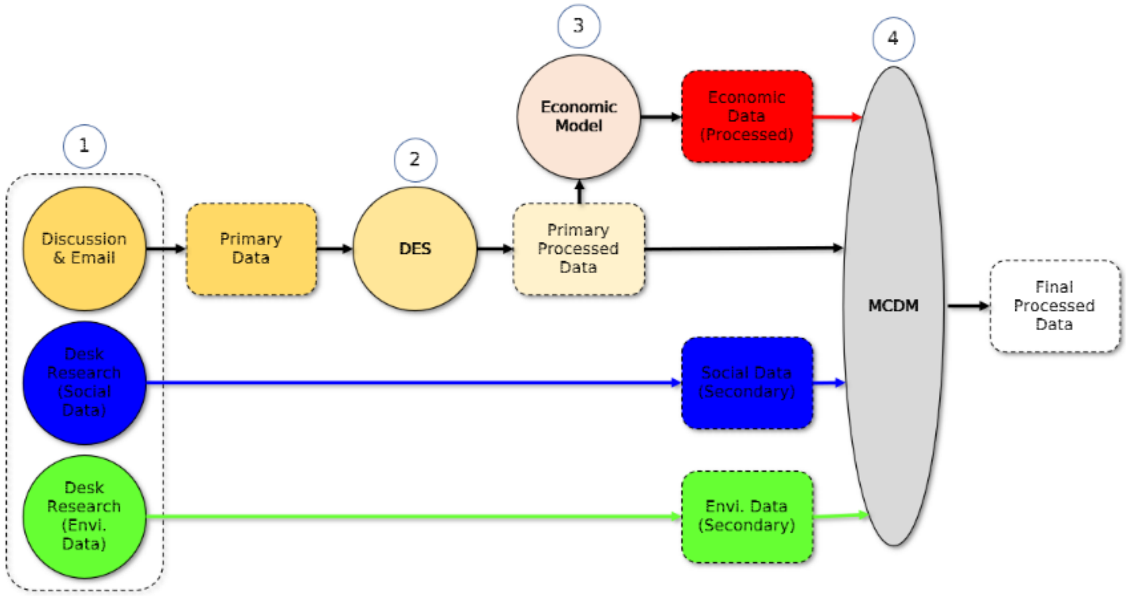
Forestry is the third largest export industry in New Zealand, contributing $6 billion annually to the nation’s economy (Forestry New Zealand, 2020). In 2019, a project named “Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age” (FWMA) was started as a joint venture between the government and the forest industry. The aims of the project is to generate more added value and profit and to improve sustainability for the New Zealand forestry value chain through innovation (Forest Value Chain Consortium, 2018). The project proposes a new SCND to replace a current one on a country level, and a feasibility study including a sustainability assessment is required to sign-off the project into prototype development. This study was conducted within the context of one SCNR case in the proposed FWMA project.

It is important to introduce some key project partners who provided the data for this study. Forest Growers Research (FGR) is the managing partner for the development and commercialisation parts of the project (Forest Value Chain Consortium, 2018), who was appointed thanks to the coordinator role in New Zealand forest industry research (Forest Growers Research, 2020), the significant success and the vast experience in the New Zealand forestry industry (Forest Value Chain Consortium, 2018). Scion, a Crown research institute specialising in research, science and technology development for the forestry sector, is a research partner of the project who is responsible for the feasibility study, with the technology support from Awdon Technologies Ltd (Forest Value Chain Consortium, 2018).

There are two types of data collected in this study: primary data and secondary data. Primary data are the data collected directly by the researcher via observation, surveys, or interviews (W. C. Booth et al., 2016), whereas secondary data are collected by others and only used by the researcher (Greener, 2008). In this research primary data relate to the supply chain processes, and secondary data mainly relate to the TBL.

The data generation and flow in this study followed four main steps which are presented in Figure 13. The first step (1) is the collection of primary data and secondary data. The second step (2) is the processing of the primary data in the DES to produce the primary processed data. In the third step (3), the primary processed data were then processed in an economic model to produce the economic data. In the fourth step (4), the primary processed data, the economic data, the social data and the environmental data were all processed in the MCDM to produce the final processed data for data analysis.

Figure 13 – Generation and Flow of Data



Note. Envi.: Environmental

The collection of the primary data was carried out by two main methods: discussion and email exchange. Discussions and email exchanges were carried out with the FWMA project team members including a FGR Harvesting team leader, Scion scientists and a manager from Awdon Technologies Ltd. All data were recorded in Excel files and circulated for review and confirmation. The primary data were also used in an economic model to produce economic data, as in Figure 13. The collection of secondary data was taken from desk research. In this study these data were the social and environmental one.

3.5. Measurement and analysis

3.5.1. *Measurement*

Measurement plays a core role in empirical research of any type, because measurement enables the observation of invisible concepts and constructs, by connecting technique and procedure (Neuman, 2014), and because inappropriate measurement could destroy research results (Merom & John, 2019). In order to measure a concept, researchers have to identify the attributes or objects of the concept, and to determine measurement scales for the attributes (Thorndike-Christ, 2014). This process is considered as the operationalisation of concept (Bell et al., 2018; Neuman, 2014). Sometimes, identifying the attributes of the concept or determining measurement scales are not possible in a direct way. In this case a valid surrogate (Kitchenham & Pickard, 1998), or an auxiliary theory (Neuman, 2014) could be an alternative to link conceptual definitions to concrete operations for the measuring purpose.

There are four different scales of measurement in research (Cooksey, 2020). The first scale is the nominal one, which is the simplest measurement scale. This scale allows the classification of objects into categories representing some common characteristics. This classification reflects the qualitative basis in all research methodologies (David & Sutton, 2011). The second scale is the ordinal one, which could provide the ranking for the objects but cannot indicate the distances between them. The third and the fourth scales are the interval and ratio ones, which could measure the objects continuously. However, only the ratio scale has the true zero point. The ratio scale is the most complex and precise measurement.

In this study, the operationalisation of concepts with the specific measurement scales is developed from the conceptual model in the previous chapter, and presented in Table 6. An approach in SSCM is considered holistic if it could reflect all three sustainability dimensions (Brandenburg et al., 2014), the number of sustainability dimensions addressed in an approach was identified as the attribute to measure whether an approach is holistic. The existence of numerical results which could be ranked was identified as the attribute to define the quantifiability of the results. Since the stakeholders play an important role in building integrity (Turnbull, 1995), the number of stakeholders involved in decision making processes was identified as the attribute by which to measure integrity.

Table 6 - Operationalisation of Concepts: The Measurement Scales

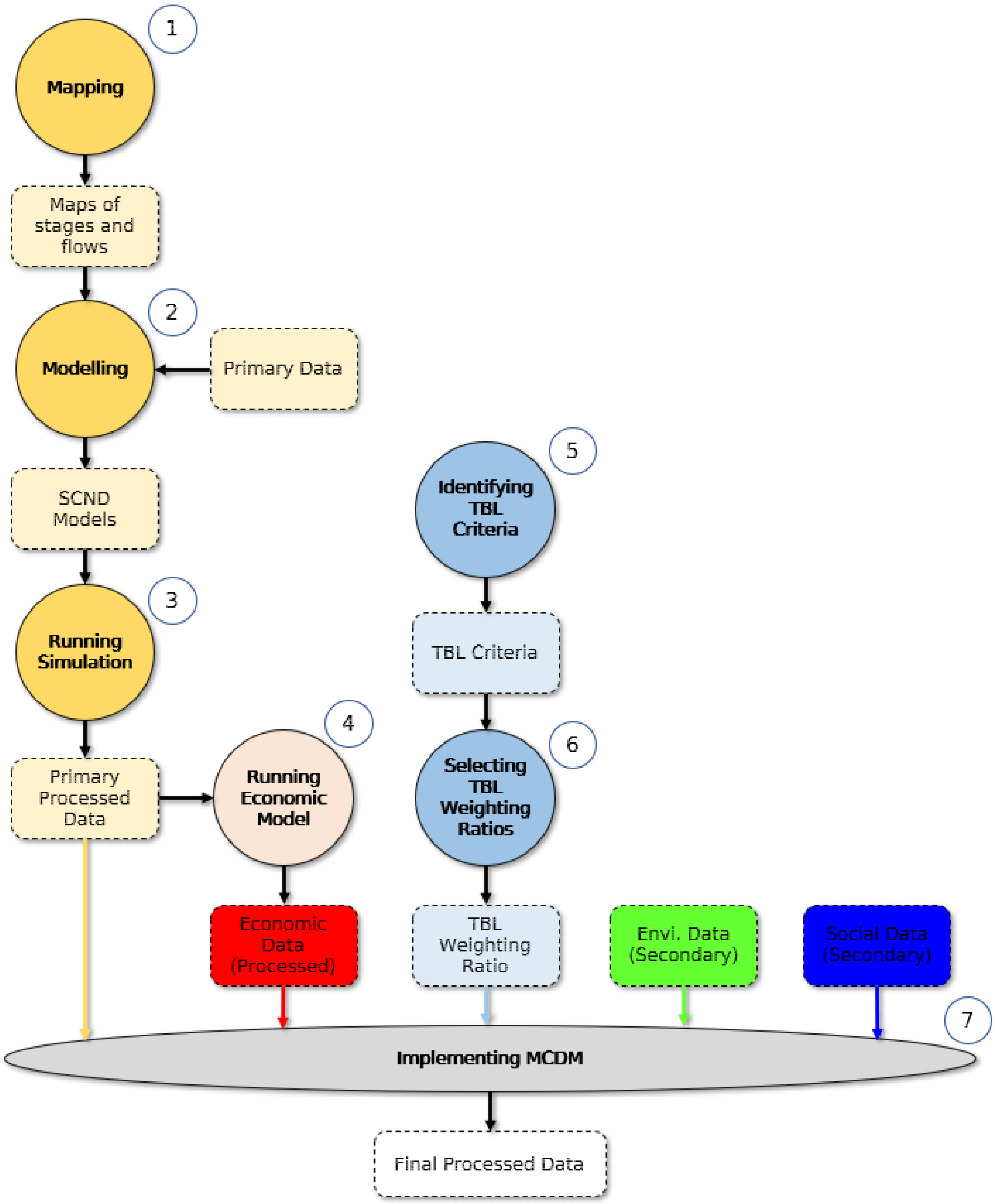
Concept	Attribute	Scale (Value)
Holistic nature of the approach	The number of sustainability dimensions addressed (social, economic, and environmental)	Ratio (Numerical)
Quantifiability of the results	The existence of numerical results which could be ranked	Nominal (True/False)
Integrity	The number of stakeholders involved in decision making process	Ratio (Numerical)

3.5.2. *Analysis*

In this study, DES and MCDM were utilised as the main analytical tools. DES is a simulation method which focuses on showing the process flow and sequences of each activity or event at a certain point of changes level that occur in the system in a discrete time, by using the top down approach and a stochastic method (Sumari et al., 2013). DES also shows the period of time for activities to wait from one state to another state of event, therefore the next event that is going to happen could be predicted. ExtendSim was selected as the DES tool for this study because it has built-in support of visual intuitive graphical user tools facilitating model development via flexible drag-and-drop style interfaces; real-time visualisation via charting to comprehend the model's adaptation, evolution and functional profiles; and it is categorised as moderate development and between medium and small scale in computation modelling strength (Abar et al., 2017).

MCDM is a method to search for an optimal decision or solution from a set of alternatives and a set of decision criteria (Triantaphyllou, 2000). In this study, Weighted Product Model (WPM) was selected as the MCDM because it is the most common and suitable method for implementing the multi criteria analysis, in cases where the criteria measurement units are different (Triantaphyllou, 2000). In a WPM, each alternative is compared with others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. The analysis of data in this study followed the steps presented in Figure 14.

Figure 14 – Data Analysis Steps



Note. Envi.: Environmental

In the first step in Figure 14, all supply chain operational stages and flows of different SCND processes were illustrated in detailed maps, then the SCND processes were modelled on ExtendSim in the second step based on these maps and the input from the primary data. In the third step, the SCND models were run to produce the primary processed data. The economic model was run to produce economic data in the fourth step. In the fifth step, specific TBL impacts and criteria were identified among social, economic and environmental dimensions. The sixth step was selecting different weighting ratios for the TBL criteria. WPM method in MCDM was then implemented to calculate the sustainability assessment results of from the primary processed data, the economic/social/environmental data and the weighting ratios in the last step. Detailed analysis is presented in the next chapter.

3.6. Ethical considerations

Research should follow norms or standards to ensure that no one is harmed or suffers adverse consequences from research activities (Cooper & Schindler, 2014). As this study was conducted under Massey University, the university's *Code of Ethical Conduct for Research, Teaching and Evaluations involving Human Participants* (the Code) was followed strictly. In general, there are two major characteristics of the study which mostly affect ethics, which are the research theme and the research relation with participants. These will be discussed below.

Regarding the research theme, this study is conducted for the sustainable supply chain of New Zealand forestry, which is a major industry of the nation. Therefore, the spirit of the Treaty of Waitangi, especially the social responsibility part, was strongly promoted.

In relations with participants, this study had little direct contact with participants in real life. This is because this study was a simulation-based case study with a specific context from a normal business, and data processing occupied much more time compared with data collection, including discussions. Moreover, most of the communication was carried out electronically via email, telephone and online meeting. Therefore, data handling is the most important ethical issue. Regarding data handling, all data carrying objects (documents, electronic storage and emails) were considered as materials for the research, and confidentiality was carefully considered. No specific name of location was revealed in the study. An agreement relating to the FWMA project was also signed to ensure the data handling requirements were understood and adhered to.

In reviewing the implementation of the Code of this study on other principles, as regards autonomy, participants were given all related information prior to the interview and the data collected was also communicated back to participants for review and confirmation. In terms of harm, there was no hazardous threat identified in this research for any beings. With regard to relationship, no conflict of interest was detected.

3.7. Validity and Reliability

Validity and reliability are two important aspects influencing the quality of a research project. While validity deals with the correctness of the measurement of the concept in that research, reliability concerns the consistency of measures (Bell et al., 2018). In a case study research, there are three types of validity (Yin, 2018). Construct validity is the first type which identifies correct operational measures for the concepts being studied. Internal validity is the second type which seeks to establish a causal relationship. External validity is the third type which shows whether and how a case study's findings could be generalised.

In order to increase the research validity and reliability of this study, different actions were carried out, following the tactics recommended by Yin (2018), which are presented as follows. To increase the construct validity, the use of multiple sources of evidence was suggested to establish a chain of evidence in data collection, and to have the case study reviewed by key informants. This study collected information from various documents, observations and interviews with different industry and academic experts, and kept all evidence in versions to be traceable. To achieve internal validity, pattern matching, explanation building, and using logic models were recommended. This study took the matching pattern from a similar case study utilising DES and MCDA in maritime transport, built explanation by comparing the results of data analysis against the proposed conceptual model initiated and revising it, and used DES as the main logic model for all activities. The DES logic model was also tested by a sensitivity analysis. To strive for external validity, appropriate theory was encouraged. This case study developed the conceptual model and the research questions which could allow analytical generalising to certain managerial/policy implications from the results. The actions above are presented in Table 7 (next page).

In summary, to tackle the research question on how utilising TBL, DES and MCDM could help in improving sustainability assessment of a SCNR, this study utilised a quantitative method with the view of objectivism and positivism, and was designed as a formal ex post facto longitudinal simulation case study to examine the actual implementation of TBL, DES and MCDM in sustainability assessment and decision making of a New Zealand forestry project proposing a SCNR. The examination results are presented in the next chapter, Chapter 4: Data analysis.

Table 7 - Validity and Reliability Tactics and Actions (Yin, 2018)

Item	Tactic	Actual action taken
Construct validity	Multiple sources of evidence	Documents, direct observations and interviews with different experts were carried out
	Chain of evidence	Evidence was recorded in versions to be traceable
	Key informants review	Industry and academic experts were consulted
Internal validity	Pattern matching	A similar case study utilising DES and MCDA in transport was reviewed
	Explanation building	The data was compared against the conceptual model initiated for revision
	Rival explanations	N/A
	Logic models	DES was used as the main logic model for all activities. A sensitivity analysis was also conducted to evaluate the model
External validity	Theory	Certain managerial/policy implications could be generalised from the specific context but common SCND of the case study
Reliability	Case study protocol	The context of the case study and research question were defined clearly, the research design was built carefully, and the data was collected accordingly; The logic of the case study could be replicated in certain different contexts or cases
	Case study database	Excel file format was used to store, calculate and communicate all data, which could be easily reviewed
	Chain of evidence	Evidence was recorded in versions to be traceable

Note. N/A: Not applicable.

Chapter 4. Data analysis

This chapter details the examination of the modelling method of TBL, DES and MCDM in sustainability assessment a New Zealand forestry industry SCNR project to support the decision making by comparing the sustainability of the current SCND and the proposed alternatives. The first section of the chapter provides the overview of the New Zealand forest supply chain change case study. The second section describes the simulation set up for the case. The third section explores the multi criteria analysis working method. The fourth section discusses the results. The fifth section summarises the chapter.

4.1. Overview of the case study

4.1.1. *New Zealand forest supply chain*

The role of forests in New Zealand

New Zealand is an island nation located on the boundary of the Pacific and Indo-Australian tectonic plates, and comprising one large island in the North, another large island in the South and several smaller islands (Ministry for the Environment, 2007). The land was first explored by the ancestors of Māori between 1200 and 1300 AD, then by Europeans in the 17th century (New Zealand Immigration, 2020). More than 80% of the land was covered by forests before people arrived in New Zealand, however current forest coverage is only 38% as many forests were cleared for human housing and food production (Ministry for Primary Industries, 2020). Forests are crucial to New Zealand because they represent significant commercial value, and also contribute to the nation’s spiritual, social, cultural, and environmental values (Forestry New Zealand, 2020).

Forestry is a key economic factor in New Zealand because it is the third largest export industry, contributing $6 billion annually to New Zealand's economy, which accumulates to 1.6% of the nation’s GDP (Forestry New Zealand, 2020). The harvested log volume in 2018, which was 35.4 million m^3, was an increase of 10% over 2017 (New Zealand Forest Owners Association, 2020a). Moreover, the volume is expected to be high in the next decade, because forests planted in past decades will become harvestable (Forestry New Zealand, 2019). The forecasted forestry export revenue is $6.9 billion in 2019, which will be an 7.8% increase from 2018 (New Zealand Forest Owners Association, 2020a).

Forests are vital in spiritual and cultural heritages in New Zealand. In the mythology of Māori, who are one of the first native people of New Zealand, humans and forests were created and connected together from the beginning, and the beauty and spiritual value of forests have been honoured since then (Forestry New Zealand, 2020). This cosmology has been recognised and upheld in law in New Zealand since the 1980s (Magallanes, 2015).

New Zealand forests play a key role in society. Different forest types like national parks, scenic reserves, and other conservation areas are host many social activities such as recreation, adventure and making memories (Forestry New Zealand, 2020). Forest industry also provides employment to approximately 35,000 employees in production, processing and trading (Forestry New Zealand, 2019).

Forests are essential for the New Zealand environment. Forestry New Zealand (2020) remarked that forests preserve different plants and animals. They also reported that forests act as a carbon sink which absorbs and retains carbon dioxide in the roots, leaves, branches and trunks, therefore the amount of greenhouse gases released into the air could be reduced and climate change could be mitigated. Furthermore, forests play a crucial role in cleaning the air and water, and reducing land erosion (Forestry New Zealand, 2020).

Facts and figures of New Zealand forestry industry

This part of the research provides some facts and figures regarding forestry industry in New Zealand from the following aspects: geography and plantation, size and management, authority and distribution.

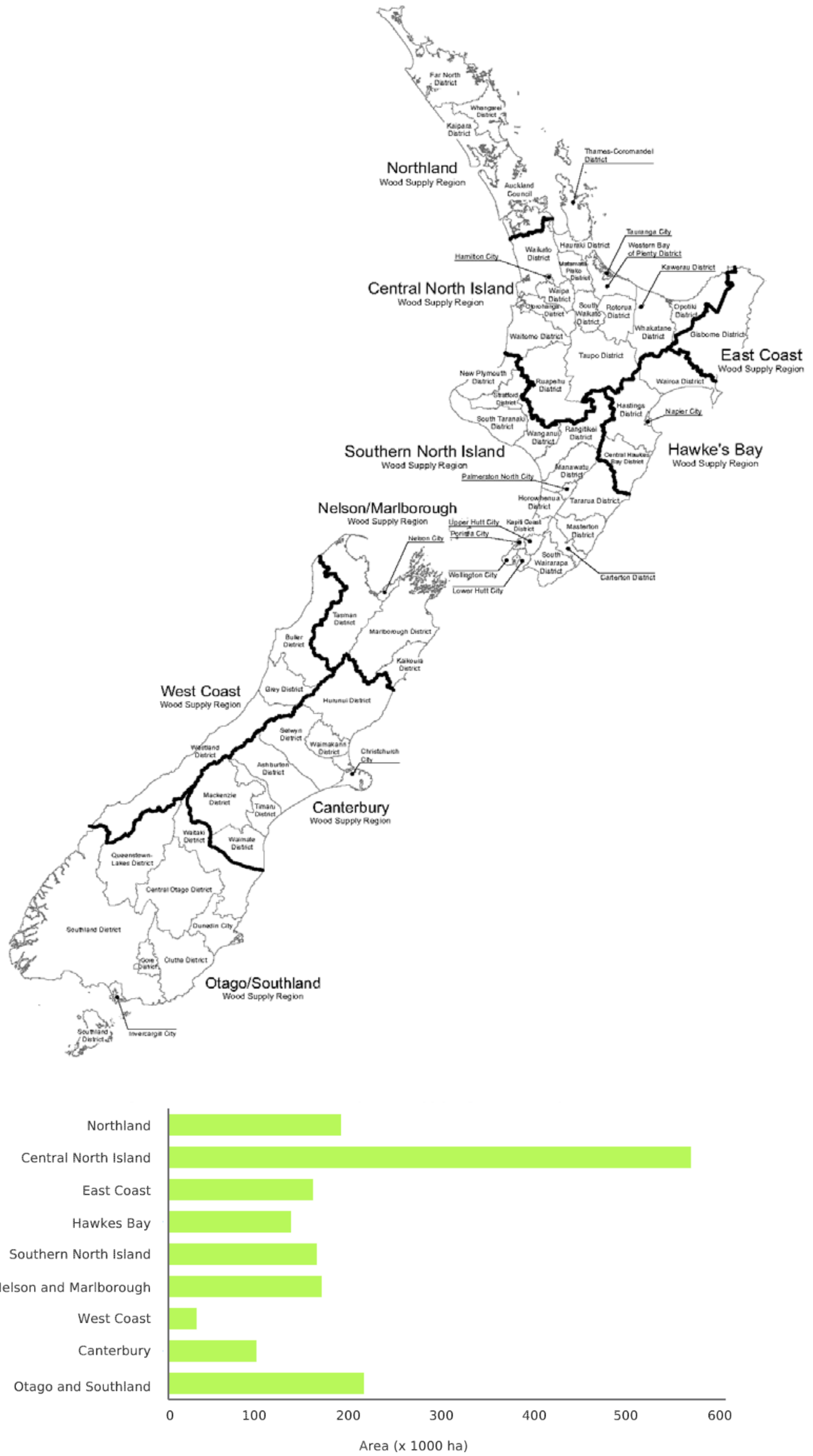
Today forests occupy 10.1 million hectares, equal to 38% of land area in New Zealand; plantation forest takes 2.1 million hectares (including the productive area of 1.7 million hectares and reserve areas) and native forest occupies 8.0 million hectares (Ministry for Primary Industries, 2020). Most of the plantation forests are in the hillier, steeper parts of the country and these terrain factors influence timber harvesting efficiency (Obi & Visser, 2017; Phillips et al., 2017). Mass plantations of exotic species were carried out in the 1920s, 1930s, 1960s and many in the 1990s to replace the fast destruction of native forests leading up to the 1910s, and prepare for domestic needs as well as future exports (Ministry for Primary Industries, 2020; Page et al., 2000).

Approximately 20% of plantation forests are less than 100 hectares, and more than 50% of timber volume produced is not from large forestry companies (Visser, 2016). The majority of plantation forests (96%) are owned by private companies for production purposes and most of the New Zealand government’s commercial forests are managed by Crown Forestry (Ministry for Primary Industries, 2020).

All districts and cities in New Zealand with generally similar growth patterns of forests and representative wood supply and processing catchments are grouped under the National Exotic Forest Description (NEFD) into nine areas: Northland, Central North Island, East Coast, Hawke’s Bay, Southern North Island, Nelson and Marlborough, West Coast, Canterbury, and Otago and Southland (Ministry for Primary Industries, 2019b).

Regarding the distribution, the Central North Island of about 580,000ha is the biggest region taking one third of the total area, while other North Island regions occupy 37% and South Island regions hold 30% of the total (Forest Value Chain Consortium, 2018). The smallest region is the West Coast in the South Island, having only around 30,000ha of forest. All other regions have approximately the same area of forest which is about 190,000ha. The wood supply areas and their distributions and are illustrated in Figure 15 (next page).

Figure 15 - Wood Supply Areas and Distributions (Ministry for Primary Industries, 2019b)



The forest supply chain configuration

In order to best describe the scope of this research, the approach which considers that a forest supply chain consists of harvesting and transportation, and that their planning are mostly combined together was adopted in this study, among different perspectives (D'amours et al., 2008). The harvesting and transportation operations are discussed next.

Although the harvesting operations in New Zealand differ across sites, they all consist of four basic stages: felling, extracting, processing, and loading (Visser, 2016). These stages are described in Table 8.

Table 8 – Forest Supply Chain Stages (Visser, 2016)

Stage	Description
Felling	This is the work to cut the tree down at the base so it will lay down on the ground, using mainly chainsaws or felling machines. Chainsaws are easy to operate and maintain with a low cost. They could be used on any terrain, including steep slopes and in very soft soils where machines hardly work. Chainsaws are typically used to harvest big trees because most machines could only cut down the tree with a maximum diameter of 80cm. On the other hand, felling machines normally have a higher cost, but they are still economical when operating on flat or rolling terrain, due to their higher productivity.
Extracting	This is the work to transport the tree from the forest to a landing area. The trees could be dragged on the ground or moved by machines using a ground-based process, or lifted by wire ropes which are suspended in the air in a cable yarding process. In a ground-based process, if the trees are dragged by a grapple skidder, then the step is named as skidding, if the trees are moved by a wheeled machine like a forwarder then the step is called forwarding. The ground-based process is implemented more widely because of its higher production and lower cost.
Processing	This is the work to process trees to logs by using grapple processors mostly. These machines are equipped with a processing head attachment which has powerful rollers, knives, a measuring device and holding arms to pull and cut the trees according to the requirement set forth in the on-board computer.
Loading	This is the work to place the logs onto trucks by mainly using loaders. Before loading, logs are normally sorted and stored in separate log stacks according to their types and destinations. Loading is the final work, to place the logs onto trucks for transportation to sawmills, processing plants or ports for export.

Transportation operation is the major phase to bring the logs to customers or export ports, as it may take up to 40% of the total forest operation cost (D'amours et al., 2008). In New Zealand, High Productivity Motor Vehicles (HPMV) have been used increasingly, especially the 50 Max trucks which could carry more load (New Zealand Forest Owners Association, 2012; NZ Transport Agency, 2020), and thus reduce the transport cost.

The forest supply chain network

New Zealand has quite a complex forest supply chain network, which consists of the harvesting areas, sawmills and processing plants, and ports. These are discussed in turn in the following sections.

Harvesting areas vary substantially in size and location. They are marked green in the planted forests shown in Appendix A (Ministry of Primary Industries, 2014). There are a few large concentrated harvesting areas in the Central North Island region. Harvesting areas in other regions are much smaller and scattered differently over wide regions.

There are 93 sawmills and processing plants of different sizes in New Zealand as shown in Appendix B, in which 65 factories are in the North Island, and 28 factories are in the South Island (New Zealand Forest Owners Association, 2019). Most of the factories are located in the Central North Island where there are 32 factories operating to serve the largest forest area in the country. The West Coast region in the South Island has the least number of factories, with only two operating.

Normally, sawmills and processing plants are located near the forest harvesting areas and ports for easy transportation. In New Zealand, the locations of sawmills and processing plants are distributed differently from region to region. In the Central North Island, the factories are scattered over the whole area, while in other areas the factories are located mainly near the ports. Therefore, the logistical setups differ across regions.

There are 13 seaports in New Zealand as shown in Appendix C. These ports handle 84.9% of the total export value of the whole country (Layton, 2010). The North Island has 7 ports and the South Island has 6. There is only one port in the largest region of Central North Island, which is the Port of Tauranga, and there is no port in the West Coast region, so the logs in these two regions may need to go through neighbour ports for export.

The above section has shown in general that the New Zealand forest supply chain is quite diverse. This is due to significant differences in land terrain, forest sizes, the distribution of harvesting areas, and the locations of sawmills, processing plants and ports. In the next section a specific case study of the New Zealand forest supply chain is discussed, where both current and recommended new processes are introduced as the base for the sustainability assessment later.

4.1.2. *"Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age"*

The FWMA is a seven-year project to generate more added value and profit and to improve sustainability for the whole New Zealand forestry value chain through innovation (Forest Value Chain Consortium, 2018). This project was chosen as the case study for this research because of its similarity to the scope and objectives of the study. The following subsections provide the background and key factors of the project.

<u>Background: the development and challenges of the New Zealand forest industry</u>

In a business case developed two years ago, Forest Value Chain Consortium (2018) , forecasted a huge increase in forest harvest, being over 35 million m^3 per year in the next decade, increasing from 33 million m^3 in 2017. This group of partners consists of major forest owners, management companies, harvesting and transport contractors, and equipment-developing and manufacturing companies in New Zealand. They explain that this predicted growth is the result of both international demand and national forest maturation of mass plantation during the 1990s. Their prediction also points to the challenges the forest industry will encounter, which include:

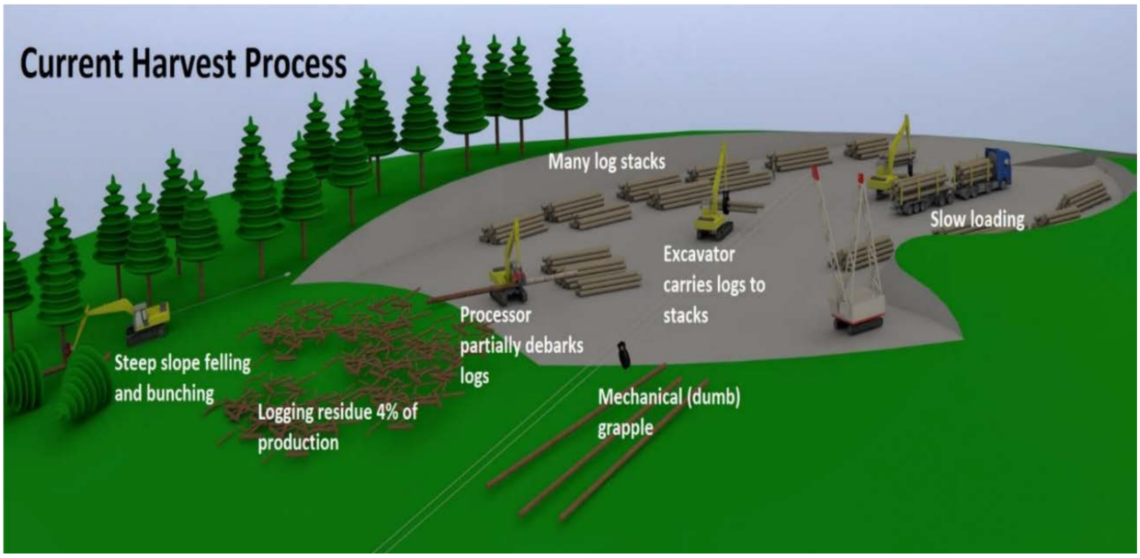
- the higher cost in forest harvesting due to the proportion of forest harvest in steep terrain areas will increase 40% by 2025. This will result in approximately 10% reduction of the harvest from small forests, which leads to the competitive loss for New Zealand in comparison with other flat forest export countries like Australia, Chile and North America, and therefore a change in harvesting technologies and approaches may be necessary;
- the decrease in future market prices, as prices were at the peak of the cycle at the time of reporting. This also leads to sensitivity of cost issues;
- the limited overall harvesting productivity, especially the bottlenecks at the log sorting process at the landing area. This also causes the requirement for large cleared landing area which is a main environmental risk on steep terrain;
- the shortage of labour in the harvesting and transport sector, influenced by poor safety records; and
- the increasing demand for sustainable forestry, especially in regard to creating more positive social and environmental impacts.

The current harvest process and issues are presented in Figure 16.

<u>The project key factors</u>

Under the above circumstances, in March 2019 the FWMA project was launched under the Primary Growth Partnership (PGP) programme, which is a collaboration between the Ministry for Primary Industries, Forest Growers Research Ltd, and the Forest Value Chain Consortium (Ministry for Primary Industries, 2019a). The first key work stream is the introduction of new automated technology in forest harvesting and logistics, such as log sorting and load securing, to expedite efficient and safer logging (Ministry for Primary Industries, 2019c). Therefore, a feasibility study, including a sustainability assessment, is required to sign-off the project into prototype development.

Figure 16 - Current Harvest Process (Forest Value Chain Consortium; 2018)



According to Forest Value Chain Consortium (2018), as the current forestry supply chain could be seen as an interdependent system, the collaboration project proposes a new SCND, a hub-spoke setup, which is expected to improve the flexibility and efficiency of the harvesting supply chain. In this setup, a robotic log sort yard (the hub) is relocated to serve for up to eight harvesting landing sites (the spokes) and the sorted grades of logs from the sort yard will then be transported to customers, using transport alternatives such as the full utilisation of High productivity motor vehicles (HPMV). In a new sort yard, the main machines are: a robotic log sorter to pick up the mixed grade logs from the hauler log landing, scan the log with a shape recognition scanner, and sort logs accordingly; an automated truck loading gantry to load sorted logs direct to HPMV trucks in less than 10 minute per load, which is one quarter of the current loading time; and an automated log load securing system for the 58-tonne gross HPMV truck and trailer units. Semi-automation will also be incorporated into log extraction using a “smart” grapple and hauler control system, in forest debarking and log processing and in a log residue management system (Forest Value Chain Consortium, 2018). The new harvesting process and the sort yard operations are illustrated in Figure 17 and Figure 18.

In the plan, Forest Value Chain Consortium (2018) clearly define that the first project objective will focus on the design and development of the new sort yard and hub-spoke SCND system, including the minimum viable prototype system for initial implementation, and then the testing and improvement of the system for future mass deployment which expects that five log sort yards and 40 harvesting contractors will be deployed in the new system up to 2025, and 55 sort yards and 440 harvesting contractors will be deployed in the new system up to 2030 for the whole New Zealand. In order to achieve that target, one of the first milestones of the project is to carry out the feasibility study for sign-off to push the project into the next prototype development. The feasibility report will then be used as a crucial base to encourage current forest owners and harvesting contractors to become first adopters of the new system.

Figure 17 - Improved Harvesting Processes (Forest Value Chain Consortium, 2018)

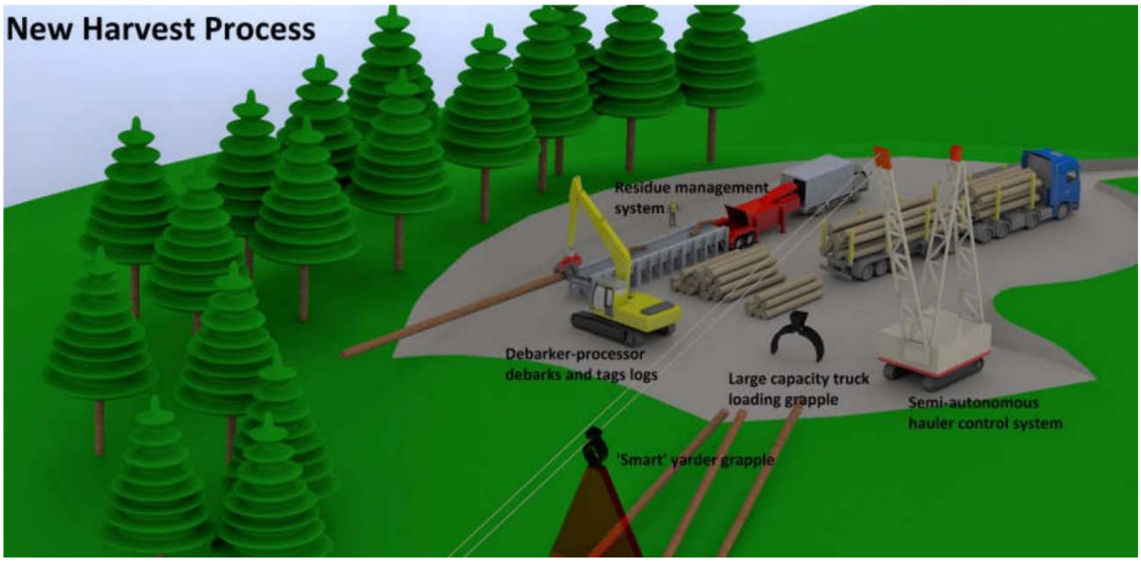
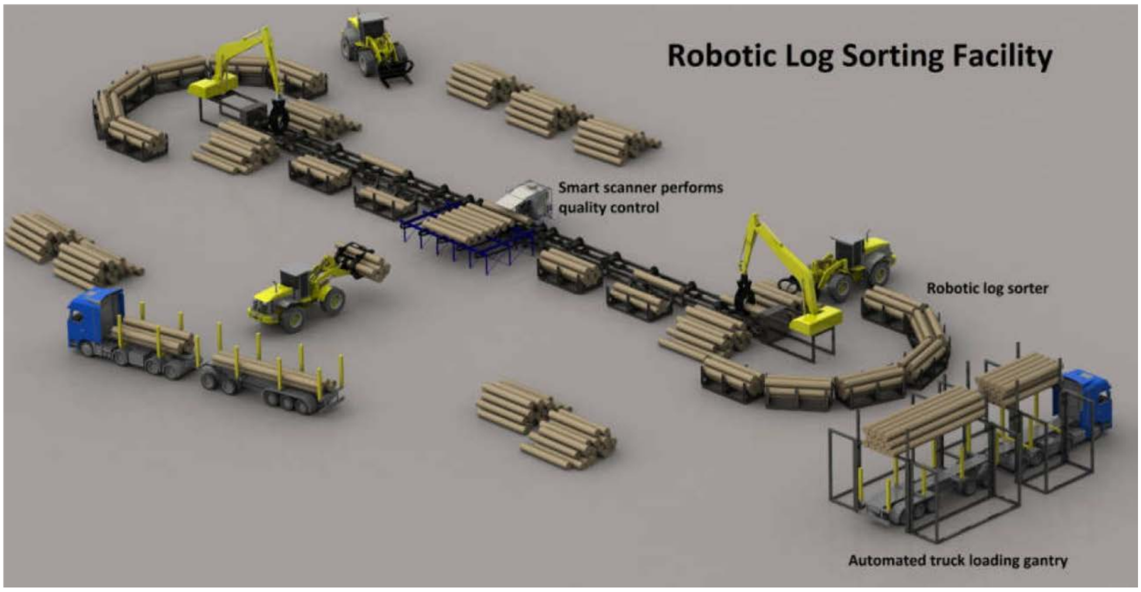


Figure 18 - Improved Sorting-Loading Processes (Forest Value Chain Consortium, 2018)



In this study, one new sort yard with its hub-spoke SCND system and current SCND were selected to be the subject of the feasibility study. There are eight different harvesting sites in four processing setups for the current harvesting processes, and the same number of sites and same number of setups for the new harvesting processes. The modelling method of TBL, DES and MCDM proposed in the previous chapter was then utilised for the sustainability assessment of those processes as part of the project feasibility study, based on the guide of Data Analysis Steps in Figure 14. The next subsection presents the simulation setup for the DES.

4.2. Simulation setup

The simulation model of this research was developed based on the basic steps suggested by Laguna and Marklund (2013) as it best suits this work. The steps and their correspondent sections in this research are described in Table 9.

Table 9 – Simulation Steps (Laguna & Marklund, 2013)

Step	Description	Corresponding section
1	Specify the goals of the simulation	4.2.1. Simulation goal
2	Comprehend the process and describe it in flowcharts	4.2.2. Process mapping
3	Symbolise each component of the process in a block sketch	4.2.2. Process mapping
4	Define values for each block	4.2.3. Input data
5	Determine the interrelations and connections between blocks	4.2.4. Simulation building
6	Verify and validate the work	4.2.5. Model verification and validation, and 4.2.6. Sensitivity analysis
7	Attach input windows and graphs for analysing	4.4. Result presentation
8	Interpret and summarise the results	4.4. Result presentation

Additional section “4.2.7. New process cases” and section “4.3. Multi criteria” are also added in after step 6 to explore additional variations in the research analysis and to provide more detail about the working method.

4.2.1. *Simulation goal*

The goal of the simulation in this research was to develop different models for the New Zealand forestry supply chain, so that the models could generate the primary processed data from the primary data, as discussed in the previous chapter. This primary processed data then became the input data for the MCDM analysis for further processing. Therefore, it is important to build the simulation model which could produce data as much accurate as possible.

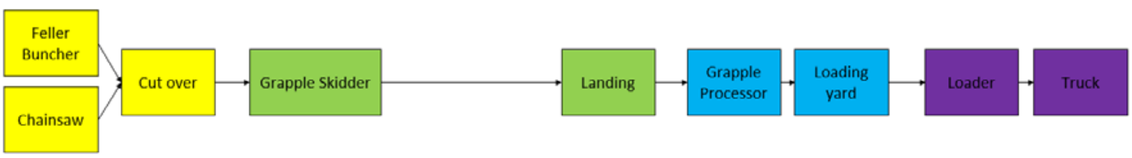
There could be different detail levels when developing a simulation model in SCM, and simulation developers normally choose the low detail levels in order to manage easily the complication of the model and the simulating resources (Jain et al., 1999). However, the models at low detail levels also have lower accuracy than the ones at high detail levels (Jain et al., 1999; Persson & Olhager, 2002). In order to get the highest possible data accuracy for analysing in this research, the simulation models were developed at a high detail level, which could simulate the batch movements of the machines participating in the forestry supply chain activities. The models covered the entire SCND including both harvesting and transportation operations for eight harvesting sites under current and new processes setups.

4.2.2. *Process mapping*

Understanding operational process is an important step in building an effective simulation (Laguna & Marklund, 2013). In this study, there are 11 separate process setups to be explored in total: four harvesting setups and one transportation setup for the eight sites in the current process; and, in the new process, four corresponding harvesting setups, plus one sorting setup and one transportation setup for the eight harvesting sites. These setups are different in the number and type of machines used in each harvesting work, and advanced machines are utilised more in the new harvesting process setups. They are illustrated in Appendix D, and explained as follows.

The four harvesting setups in the current process are Conventional Ground-based (CGB) with three sites having this setup, Conventional Hauler (CH1) with two sites, Conventional Hauler with 2 stage (CH1-2) with one site, and Mechanised Hauler (CH2) with two sites. The four harvesting setups in the new process are Automated Ground-based (AGB) with three sites having this setup, Automated Hauler (AH1) with two sites, Automated Hauler with 2 stage (AH1-2) with one site, and Automated Hauler 2 (AH2) with two sites. The setup for a CGB site is illustrated in Figure 19 as an example.

Figure 19 – Conventional Ground-based (CGB)



Note. Yellow is for the felling stage; green is for the extracting stage; light blue is for the processing stage; and purple is for the loading stage.

In the felling stage, only chainsaws are used in CH1 and CH1-2, while both chainsaws and feller bunchers are used in CGB and CH2. Only the feller bunchers in AH2 and CH2 are winch-assist types. All setups in the new process (AGB, AH1, AH1-2 and AH2) only use feller bunchers and no chainsaw.

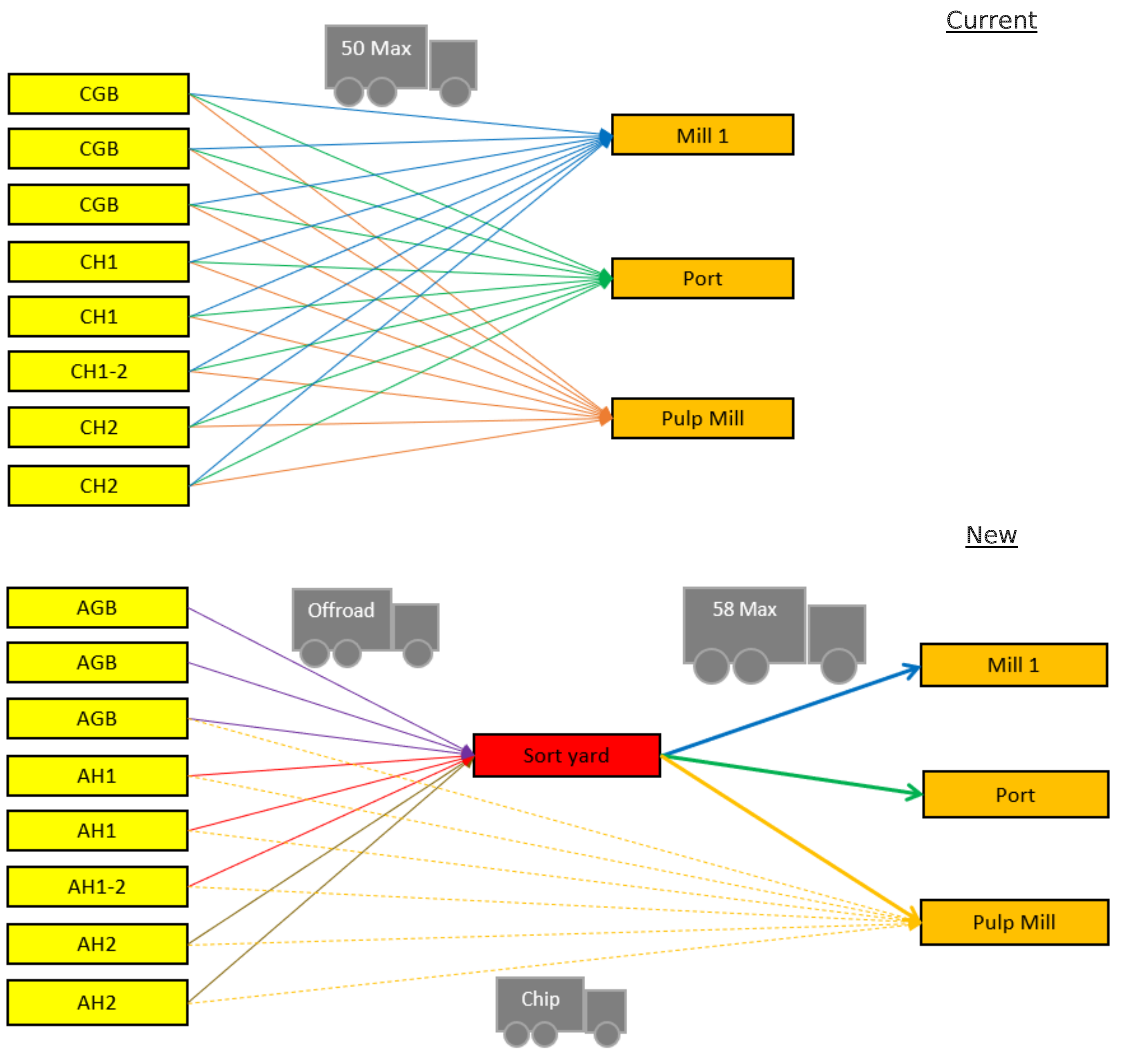
In the extracting stage, only grapple skidders are used in CGB and AGB, and only Madill 124 swing yarders with tail hold are used in CH1, CH2 and AH1. Both Madill 124 swing yarders with tail hold and grapple skidders are used in CH1-2 and AH1-2. Only semi-automated Madill 124 swing yarders with tail hold are used in AH2.

In the processing stage, grapple processors are used in all current harvesting process setups: CGB, CH1, CH1-2, CH2. They are also used in two new harvesting process setups AH1 and AH2. Processor-debarkers are used in AGB and processor-debarker-loaders are used in AH2.

In the loading stage, loaders are used in all setups except AH2, which utilises processor-debarker-loaders for loading. Automated chippers are added in all new harvesting process setups to utilise the waste from the processing work, and they could also load the chip trucks.

The current and new SCND are illustrated in Figure 20, and are explained next.

Figure 20 - Supply Chain Network Designs



In Figure 20, the current SCND setup utilises only 50 Max HPMV trucks to carry the logs from all eight harvesting sites directly to local mills (Mill 1), pulp mills and ports. In contrast, the new SCND deploys off road trucks to carry the logs from all eight harvesting sites to the sort yard for sorting first, then uses 58 Max HPMV trucks to carry the logs from the sort yard to all customers. Chip trucks are used to transport the chip from six harvesting sites in the new SCND to the pulp mills, as other sites do not utilise the waste.

The Sort Yard (SY) is an additional setup in the new SCND in comparison with the current one. Loaders type 1 are used to unload the logs coming from harvesting sites to feed the log sorter. The log sorter then sorts the logs and stacks them into the log storage. Loaders type 2 feed part of the sorted logs to the truck loading gantry. Logs could be loaded onto trucks for transportation to customers by the truck loading gantry or by the loaders type 3 which pick up the logs from the log storage.

4.2.3. *Input data*

The primary data collected in this study was grouped into two categories, which are the general assumption and operational data. These data groups were used as the inputs to define different values of the simulation models in the next section.

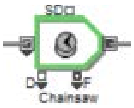
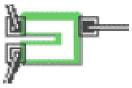
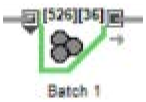
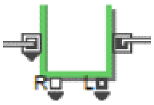
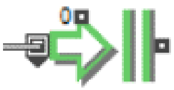
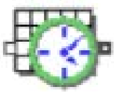
The general assumption is the group of information needed for general simulation settings. As a non-terminating system operating on shifts, the length of the simulation in this study should be enough for a steady output, and the number of runs of the simulation should be effective for creating statistical data (Laguna & Marklund, 2013; Sackett et al., 2013). Considering this suggestion and the limitation of the available calculating resources, the simulating time length was selected as 7,200 minutes (equivalent to five working days) and the number of simulating runs was defined as four times (equivalent to four weeks). This combination of simulating time and run number made the total running time equal to one month of operation in real-time, which was sufficient for covering all possible situations.

The operational data is the group of information needed to define block values of the simulation models. This group includes the harvesting and transportation data. The harvesting data basically consists of the capacity, the batch configuration, the buffer stock, the processing time, the waste and the utilisation of each machine. The transportation data contains the truck payload and speeds, the fleet sizes, the transport distances, the loading/unloading times, the queueing times, and the break time. The primary data details are presented in Appendix E.

4.2.4. *Simulation building*

Blocks and connections are the most basic elements in ExtendSim simulation, because each block plays a role as a part of the process being simulated, and when a model is run the information carried by connections between blocks will be modified, depending on the values and attributes set forth in their dialogues (Sackett et al., 2013). In the coming sections, the major ExtendSim blocks used in the model are described in Table 10, and the trees and logs going through the model are mentioned as the items.

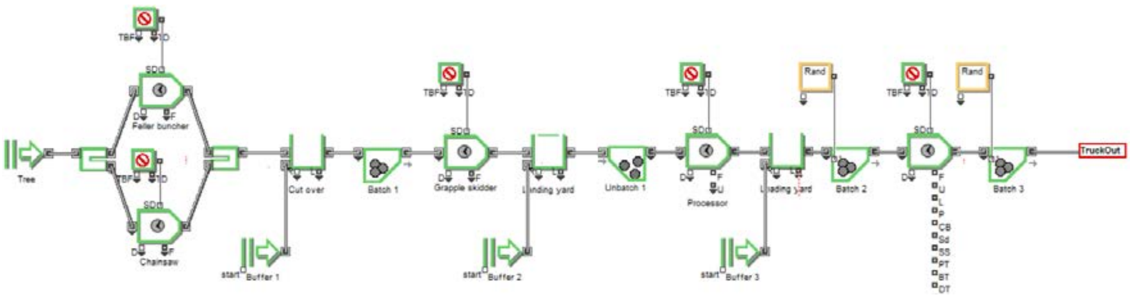
Table 10 – ExtendSim Block Functions (Sackett et al., 2013)

Block	Icon	Function
Create		To create items or initial buffers for eliminating the unstable warm-up period by defining the item's quantity and distribution.
Activity		To represent a machine or truck performing different work by defining the processing time.
Select item Out		To direct the flow from one input to multiple outputs by defining the proportion of outputs.
Select item In		To direct the flow from multiple inputs to one output by defining the proportion of inputs.
Shutdown		To replicate machine utilisation by defining the proportion of working and non-working time.
Batch		To reflect the joining of multiple items into a combined item when going through a machine by defining the number of joining items for a combined item.
Unbatch		To reflect the separation of an item into multiple items when going through a machine by defining the number of separated items from an original item.
Hierarchical		To represent a single and complete harvesting process in a transport setup for the purpose of simplifying the model.
Resource pool		To simulate a common shared resource, like a truck fleet, by defining the quantity of the resource in the pool.
Queue		To hold the item until it could be processed until the next available slot, due to limited of resources.
Resource Release		To release a resource to the pool after completing a work.
Exit		To complete a process when items arrive at their end customers (mills, pulp mills, or ports).
Shift		To set up the working time schedule by defining the start and stop times.
Log Manager		To record the primary data created when running the simulation onto a database for calculating the secondary data.

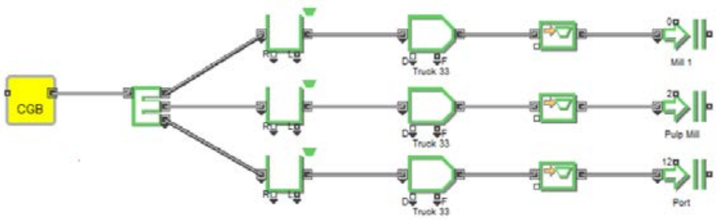
The actual models were built by connecting relevant blocks to reflect the harvesting and transporting process setups defined in the process mapping section. The simulation model for a CGB harvesting setup and transportation is presented in Figure 23, as examples.

Figure 21 - CGB ExtendSim Model

Harvesting process



Transport process



When all the models were built and all the block values were defined, the simulation was set for running accordingly and then the Item Log Manager block recorded all data into a database. This database was extracted to Excel files for calculating the daily machine processing times and harvesting yields by using the Pivot Tables function.

4.2.5. *Model verification and validation*

A model building process should be controlled, in order to guarantee that it runs according to the expected logic, by building and checking at each modelling stage or by adding animation (Laguna & Marklund, 2013). Implementing these techniques into this research, the ExtendSim models were built and tested for each harvesting and transport process separately. When all processes were run as expected, they were then added up one by one into hierarchy structures and tested again after each modification. Moreover, animation was also set up for all processes for double checking and easy visuals, and there were no issues discovered when running the model.

To validate the models, three types of action were taken: asking for expert consultations, comparing simulation results with actual data, and conducting a sensitivity analysis, as suggested by Laguna and Marklund (2013), and all three actions were taken in this study. During the model building process, the ExtendSim simulation files and data were sent via email to three people for checking and feedback: an experienced ExtendSim postgraduate from Massey University who used ExtendSim for a similar study on forestry supply chain with Scion; a Scion ex-researcher who conducted similar forestry simulation using ExtendSim; and a support expert from the ExtendSim company. All feedbacks were taken into consideration and the models was adjusted accordingly. The simulation results were also discussed with other experts from the FWMA project team for benchmarking with actual data. After many working sections, the final models were of the 23rd version which then was endorsed by the experts. The results were also presented in several industrial meetings, with appreciation shown by forestry professionals. The conclusion from the sensitivity analysis was also positive, which will be explained in detail in the next subsection.

4.2.6. *Sensitivity analysis*

One of the first basic steps in a sensitivity analysis is to define the high impact variables for the outputs (Saltelli et al., 2004). Before doing so, for the processing time and the harvesting yield of a complete forest supply chain setup, firstly the variables of a single machine were studied. In this research the daily productivity of a machine is calculated by Formula (1).

$$P = C \times U \times T \qquad (1)$$

Where: P is the daily productivity;
C is the hourly capacity;
U is the utilisation in percentage; and
T is the daily processing time in hours.

It is observed that, both capacity and utilisation are directly proportional to productivity: the higher the machine's utilisation the more productivity, and the higher the machine's capacity, the higher the productivity. On the other hand, capacity is inversely proportional to processing time at a given productivity and utilisation: the higher the capacity, the lower the processing time. Utilisation is also inversely proportional to processing time at a given productivity and capacity: the higher the utilisation the lower the processing time. Therefore, productivity and processing time are highly influenced by capacity and utilisation. Since the forest supply chain consists of a chain of activities performed by different machines, the utilisation and the capacity could be chosen as the most affecting parameters to the processing time and the yield of the simulation.

The hourly capacity depends primarily on two sub-factors which are the move processing time (the time required for one complete move) and average batch capacity (the volume processed in one complete move). The processing time was excluded from this analysis, because it is also an output to be examined, and it hardly changes since normally a machine is running at its designed operating speed. The batch capacity then became the main influencing factor on the machine's capacity, as it could be more easily changed during operation when the normal batch capacity is usually kept lower than the maximum capacity. This assumption of batch capacity variation was not applied for the trucks as they are supposed to run at the designed speed and capacity at all times. To conclude, the machine's utilisation and the batch capacity were taken into consideration in this sensitivity analysis.

To determine the extent of the effect of the machine's utilisation and the batch capacity on the processing time and the yield, different scenarios with different input data were simulated and the outputs of all scenarios were compared with those of the base scenario. Since the maximum machine's utilisation in the previous initial assumption is 94%, and a machine's utilisation could not be higher 100%, the maximum deviation of the machine's utilisation is 106.4% which is the result of 100/94. In order to be consistent, this deviation range of 6.4% (a result of 106.4% minus 100%), was applied to both high and low scenarios, in both parameters of the machine's utilisation and batch capacity. To summarise, the low scenarios would have the input deviation of 93.6% (a result of 100% minus 6.4%) and the high scenarios would have the input deviation of 106.4% (a result of 100% plus 6.4%), in comparison with the base scenario.

In the base scenario (scenario 0) the machine's utilisation and the batch capacity were both kept at 100% of the original assumption. In scenario 1 and 2, the machine's utilisation was kept unchanged while the batch capacity was increased to 106.4% and decreased to 93.6% respectively. In scenario 3 and 4, the batch capacity was kept unchanged while the machine's utilisation was increased to 106.4% and then decreased to 93.6% respectively. These changes applied for all machines except the trucks. The scenario assumptions are demonstrated in Table 11.

Table 11 - Sensitivity Analysis Scenarios

Scenario	Machine's utilisation (%)	Batch capacity (%)
0	100.0	100.0
1	100.0	106.4
2	100.0	93.6
3	106.4	100.0
4	93.6	100.0

Based on Table 11, the input data was modified accordingly and the simulation models were run repeatedly to calculate the daily machine processing times and harvesting yields for each scenario. These results are presented in Appendix F and their comparison with the result of the base scenario is illustrated in decimal ratio in Figure 22 and 23.

Figure 22 - Comparison of Daily Yields (decimal ratio)

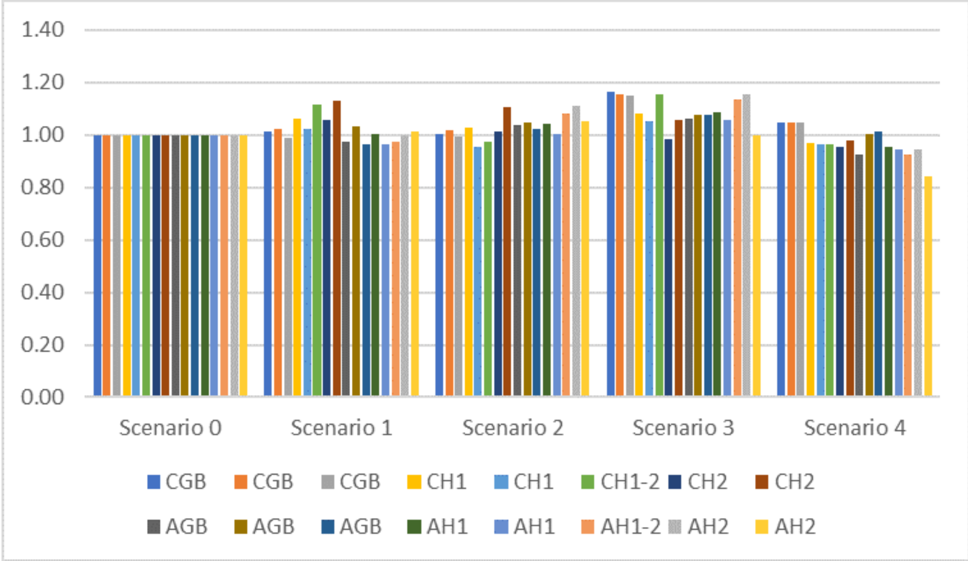
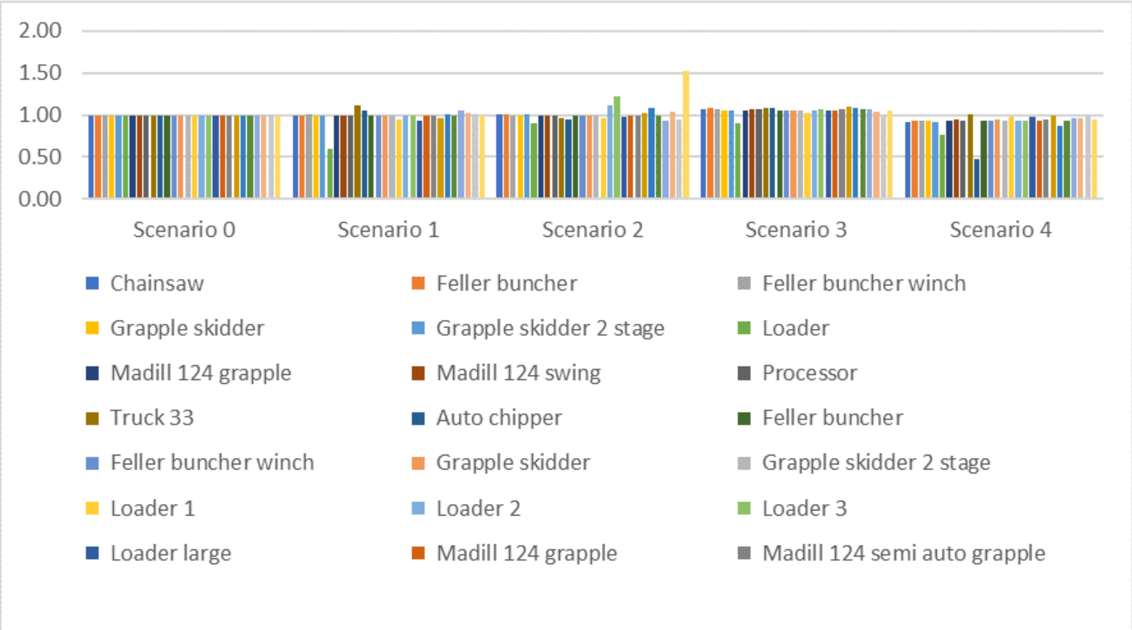


Figure 23 - Comparison of Daily Processing Times (decimal ratio)



From the figures above, when the machine's utilisation was kept unchanged while the batch capacity was increased and decreased by 6.4% in scenarios 1 and 2, the change in the yields and processing times were inconsistent. Some ratios were higher than 1 when the batch capacity was increased, while others were lower than 1. The same phenomenon occurred when the batch capacity was decreased. This could be considered as the normal variation in simulation running, because when the batch capacity of all machines was altered with the same proportion, it changed nothing in the simulation setup, except some small changes in the batch ratios between loaders and trucks (because the truck capacity was unchanged).

In scenarios 3 and 4, when the batch capacity was kept unchanged while the machine's utilisation was increased and decreased by 6.4%, the change in the yields and processing times of each machine were quite consistent. Most ratios were higher than 1 when the machine's utilisation was increased, and most were lower than 1 when the machine's utilisation was decreased. This is logical because the machine's utilisation is measured by comparing the machine's actual working time and the total presenting time as a percentage. The absolute changes in percentage of the processing time in both cases were similar to the absolute change in percentage of the machine's utilisation, so those changes are directly proportional.

From the above findings, it could be concluded that the machine's utilisation has significant impacts on both the processing time and daily yield, while the batch capacity has no clear impact, which is logical. Within the input data variation limit in our assumption, the absolute change in percentage fluctuated, which may due to the normal variation of simulation running, so the extent of the impact of the machine's utilisation could not be accurately defined. Therefore, the model could be accepted as valid.

4.2.7. *New SNCD cases*

This research has a base scenario set up from the original data for the current SCND and one new SCND. Additional scenarios were also developed to examine the different results of new SCND alternatives, when the current process arrangement was kept unchanged.

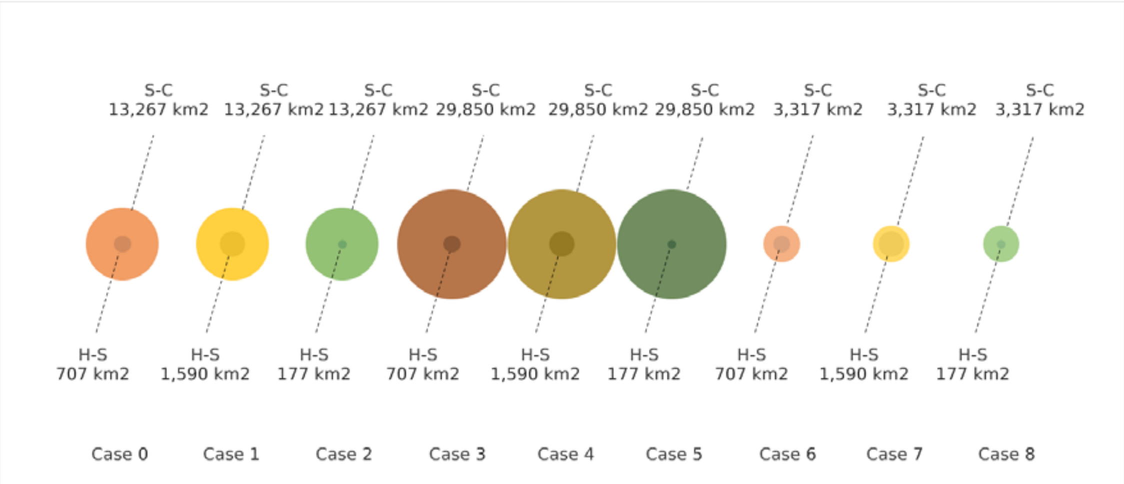
There are different factors to alter the initial new SCND: the trucking distances, the number and the ratio of the harvesting sites supplying the sort yard, the machines' capacities (K. Raymond, personal communication, March 30, 2020). As the new SCND in the base case was built up on a geographical coverage assumption of the harvesting sites, the sort yard and the customers (the principle), in this research the trucking distances were chosen to be adjusted for making the new SCND alternatives, in order to keep the principle consistent.

It was assumed that in each new SCND case, the changes of trucking distances would be either 50% more or 50% less. This would lead to an increase or decrease of the estimated coverage areas by 225% or 75% respectively, using the basic formula to calculate the area of a circle. Based on the above assumption, eight more new SCND cases were created. Their distances with their ratios, and the estimated coverage areas in the new process cases are compared to the base case in Table 12 and Figure 24.

Table 12 – New SCND Trucking Distances

Case	Distance in km (Decimal ratio)	
	Harvesting sites to Sort Yard H-S	Sort Yard to Customers S-C
0 - Base case	15.0 (1.0)	65.0 (1.0)
1	22.5 (1.5)	65.0 (1.0)
2	7.5 (0.5)	65.0 (1.0)
3	15.0 (1.0)	97.5 (1.5)
4	22.5 (1.5)	97.5 (1.5)
5	7.5 (0.5)	97.5 (1.5)
6	15.0 (1.0)	32.5 (0.5)
7	22.5 (1.5)	32.5 (0.5)
8	7.5 (0.5)	32.5 (0.5)

Figure 24 – Estimated New SCND Coverage Areas (km^2)



Note. S-C: Sort Yard to Customer; H-S: Harvesting Site to Sort Yard.

Based on these cases and the simulation models built previously, the results of yearly machine processing times and harvesting yields of the new process cases were then calculated and are presented in Table 13. All data is shown in Appendix G.

Table 13 - Yearly Machine Processing Times and Harvesting Yields, New SCND Cases

Case	Machine processing time (hour)	Harvesting yield (tonne)
0	85,502.45	544,212.20
1	86,005.50	532,101.55
2	78,099.12	528,053.55
3	85,838.82	548,967.45
4	86,567.13	544,920.60
5	78,866.72	543,847.65
6	85,152.56	534,465.95
7	86,066.09	543,729.20
8	78,685.09	519,588.40

The above sections have discussed the simulation setup of the research. In the following sections, the multi criteria is presented, before the results are discussed.

4.3. Multi criteria

According to Triantaphyllou (2000), MCDM is one of the suitable methods to search for an optimal decision or solution from a set of alternatives and a set of decision criteria. He noticed that every issue is attached with a number of attributes which could be considered as decision criteria. While these criteria show the different ways of evaluating the alternatives, they have varying importance, and they may also include sub-criteria (Triantaphyllou, 2000). Since many parameters need to be managed in evaluating sustainability, multi criteria decision analysis is considered as suitable to assess sustainability, thanks to its adjustability and the stakeholders' participation possibility (Cinelli et al., 2014). The three main pillars of sustainability are social, economic and environmental (Gibson et al., 2005). These criteria are discussed in detail in the following sections.

4.3.1. *Social criteria*

Forestry is one of the most dangerous industries, not only in New Zealand where the logging sector has the highest rates of work related injury and mortality incidents of employees, but also on globally (Bentley et al., 2002). Therefore, safety is a crucial indicator in measuring sustainability in forest industry, and it was selected to represent social impact in this study, symbolised by the S value.

Safety performance in the logging industry is measured by the reported number of injuries (Bentley et al., 2005). In this research, the absolute number of injuries in two processes were compared. Statistics reveal that the majority of the incidents relate to machine operation (Bentley, 2002), so the injury data could be calculated based on the machine operating time of workers. Because the number of injuries is inversely proportional to safety performance, the S value is then calculated as the inverse number of the estimated number of injuries in Formula (2).

$$S = 1{,}000{,}000 / (T \times r_s) \quad (2)$$

Where: S is the social sustainability value;
T is the yearly labour working time; and
r_s is the Lost Time Injury (LTI) rate, which is the number of injuries per million hours worked (Bentley et al., 2005).

Note. The labour working time equals to the total processing time of all man-operated machines.

4.3.2. *Economic criteria*

There are a wide range of approaches in the economic assessment of an innovation project (Ryan, 2002). However, the most common evaluation method is the Net Present Value (NPV) approach, which is the consideration of the sum of all projected cash flows with a given discount rate (Žižlavský, 2014). Therefore, in this research the NPV was selected to calculate the economic criteria which is symbolised by E: economic sustainability value. As the NPV is directly proportional to profitability, the E value was calculated by Formula (3).

$$E = NPV / 1{,}000{,}000 \quad (3)$$

The NPV values were calculated using Scion's economic model (M. Welsh, personal communication, April 3, 2020).

4.3.3. *Environmental criteria*

Greenhouse gas emissions are the primary environment indicator (Afgan & da Graça Carvalho, 2000). In New Zealand, the Climate Change Response (Zero Carbon) Amendment Bill 2019 set net zero emission by 2050 as the new domestic target for all greenhouse gases except biogenic methane. According to Lashof & Ahuja (1990), 80% of the contribution of greenhouse gases to global warming derive from CO_2 emissions, and CO_2 was set as the base for calculating an index of Global Warming Potential (GWP) for all greenhouse gases. CO_2 equivalent, which is the volume of a greenhouse gas emission in tonnes converted into CO_2 emissions by multiplying by its GWP ratio, is used by all countries in environment assessment, including New Zealand (United Nations Climate Change, 2020). In this research, CO_2 emissions were selected as the environmental criterion, which is symbolised by the e value.

Because the CO_2 emission is inversely proportional to the environment performance, the e value was calculated as the inverse number of the estimated yearly CO_2 equivalent as in Formula (4).

$$e = 1 / (Y \times r_e) \quad (4)$$

Where: e is the environmental sustainability value;
Y is the yearly yield of a process; and
r_e is the CO_2 equivalent rate.

4.3.4. *Multi criteria analysis working method*

In this study, the Weighted Product Model (WPM) was adopted as it is the most common and suitable method in implementing the multi criteria analysis, in case the criteria measurement units differ (Triantaphyllou, 2000). In implementing this method in the research, the R value needs to be calculated for comparing two processes, as shown in Formula (5).

$$R(A_K/A_L) = \prod_{j=1}^{n} \left(a_{Kj} / a_{Lj}\right)^{w_j} \quad (5)$$

Where: R is the comparison value between two alternatives;
A_K is the alternative K;
A_L is the alternative L;
N is the number of criteria;
a_{ij} is the actual value of the i-th scenario in terms of the j-th criterion;
w_j is the weighting ratio of the j-th criterion.

In this method, the conclusion is that, if the $R(A_K/A_L)$ value is greater than or equal to one, then the scenario A_K is better than the scenario A_L. It could also be deduced that, to compare two alternatives of A_{K1} and A_{K2} by comparing their $R_1(A_{K1}/A_L)$ and $R_2(A_{K2}/A_L)$ when both the R values are already greater than one, the alternative with a higher R value is the better one.

Applying multi criteria in analysing the simulation results

In this study, the basic WPM from Formula (5) was deployed as details in Formular (6):

$$R_{ij}(N_i/C) = I_{Si}^{Wsj} \times I_{Ei}^{WEj} \times I_{ei}^{Wej} \quad (6)$$

Where: R_{ij} is the relative value of the new and current SCND at the i-th case and j-th option;
N_i is the new SCND in the i-th case;
C is the current SCND;
S_{Ni} is the number of injuries of the new SCND in the i-th case;
S_C is the number of injuries of the current SCND;

E_{Ni} is the NPV of the new SCND in the i-th case;
E_C is the NPV of the current SCND;
e_{Ni} is the CO_2 equivalent emission of the new SCND in the i-th case;
e_C is the CO_2 equivalent emission of the current SCND;
I_{Si} is the social index in the i-th case, $I_{Si} = S_{Ni} / S_C$;
I_{Ei} is the economic index in the i-th case, $I_{Ei} = E_{Ni} / E_C$;
I_{ei} is the environment index in the i-th case, $I_{ei} = e_{Ni} / e_C$; and
Wsj, W_Ej, Wej are the weighting ratios for each criterion respectively in the j-th option.

Weighting ratio is an important factor in the formula, where different weighting sets may influence the final result of the R value. Among many weighting methods, the most appropriate approaches from a previous study of Gan et al., (2017) were utilised, equal weighting and public opinion weighting. Wu & Pagell (2011) make similar recommendations for weighting methods, in which the Equal Footing (Option 1) emphasises all aspects equally, the Community First (Option 2) emphasises the social aspect the most, the Opportunity First (Option 3) emphasises the economic aspect the most, and the Environment First (Option 4) emphasises the environmental aspect the most. The weighting ratio assumptions are presented in Table 14, with the most important ratio of each option marked in green.

Table 14 - Weighting Ratio Assumptions

Option (No.)	Ws	W_E	We
Equal Footing (1)	0.33	0.33	0.33
Community First (2)	0.50	0.25	0.25
Opportunity First (3)	0.25	0.50	0.25
Environment First (4)	0.25	0.25	0.50

<u>Social results</u>

In this study, the LTI rate was adopted from the results of the latest Incident Recording Information System New Zealand report in 2018-2019 which showed the value of r_s is 10 cases per million hours worked in the forest industry (WorkSafe New Zealand, 2019). The S values for all processes were then calculated by Formula (2), and are presented in Table 15 (next page). In this table and all following tables, “C” represents the current process case, “N_i” represents the new process case number i-th.

<u>Economic results:</u>

The E values calculated by Formula (3) are summarised in Table 16 (next page).

Table 15 - S Value Results

Process case	T (hour)	S
C	52,087	191.99
N_0	82,761	120.83
N_1	83,268	120.09
N_2	75,360	132.70
N_3	83,103	120.33
N_4	83,830	119.29
N_5	76,128	131.36
N_6	82,415	121.34
N_7	83,332	120.00
N_8	75,951	131.66

Table 16 - E Value Results

Process case	NPV (NZD)	E
C	201,567,296.04	201.57
N_0	617,717,354.38	617.72
N_1	607,817,328.16	607.82
N_2	601,005,950.73	601.01
N_3	631,507,040.44	631.51
N_4	625,832,397.02	625.83
N_5	624,016,816.28	624.02
N_6	610,316,877.08	610.32
N_7	624,641,971.37	624.64
N_8	587,805,181.92	587.81

<u>Environmental results</u>

In this study, McCallum's (2009) results were adopted as the base environment criteria for sustainability assessment of the two processes: his study of Nelson Forest Ltd shows the CO_2 equivalent rate of 0.0187 tonne CO_2e/m^3 (r_e is 0.0187) for New Zealand domestic log supply chain. This rate was applied to Formula (4), and the e values were calculated, as shown in Table 17.

Table 17 - e Value Results

Process case	Y (m^3)	e
C	254,403	210.20
N_0	544,212	98.26
N_1	532,102	100.50
N_2	528,054	101.27
N_3	548,967	97.41
N_4	544,921	98.14
N_5	543,848	98.33
N_6	534,466	100.05
N_7	543,729	98.35
N_8	519,588	102.92

With the results above, all basic elements for the sustainability assessment of the forest supply change are now available. In the next sections, the multi criteria calculation from Formula (6) will be deployed to calculate the final results.

4.4. Sustainability assessment results of the new SCND cases

Based on different combinations of the current SCND, the nine new SCND cases and the four weighting options discussed previously, there were 36 alternatives to be examined. In order to utilise Formula (6) in calculating the R value for sustainability assessment, all social index I_S, economic index I_E, and environment index I_e factors were calculated from the results in Table 15, Table 16, and Table 17. The results of the indexes are shown in Table 18.

Table 18 - Social Index, Economic Index, and Environment Index Results

i (Case)	I_{Si}	I_{Ei}	I_{ei}
0	0.63	3.06	0.47
1	0.63	3.02	0.48
2	0.69	2.98	0.48
3	0.63	3.13	0.46
4	0.62	3.10	0.47
5	0.68	3.10	0.47
6	0.63	3.03	0.48
7	0.63	3.10	0.47
8	0.69	2.92	0.49

The R values were then calculated using Formula (6) and the data from Table 14 and Table 18, and summarised in Table 19. When the R values are greater than 1, the new SCND cases are more sustainable than the current SCND, and the higher the R value, the more sustainable the new SCND case. When the R values are less than 1, the new SCND cases are less sustainable than the current SCND, and the lower the R, the less sustainable the new SCND case.

From the sustainability assessment results in Table 19, the first finding was that only the SCND cases with weighting option 3 were more sustainable than the current SCND, and the rest of the new SCND cases were less sustainable than the current SCND.

The second finding relates to the identification of the most and the least sustainable new SCND cases. The most sustainable new SCND case, with the highest R_{53} value of 1.323 highlighted in green, was the new SCND case 5 in Economic weighting option 3, in which the distances between Harvesting sites and Sort Yard were 7.5 km, decreased by 50% from the base case, and the distances between Sort Yard and customers were 97.5 km, increased by 50% from the base case, with weighting ratios for W_S3, W_E3, W_e3 were 0.25, 0.5 and 0.25 respectively. The least sustainable new SCND case, with the lowest R_{44} value of 0.805 highlighted in yellow, was the new SCND case 4 in Environment weighting option 4, in which the distances between Harvesting sites and Sort Yard were 22.5 km, increased by 50% from the base case, and the distances between Sort Yard and customers were 97.5 km, increased by 50% from the base case, and the weighting ratios W_S3, W_E3, W_e3 were 0.25, 0.25 and 0.5 respectively.

Table 19 - R Values

i (Case)	R_{ij}			
	j = 1	j = 2	j = 3	j = 4
0	0.966	0.868	1.289	0.806
1	0.966	0.867	1.284	0.810
2	0.998	0.910	1.312	0.832
3	0.969	0.869	1.299	0.806
4	0.966	0.865	1.293	0.805
5	0.997	0.907	1.323	0.825
6	0.970	0.871	1.289	0.811
7	0.968	0.868	1.295	0.807
8	0.993	0.905	1.300	0.832

The third finding was that changing the trucking distances in the new SCND and changing weighting options led to the changes in the sustainability results, because the R values varied in different new SCND cases and weighting options.

The fourth finding was that the R values shared the same patterns over the cases when being illustrated on the charts in Figure 25 and Figure 26. This finding may confirm the reliability of the results. Resulting from this finding, the R mean value in each case of the following detailed analysis, which was symbolised by R’, could be considered to represent all R values in that case.

Figure 25 - R Values, Grouped by New SCND Cases

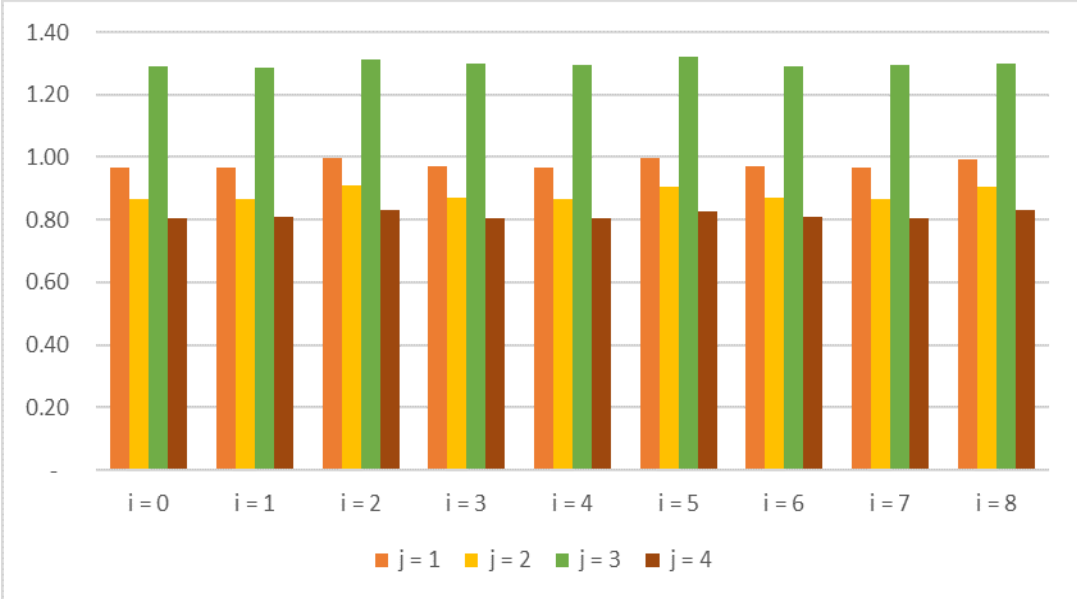
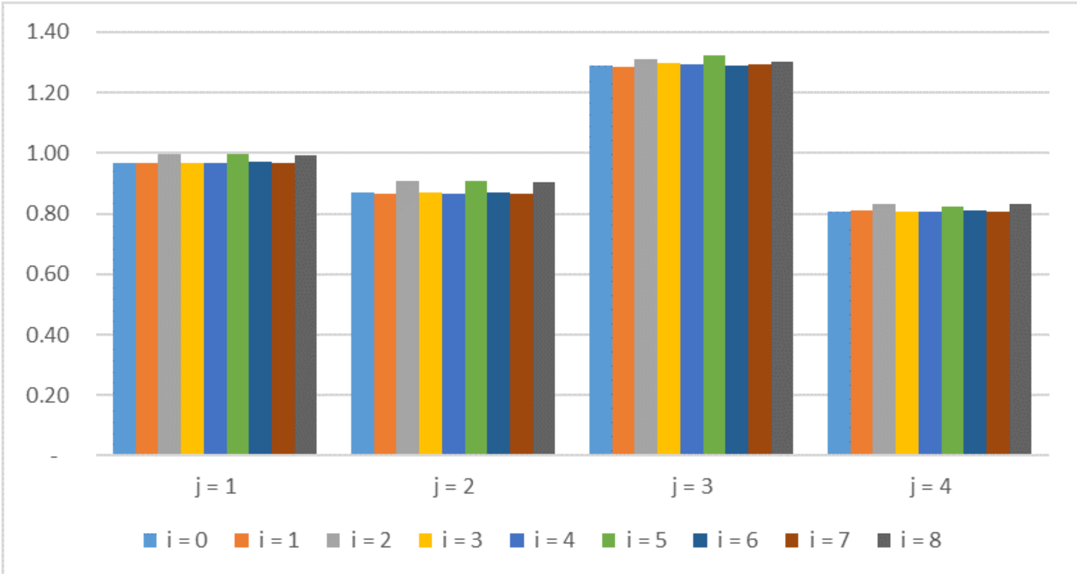
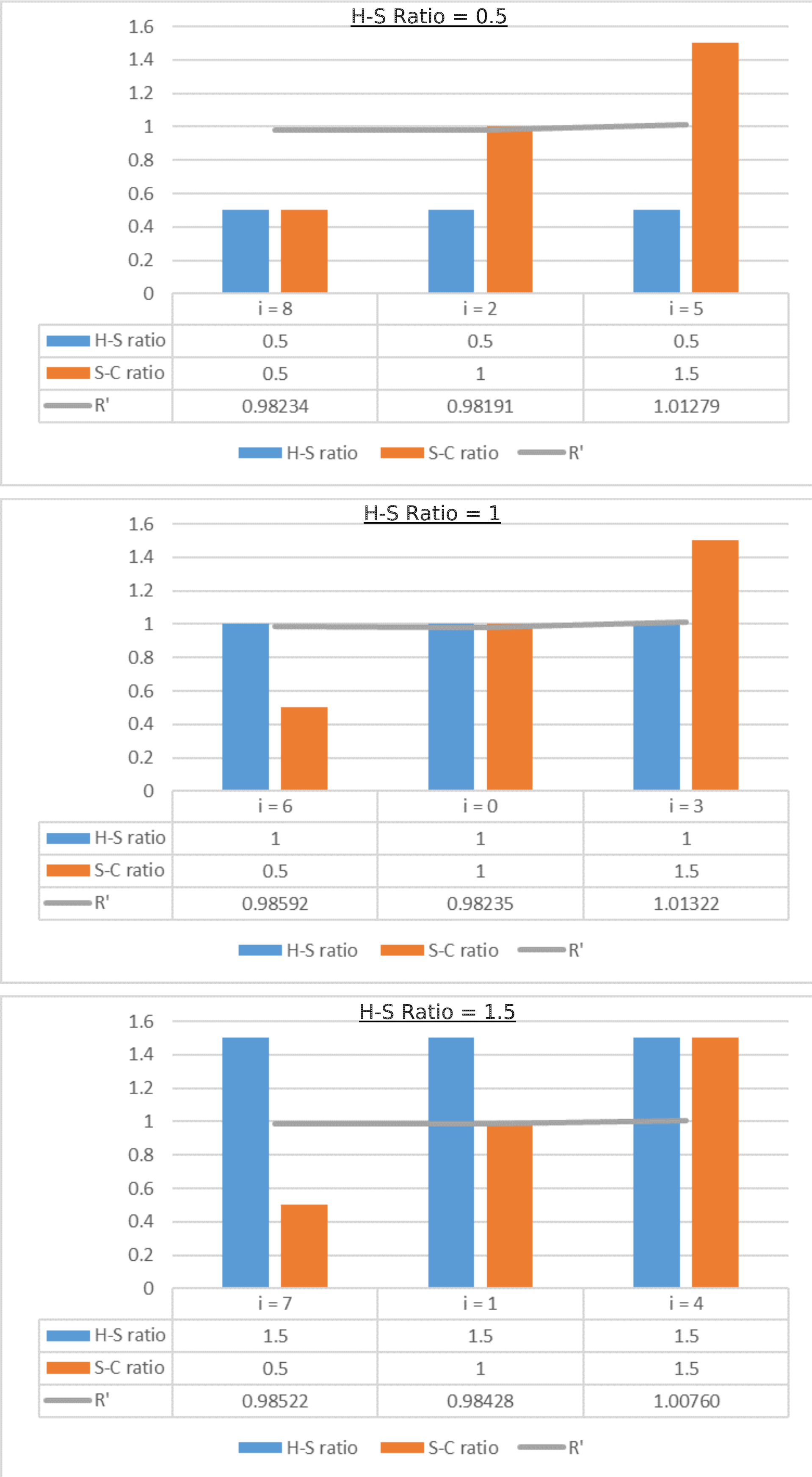


Figure 26 - R Values, Grouped by Weighting Options



Next, the impact analysis of different geographical coverage of the new SCND cases on the R' values was carried out by observing the R' values change when the distances varied. In order to improve observation, first the R' values were compared in the cases with the same H-S ratios, then in the cases with the same S-C ratios. The R' values charts, grouped by weighting options in the first comparisons are demonstrated in Figure 27 (next page).

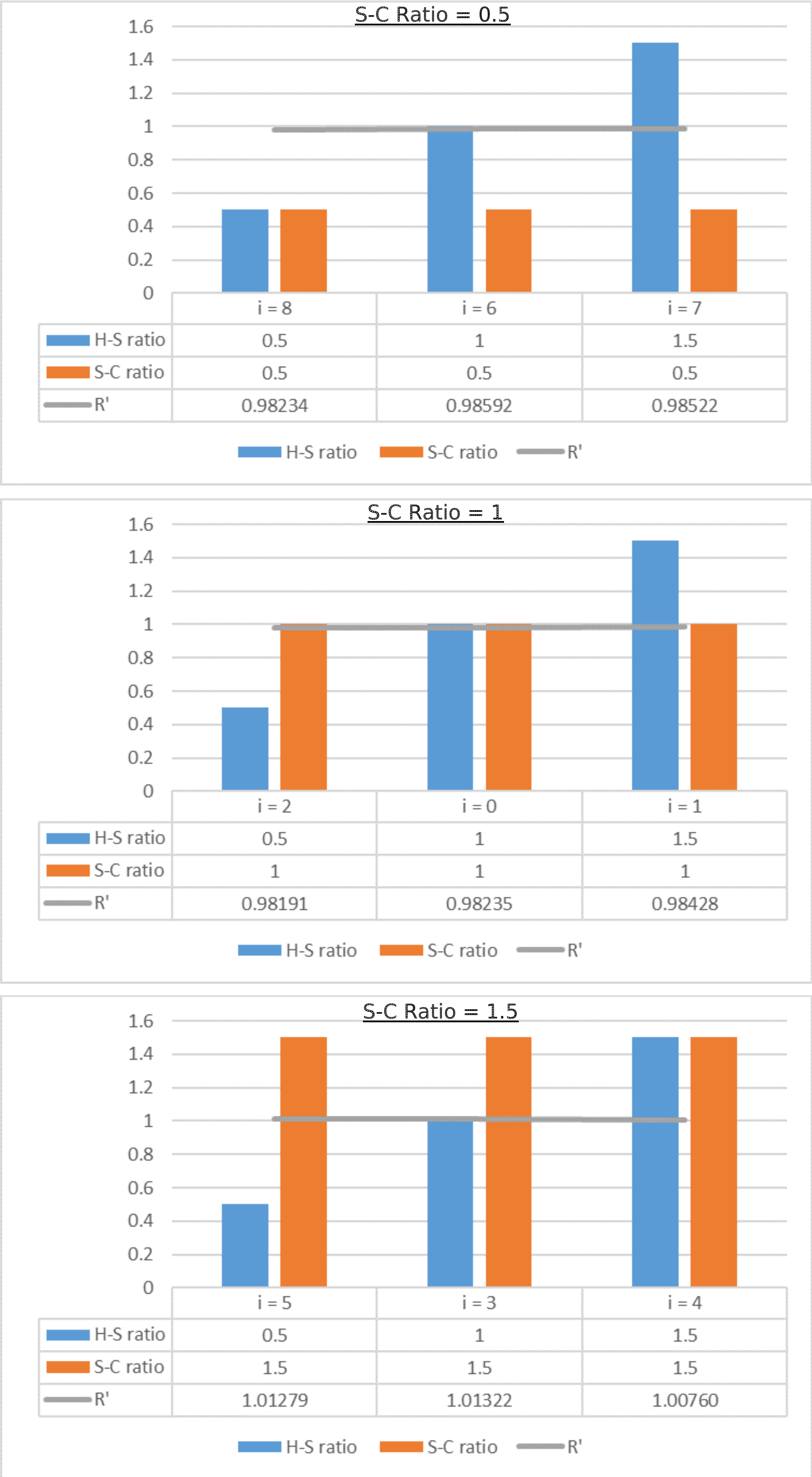
Figure 27 - R' Values when H-S Ratio unchanged



The fifth finding was that the R’ value was not directly proportional to the S-C ratio, because in the cases with the same H-S ratios, all the R’ values decreased when the S-C ratios increased from 0.5 to 1, while they all increased when the S-C ratios continued to increase from 1 to 1.5, as observed in Figure 28. This indicates that, while the distances between Harvesting sites and Sort Yard were unchanged, the average sustainability of the new SCND were not always increased when the distances between Sort Yard and customers increased.

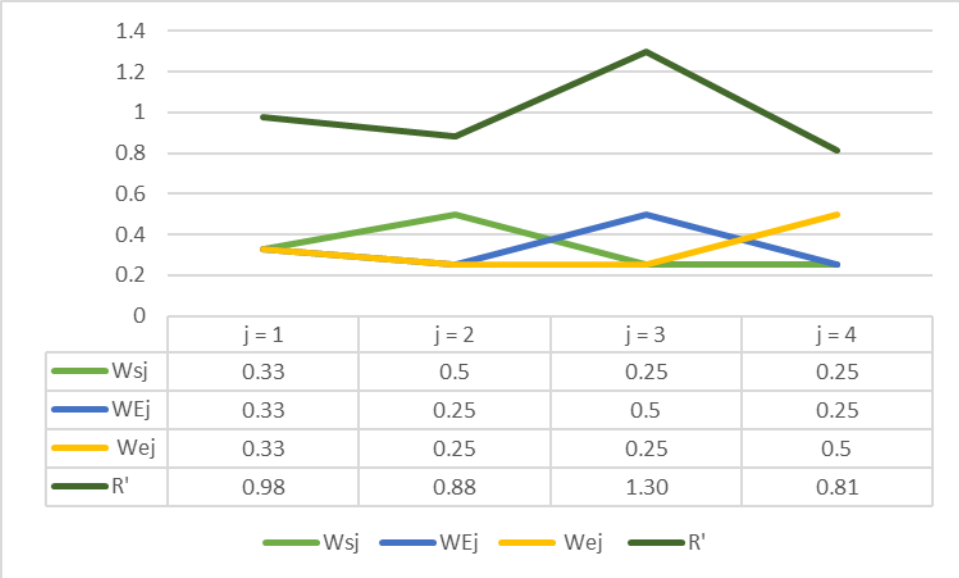
Figure 28 (next page), showing the R’ values charts grouped by weighting options in the cases with the same S-C ratios, revealed the sixth finding that the R’ value was not directly proportional to the H-S ratio, because in the cases with the same S-C ratios, when the H-S ratios increased step by step from 0.5 to 1 and then 1.5, the R’ values changed into two opposite directions. When S-C ratio was 0.5, the R’ value increased in step 1 then decreased in step 2 to a higher value than its first value. When S-C ratio was 1, it increased in both steps. When S-C ratio was 1.5, it increased then decreased to a lower value than its first value. This finding indicates that, while the distances between Sort Yard and customers were unchanged, the average sustainability of the new SCND were not always increased when the distances between Harvesting sites and Sort Yard increased.

Figure 28 - R’ Values when S-C Ratio unchanged



In the following sections, the impact analysis of different weighting options on the R’ values was carried out by observing the R’ changes when the weighting ratios varied. The R’ values, which were grouped by weighting options, are presented in Figure 29.

Figure 29 - R’ Values, grouped by Weighting Options



	j = 1	j = 2	j = 3	j = 4
Wsj	0.33	0.5	0.25	0.25
WEj	0.33	0.25	0.5	0.25
Wej	0.33	0.25	0.25	0.5
R'	0.98	0.88	1.30	0.81

The seventh finding from Figure 29 was that the R’ value was highest when j=3, meaning the economic weighting ratio W_E was the highest ratio in the weighting option, and only the W_E line shared the same pattern with the R’ value line. This indicates that the W_E had the most influence on the R’ value in this research. This could be explained by the fact that the absolute values of the percentage changes of E values between current and new processes were much higher than those of S values and e values. This may also explain the second finding on the identification of the most and the least sustainable new SCND cases which was mentioned previously.

The eighth finding concerns the interrelationship between the sustainability indexes and the R value. From Table 16, it was observed that only the economic indexes I_E were larger than 1, while both the social indexes I_S and the environment indexes I_e were less than 1. As the weighting ratios were always less than 1, the exponents I_S^{WS} and I_e^{We} would decrease when the weighting ratios increased, and vice versa. Knowing that the indexes were for calculating the R in Formula (6), it was concluded that the weighting ratios negatively impacted on the R values when the indexes were less than 1. The opposite conclusion could also be made for the cases with the indexes larger than 1.

4.5. Summary

In this chapter, a modelling method of TBL, DES and MCDM was deployed in a sustainability assessment in a forestry SCNR project from New Zealand. First, a DES built the simulation models for the SCNDs then the data from the simulation results and other TBL data were examined by using the MCDM method. The findings reported above have led to some insights as follows.

Firstly, in specific circumstances, this modelling method could be used to calculate the relative sustainability values of alternative SCND cases, to classify the cases based on their level of sustainability, and to identify the most and least sustainable cases. Therefore, this could be a reasonable base for the sustainability assessment and decision making process.

Secondly, any change in trucking distances would lead to a change in the sustainability level of the whole forest supply chain. However, the changes would not always be directly proportional to the sustainability level. An increase in the distance may lead to both an increase or a decrease in sustainability, and the same for the contrary.

Thirdly, the change in weighting ratio options would also lead to a change in the sustainability level of the whole forest supply chain. As an increased percentage change of the sustainability value (S, E and e) has greater potential impact on the final results, weighting ratio options should be chosen carefully when the percentage changes of the sustainability values are different.

Chapter 5. Discussion

This chapter discusses the research findings in relation to the literature gaps, the conceptual model, the research questions and the research hypotheses. At first, the conceptual model is reflected. Next, the correlation of findings with previous literature is presented. Then managerial/policy implementations are discussed. Finally, the critique of the research and future research suggestion are presented.

5.1. Review of conceptual model

Based on the literature review and data analysis in previous chapters, this section reviews the influences of the utilisation of the modelling method of TBL, DES, and MCDM on sustainability assessment. The purpose of this review is to examine the conceptual model and the three hypotheses of this study, which expected that the integration of TBL could bring a holistic approach to sustainability assessment; the implementation of DES could provide the quantifiable results for decision making justification; and the utilisation of MCDM could ensure the integrity the decision making process.

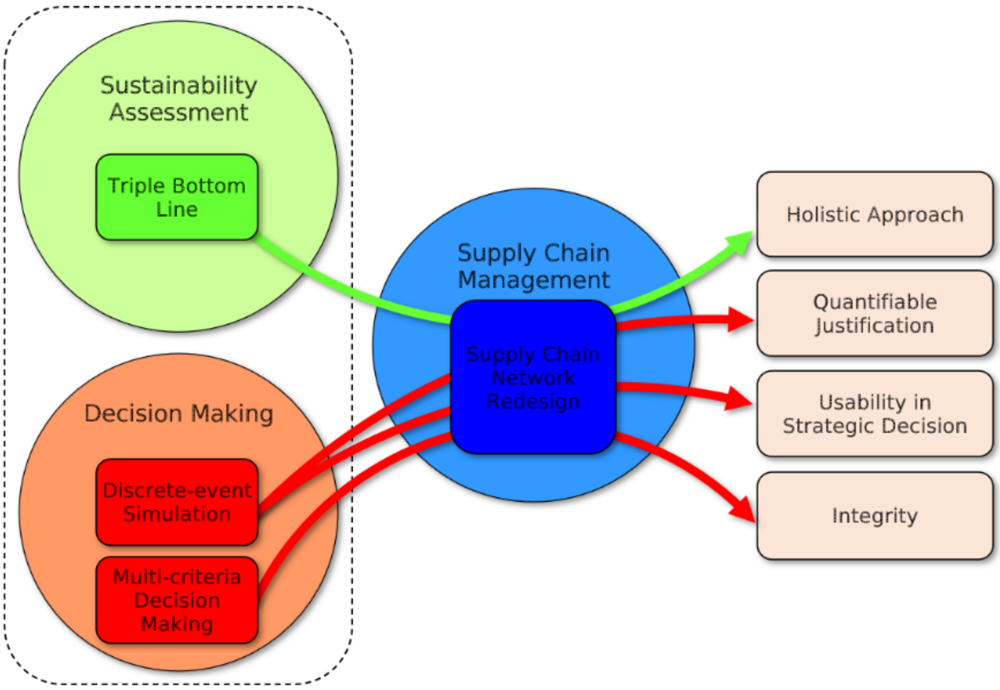
Starting with TBL, this study considered all three main dimensions of sustainability: social, economic, and environmental. These elements were factored into the assessment of supply chain change, and were represented by different criteria: LTI, NPV, and CO_2 emissions. The sustainability performances of ten SCND cases, including current and the new setups, were evaluated based on all criteria and the overall result was calculated from those performances so that a holistic assessment was achieved (Table 19). Compared with the majority of previous research, which focuses on only one of the three sustainability aspects (Elhedhli & Merrick, 2012; Hassini et al., 2012; Seuring, 2013; Singh et al., 2009; Van Der Vorst et al., 2009), this study achieved a more holistic approach (Brandenburg et al., 2014), hence it supports the first hypothesis of the study. In principle, an even more holistic result could be achieved by considering additional criteria for each sustainability dimension, and also examining the interrelations between the main dimensions, which are eco-efficiency, environmental justice, and business ethics (Elkington, 1997).

DES is the key factor in this study in building simulation models of all the cases in SCND. It is used in order to obtain the primary operational data of machine processing times and harvesting yields for the analysis (Table 13), which is a base for calculating sustainability indexes (Table 18) and synthesised performances (Table 19). All the data and results are reported in numerical form showing the comparative values of different alternatives, which could be ranked for easier analysis. Diverging from the decision making practice based on trust, experiences, and general estimated benefits in previous papers (Yingling & Detty, 2000), this study provides an explicit quantifiable justification for decision making. Thus, this supports the second hypothesis of the study.

Moving to the analysis of the MCDM, this is the essential method to calculate the final results for this study (Table 19). The three main criteria and values were chosen based on the assumption and argument of their importance, and their weighting ratios were selected based on the four common postures: Equal Footing, Community First, Environment First and Opportunity First (Wu & Pagell, 2011). As the data illustrates (Table 18), different combinations of the weighting ratios led to different results, thus affecting the final decision, and this may reflect a concern about the risk of manipulating the data (Zardari et al., 2015). However, unlike other areas where decision makers could act independently, sustainability assessment requires the inclusion of stakeholders in decision making processes (Morioka & Carvalho, 2016). Therefore, in practice, at least three representatives from the social, economic, and environmental stakeholder groups participate and contribute equal voices in the selection process of the criteria and weighting ratios, hence there is little chance for manipulating the data in favour of an interest group, and the integrity of the decisions could be secured. Therefore, this supports the third hypothesis of the study.

Surprisingly, there is one new result from the findings in this study about the usability of DES which was not expected from the initial conceptual model and hypotheses. The result shows that implementing DES could actually be used for strategic decision making, which contrasts with other opinions that DES is more suitable in solving issues solely at the operational and tactical levels (Baines & Harrison, 1999; Kelton & Law, 1991; Oyarbide et al., 2003; Yingling & Detty, 2000). In fact, in this study DES was also utilised to simulate operation activities. However, as this specific simulation was set up to run in an adequate period of time so that the processed data was properly accumulated, together with the support from the secondary economic data source providing financial information, this method is capable of presenting the ranking of different alternatives for the selection of investment options and it could support the strategic decision making in supply chain change. Therefore, the conceptual model could now be revised in Figure 35, with an additional box of “Usability in Strategic Decision Making” in the third group on the right representing possible outcomes from the modelling method.

Figure 30 – Revised Conceptual Model: Modelling Supply Chain Sustainability



5.2. Correlation of findings with previous literature

This section discusses the correlation of findings with the literature presented previously. The discussion is organised into three major areas: research focus, research methodology, and research boundary. In each, the literature is summarised first, followed by the correlation.

In terms of research focus, prior SCM studies show that the majority of research focuses on non-sustainable SCM, as SSCM study is still considered a separate stream of SCM research (Pagell & Shevchenko, 2014; Seuring & Müller, 2008). Additionally, other research reveals that there are only few studies on sustainability assessment in SCM (Taticchi et al., 2013). Moreover, it was identified that the norms and measurement in SSCM research have improved in order to develop true sustainable supply chains (Pagell & Shevchenko, 2014). Therefore, by addressing sustainability assessment in supply chain change, this study provides more understanding on the knowledge body of SSCM in general, and on SSCM norms and measurement particularly.

Regarding the SSCM norms and measurement, most of the research cases to date address only one of the three aspects of sustainability: the economy, society, or the environment (Elhedhli & Merrick, 2012; Hassini et al., 2012; Seuring, 2013; Singh et al., 2009; Van Der Vorst et al., 2009). Even in research studying only one aspect, studies to date do not address all the sub-topics equally (Wang & Lin, 2007). In the SCND area, there is a similarly limited number of studies focusing on environmental issues, or integrating two approaches on economic and environmental impacts (Bloemhof-Ruwaard et al., 2004; Elhedhli & Merrick, 2012; Eskandarpour et al., 2015). Applying TBL and considering all three sustainable aspects equally in this study may address some of these gaps. This study also complements those of early review papers which suggest that more research using the TBL approach should be conducted to fully integrate sustainability into SCM (Ahi & Searcy, 2013; Ashby et al., 2012; Seuring, 2013; Seuring & Müller, 2008; Taticchi et al., 2013; Wu & Pagell, 2011).

In the research methodology, the quantitative method, along with DSS, DES, and MCDM, are discussed in order. First, it was argued that most of the research approaches in SSCM are qualitative ones (Seuring, 2013), thus a quantitative method approach is encouraged for future research (Benjaafar et al., 2012). Likewise, prior studies claim that a DSS possessing quantifiable justification capability is much needed in making difficult decisions in supply chain change (Stank et al., 2001), while DSS is not widely used in areas other than supplier related activities (Teniwut & Hasyim, 2020). Moreover, there is a lack of study on DSS relating to SSCM indicators (Taticchi et al., 2015), and most of the DSS studies on SSCM only tackled separate issues within the supply chains (Bai & Sarkis, 2010). In this study, the numerical results when utilising DSS and MCDM in sustainability assessment of a forest supply chain provides further support for the viability of the suggestions and help to address these research gaps.

Second, in relation to DES, though it was considered to be able to handle complex systems (Kogler & Rauch, 2018), it was previously observed that DES is infrequently used in connection with sustainability (Van Der Vorst et al., 2009). On the other hand, some studies argue that DES is more suitable in solving issues at operational and tactical levels, rather than on a strategic level (Baines & Harrison, 1999; Kelton & Law, 1991; Oyarbide et al., 2003; Yingling & Detty, 2000), whereas others claim that the difference between the approaches might not be so visible (Tako & Robinson, 2012). In this study, DES is used in assessing the sustainability of different SCND in order to support investment decisions. This proves that DES could be usefully employed to handle complex systems like SSCM, and to solve strategic decision making issues.

Third, with respect to MCDM, although it is widely used for DSS, this method is still under dispute as a viable option in SSCM, due to the risk of manipulation (Zardari et al., 2015), despite its benefits of having a systematic and transparent approach (Janssen, 2001). With the ability for all stakeholders from three main dimensions of sustainability (social, economic, and environmental) to participate and contribute equally in the decision making process, this study suggests that MCDM could still be used in SSCM to benefit the systematic and transparent approach with low risk of manipulation.

Fourth, regarding the modelling method of TBL, DES and MCDM, this combination was proven effective in a limited number of SCM research studies. Those research studies mainly focused on a part of the whole supply chain in specific industries, such as on production planning for a semiconductor manufacturing plant (Altuger & Chassapis, 2009), on maritime transport optimisation for a steel plant (Celestino et al., 2011), and on production design for an automotive products plant (Kurkin & Šimon, 2011). By implementing this combination in the complete forest supply chain, this study further supports the effectiveness of the modelling method of TBL, DES and MCDM in the supply chain as a whole and in a new specific industry.

Finally, regarding the research boundary, the literature reveals that some assessment tools in SSCM are tied to the product, and that there is a demand for assessment performance approaches that are more specific to industry and site (Ness et al., 2007). Previous research also indicates a lack of research of SDS at the industrial level and also on the individual business level, because relevant studies are mainly of theoretical or conceptual (Hilletofth et al., 2016). More specifically, a recent review reveals that DSS is utilised more in certain industries, and much less in others, like in forestry (Teniwut & Hasyim, 2020). Simultaneously, the majority of SSCM research cases are in North American and Europe (Taticchi et al., 2013). By exploring a case study of forest supply chain in New Zealand, this study contributes some more specific knowledge in sustainability assessment of forest supply chain in New Zealand to extend common knowledge.

5.3. Managerial/policy implications

This study recommends a modelling method in sustainability which could provide sufficient support for decision makers a SCNR case. From the research findings, this study makes a positive impact on three levels.

On the operational level, using the simulation model in this study may help harvesting operation and transport managers in improving daily performance. Thanks to the user-friendly virtual interaction of the simulation software, issues in daily activities could be detected easily. For example, bottlenecks, one of the most important issues in supply chains, could be observed by users during the simulation, either by looking at the queuing number of items before the activities, or by looking directly at the items in transit on the connections between simulation blocks. The bottlenecks could also be detected by looking at the output data after running a simulation. Based on the findings, a corrective action could be tested, such as by modifying input data or rearranging the SCND. When the simulation is running smoothly, the actual adjustment could be made in reality.

On the strategic level, the combination of using the combination of TBL, DES and MCDM from this study may help forest owners, and harvesting and transport contractors make decisions on long term projects, resource mobilisation, and investments based on the results from sustainability assessment of SCND alternatives. Due to the flexibility of the simulation model and the weighting ratio setting, different scenarios and criteria could be built up, simulated, tested and modified easily with different input data. The utilisation of MCDM also encourages the active participation of all stakeholders in contributing to common sustainable goals.

On the policy-making level, applying the approach of this study form on a regional or national level will help policy makers gain an overview for long-term development. This is not only because the outputs of the study should be taken into consideration, but the inputs/assumptions could also be examined as well. Modifying the machine capacity or truck load for harvesting or transporting process on a certain level, for example, will not only change the processing time or the yield of the site but could also impact the labour working with machines, the CO_2 emissions from supply chain activities, equipment manufacturing and also investment and financial support entities. Adjusting the yield on a certain level will not only alter the cash flow, but also impact on storage capacity, road, safety, working conditions, and export facilities at the port. Furthermore, the effectiveness of the modelling method of TBL, DES and MCDM in sustainability assessment suggests policy-makers consider certain levels of regulation in terms of specifying this specific set of tool and method as a recommendation and/or requirement in feasibility studies of public investment projects.

For all three levels above, the basic set-up of the similar modelling method of TBL, DES and MCDM may also be implemented in different industries with corresponding SCND, and for various groups of criteria.

5.4. Critique of the research and future research suggestion

This section discusses the limitations of the study and suggests future research avenues.

The limitation of this study relates to the finding a sufficient modelling method in sustainability assessment to provide sufficient support for decision makers in a SCNR. In this study, TBL, DES and MCDM are combined as a method for the specific research questions. The benefits of this method set may open up some more questions such as whether this set could be utilised in other cases, or how a different set of methods could produce similar results. Thus, this study may inspire future research to explore the same set of methods in other contexts or industries, or to try different combinations of tools and methods for the same research objective of how to sufficiently support decision makers in making better sustainability assessment in supply chain change.

Regarding the TBL approach, the full range of TBL includes not only three individual sustainability aspects (social, economic, and environmental) but also three other joint dimensions of eco-efficiency, environmental justice, and business ethics (Elkington, 1997). In this study only three individual dimensions are addressed while the other three joint dimensions are not mentioned. In addition, only one criterion is selected for each dimension (LTI as a social criterion, NPV as an economic criterion, and CO_2 emissions as an environmental criterion). Future research may include those TBL joint dimensions as well as additional criteria for each dimension to achieve an even more holistic result.

As far as the selection process of criteria and weighting ratios is concerned, in this study the input data for this part was based on desk research and assumption, rather than actual opinions of stakeholders. Future research may consider inviting real stakeholders into the selection process of criteria and weighting ratios so that the input data will be closer to actual situations and results will be more practical.

When building the simulation model, this study did not use the option to set up scenarios directly in the ExtendSim software, due to the complexity of the process and the limited availability of the input data. On the other hand, there may be a minor concern relating to the simulation building approach as some may argue that a low detail level of simulation should be used to avoid the complexity of the simulation models, while this study deploys a high detail level. Future study may try new simulation detail levels and then explore different trade-offs between the complexity and accuracy of the simulation.

From the qualitative aspect, while the study shows that the method set has the capability to deliver the expected results, it does not show how well the method set performs. In other words, the detailed qualitative measurement of the method performance is not provided. Future research may consider additional methods, for example conducting an evaluation survey, or carry out multiple case studies, in order to provide a more detailed qualifiable result of the performance levels of the method set.

In view of the process of change, the assessment of sustainability in this study was conducted when the SCNDs are in static conditions, which are the current and the new ones. The process of change from the current conditions to the new ones has not been discussed. Future research may consider this, as well as covering a broader assessment area.

Chapter 6. Conclusion

In an endeavour to fill some gaps identified from the literature which are the lack of a holistic approach in performance assessment, the scarcity of quantifiable justification, and the integrity question in MCDM implementation, this study aims to provide a recommendation for a sustainability assessment method to sufficiently support decision makers in SSCM. It examines the utilisation of a modelling method which combines TBL, DES and MCDM in the sustainability assessment of a New Zealand forest SCNR case study. Following the discussion of the examination results in the previous chapter, this chapter provides the succinct answers to the research question and the original contributions of the study.

6.1. Succinct answers to the research question

The primary research question of this study is: how could utilising a modelling method of combining TBL, DES and MCDM influence the sustainability assessment of a SCNR? From the results of this study, the answers have emerged.

The integration of TBL in the modelling method could bring a holistic approach in sustainability assessment of a SCNR case. This was achieved by considering all three main dimensions of sustainability, social, economic, and environmental, into the assessment. Each sustainability dimension was represented by one criterion as the minimum. A more holistic approach could be achieved when additional criteria for each sustainability dimension and for the interrelations between the dimensions are taken into consideration.

The implementation of DES could provide the quantifiable justification for decision making in a SCND change case. This is because the study reported all sustainability assessment results from different SCND cases and options in numerical form. These results in numbers could also be ranked easily for further analysis and comparison in order to define the best/worst alternatives.

DES could be utilised for strategic decision making, as the sustainability assessment results in this study were supposed to be used as part of the feasibility study to sign-off and push the project into the next prototype development and investment. This answer was not expected in the initial hypotheses, because it contrasts with other opinions from literature which consider DES as suitable only to address operational and tactical levels.

The utilisation of MCDM could secure the integrity of the decision making. This is due to the ability for all stakeholders from three main dimensions of sustainability (social, economic, and environmental) to participate and contribute equally in the main decision making processes which are the selection of the criteria and weighting ratios. Thus, the manipulation risk could be eliminated.

In summary, combining TBL, DES and MCDM in a modelling method for sustainability assessment of a SCND change could achieve a more holistic approach, provide quantifiable justification for decision makers, be useful in strategic decision making, and secure the integrity of the decision making.

6.2. Original contributions

This study's results represent both theoretical and empirical contributions. The theoretical contributions consist of addressing gaps in previous research, and providing both a link to, and recommendations for future research. The empirical contributions include the implementations for practitioners and policy makers.

In addressing gaps from the previous research, this study provides more understanding on the knowledge of SSCM in general, and on SSCM norms and measurement particularly, by tackling sustainability assessment issues. Integrating with TBL, this study addresses the lack of a holistic approach in the SSCM literature. The quantitative approach of this study decreases the dominance of the qualitative method in SSCM research. The DES utilisation in this study lessens the scarcity of implementing DSS in non-supplier related activities, in SSCM indicators, and in the supply chain as a whole. Implementing DES in this study demonstrates a new problem-solving capability at the strategic decision making level, rather than at operational and tactical levels, and in tackling sustainability related matters, as argued in previous literature. Moreover, this DES implementation contributes additional knowledge to the current literature which asks for more research on SDS at the industrial level and also on the individual business level to cover the lack of study in this area, for more DSS implementation in low DSS utilising industries such as forestry. This study responds to criticism concerning the risk of manipulation in common MCDM implementation, by showing that the risk in the SSCM context could be eliminated when all sustainability stakeholders participate and contribute equally in the decision making process. By combining DES and MCDM in a complete forest supply chain, this study provides more evidence to show that this combination is effective not only in separate supply chain activities and in other industries as mentioned in previous literature, but also in the supply chain as a whole in general, and in the forest industry specifically. In performing a sustainability assessment case study of the forest supply chain in New Zealand, this study contributes some more specific knowledge to extend the current knowledge which demands for more assessment approaches that are specific to industry and site rather than being tied to the product, and for more SSCM study in countries other than in North American and Europe.

For future research, the tools used in this study inspire more research to explore the same combination of TBL, DES and MCDM in other contexts or industries, or to try combinations of different tools and methods for the same research objective of how to sufficiently support decision makers in improving sustainability assessment in supply chain. The approach of this study recommends future research consider including other TBL joint dimensions of eco-efficiency, environmental justice, and business ethics and additional criteria for each dimension to achieve an even more holistic result. The data collection in this study suggests new research to consider inviting real stakeholders into the selection process of criteria and weighting ratios so that the results will be more practical. The simulation in this study triggers different building options in new research. This study's method invites additional evaluation surveys or multiple case study research to provide statistical or qualifiable results on the performance levels of the set of tools. The boundary of this study prompts future research to include the process of change and a broader assessment area than SCND into consideration.

With practitioners, the combination of DES and MCDM as a set of tool and method could help forest owners, and harvesting and transport contractors in testing alternatives and making decisions on long term projects, resource mobilisation, and investments based on the results from sustainability assessment of SCND alternatives. The basic set-up of this set of tool and method could also be implemented in different industries with corresponding SCND, and for various groups of criteria. Using the simulation models built in this study may help harvesting operations and transport managers improve daily performance, for example to identify bottlenecks, and test corrective action before making changes. The utilisation of MCDM is also a useful tool to encourage the active participation of all stakeholders in contributing to common sustainable goals.

From policy maker viewpoints, using this study's approach and form on a regional or national level will help policy makers to gain an overview for long term development on key areas such as investment and finance, manufacturing, transportation, safety, labour, export, and port development. Furthermore, the effectiveness of the modelling method of TBL, DES and MCDM in sustainability assessment suggests the need for policy-makers to consider certain levels of regulation in terms of using the set of tool and method as a recommendation and/or requirement in feasibility studies of publicly funded projects.

References

1. Abar, S., Theodoropoulos, G. K., Lemarinier, P., & O'Hare, G. M. P. (2017). Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Computer Science Review*, *24*, 13–33. https://doi.org/10.1016/j.cosrev.2017.03.001

2. Afgan, N. H., & da Graça Carvalho, M. (2000). Energy System Assessment Introduction. In *Sustainable Assessment Method for Energy Systems* (pp. 83–125). Springer.

3. Ahi, P., & Searcy, C. (2013). A comparative literature analysis of definitions for green and sustainable supply chain management. *Journal of Cleaner Production*, *52*, 329–341. https://doi.org/10.1016/j.jclepro.2013.02.018

4. Ahi, P., & Searcy, C. (2015). An analysis of metrics used to measure performance in green and sustainable supply chains. *Journal of Cleaner Production*, *86*, 360–377. https://doi.org/10.1016/j.jclepro.2014.08.005

5. Allaoui, H., Guo, Y., & Sarkis, J. (2019). Decision support for collaboration planning in sustainable supply chains. *Journal of Cleaner Production*, *229*, 761–774. https://doi.org/10.1016/j.jclepro.2019.04.367

6. Altuger, G., & Chassapis, C. (2009). Multi criteria preventive maintenance scheduling through arena based simulation modeling. *Proceedings - Winter Simulation Conference, WSC, IEEE*, 2123–2134. https://doi.org/10.1109/WSC.2009.5429668

7. Andersen, M., & Skjoett-Larsen, T. (2009). Corporate social responsibility in global supply chains. *Supply Chain Management: An International Journal*, *14*(2), 75–86. https://doi.org/10.1108/13598540910941948

8. Arghode, V. (2012). Qualitative and Quantitative Research: Paradigmatic Differences. *Global Education Journal*, *2012*(4), 155–163.

9. Asemi, A., Safari, A., & Asemi Zavareh, A. (2011). The Role of Management Information System (MIS) and Decision Support System (DSS) for Manager's Decision Making Process. *International Journal of Business and Management*, *6*(7), 164–173. https://doi.org/10.5539/ijbm.v6n7p164

10. Asgharizadeh, E., Torabi, S. A., Mohaghar, A., & Zare-Shourijeh, M. A. (2019). Sustainable Supply Chain Network Design: A Review on Quantitative Models Using Content Analysis. *Environmental Energy and Economic Research*, *3*(2), 143–176. https://doi.org/10.22097/eeer.2019.184458.1081

11. Ashby, A., Leat, M., & Hudson-Smith, M. (2012). Making connections: A review of supply chain management and sustainability literature. *Supply Chain Management*, *17*(5), 497–516. https://doi.org/10.1108/13598541211258573

12. Auger, P., Burke, P., Devinney, T. M., & Louviere, J. J. (2003). What Will Consumers Pay for Social Product Features? *Journal of Business Ethics*, *42*(3), 281–304. http://www.jstor.org/stable/25074960?seq=1#page_scan_tab_contents

13. Autry, C. W., Goldsby, T. J., Bell, J., Moon, M. A., Munson, C., Watson, M., Lewis, S., Cacioppi, P., & Jayaraman, J. (2013). *The definitive guide to modern supply chain management (collection)*. FT Press.

14. Bai, C., & Sarkis, J. (2010). Integrating sustainability into supplier selection with grey system and rough set methodologies. *International Journal of Production Economics*, *124*(1), 252–264. https://doi.org/10.1016/j.ijpe.2009.11.023

15. Baines, T. S., & Harrison, D. K. (1999). An opportunity for system dynamics in manufacturing system modelling 2 . The origin of SD and its application to manufacturing systems modelling. *Production Planning & Control*, *10*(6), 542–552.

16. Bardi, U. (2011). The Limits to Growth Revisited. In *Springer Briefs in Energy: Energy Analysis*. Springer. https://doi.org/10.1007/s00277-011-1156-9

17. Barkemeyer, R., Holt, D., Preuss, L., & Tsang, S. (2014). What happened to the “development” in sustainable development? Business guidelines two decades after Brundtland. *Sustainable Development*, *22*(1), 15–32. https://doi.org/10.1002/sd.521

18. Bell, E., Bryman, A., & Harley, B. (2018). *Business Research Methods* (5th ed.). Oxford University Press.

19. Bell, P. C., & O’Keefe, R. M. (1987). Visual Interactive Simulation - History, recent developments, and major issues. *SIMULATION*, *49*(3), 109–116.

20. Benjaafar, S., Li, Y., & Daskin, M. (2012). Carbon Footprint and the Management of Supply Chains: Insights From Simple Models. *IEEE Transactions on Automation Science and Engineering*, *10*(1), 99–116. https://doi.org/10.1109/TASE.2012.2203304

21. Bennett, N., & Lemoine, G. J. (2014). What VUCA Really Means for You. *Harvard Business Review*, *92*(February), 2014.

22. Bentley, T. A., Parker, R. J., Ashby, L., Moore, D. J., & Tappin, D. C. (2005). The role of the New Zealand forest industry injury surveillance system in a strategic Ergonomics, Safety and Health Research Programme. *Applied Ergonomics*, *36*(2), 165–175. https://doi.org/10.1016/S0003-6870(02)00037-6

23. Beske-Janssen, P., Johnson, M. P., & Schaltegger, S. (2015). 20 Years of Performance Measurement in Sustainable Supply Chain Management – What Has Been Achieved? *Supply Chain Management*, *20*(6), 664–680. https://doi.org/10.1108/SCM-06-2015-0216

24. Bitektine, A. (2008). Prospective case study design: Qualitative method for deductive theory testing. *Organizational Research Methods*, *11*(1), 160–180. https://doi.org/10.1177/1094428106292900

25. Blanco, E. E., & Sheffi, Y. (2017). Green Logistics. In *Sustainable Supply Chains* (pp. 147–187). Springer, Cham. https://doi.org/10.1007/978-3-319-29791-0

26. Bloemhof-Ruwaard, J. M., Krikke, H., & Wassenhove, L. N. Van. (2004). OR Models for Eco-eco Closed-loop Supply Chain Optimization. *Reverse Logistics*, 357–379. https://doi.org/10.1007/978-3-540-24803-3_15

27. Bloemhof-Ruwaard, J. M., van Beek, P., Hordijk, L., & Van Wassenhove, L. N. (1995). Interactions between operational research and environmental management. *European Journal of Operational Research*, *85*(2), 229–243. https://doi.org/10.1016/0377-2217(94)00294-M

28. Booth, M. E., & Philip, G. (1998). Technology, competencies, and competitiveness: The case for reconfigurable and flexible strategies. *Journal of Business Research*, *41*(1), 29–40. https://doi.org/10.1016/S0148-2963(97)00009-X

29. Booth, W. C., Colomb, G. G., Williams, J. M., Bizup, J., & FitzGerald, W. T. (2016). *The Craft of Research* (4th ed.). The University of Chicago Press. https://doi.org/10.7208/chicago/9780226239873.001.0001

30. Brandenburg, M., Govindan, K., Sarkis, J., & Seuring, S. (2014). Quantitative models for sustainable supply chain management: Developments and directions. *European Journal of Operational Research*, *233*(2), 299–312. https://doi.org/10.1016/j.ejor.2013.09.032

31. Brundtland, G. H., Khalid, M., Agnelli, S., Al-Athel, S. A., & Chidzero, B. (1987). *Our Common Future*. Oxford University Press.

32. Bryman, A. (1984). The Debate about Quantitative and Qualitative Research : A Question of Method or Epistemology? *The British Journal of Sociology*, *35*(1), 75–92. https://www.jstor.org/stable/590553

33. Caradonna, J. L. (2014). *Sustainability: a history*. Oxford University Press. https://doi.org/10.5860/choice.187122

34. Carson, R. (2002). *Silent Spring*. First Mariner Books. https://doi.org/10.1017/CBO9781107415324.004

35. Carter, C. R., & Easton, P. L. (2011). Sustainable supply chain management: Evolution and future directions. In *International Journal of Physical Distribution and Logistics Management* (Vol. 41, Issue 1). https://doi.org/10.1108/09600031111101420

36. Carter, C. R., & Jennings, M. M. (2002). Logistics social responsibility: an integrative framework. *Journal of Business Logistics*, *23*(1), 145–180.

37. Carter, C. R., & Rogers, D. S. (2008). A framework of sustainable supply chain management: Moving toward new theory. *International Journal of Physical Distribution and Logistics Management*, *38*(5), 360–387. https://doi.org/10.1108/09600030810882816

38. Celestino, R., Brito, T. B., Botter, R. C., & Pereira, N. N. (2011). Modeling of a Closed-Loop Maritime Transportation System with Discrete Event Simulation and Multi-Criteria Decision Analysis. *Lecture Notes in Engineering and Computer Science*, *2194*(1), 956–961.

39. Chandra, C., & Kumar, S. (2000). Supply chain management in theory and practice: A passing fad or a fundamental change? *Industrial Management and Data Systems*, *100*(3), 100–113. https://doi.org/10.1108/02635570010286168

40. Chen, I. J., & Paulraj, A. (2004). Towards a theory of supply chain management: The constructs and measurements. *Journal of Operations Management*, *22*(2), 119–150. https://doi.org/10.1016/j.jom.2003.12.007

41. Chen, S.-J., & Hwang, C.-L. (1992). *Fuzzy Multiple Attribute Decision Making Methods*. Springer-Verlag. https://doi.org/10.1007/978-3-642-46768-4_5

42. Childerhouse, P., Childerhouse, P., & Towill, D. R. (2015). Simplified material flow holds key to supply chain integration Simpliÿed material ow holds the key to supply chain integration. *The International Journal of Management Science*, *31*(February 2003), 17–27. https://doi.org/10.1016/S0305-0483(02)00062-2

43. Choi, T. Y., Dooley, K. J., & Rungtusanatham, M. (2001). Supply networks and complex adaptive systems: Control versus emergence. *Journal of Operations Management*, *19*(3), 351–366. https://doi.org/10.1016/S0272-6963(00)00068-1

44. Choo, E. U., Schoner, B., & Wedley, W. C. (1999). Interpretation of criteria weights in multicriteria decision making. *Computers and Industrial Engineering*, *37*(3), 527–541. https://doi.org/10.1016/S0360-8352(00)00019-X

45. Christopher, M. (2011). *Logistics & Supply Chain Management* (4th ed.). Pearson Education Limited.

46. Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Pearson.

47. Christopher, M., & Holweg, M. (2011). “Supply Chain 2.0”: Managing supply chains in the era of turbulence. *International Journal of Physical Distribution and Logistics Management*, *41*(1), 63–82. https://doi.org/10.1108/09600031111101439

48. Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, *46*, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

49. Cooksey, R. W. (2020). Illustrating Statistical Procedures: Finding Meaning in Quantitative Data. In *Illustrating Statistical Procedures: Finding Meaning in Quantitative Data*. Springer. https://doi.org/10.1007/978-981-15-2537-7

50. Cooper, D. R., & Schindler, P. S. (2014). *Business research methods* (12th ed.). McGraw-Hill.

51. Cruz, J. M. (2009). The impact of corporate social responsibility in supply chain management: Multicriteria decision-making approach. *Decision Support Systems*, *48*(1), 224–236. https://doi.org/10.1016/j.dss.2009.07.013

52. D'amours, S., Rönnqvist, M., & Weintraub, A. (2008). Using Operational Research for supply chain planning in the forest products industry. *INFOR: Information Systems and Operational Research*, *46*(4), 265–281. https://doi.org/10.3138/infor.46.4.265

53. David, M., & Sutton, C. D. (2011). *Social research: An introduction* (2nd ed.). SAGE Publications Ltd.

54. Davis, G. F., Whitman, M. V. N., & Zald, M. N. (2011). The Responsibility Paradox: Multinational Firms and Global Corporate Social Responsibility. *SSRN Electronic Journal*, *4*. https://doi.org/10.2139/ssrn.899112

55. Devika, K., Jafarian, A., & Nourbakhsh, V. (2014). Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. *European Journal of Operational Research*, *235*(3), 594–615. https://doi.org/10.1016/j.ejor.2013.12.032

56. Diesendorf, M. (2000). Sustainability and Sustainable Development. In *Sustainability: The corporate challenge of the 21st century* (Vol. 2, pp. 19–37). https://doi.org/10.4324/9781315442044-11

57. Du Pisani, J. A. (2006). Sustainable development – historical roots of the concept. *Environmental Sciences*, *3*(2), 83–96. https://doi.org/10.1080/15693430600688831

58. Dubey, R., Gunasekaran, A., Childe, S. J., Papadopoulos, T., & Fosso Wamba, S. (2017). World class sustainable supply chain management: critical review and further research directions. *International Journal of Logistics Management*, *28*(2), 332–362.

59. Elhedhli, S., & Merrick, R. (2012). Green supply chain network design to reduce carbon emissions. *Transportation Research Part D: Transport and Environment*, *17*(5), 370–379. https://doi.org/10.1016/j.trd.2012.02.002

60. Elkington, J. (1994). Towards the sustainable corporation: Win-win-win business strategies for sustainable development. *California Management Review*, *36*(2), 90–100.

61. Elkington, J. (1997). *Cannibals With Forks: the Triple Bottom Line of 21st Century Business*. Capstone Publishing Limited.

62. Elliott, J. A. (2012). An Introduction to Sustainable Development : Routledge Perspectives on Development. In *International Journal of Sustainability in Higher Education* (Fourth, Vol. 9, Issue 3). Routledge. https://doi.org/10.1108/ijshe.2008.24909cae.004

63. Erol, I., Sencer, S., & Sari, R. (2011). A new fuzzy multi-criteria framework for measuring sustainability performance of a supply chain. *Ecological Economics*, *70*(6), 1088–1100. https://doi.org/10.1016/j.ecolecon.2011.01.001

64. Eskandarpour, M., Dejax, P., Miemczyk, J., & Péton, O. (2015). Sustainable supply chain network design: An optimization-oriented review. *Omega, Elsevier*, *54*, 11–32. https://doi.org/10.1016/j.omega.2015.01.006

65. Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

66. Firestone, W. A. (1987). Meaning in Method: The Rhetoric of Quantitative and Qualitative Research. *Educational Researcher*, *16*(7), 16–21. https://doi.org/10.3102/0013189X016007016

67. Forest Growers Research. (2020). *Our Role*. https://fgr.nz/about/our-aim/

68. Forest Value Chain Consortium. (2018). *Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age* (Issue September). https://fgr.nz/documents/download/6855

69. Forestry New Zealand. (2019). *New Zealand's forest industry*. https://www.teururakau.govt.nz/growing-and-harvesting/forestry/new-zealand-forests-and-the-forest-industry/new-zealands-forest-industry/

70. Forestry New Zealand. (2020). *Importance of New Zealand forests*. https://www.teururakau.govt.nz/growing-and-harvesting/forestry/new-zealand-forests-and-the-forest-industry/importance-of-new-zealand-forests/

71. Forrester, J. W. (1971). *World Dynamics*. Wright-Allen Press, Inc.

72. Gan, X., Fernandez, I. C., Guo, J., Wilson, M., Zhao, Y., Zhou, B., & Wu, J. (2017). When to use what: Methods for weighting and aggregating sustainability indicators. *Ecological Indicators*, *81*(May), 491–502. https://doi.org/10.1016/j.ecolind.2017.05.068

73. Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. C. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega (United Kingdom)*, *66*, 344–357. https://doi.org/10.1016/j.omega.2015.05.015

74. Gibson, R. B., Hassan, S., Holtz, S., Tansey, J., & Whitelaw, G. (2005). *Sustainability Assessment: Criteria, Processes, and Applications*.

75. Gladwin, T. N., Kennelly, J. J., & Krause, T. (1995). Shifting Paradigms for Sustainable for Implications Development : and Theory. *Academy of Management Review*, *20*(4), 874–907. https://doi.org/10.5465/AMR.1995.9512280024

76. Goldsmith, E., Allen, R., Allaby, M., Davoll, J., & Lawrence, S. (1972). A Blueprint for Survival. *The Ecologist*, *2*(1).

77. Govindan, K., Khodaverdi, R., & Jafarian, A. (2013). A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. *Journal of Cleaner Production*, *47*, 345–354. https://doi.org/10.1016/j.jclepro.2012.04.014

78. Greener, S. (2008). *BUSINESS RESEARCH METHODS*. Dr. Sue Greener & Ventus Publishing ApS.

79. Gunasekaran, A., & Kobu, B. (2007). Performance measures and metrics in logistics and supply chain management: A review of recent literature (1995-2004) for research and applications. *International Journal of Production Research*, *45*(12), 2819–2840. https://doi.org/10.1080/00207540600806513

80. Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International Journal of Production Economics*, *87*(3), 333–347. https://doi.org/10.1016/j.ijpe.2003.08.003

81. Hardin, G. (1968). The Tragedy of the Commons. *Science*, *162*(3859), 1243–1248.

82. Hardy, M., & Bryman, A. (2009). Handbook of Data Analysis. In *Handbook of Data Analysis*. SAGE Publications Ltd. https://doi.org/10.4135/9781848608184

83. Hassini, E., Surti, C., & Searcy, C. (2012). A literature review and a case study of sustainable supply chains with a focus on metrics. *International Journal of Production Economics*, *140*(1), 69–82. https://doi.org/10.1016/j.ijpe.2012.01.042

84. Hervani, A. A., Helms, M. M., & Sarkis, J. (2005). Performance measurement for green supply chain management. *Benchmarking: An International Journal*, *12*(4), 330–353. https://doi.org/10.1108/14635770510609015

85. Hilletofth, P., Hilmola, O.-P., & Wang, Y. (2016). Simulation based decision support systems in the supply chain context. *Industrial Management & Data Systems*, *116*(2).

86. Huang, G. Q., Lau, J. S. K., & Mak, K. L. (2003). The impacts of sharing production information on supply chain dynamics: A review of the literature. *International Journal of Production Research*, *41*(7), 1483–1517. https://doi.org/10.1080/0020754031000069625

87. Hutchins, M. J., & Sutherland, J. W. (2008). An exploration of measures of social sustainability and their application to supply chain decisions. *Journal of Cleaner Production*, *16*(15), 1688–1698. https://doi.org/10.1016/j.jclepro.2008.06.001

88. Jahani, H., Abbasi, B., Alavifard, F., & Talluri, S. (2018). Supply chain network redesign with demand and price uncertainty. *International Journal of Production Economics*, *205*, 287–312. https://doi.org/10.1016/j.ijpe.2018.08.022

89. Jain, S., Lim, C.-C., Gan, B.-P., & Low, Y.-H. (1999). Criticality of detailed modeling in semiconductor supply chain simulation. *Proceedings of the 31st Conference on Winter Simulation: Simulation - a Bridge to the Future*, *1*, 888–896.

90. Jain, S., Workman, R. W., Collins, L. M., Ervin, E. C., & Lathrop, A. P. (2001). Development of a high-level supply chain simulation model. *Proceedings of the 2001 Winter Simulation Conference (Cat. No. 01CH37304)*, *2*, 1129–1137.

91. Janssen, R. (2001). On the use of multi-criteria analysis in environmental impact assessment in the Netherlands. *Journal of Multi-Criteria Decision Analysis*, *10*(2), 101–109. https://doi.org/10.1002/mcda.293

92. Jia, J., Fischer, G. W., & Dyer, J. S. (1998). Attribute weighting methods and decision quality in the presence of response error: A simulation study. *Journal of Behavioral Decision Making*, *11*(2), 85–105. https://doi.org/10.1002/(SICI)1099-0771(199806)11:2<85::AID-BDM282>3.0.CO;2-K

93. Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., Mccarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grubler, A., Huntley, B., Jager, J., Jodha, N. S., Kasperson, R. E., Mabogunje, A., Matson, P., … Svedin, U. (2001). Sustainability Science. *Science*, *292*(5517), 641–642.

94. Kelly, M. E. O. (1998). A geographer 's analysis of hub-and- spoke networks. *Journal of Transport Geography*, *6*(3), 171–186.

95. Kelton, W. D., & Law, A. M. (1991). *Simulation Modeling and Analysis* (3rd ed.). McGraw-Hill.

96. Kitchenham, B. A., & Pickard, L. M. (1998). Evaluating Software Engineering Methods and Tools. Part 9: Quantitative Case Study Methodology. *ACM SIGSOFT Software Engineering Notes*, *23*(1), 24–26. https://doi.org/10.1145/272263.272268

97. Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. *European Journal of Operational Research*, *203*(2), 283–293. https://doi.org/10.1016/j.ejor.2009.06.011

98. Kogler, C., & Rauch, P. (2018). Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: A literature review. *Silva Fennica*, *52*(4). https://doi.org/10.14214/sf.9984

99. Kremer, M., Lieshout, P. Van, & Went, R. (2009). Doing Good or Doing Better: Development Policies in a Globalising World. *Scientific Council for Government Policy*. https://doi.org/10.5117/9789089641076

100. Kurkin, O., & Šimon, M. (2011). Optimization of layout using discrete event simulation. *IBIMA Business Review*, *1*, 268–276. https://doi.org/10.5171/2011.180343

101. Laguna, M., & Marklund, J. (2013). *BUSINESS PROCESS MODELING, SIMULATION AND DESIGN* (2nd ed.). CRC Press, Taylor & Francis Group. https://doi.org/10.1201/9780203507223.ch32

102. Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management in Indian agriculture. *Industrial Marketing Management*, *29*, 65–83. https://doi.org/10.1017/UPO9788175968462.008

103. Lashof, D. A., & Ahuja, D. R. (1990). Relative contributions of greenhouse gas emissions to global warming. In *Nature* (Vol. 344, Issue 6266, pp. 529–531). https://doi.org/10.1038/344529a0

104. Layton, B. (2010). *Port Performance and Ownership An assessment of the evidence* (Issue August).

105. Lenny Koh, S. C., Genovese, A., Acquaye, A. A., Barratt, P., Rana, N., Kuylenstierna, J., & Gibbs, D. (2013). Decarbonising product supply chains: Design and development of an integrated evidence-based decision support system-the supply chain environmental analysis tool (SCEnAT). *International Journal of Production Research*, *51*(7), 2092–2109. https://doi.org/10.1080/00207543.2012.705042

106. Li, J., Hallsworth, A. G., & Coca-Stefaniak, J. A. (2020). Changing Grocery Shopping Behaviours Among Chinese Consumers At The Outset Of The COVID-19 Outbreak. *Tijdschrift Voor Economische En Sociale Geografie*, *111*(3), 574–583. https://doi.org/10.1111/tesg.12420

107. Liu, S., Leat, M., & Smith, M. H. (2011). State-of-the-art sustainability analysis methodologies for efficient decision support in green production operations. *International Journal of Sustainable Engineering*, *4*(3), 236–250. https://doi.org/10.1080/19397038.2011.574744

108. Lummus, R. R., Krumwiede, D. W., & Vokurka, R. J. (2001). The relationship of logistics to supply chain management: developing a common industry definition. *Industrial Management & Data Systems*, *101*(8), 426–431. https://doi.org/10.4081/ijas.2007.s2.731

109. Lummus, R. R., & Vokurka, R. J. (1999). Defining supply chain management: A historical perspective and practical guidelines. *Industrial Management & Data Systems*, *99*(1), 11–17.

110. Lutts, R. H. (1985). Chemical Fallout: Carson’ s Silent Spring, Radioactive Fallout, and the Environmental Movement. *Environmental Review*, *9*(3), 210–225.

111. Mackenzie, N., & Knipe, S. (2006). Research dilemmas: Paradigms, methods and methodology [Electronic Version]. *Issues In Educational Research*, *16*(2), 193–205. http://www.iier.org.au/iier16/mackenzie.html

112. Magallanes, C. J. I. (2015). Maori cultural rights in Aotearoa New Zealand: Protecting the cosmology that protects the environment. *Widener Law Review*, *21*(273), 273–327. www.waitangitribunal.govt.nz.

113. Magnanti, T. L., & Wong, R. T. (1984). Network Design and Transportation Planning: Models and Algorithms. *Transportation Science*, *18*(1), 1–55. https://doi.org/10.1287/trsc.18.1.1

114. Martins, C. L., Melo, M. T., & Pato, M. V. (2019). Redesigning a food bank supply chain network in a triple bottom line context. *International Journal of Production Economics*, *214*, 234–247. https://doi.org/10.1016/j.ijpe.2018.11.011

115. McCallum, D. (2009). *Carbon Footprint Report* (Issue June).

116. McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, *11*(3), 239–256. https://doi.org/10.1016/0272-6963(93)90002-7

117. McKenzie, S. (2004). Social sustainability: Towards some definitions. In *Hawke Research Institute* (27).

118. Meadows, D. H., Meadows, D. L., Randers, J., & III, W. W. B. (1972). *The Limits to Growth*. Universe Books. https://doi.org/10.1128/iai.65.9.3944-3946.1997

119. Mebratu, D. (1998). Sustainability and sustainable development: Historical and conceptual review. *Environmental Impact Assessment Review*, *18*(6), 493–520. https://doi.org/10.1016/S0195-9255(98)00019-5

120. Mefford, R. N. (2011). The Economic Value of a Sustainable Supply Chain. *Business and Society Review*, *116*(1), 109–143. https://doi.org/10.1111/j.1467-8594.2011.00379.x

121. Melo, M. T., Nickel, S., & Saldanha-da-Gama, F. (2009). Facility location and supply chain management - A review. *European Journal of Operational Research*, *196*(2), 401–412. https://doi.org/10.1016/j.ejor.2008.05.007

122. Melo, M. T., Nickel, S., & Saldanha Da Gama, F. S. (2006). Dynamic multi-commodity capacitated facility location: A mathematical modeling framework for strategic supply chain planning. *Computers and Operations Research*, *33*(1), 181–208. https://doi.org/10.1016/j.cor.2004.07.005

123. Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (1992). Defining Supply Chain Management. *Journal of Business Logistics*, *13*(2), 1–25.

124. Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining Supply Chain Management. *Journal of Business Logistics*, *22*(2), 1–25. https://doi.org/10.1002/j.2158-1592.2001.tb00001.x

125. Merom, D., & John, J. R. (2019). Measurement issues in quantitative research. *Handbook of Research Methods in Health Social Sciences*, 663–679. https://doi.org/10.1007/978-981-10-5251-4_95

126. Ministry for Primary Industries. (2019a). *Boosting forest harvesting productivity, safety and skills focus of new programme launched today*. https://www.mpi.govt.nz/news-and-resources/media-releases/boosting-forest-harvesting-productivity-safety-and-skills-focus-of-new-programme-launched-today/

127. Ministry for Primary Industries. (2019b). *National exotic forest description*.

128. Ministry for Primary Industries. (2019c). *Te Mahi Ngahere i te Ao Hurihuri – Forestry work in the modern age*. https://www.agriculture.govt.nz/funding-and-programmes/sustainable-food-and-fibre-futures/primary-growth-partnership/current-pgp-programmes/te-mahi-ngahere-i-te-ao-hurihuri-forestry-work-in-the-modern-age/

129. Ministry for Primary Industries. (2020). *New Zealand's forests*. https://www.mpi.govt.nz/growing-and-harvesting/forestry/new-zealand-forests-and-the-forest-industry/new-zealands-forests/

130. Ministry for the Environment. (2007). Environment New Zealand 2007. In *Environment New Zealand 2007*. Ministry for the Environment. www.mfe.govt.nz

131. Ministry of Primary Industries. (2014). *National Exotic Forest Description* (Issue 31). https://doi.org/10.1017/CBO9781107415324.004

132. Mobini, M., Sowlati, T., & Sokhansanj, S. (2011). Forest biomass supply logistics for a power plant using the discrete-event simulation approach. *Applied Energy*, *88*(4), 1241–1250. https://doi.org/10.1016/j.apenergy.2010.10.016

133. Morioka, S. N., & Carvalho, M. M. (2016). Measuring sustainability in practice: exploring the inclusion of sustainability into corporate performance systems in Brazilian case studies. *Journal of Cleaner Production*, *136*, 123–133. https://doi.org/10.1016/j.jclepro.2016.01.103

134. Murphy, P. R., & Poist, R. F. (2002). Socially responsible logistics an exploratory study. *Transportation Journal*, 23–35.

135. Nagurney, A. (2010). Optimal Supply Chain Network Design and Redesign at Minimal Total Cost and with Demand Satisfaction. *International Journal of Production Economics*, *128*(1), 200–208.

136. Nagurney, A., & Nagurney, L. S. (2010). Sustainable Supply Chain Network Design: A Multicriteria Perspective. *International Journal of Sustainable Engineering*, *3*(3), 189–197. https://doi.org/10.1017/CBO9781107415324.004

137. Nance, R. E. (1993). A history of discrete event simulation programming languages. In *2nd ACM SIGPLAN Conference on History of Programming Languages, HOPL 1993* (pp. 149–175). https://doi.org/10.1145/154766.155368

138. Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. *Ecological Economics*, *60*(3), 498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023

139. Neto, J. Q. F., Bloemhof-Ruwaard, J. M., Nunen, J. A. E. E. Van, & Heck, H. W. G. M. Van. (2008). Designing and Evaluating Sustainable Logistics Networks. *International Journal of Production Economics*, *111*(2), 195–208.

140. Neuman, W. L. (2014). Social Research Methods: Qualitative and Quantitative Approaches. In *Teaching Sociology* (7th ed., Vol. 30, Issue 3). Pearson. https://doi.org/10.2307/3211488

141. New Zealand Forest Owners Association. (2012). *New Zealand Forest Road Engineering Manual*. New Zealand Forest Owners Association.

142. New Zealand Forest Owners Association. (2019). *Facts & Figures 2018/19 New Zealand Plantation Forest Industry*.

143. New Zealand Forest Owners Association. (2020). *Exports*. https://www.nzfoa.org.nz/plantation-forestry/plantation-forestry-overview

144. New Zealand Immigration. (2020). *A brief history*. https://www.newzealandnow.govt.nz/living-in-nz/history-government/a-brief-history

145. Climate Change Response (Zero Carbon) Amendment Bill, House of Representatives (2019).

146. NZ Transport Agency. (2020). *50MAX – information for road controlling authorities*. https://www.nzta.govt.nz/commercial-driving/high-productivity/50max/50max-information-for-road-controlling-authorities/

147. O'Kelly, M. E., & Miller, H. J. (1994). The hub network design problem. *Journal of Transport Geography*, *2*(1), 31–40.

148. Obi, O. F., & Visser, R. (2017). Influence of the operating environment on the technical efficiency of forest harvesting operations. In *International Journal of Forest Engineering* (Vol. 28, Issue 3). Taylor & Francis. https://doi.org/10.1080/14942119.2017.1357391

149. Oliver, R. K., & Webber, M. D. (1982). Supply-chain management: logistics catches up with strategy. *Outlook*, *5*(1), 42-47.

150. Orlitzky, M., Schmidt, F. L., & Rynes, S. L. (2003). 57-orlitzky2003-Social & Financial performance-Meta Analysis.pdf. *Organization Studies*, *24*(3), 403–441.

151. Oyarbide, A., Bsines, T. S., Kay, J. M., & Ladbrook, J. (2003). Manufacturing Systems Modelling Using System Dynamics: Forming a Dedicated Modelling Tool. *Journal of Advanced Manufacturing Systems*, *02*(01), 71–87. https://doi.org/10.1142/s0219686703000228

152. Page, M., Trustrum, N., & Gomez, B. (2000). Implications of a century of anthropogenic erosion for future land use in the Gisborne-East coast region of New Zealand. *New Zealand Geographer*, *56*(2), 13–24. https://doi.org/10.1039/b005701k

153. Pagell, M., & Shevchenko, A. (2014). Why research in sustainable supply chain management should have no future. *Journal of Supply Chain Management*, *50*(1), 44–55. https://doi.org/10.1111/jscm.12037

154. Paul, B. D. (2008). A history of the concept of sustainable development: Literature review. *The Annals of the University of Oradea, Economic Sciences Series*, *17*(2), 576–580. https://doi.org/10.7870/cjcmh-1999-0013

155. Persson, F., & Araldi, M. (2009). The development of a dynamic supply chain analysis tool-Integration of SCOR and discrete event simulation. *International Journal of Production Economics*, *121*(2), 574–583. https://doi.org/10.1016/j.ijpe.2006.12.064

156. Persson, F., & Olhager, J. (2002). Performance simulation of supply chain designs. *International Journal of Production Economics*, *77*(3), 231–245. https://doi.org/10.1016/S0925-5273(00)00088-8

157. Phillips, C., Marden, M., & Basher, L. R. (2017). Geomorphology and forest management in New Zealand's erodible steeplands: An overview. *Geomorphology*, *307*, 107–121. https://doi.org/10.1016/j.geomorph.2017.07.031

158. Power, D. J. (2007). A brief history of decision support systems. *DSSResources. Com*, *3*.

159. Ravet, D. (2013). Delivering Sustainability Through Supply Chain Distribution Network Redesign. *Central European Business Review*, *2*(3), 22–29. https://doi.org/10.18267/j.cebr.51

160. Roberts, R. W. (1992). Determinants of corporate social responsibility disclosure: An application of stakeholder theory. *Accounting, Organizations and Society*, *17*(6), 595–612. https://doi.org/10.1016/0361-3682(92)90015-K

161. Robinson, S. (2005). Discrete-event simulation: From the pioneers to the present, what next? *Journal of the Operational Research Society*, *56*(6), 619–629. https://doi.org/10.1057/palgrave.jors.2601864

162. Roman, R. M., Hayibor, S., & Agle, B. R. (1999). The relationship between social and financial performance: Repainting a portrait. *Business and Society*, *38*(1), 109–125. https://doi.org/10.1177/000765039903800105

163. Rust, R. T., Moorman, C., & Dickson, P. R. (2002). Getting return on quality: Revenue expansion, cost reduction, or both? *Journal of Marketing*, *66*(4), 7–24. https://doi.org/10.1509/jmkg.66.4.7.18515

164. Ryan, P. A. (2002). Capital budgeting practices of the fortune 1000: how have things changed? *Journal of Business and Management*, *8*(4), 355–364.

165. Sackett, C., Diamond, P., & Hansen, K. (2013). ExtendSim 9 User Guide. In *Imagine That Inc.* Imagine That Inc. https://doi.org/10.1007/1-4020-0613-6_20584

166. Sale, J. E. M., Lohfeld, L. H., & Brazil, K. (2002). *Revisiting the Quantitative-Qualitative Debate : Implications for Mixed-Methods Research*. 43–53.

167. Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). *SENSITIVITY ANALYSIS IN PRACTICE: A GUIDE TO ASSESSING SCIENTIFIC MODELS*. John Wiley & Sons Ltd. https://doi.org/10.1002/0470870958.ch6

168. Sandbach, F. (1978). The Rise and Fall of the Limits to Growth Debate. *Social Studies of Science*, *8*(4), 495–520. https://doi.org/10.1177/030631277800800404

169. Saunders, M., Lewis, P., & Thornhill, A. (2016). *Research methods for business students* (7th ed.). Pearson Education Limited.

170. Seuring, S. (2013). A review of modeling approaches for sustainable supply chain management. *Decision Support Systems Support Syst*, *54*(4), 1513–1520. https://doi.org/10.1016/j.dss.2012.05.053

171. Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020

172. Sharda, R., Barr, S. H., & McDonnell, J. C. (1988). Decision Support System Effectiveness: A Review and an Empirical Test. *Management Science*, *34*(2), 139–159. https://doi.org/10.1287/mnsc.34.2.139

173. Siebers, P. O., MacAl, C. M., Garnett, J., Buxton, D., & Pidd, M. (2010). Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation*, *4*(3), 204–210. https://doi.org/10.1057/jos.2010.14

174. Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators*, *9*(2), 189–212. https://doi.org/10.1016/j.ecolind.2008.05.011

175. Sinrat, S., & Atthirawong, W. (2018). Integrated Factor Analysis and Fuzzy Analytic Network Process (FANP) Model for Supplier Selection Based on Supply Chain Risk Factors. *Research Journal of Business Management*, *9*(1), 106–123.

176. Sisco, C., Chorn, B., & Pruzan-Jorgensen, P. M. (2015). *Supply Chain Sustainability: A Pracitical Guide for Continuous Improvement - Second Edition*. https://doi.org/10.1057/978-1-137-43576-7_8

177. Slaper, T. F., & Hall, T. J. (2011). The Triple Bottom Line: What Is It and How Does It Work? *Indiana Business Review*, *86*(1), 4–8. https://doi.org/10.1023/A:1008381314159

178. Smew, W., Young, P., & Geraghty, J. (2013). Supply chain analysis using simulation, gaussian process modelling and optimisation. *International Journal of Simulation Modelling*, *12*(3), 178–189. https://doi.org/10.2507/IJSIMM12(3)4.239

179. Spangenberg, J. H. (2005). Economic sustainability of the economy: Concepts and indicators. *International Journal of Sustainable Development*, *8*(1–2), 47–64. https://doi.org/10.1504/ijsd.2005.007374

180. Stank, T. P., Keller, S. B., & Closs, D. J. (2001). Performance benefits of supply chain logistical integration. *Transportation Journal*, *41*, 32–46.

181. Stevens, G. C., & Johnson, M. (2016). Integrating the Supply Chain … 25 years on. *International Journal of Physical Distribution and Logistics Management*, *46*(1), 19–42. https://doi.org/10.1108/IJPDLM-07-2015-0175

182. Sumari, S., Ibrahim, R., Zakaria, N. H., & Ab Hamid, A. H. (2013). Comparing Three Simulation Model Using Taxonomy: System Dynamic Simulation, Discrete Event Simulation and Agent Based Simulation. *International Journal of Management Excellence*, *1*(3), 54. https://doi.org/10.17722/ijme.v1i3.9

183. Sundarakani, B., De Souza, R., Goh, M., Wagner, S. M., & Manikandan, S. (2010). Modeling carbon footprints across the supply chain. *International Journal of Production Economics*, *128*(1), 43–50. https://doi.org/10.1016/j.ijpe.2010.01.018

184. Tajbakhsh, A., & Hassini, E. (2015). Performance measurement of sustainable supply chains: a review and research questions. *International Journal of Productivity and Performance Management*, *64*(6), 744–783.

185. Tako, A. A., & Robinson, S. (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems*, *52*(4), 802–815. https://doi.org/10.1016/j.dss.2011.11.015

186. Tang, C. S., & Zhou, S. (2012). Research advances in environmentally and socially sustainable operations. *European Journal of Operational Research*, *223*(3), 585–594. https://doi.org/10.1016/j.ejor.2012.07.030

187. Taticchi, P., Garengo, P., Nudurupati, S. S., Tonelli, F., & Pasqualino, R. (2015). A Review of Decision-Support Tools and Performance Measurement for Sustainable Supply Chain Management. *International Journal of Production Research*, *53*(21), 6473–6494.

188. Taticchi, P., Tonelli, F., & Pasqualino, R. (2013). Performance measurement of sustainable supply chains: A literature review and a research agenda. *International Journal of Productivity and Performance Management*, *62*(8), 782–804. https://doi.org/10.1108/IJPPM-03-2013-0037

189. Teniwut, W. A., & Hasyim, C. L. (2020). Decision support system in supply chain: A systematic literature review. *Uncertain Supply Chain Management*, *8*(1), 131–148. https://doi.org/10.5267/j.uscm.2019.7.009

190. Thorndike-Christ, T. (2014). Measurement and Evaluation in Psychology and Education. In *Journal of the American Statistical Association* (8th ed., Vol. 56, Issue 296). Pearson Education Limited. https://doi.org/10.2307/2282039

191. Tognetti, A., Grosse-Ruyken, P. T., & Wagner, S. M. (2015). Green supply chain network optimization and the trade-off between environmental and economic objectives. *International Journal of Production Economics*, *170*, 385–392. https://doi.org/10.1016/j.ijpe.2015.05.012

192. Triantaphyllou, E. (2000). Multi-Criteria Decision Making Methods. In *Multi-criteria Decision Making Methods: A Comparative Study* (pp. 5–21). Springer.

193. Tummala, R., & Schoenherr, T. (2011). Assessing and managing risks using the Supply Chain Risk Management Process (SCRMP). *Supply Chain Management: An International Journal*, *16*(6), 474–483. https://doi.org/10.1108/13598541111171165

194. Turban, E., Aronson, J., & Llang, T. (2007). Decision Support Systems and Intelligent Systems. In *Decision Support Systems and Intelligent Systems* (7th ed.). Prentice Hall of India Private Limited.

195. Turnbull, S. (1995). The Need for Stakeholder Councils in Social Audits. *Social and Environmental Accountability Journal*, *15*(2), 10–13. https://doi.org/10.2139/ssrn.55769

196. United Nations. (1972). Report of the United Nations Conference on the Human Environment. In *Report of the United Nations conference on the Human Environment* (Issue June). https://digitallibrary.un.org/record/523249

197. United Nations. (1992). UN Conference on Environment and Development. In *Sustainable Development* (Issue June). https://doi.org/10.4135/9781412971867.n128

198. United Nations. (2000). United Nations Millennium Declaration. In *Resolution adopted by the General Assembly* (Issue September). http://www.un.org/en/events/pastevents/millennium_summit.shtml

199. United Nations. (2015). *Sustainable development: President of the 65th session - General assembly of the United Nations*. United Nations. http://www.un.org/en/ga/president/65/issues/sustdev.shtml

200. United Nations Climate Change. (2020). *Frequently Asked Questions*. https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/frequently-asked-questions#eq-15

201. Van Der Vorst, J. G. A. J., & Beulens, A. J. M. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Management*, *32*(6), 409–430. https://doi.org/10.1108/09600030210437951

202. Van Der Vorst, J. G. A. J., Tromp, S. O., & Van Der Zee, D. J. (2009). Simulation modelling for food supply chain redesign; Integrated decision making on product quality, sustainability and logistics. *International Journal of Production Research*, *47*(23), 6611–6631. https://doi.org/10.1080/00207540802356747

203. Varsei, M., & Polyakovskiy, S. (2017). Sustainable supply chain network design: A case of the wine industry in Australia. *Omega (United Kingdom)*, *66*, 236–247. https://doi.org/10.1016/j.omega.2015.11.009

204. Varsei, M., Soosay, C., Fahimnia, B., & Sarkis, J. (2014). Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Management*, *19*(3), 242–257. https://doi.org/10.1108/SCM-12-2013-0436

205. Visser, R. (2016). *Timber Harvesting in New Zealand: A guide for Small Scale Forest Landowners*. https://www.nzffa.org.nz/farm-forestry-model/the-essentials/roads-earthworks-and-harvesting/reports/timber-harvesting-in-new-zealand/#Harvesting_Machines_and_Systems

206. Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021

207. Wang, L., & Lin, L. (2007). A methodological framework for the triple bottom line accounting and management of industry enterprises. *International Journal of Production Research*, *45*(5), 1063–1088. https://doi.org/10.1080/00207540600635136

208. WorkSafe New Zealand. (2019). *Annual Report 2018-2019*.

209. Wu, H.-J., & Dunn, S. C. (1995). Environmentally responsible logistics systems. *International Journal of Physical Distribution & Logistics Management*, *25*(2), 20–38. https://doi.org/10.1108/09600039510083925

210. Wu, Z., & Pagell, M. (2011). Balancing priorities: Decision-making in sustainable supply chain management. *Journal of Operations Management*, *29*(6), 577–590. https://doi.org/10.1016/j.jom.2010.10.001

211. Xiao, Z., Chen, W., & Li, L. (2012). An integrated FCM and fuzzy soft set for supplier selection problem based on risk evaluation. *Applied Mathematical Modelling*, *36*(4), 1444–1454. https://doi.org/10.1016/j.apm.2011.09.038

212. Yilmaz, K. (2013). Comparison of quantitative and qualitative research traditions: {Epistemological}, theoretical, and methodological differences. *European Journal of Education*, *48*(2), 311–325.

213. Yin, R. K. (2018). Designing Case Studies. In *Case Study Research and Applications: Design and Methods* (6th ed.). SAGE Publications, Inc.

214. Yingling, J. C., & Detty, R. B. (2000). Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study. *International Journal of Production Research*, *38*(2), 429–445.

215. You, F., & Wang, B. (2011). Life cycle optimization of biomass-to-liquid supply chains with distributed-centralized processing networks. *Industrial and Engineering Chemistry Research*, *50*(17), 10102–10127. https://doi.org/10.1021/ie200850t

216. Zardari, H. N., Ahmed, K., Shirazi, S. M., & Yusop, Z. Bin. (2015). *Weighting Methods and their Effects on Multi- Criteria Decision Making Model Outcomes in Water Resources Management*. Springer.

217. Zimmermann, H. J. (1996). *Fuzzy Set Theory and Its Applications* (3rd ed.). Kiuwer Academic Publishers.

218. Žižlavský, O. (2014). Net Present Value Approach: Method for Economic Assessment of Innovation Projects. *Procedia - Social and Behavioral Sciences*, *156*(26), 506–512. https://doi.org/10.1016/j.sbspro.2014.11.230

219. Zopounidis, C., & Pardalos, P. M. (2010). Handbook of Multicriteria Analysis. In *Applied Optimization*. Springer.

Appendix A. New Zealand Planted Forest

Figure A1 - North Island Planted Forest (Ministry of Primary Industries, 2014)

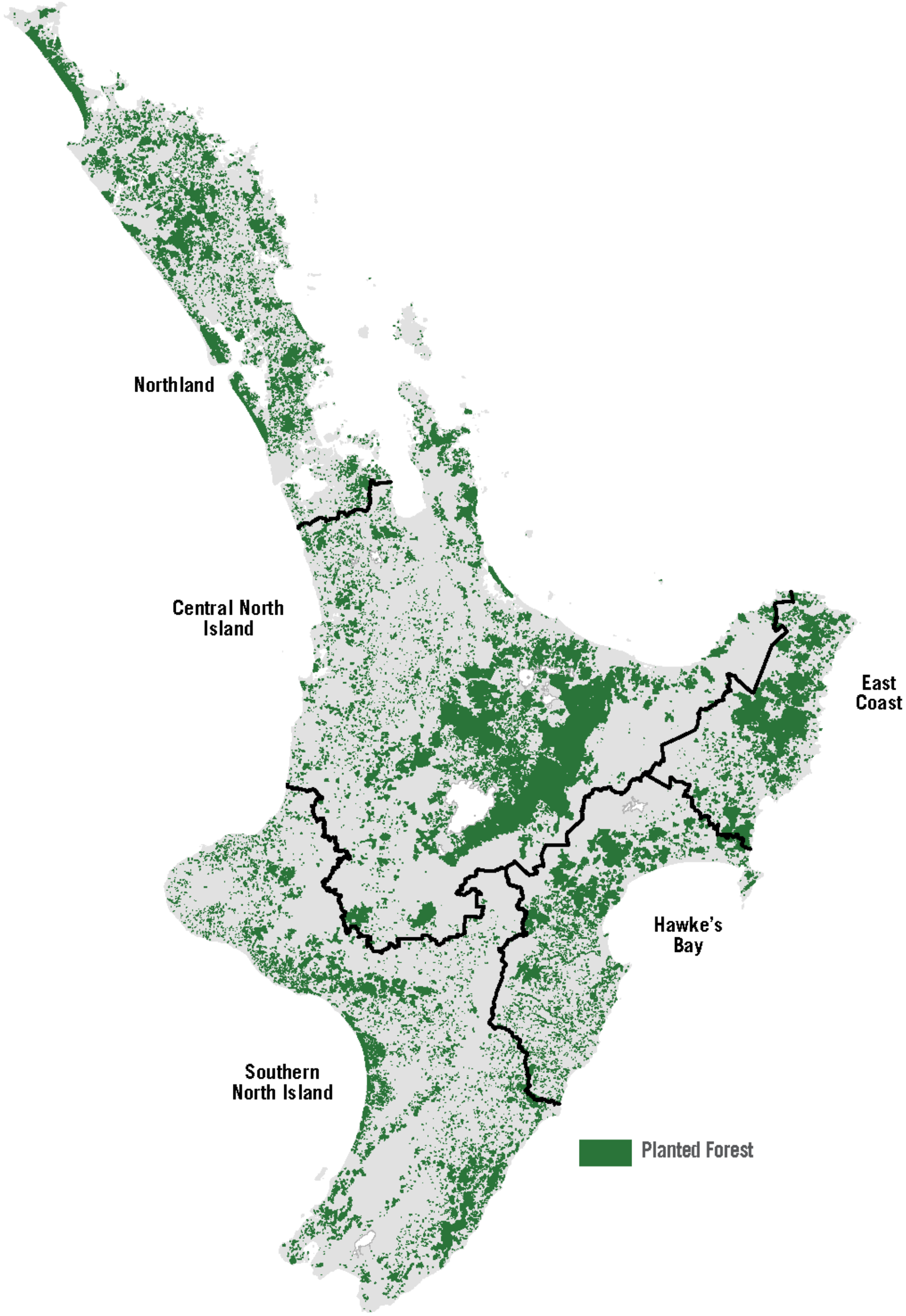
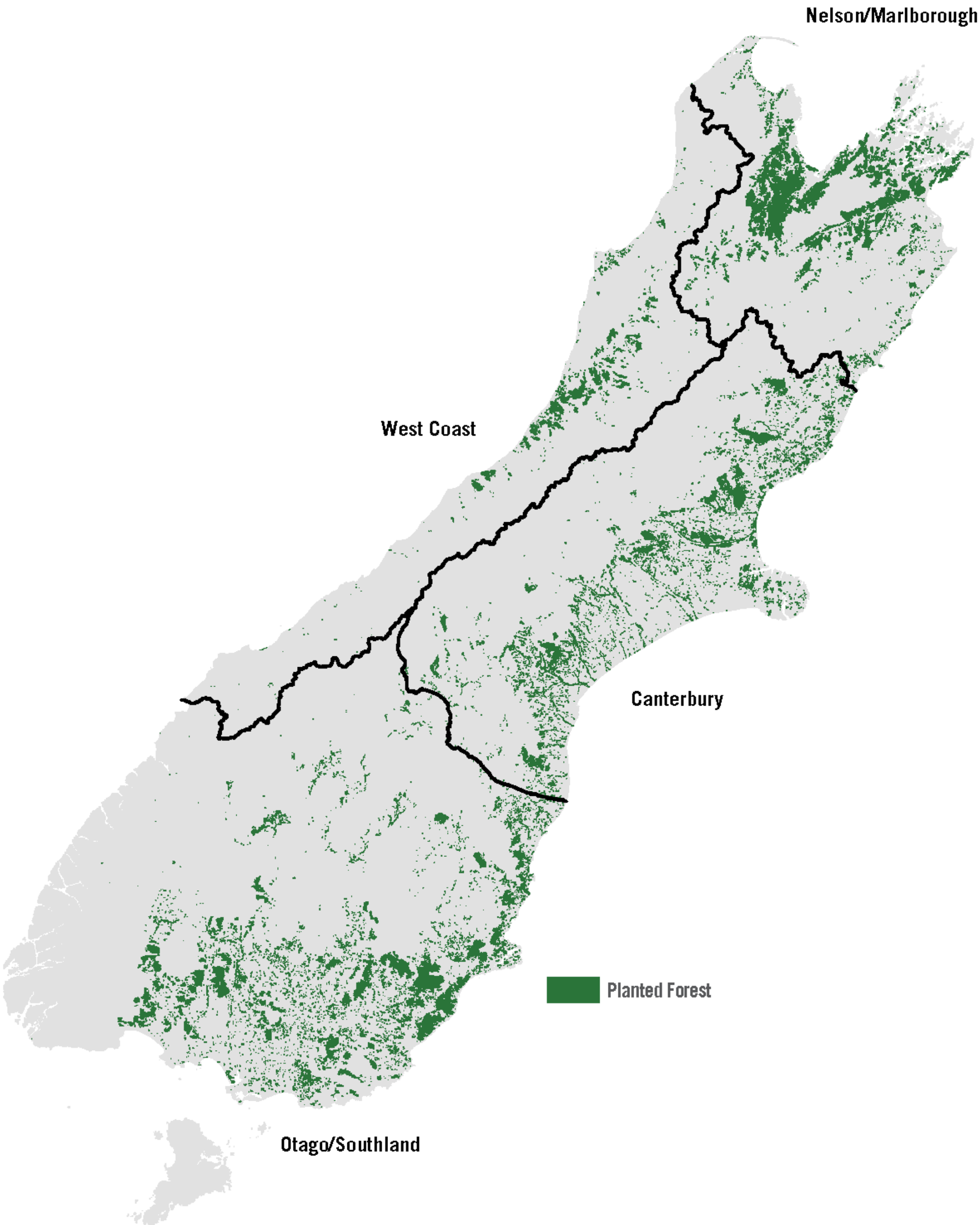
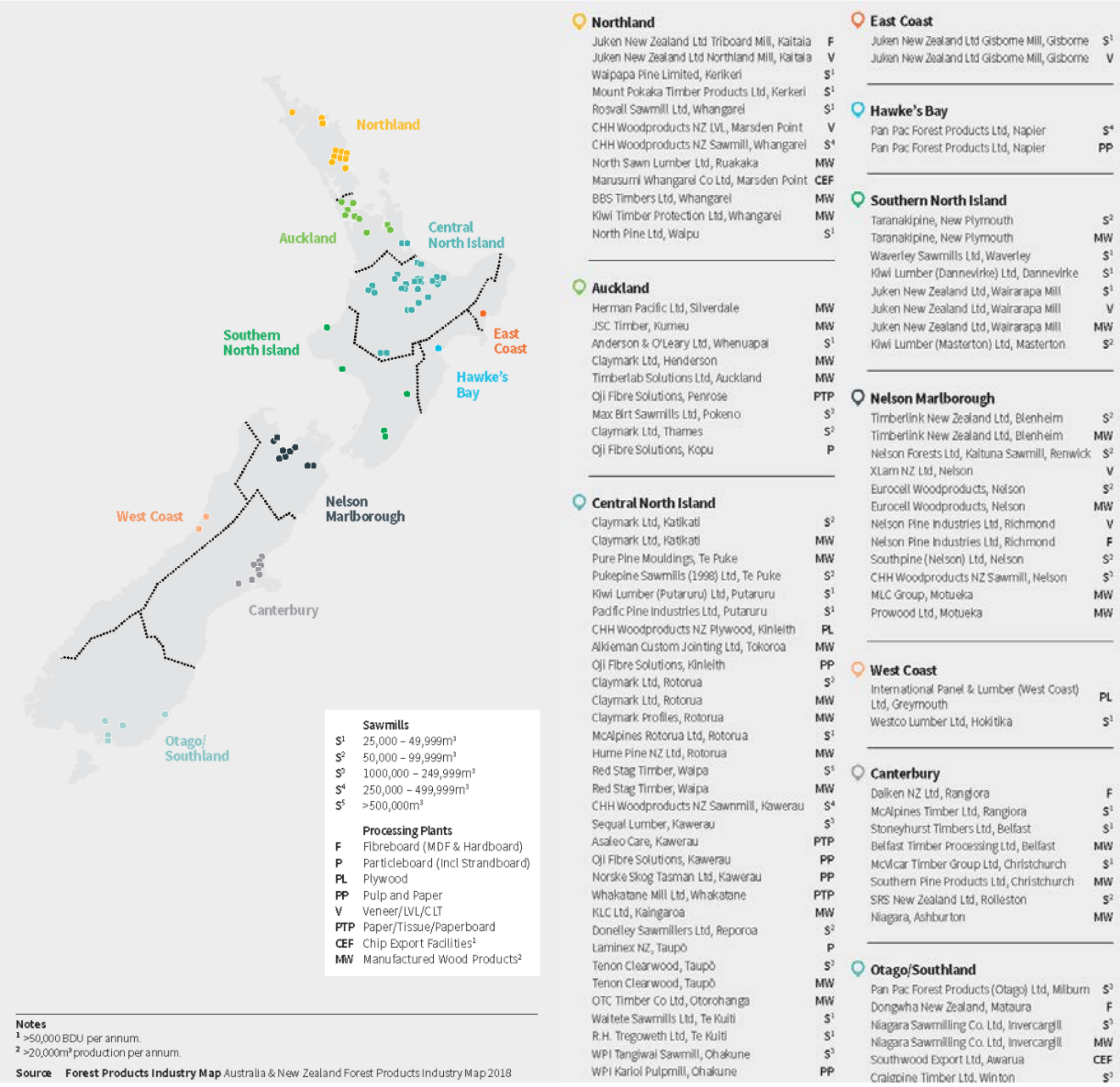


Figure A2 - South Island Planted Forest (Ministry of Primary Industries, 2014)



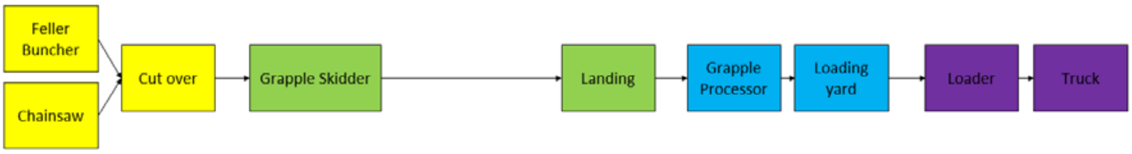
Appendix B. Forest Industry Map (New Zealand Forest Owners Association, 2019)



Appendix C. New Zealand Seaports (Layton, 2010)

Appendix D. Process Maps

Figure D1 - Conventional Ground-based (CGB)



Note. Yellow is for the felling stage; green is for the extracting stage; light blue is for the processing stage; and purple is for the loading stage.

Figure D2 - Conventional Hauler (CH1)

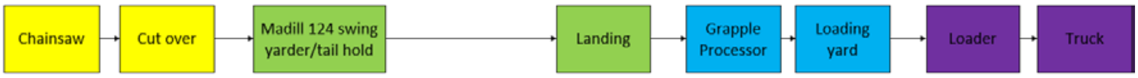


Figure D3 - Conventional Hauler with 2 stage (CH1-2)

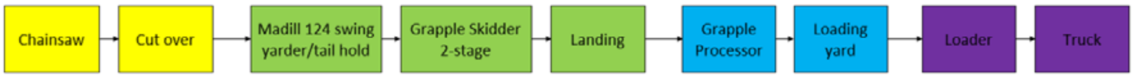


Figure D4 - Mechanised Hauler (CH2)

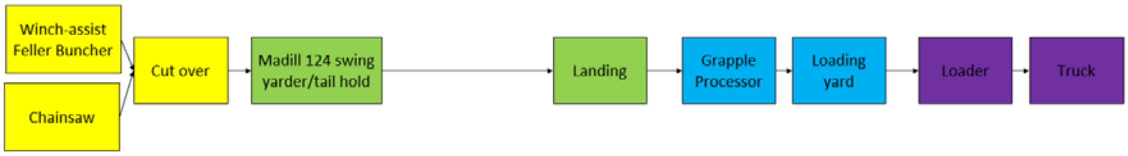


Figure D5 - Automated Ground-based (AGB)

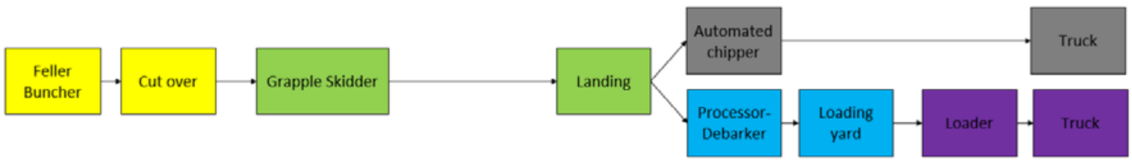


Figure D6 - Automated Hauler (AH1)

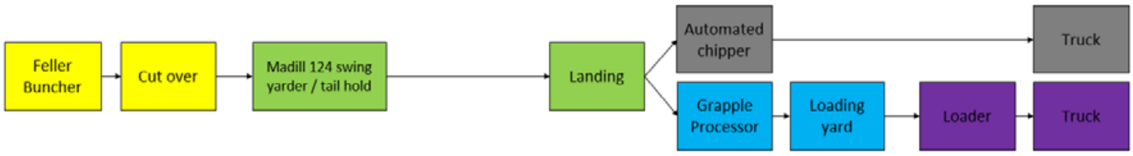


Figure D7 - Automated Hauler with 2 stage (AH1-2)

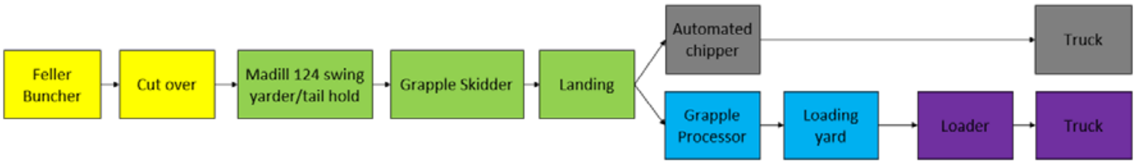


Figure D8 - Automated Hauler 2 (AH2)

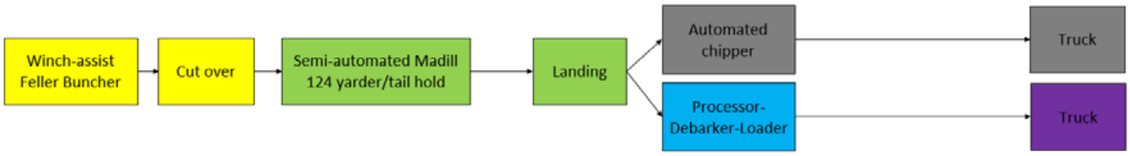
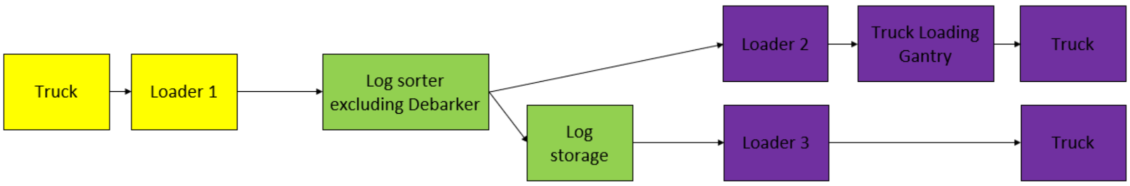


Figure D9 - Sort yard (SY)



Appendix E. Primary Data

Table E1 - General Assumption

No.	Assumption
1	The average batch capacity is the weight which could be carried during one move of machine or processing step
2	The average buffer volume after each process is maintained as equal to 3 hours of capacity so all machines could work immediately the next day without waiting
3	The working time for a 4-hour shift is from 13:00-17:00 (chainsaw only)
4	The working time for an 8-hour (8.5-hour) shift is from 8:00-12:00 and 13:00-17:00 (17:30)
5	The working time for a 13-hour shift is from 8:00-12:00; 13:00-17:00 and 18:00-23:00 (truck only)
6	The machine actual working days = Total work days x Utilisation
7	There are always enough operators for all machines when running (operator delays are accounted for in the utilisation rate) so machines will never wait for operators
8	Breakdowns and scheduled maintenance are included in the utilisation percentage
9	In AGB, AH1, AH1-2 and AH2, the processor-debarker-loader and automated chipper could load directly to trucks
10	The deviation of batch capacity is 0%
11	The waste (chip) after debarking/cutting process is 8% of volume
12	The waste at other process steps is 0%
13	The simulation running time is 7,200 minutes
14	The number of simulation runs is 4 times
15	The number of working days in a week is 5

Table E2 – Current Harvesting Process Data

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
CGB	Tree felling	Feller Buncher	1	1	8	68.75	1.41	1.73	1.57	1.80	0.10	115	0.63	349
		Chainsaws	1	1	4	12.93	7.51	9.18	8.35	1.80	0.10	22	0.75	39
	Extraction to Landing	Grapple Skidder	1	1	8	71.33	4.09	5.00	4.54	5.40	0.10	40	0.68	388
		QC/skiddy		1	8									
	Processing stems to logs	Grapple Processor	1	1	8	64.67	1.50	1.84	1.67	1.80	0.10	108	0.75	388
	Loading	Loader	1	1	8	58.72	2.07	2.53	2.30	2.25	0.10		0.76	357
CH1	Tree felling	Chainsaws	2	2	8	21.52	4.52	5.52	5.02	1.80	0.10	72	0.74	255
	Extraction to Landing	Madill 124 swing yarder/tail hold	1	1	8	53.84	5.42	6.62	6.02	5.40	0.10	30	0.59	255
		Breaker-outs		2	8									
	Processing stems to logs	Grapple Processor	1	1	8	64.67	1.50	1.84	1.67	1.80	0.10	108	0.49	255
	Loading	Loader	1	1	8	58.75	2.30	2.81	2.55	2.50	0.10		0.50	235
CH1-2	Tree felling	Chainsaws	2	2	8	21.52	4.52	5.52	5.02	1.80	0.10	72	0.74	255
	Extraction to Landing	Madill 124 swing yarder/tail hold	1	1	8	53.84	5.42	6.62	6.02	5.40	0.10	30	0.59	255
		Breaker-outs		2	8									
		Grapple Skidder 2 stage	1	1	8	60.59	4.81	5.88	5.35	5.40	0.10	34	0.53	255
	Processing stems to logs	Grapple Processor	1	1	8	64.67	1.50	1.84	1.67	1.80	0.10	108	0.49	255
	Loading	Loader	1	1	8	58.75	2.30	2.81	2.55	2.50	0.10		0.50	235
CH2	Tree felling	Winch-assist Feller Buncher	1	1	8	61.80	1.57	1.92	1.75	1.80	0.10	103	0.74	365
		Chainsaws	1	1	4	13.51	7.19	8.79	7.99	1.80	0.10	23	0.75	41
	Extraction to Landing	Madill 124 yarder/tail hold with grapple	1	1	8	72.61	4.02	4.91	4.46	5.40	0.10	40	0.70	405
		Spotter		1	8									
	Processing stems to logs	Grapple Processor	1	1	8	64.72	1.50	1.84	1.67	1.80	0.10	108	0.78	405
	Loading	Loader	2	2	8	58.75	2.30	2.81	2.55	2.50	0.10		0.40	373

Note. A Process
B Stage
C Machine type/Job
D No of machine (unit)
E No of operator (person)
F Daily working time (hour)
G Average capacity (tonne/PMH)
H Min batch processing time (min)
I Max batch processing time (min)
J Batch processing time (min/move)
K Average batch capacity (tonne/move)
L Batch processing time deviation (+/- %)
M Average buffer after each process (number of batch)
N Utilization (%)
O Daily throughput (tonne)

Table E3 – New Harvesting Process Data

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
AGB	Tree felling	Feller Buncher	1	1	8	68.74	1.41	1.73	1.57	1.80	0.10	115	0.71	388
	Extraction to Landing	Grapple Skidder	1	1	8	71.33	4.09	5.00	4.54	5.40	0.10	40	0.68	388
	Processing stems to logs	Processor-Debarker	1	1	8	53.89	1.80	2.20	2.00	1.80	0.10	90	0.90	388
	Loading	Loader with large grapple	1	1	8	63.75	2.12	2.59	2.35	2.50	0.10		0.70	357
	Chipping	Automated Chipper run by foreman	1	1	8	18.79	63.23	77.28	70.25	22.00	0.10		0.19	29
AH1	Tree felling	Winch-assist Feller Buncher	1	1	8	61.87	1.57	1.92	1.75	1.80	0.10	103	0.82	405
	Extraction to Landing	Madill 124 yarder/tail hold with grapple	1	1	8	72.61	4.02	4.91	4.46	5.40	0.10	40	0.70	405
		Spotter		1	8									
	Processing stems to logs	Processor-Debarker	1	1	8	53.91	1.80	2.20	2.00	1.80	0.10	90	0.94	405
	Loading	Loader with large grapple	1	1	8	63.78	2.12	2.59	2.35	2.50	0.10		0.73	373
	Other	QC/skiddy		1	8									
	Chipping	Automated Chipper run by foreman	1	1	8	18.65	63.70	77.86	70.78	22.00	0.10		0.20	30
AH1-2	Tree felling	Winch-assist Feller Buncher	1	1	8	61.87	1.57	1.92	1.75	1.80	0.10	103	0.82	405
	Extraction to Landing	Madill 124 yarder/tail hold with grapple	1	1	8	72.61	4.02	4.91	4.46	5.40	0.10	40	0.70	405
		Spotter		1	8									
		Grapple Skidder 2 stage	1	1	8	60.63	4.81	5.88	5.34	5.40	0.10	34	0.84	405
	Processing stems to logs	Processor-Debarker	1	1	8	53.91	1.80	2.20	2.00	1.80	0.10	90	0.94	405
	Loading	Loader with large grapple	1	1	8	63.74	2.12	2.59	2.35	2.50	0.10		0.73	373
	Other	QC/skiddy		1	8									
	Chipping	Automated Chipper run by foreman	1	1	8	18.65	63.70	77.86	70.78	22.00	0.10		0.20	30
AH2	Tree felling	Winch-assist Feller Buncher	1	1	8	61.87	1.57	1.92	1.75	1.80	0.10	103	0.66	326
	Extraction to Landing	Semi-automated Madill 124 yarder/tail hold with grapple	1	1	8	76.24	3.82	4.67	4.25	5.40	0.10	42	0.53	326
	Processing stems to logs and Loading	Processor-Debarker-Loader	1	1	8	53.92	1.80	2.20	2.00	1.80	0.10		0.76	326
	Chipping	Automated Chipper run by foreman	1	1	8	18.75	63.36	77.44	70.40	22.00	0.10		0.16	24

Note. A Process
B Stage
C Machine type/Job
D No of machine (unit)
E No of operator (person)
F Daily working time (hour)
G Average capacity (tonne/PMH)
H Min batch processing time (min)
I Max batch processing time (min)
J Batch processing time (min/move)
K Average batch capacity (tonne/move)
L Batch processing time deviation (+/- %)
M Average buffer after each process (number of batch)
N Utilization (%)
O Daily throughput (tonne)

Table E4 – New Sort Yard Process Data

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
SY	Feed	Loader 1 (Infeed)	3	3	8.5	136.76	0.33	0.40	0.37	2.50	0.10	164	0.80	2,790
	Sorting	Log sorter excluding Debarker	1		8.5	360.70	0.27	0.33	0.30	1.80	0.10	601	0.91	2,790
	Moving	Loader 2 (Sort to Stack)	1	1	8.5	76.93	1.75	2.14	1.95	2.50	0.10	92	0.80	523
	Loading	Truck Loading Gantry	1		8.5	118.35	1.14	1.39	1.27	2.50	0.10	142	0.52	523
	Loading	Loader 3 (Sort to Gantry)	1	1	8.5	307.72	0.44	0.54	0.49	2.50	0.10	369	0.80	2,093

Note. A Process
B Stage
C Machine type/Job
D No of machine (unit)
E No of operator (person)
F Daily working time (hour)
G Average capacity (tonne/PMH)
H Min batch processing time (min)
I Max batch processing time (min)
J Batch processing time (min/move)
K Average batch capacity (tonne/move)
L Batch processing time deviation (+/- %)
M Average buffer after each process (number of batch)
N Utilization (%)
O Daily throughput (tonne)

Table E5 - Current Transport Process Data

Item	Quantity
50 Max HPMV Payload (tonne)	33
Daily operating time (min)	780
Distance from each harvesting site to Mill 1 (km)	80
Distance from each harvesting site to Pulp Mill (km)	80
Distance from each harvesting site to Port (km)	80
Distance from each harvesting site to Highway (km)	19
Volume proportion to Mill 1 (%)	28.0
Volume proportion to Pulp Mill (%)	11.2
Volume proportion to Port (%)	60.8
50 Max HPMV load time (min)	30
50 Max HPMV loaded speed in forest (km/hour)	40
50 Max HPMV loaded speed on highway (km/hour)	70
50 Max HPMV unload time (min)	20
50 Max HPMV waiting time (min)	20
50 Max HPMV empty speed in forest (km/hour)	50
50 Max HPMV empty speed on highway (km/hour)	80
50 Max HPMV cycle time between harvesting site and Mill 1 (min)	219
50 Max HPMV cycle time between harvesting site and Pulp Mill (min)	219
50 Max HPMV cycle time between harvesting site and Port (min)	219
Quantity of 50 Max HPMV trucks servicing Mill 1 (unit)	7
Quantity of 50 Max HPMV trucks servicing Pulp Mill (unit)	3
Quantity of 50 Max HPMV trucks servicing Port (Unit)	15

Table E6 - New Transport Process Data

Item	Quantity
Off-road Truck Payload (tonne)	28
58 Max HPMV Payload (tonnes)	40
Chip Truck Payload (tonne)	22
Daily operating time (min)	780
Distance from each harvesting site to Sort Yard (km)	15
Distance from Sort Yard to Mill 1 (km)	65
Distance from Sort Yard to Pulp Mill (km)	65
Distance from Sort Yard to Port (km)	65
Distance from each harvesting site to Pulp Mill (km)	80
Volume proportion to Mill 1 (%)	28.0
Volume proportion to Pulp Mill (%)	11.2
Volume proportion to Port (%)	60.8
Off-road Truck load time (min)	15
Off-Road Truck loaded speed in forest (km/hour)	40
Off-road Truck unload time (min)	10
Off-Road Truck empty speed in forest (km/hour)	50
Off-road Truck waiting time (min)	5
58 Max HPMV load time (min)	10
58 Max HPMV loaded speed on highway (km/hour)	70
58 Max HPMV unload time (min)	24
58 Max HPMV waiting time (min)	20
58 Max HPMV empty speed on highway (km/hour)	80
Off-road Truck cycle time between harvesting site and Sort Yard (min)	70.5
58 Max HPMV cycle time between Sort Yard and Mill 1 (min)	158.5
58 Max HPMV cycle time between Sort Yard and Pulp Mill (min)	158.5
58 Max HPMV cycle time between Sort Yard and Port (min)	158.5
Chip Truck cycle time between harvesting site and Pulp Mill (min)	215.0
Quantity of Off-road Trucks servicing AGB (unit)	4
Quantity of Off-road Trucks servicing AH1 (unit)	4
Quantity of Off-road Trucks servicing AH2 (unit)	2
Quantity of 58 Max HPMV servicing Mill 1 (unit)	4
Quantity of 58 Max HPMV servicing Pulp Mill (unit)	2
Quantity of 58 Max HPMV servicing Port (unit)	9
Quantity of Chip Truck servicing Pulp Mill (unit)	4

Appendix F. Sensitivity Analysis Data

Table F1 –Daily Process Time (hour), Current SCND

Machine	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Chainsaw	23.96	23.69	24.08	25.58	22.14
Feller buncher	6.82	6.80	6.84	7.37	6.40
Feller buncher winch	5.33	5.35	5.28	5.70	4.96
Grapple skidder	7.95	7.96	7.95	8.43	7.47
Grapple skidder 2 stage	2.04	2.03	2.04	2.16	1.88
Loader	38.04	22.87	34.19	34.06	29.00
Madill 124 grapple	5.46	5.47	5.47	5.78	5.07
Madill 124 swing	6.81	6.82	6.81	7.28	6.46
Processor	20.92	20.92	20.92	22.39	19.56
Truck 33	109.14	121.18	105.49	118.26	109.87

Table F2 – Daily Process Time Comparison with Scenario 0 (decimal), Current SCND

Machine	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Chainsaw	1.00	0.99	1.00	1.07	0.92
Feller buncher	1.00	1.00	1.00	1.08	0.94
Feller buncher winch	1.00	1.00	0.99	1.07	0.93
Grapple skidder	1.00	1.00	1.00	1.06	0.94
Grapple skidder 2 stage	1.00	1.00	1.00	1.06	0.92
Loader	1.00	0.60	0.90	0.90	0.76
Madill 124 grapple	1.00	1.00	1.00	1.06	0.93
Madill 124 swing	1.00	1.00	1.00	1.07	0.95
Processor	1.00	1.00	1.00	1.07	0.94
Truck 33	1.00	1.11	0.97	1.08	1.01

Table F3 – Daily Process Time (hour), New SCND

Machine	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Auto chipper	8.76	9.25	8.34	9.45	4.11
Feller buncher	17.03	17.03	17.03	17.99	15.83
Feller buncher winch	30.23	30.22	30.22	32.07	28.39
Grapple skidder	16.30	16.30	16.30	17.26	15.34
Grapple skidder 2 stage	6.71	6.71	6.71	7.11	6.23
Loader 1	7.63	7.28	7.35	7.83	7.47
Loader 2	5.36	5.32	5.97	5.68	5.00
Loader 3	6.80	6.80	8.33	7.22	6.37
Loader large	33.36	31.31	32.69	35.21	32.39
Madill 124 grapple	16.78	16.80	16.77	17.74	15.57
Madill 124 semi auto grapple	8.47	8.47	8.47	9.10	7.99
Processor - Debarker	38.12	36.96	38.96	42.03	37.63
Processor – Debarker - Loader	10.87	10.91	11.76	11.77	9.49
Sorter	7.73	7.73	7.73	8.24	7.22
Truck 22	20.07	21.14	18.81	21.32	19.35
Truck 28	95.59	98.11	98.99	99.46	92.18
Truck 40	37.78	37.91	35.93	37.64	37.64
Truck Loading Gantry	4.18	4.15	6.36	4.40	3.95

Table F4 – Daily Process Time Comparison with Scenario 0 (decimal), New SCND

Machine	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Auto chipper	1.00	1.06	0.95	1.08	0.47
Feller buncher	1.00	1.00	1.00	1.06	0.93
Feller buncher winch	1.00	1.00	1.00	1.06	0.94
Grapple skidder	1.00	1.00	1.00	1.06	0.94
Grapple skidder 2 stage	1.00	1.00	1.00	1.06	0.93
Loader 1	1.00	0.95	0.96	1.03	0.98
Loader 2	1.00	0.99	1.12	1.06	0.93
Loader 3	1.00	1.00	1.23	1.06	0.94
Loader large	1.00	0.94	0.98	1.06	0.97
Madill 124 grapple	1.00	1.00	1.00	1.06	0.93
Madill 124 semi auto grapple	1.00	1.00	1.00	1.08	0.94
Processor - Debarker	1.00	0.97	1.02	1.10	0.99
Processor - Debarker - Loader	1.00	1.00	1.08	1.08	0.87
Sorter	1.00	1.00	1.00	1.07	0.93
Truck 22	1.00	1.05	0.94	1.06	0.96
Truck 28	1.00	1.03	1.04	1.04	0.96
Truck 40	1.00	1.00	0.95	1.00	1.00
Truck Loading Gantry	1.00	0.99	1.52	1.05	0.94

Table F5 – Daily Yield (tonne), Current SCND

Site	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CGB	154.91	157.28	155.25	180.79	162.45
CGB	153.34	156.71	156.15	177.19	160.76
CGB	156.60	155.25	155.48	180.11	163.80
CH1	106.00	112.63	109.00	114.75	103.00
CH1	106.75	109.25	101.88	112.63	103.00
CH1-2	100.50	112.38	97.88	116.00	97.00
CH2	169.63	179.25	172.25	167.25	161.75
CH2	89.38	77.25	44.63	101.75	86.13

Table F6 – Daily Yield Comparison with Scenario 0 (decimal), Current SCND

Site	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CGB	1.00	1.02	1.00	1.17	1.05
CGB	1.00	1.02	1.02	1.16	1.05
CGB	1.00	0.99	0.99	1.15	1.05
CH1	1.00	1.06	1.03	1.08	0.97
CH1	1.00	1.02	0.95	1.06	0.96
CH1-2	1.00	1.12	0.97	1.15	0.97
CH2	1.00	1.06	1.02	0.99	0.95
CH2	1.00	1.13	1.10	1.06	0.98

Table F7 – Daily Yield (tonne), New SCND

Site	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
AGB	302.63	295.13	313.88	321.25	280.88
AGB	289.63	299.13	303.75	311.50	290.13
AGB	300.13	289.00	307.38	322.63	303.63
AH1	309.75	310.75	323.25	336.00	296.25
AH1	315.88	304.13	317.25	334.75	298.13
AH1-2	299.50	292.50	323.38	340.38	277.38
AH2	259.83	259.65	288.63	300.78	245.88
AH2	288.81	293.40	303.39	288.00	243.00

Table F8 – Daily Yield Comparison with Scenario 0 (decimal), New SCND

Site	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
AGB	1.00	0.98	1.04	1.06	0.93
AGB	1.00	1.03	1.05	1.08	1.00
AGB	1.00	0.96	1.02	1.07	1.01
AH1	1.00	1.00	1.04	1.08	0.96
AH1	1.00	0.96	1.00	1.06	0.94
AH1-2	1.00	0.98	1.08	1.14	0.93
AH2	1.00	1.00	1.11	1.16	0.95
AH2	1.00	1.02	1.05	1.00	0.84

Appendix G. New SCND Case Data

Table G1 – Daily Process Time (hour), New SCND Cases

Machine	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Auto chipper	8.76	8.98	8.92	8.75	8.81	8.87	8.92	8.86	8.73
Feller buncher	17.03	17.03	17.03	17.03	17.03	17.03	17.03	17.03	17.03
Feller buncher winch	30.23	30.23	30.23	30.22	30.22	30.23	30.22	30.22	30.23
Grapple skidder	16.30	16.30	16.30	16.32	16.30	16.27	17.07	16.30	16.30
Grapple skidder 2 stage	6.71	6.71	6.71	6.71	6.71	6.72	6.71	6.71	6.71
Loader 1	7.63	6.66	7.46	7.72	6.66	7.63	7.55	6.67	7.59
Loader 2	5.36	5.34	5.34	5.32	5.34	5.34	5.33	5.31	5.31
Loader 3	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Loader large	33.36	31.91	33.50	33.23	33.27	33.76	33.68	32.65	34.26
Madill 124 grapple	16.78	16.77	16.78	16.77	16.77	16.78	16.79	16.77	16.78
Madill 124 semi auto grapple	8.47	8.47	8.47	8.46	8.46	8.45	8.46	8.47	8.47
Processor - Debarker	38.12	36.75	36.76	38.18	37.89	37.73	37.11	37.23	38.72
Processor - Debarker - Loader	10.87	10.62	11.00	11.45	11.26	11.20	10.81	11.33	10.87
Sorter	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73
Truck 22	20.07	20.43	20.25	20.07	19.89	20.07	20.07	19.71	19.71
Truck 28	95.59	101.39	64.47	96.70	101.32	66.56	94.59	101.54	66.52
Truck 40	37.78	37.64	37.64	37.57	37.75	37.57	37.17	36.73	36.20
Truck Loading Gantry	4.18	4.17	4.17	4.16	4.16	4.17	4.17	4.15	4.15

Table G2 – Daily Yield (tonne), New SCND Cases

Site	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
AGB	302.63	285.25	277.38	281.75	303.63	290.50	292.13	278.88	295.25
AGB	289.63	297.00	262.63	297.00	306.00	294.00	284.75	314.88	292.88
AGB	300.13	288.38	300.50	304.25	281.13	300.50	290.13	301.50	210.87
AH1	309.75	308.63	297.25	322.50	314.75	318.13	294.38	305.13	312.88
AH1	315.88	300.00	309.50	311.25	297.63	302.38	307.88	308.25	310.13
AH1-2	299.50	300.63	296.13	299.38	305.13	298.63	310.38	290.13	299.88
AH2	259.83	259.20	270.36	277.74	278.37	264.15	279.90	282.69	269.46
AH2	288.81	274.41	282.15	292.95	282.60	296.28	264.24	282.60	267.75