Reckoning:

A Simplified LCA Methodology for Fashion Designers through a Case Study of Knitted Garments

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Abstract

This thesis endeavours to propel sustainable fashion design practices in New Zealand by developing a simplified approach to the life cycle assessment (LCA) methodology. It aims to equip fashion designers with knowledge and tools to understand and mitigate the environmental consequences of their creation. Specifically, this study pursues the following three objectives: 1. to explore and quantify the environmental impact of garments for their Global Warming Potential (GWP), 2. to simplify the LCA method for everyday fashion design operations, and 3. to share experiences and insights of navigating the scientific realm of LCA methodology, with the fashion design community.

Grounded in pragmatic epistemology, this study adopts an exploratory approach. First, a comprehensive LCA was employed to evaluate the cradle-to-grave environmental impact of knitted jumpers in eight different life cycle scenarios. Two varied textile materials – wool and polyester, three different knitwear manufacturing techniques – cut-and-sew, fully fashioned, and integral knitting, and four distinct supply chain pathways were analysed for their GWP. Through the collection of primary and secondary data for fibre production, wet-processing and dyeing, garment construction, transportation and packaging, and the subsequent use and end-of-life phases, a comprehensive analysis was conducted.

The findings highlight disparities between wool and polyester jumpers in terms of their GWP. Woollen jumpers exhibited a higher GWP owing to factors such as fibre production, wet-processing, and subsequent spinning. However, it is important to acknowledge the limitations of the calculations, as some of the data used were unreliable for a precise comparative assessment. The study identified a need for New Zealand-specific data on merino wool production. Furthermore, it examined the Ecoinvent v. 3 database for ethylene —a fundamental raw material for PET and polyester fibre production—and discovered inaccuracies in the reported CO_2 emissions. The research emphasises an urgent need to correct persistent errors in the Ecoinvent dataset for ethylene to facilitate reliable comparisons with natural materials. Processes such as the cut-and-sew method of knit garment manufacturing and transportation routes with minimal distances, in conjunction with local manufacturing, were found to be critical factors that substantially reduced emissions. The results revealed distinct use patterns and end-of-life practices for wool and polyester jumpers in New Zealand, underpinning their divergent environmental profiles.

Second, this study proposed a simplified LCA-based tool to assess the environmental impact of garments for routine usage by fashion designers. Critical elements extracted from the comprehensive LCA of knitted jumpers were utilised to devise a simplified data table. The data table showed a simplified approach for developing a tool that can instantly assess the environmental impact of garments. Along with the data table, the study presented a "Simplified LCA framework for Fashion Design," that lists ten foundational processes which serve as a blueprint for programming the envisioned assessment tool.

Third, this research provided valuable lessons for the fashion design community venturing into the scientific realm of LCA. The interdisciplinary nature of this research underscores the significance of collaboration, continuous learning, and adaptability in overcoming the challenges in academic endeavours.

This study deepens our knowledge of garment life cycles. It offers practical guidance on data collection, its validity analysis, and impact assessment for comprehensive life cycle assessments. The study examined the environmental impact of natural and synthetic materials and three major knitwear manufacturing techniques in both local and global supply chains. The primary data collected by an extensive survey in New Zealand for the use and end-of-life phases of knitted jumpers enabled a more precise estimation of their cradle-to-grave impacts. The simplified LCA-based approach will empower fashion designers to factor life cycle thinking into design processes, leading to informed decisions. In conclusion, this thesis encourages fashion designers to embrace ‘reckoning’ in conjunction to reduce, reuse and recycle, the fourth “r” for sustainability in fashion design.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

29/09/2023

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Signature Date

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Ethics Approval

Ethical clearance for this study was sought and granted by the Auckland University of Technology Ethics Committee (AUTEC) in two stages of this research, first on 26 March 2021 and subsequently on 8 December 2021, with the assigned reference number being 19/425.

Preface

In embarking on my doctoral journey, my motivation was derived from a profound aspiration to create positive change in the realm of fashion design. As a trained textile designer with extensive professional experience spanning over a decade in the fashion industry in India, my passion for clothing and textiles has always flourished. My career path includes both the industry and academia. I have worked in the garment industry, serving several high-end fashion brands, and held the position of Assistant Professor in the Fashion and Textile department at a prestigious design institute in India. Fashion has always been the cornerstone of my professional life. However, a transformative shift occurred as the industry increasingly recognised the concept of “sustainability.”

This change in focus within the fashion industry compelled me to look deeper into the implications and interconnectedness of sustainability and fashion. The industry has been widely acknowledged as one of the most environmentally polluting sectors worldwide. Throughout the life cycle of textile materials, from the production of fibres to their eventual disposal, the extensive utilisation of energy, water, and chemicals contributes to the pollution of land, air, and water bodies. As I looked deeper into the ramifications associated with the production and consumption of clothing, I was confronted by dismay. Nevertheless, I soon realised that the only way to move forward was to maintain a positive outlook and gain a comprehensive understanding of the prevailing problem in order to identify viable solutions.

Acknowledging the pressing need for change, I embarked on a quest to explore various avenues for addressing sustainability in the fashion sector. These endeavours ranged from developing environment-focused curricula for design students to investigating the feasibility of organic options in garments. However, a pivotal question emerged: Why is there no mechanism in place to assign environmental ratings to garments, akin to the systems employed for rating electronic devices or food products? Fuelled by enthusiasm, I began searching for resources that could assist me in pursuing this goal. The Higg Material Sustainability Index from the Sustainable Apparel Coalition demonstrated exciting potential, but owing to its limited application and prohibitive cost, a majority of fashion brands, especially small and medium-sized enterprises, rarely employ the tool. Moreover, it lacked a transparent methodology, raising doubts about its reliability. Consequently, a significant research gap became evident, characterised by the absence of a comprehensive analysis of the environmental impact of garments and the dearth of a transparent methodology to assess their environmental footprint.

Seizing the opportunity presented by my PhD in New Zealand, I focused on quantifying the environmental impact of garments manufactured and used in New Zealand. Given the prominence of knitwear manufacturing in New Zealand, I narrowed the scope of my research to investigate the impact of knitted jumpers made using various knitwear construction techniques. Furthermore, an initial survey of New Zealand's fashion markets revealed the country's reliance on garment imports from large-scale suppliers, predominantly situated in Asia. This scenario left the local knitwear manufacturers to explore ways to prove the environmental benefits of their products and market them as more sustainable options as compared to imported options. Consequently, the need for a comprehensive tool that enables fair assessments of the supply chain impacts of both locally produced and imported garments became apparent.

With numerous questions swirling in my mind regarding the environmental impact of diverse textile materials, the comparative assessment of garment construction techniques, and the disparities between locally produced and imported garments, I embarked on my PhD journey with the determination to find dependable solutions. My primary objective is to create an environmental impact calculator capable of enabling designers and manufacturers to comprehensively assess the life cycle impacts of garments. As a designer, I recognise the pivotal role of possessing such information during the initial stages of product development, as even minor alterations in the design phase have a substantial impact on the garment's overall environmental footprint. This thesis is a comprehensive report documenting an exploratory investigation of clearly delineated research questions and the establishment of solutions to build a methodology that can aid the environmental assessment of garments.

Glossary of Abbreviations

AoPs	Areas of Protection
CAD	Computer Aided Design
EDIF	Environmental Design of Industrial Products
EOL	End-of-life
EU	European Union
FDS	The Sustainable Fashion Design
GHG	Greenhouse gas
GLO	Global
GWP	Global Warming Potential
Higg MSI	Higg Material Sustainability Index
Higg PM	Higg Product Module
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	Kilogramme
kg CO_2 eq.	Kilogramme carbon dioxide equivalent
L	Litres
LCA	Life Cycle Assessment
LCANZ	Life Cycle Association of New Zealand
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
m	Meters
m^2	Square meter
m^3	Cubic meter
MEG	Mono-ethylene glycol

ML	Mega litres
NDC	Nationally Determined Contributions
NSMI	Nike Material Sustainability Index
NSW	New South Wales
NSW	New South Wales, Australia
NZ	New Zealand
NZD	New Zealand Dollar
PEF	Product Environmental Footprint
PET	Polyethylene terephthalate
PP	Polypropylene
PTA	Pure terephthalic acid
RoW	Rest-of-world
SAC	Sustainable Apparel Coalition
SCAP	Sustainable Clothing Action Plan
SME	Small and Medium-sized Enterprise
UNFCCC	The United Nations Framework Convention on Climate Change
Wh	Watts per hour

Chapter 1 Introduction

The fashion industry's far-reaching global presence has significantly impacted the environment, raising concerns regarding its sustainability. Consequently, understanding and addressing the environmental impact of clothing items has become increasingly urgent. New Zealand boasts a vibrant apparel industry and a commitment to sustainable development; however, limited research has been conducted on assessing the life cycle implications of the garments consumed in the country. To comprehensively assess the environmental impact of garments in New Zealand, this study investigates the impacts associated with knitted jumpers and proposes a simplified method to evaluate their Global Warming Potential (GWP). GWP is a critical metric that quantifies the relative contribution of different greenhouse gases to global warming over a specific period, typically 100 years, in comparison to carbon dioxide (CO_2). Given that GWP is a major driver of climate change, which is an urgent and severe global issue, it is essential to prioritise this impact in the environmental assessment of textile products (IPCC Working Group, 2013; Myhre et al., 2014).

This introductory chapter sets the stage and presents a comprehensive overview of the background and context relevant to this research investigation. It outlines the research problems, aims, objectives, and questions that guide the study and highlights the significance of the research. Finally, a concise outline of the thesis' seven chapters is provided to guide the reader through the research journey.

As the fashion industry grapples with its large environmental impact, this study contributes to the discussions on the environmental responsibility and resource conservation. By uncovering the environmental implications of knitted garments and proposing practical and simplified solutions for sustainable design development, this research seeks to pave the way towards a more environmentally responsible and sustainable apparel industry in New Zealand and beyond.

1.1 Background and Context

The terms' "climate change" and "global warming" are often employed interchangeably to denote the consequences of human activities that contribute to the elevation of global temperatures (Damico & Baildon, 2022). Devastating climate change-related incidents such as the Amazon rainforest fires in 2019 and the Australian bushfires of 2020, alongside droughts and flooding in various regions (Martin et al., 2022), serve as alarming reminders of the consequences of human actions and the urgent need for individuals, businesses and countries to take responsibility towards the well-being of our planet and its ecosystem.

The trajectory leading to the present state of global warming can be traced to the onset of the Industrial Revolution at the outset of the 18th century. Subsequently, the global mean temperature has escalated by over 1° C (equivalent to 1.9° Fahrenheit), a direct consequence of persistent fossil fuel combustion, a process industrialised countries have continued to use for generating energy even after the extent of their detrimental environmental impact have been known (Damico & Baildon, 2022). The introduction of power-driven machinery and mass production during the Industrial Revolution marked a turning point in human history, boosting economic growth but also instigating harmful environmental consequences (Lenton et al., 2008; Steffen et al., 2015). The unbridled pursuit of profit has led to the overconsumption of resources, excessive use of non-renewable energy, and heavy pollution caused by chemical-intensive industries (Brundtland, 1987). In addition, the linear economic system, characterised by a 'make-use-dispose' approach, has propagated a culture of rampant consumerism and wastefulness (MacArthur, 2015). Exponential population growth has further compounded the negative impacts of these practices (Steffen et al., 2015) and global warming has become a pressing issue with far-reaching consequences for the planet and its inhabitants (Hoff, 2021; Rockström et al., 2009).

Climate change and global warming are both related to the environmental aspects of the Earth. Climate change is a paramount concern, fuelled by increasing greenhouse gas (GHG) emissions that warm Earth's atmosphere. The primary GHGs responsible for greenhouse effects include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) (Stocker et al., 2014). GWP is a reliable measure of the impact of a product or process on climate change, allowing for a consistent comparison of different GHGs and their long-term effects on global warming. Rising global temperatures have fuelled climate change, provoking rising sea levels, destruction of coastal habitats, extinction of ecosystems, increased severity of weather events, water and food scarcity, and socioeconomic disruptions (Griggs et al., 2013; Rockström et al., 2009; Steffen et al., 2015).

The detrimental effects of climate change have prompted global efforts to address this issue. The United Nations Framework Convention on Climate Change (UNFCCC) brought representatives of 196 nations and territories together in 2015 to establish the Paris Agreement. This international accord aims to limit the global temperature increase to well below 2 °C (3.6 °C Fahrenheit) above pre-industrial levels, with a preferred target of 1.5 degrees Celsius (2.7 °C Fahrenheit). Additionally, the agreement emphasises the importance of building resilience against climate change impacts and providing financial support for adaptation and mitigation efforts (Kuyper et al., 2018).

As countries strive to meet their climate goals, the development of Nationally Determined Contributions (NDCs) has become increasingly important. NDCs outline each country's specific targets and strategies for reducing GHG emissions. For example, New Zealand pledged to reduce its greenhouse gas emissions by 30 percent by 2030 to achieve a level below that of 2005 (MFAT, 2020).

Despite commitments made by governments worldwide, there is a lack of progress in reducing GHG emissions. Atmospheric carbon dioxide levels have continued to rise, surpassing the highest levels in the last 800,000 years. The warmest years on record have occurred since 2014, indicating the persistence of global warming trends (Eckstein et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) has accentuated the need for urgent mitigation efforts, including a considerable reduction in greenhouse gas emissions by 2030 (Kuyper et al., 2018; Tollefson, 2018, October 8).

The clothing and textile industry played a significant role in the Industrial Revolution's growth, particularly with the advancement of textile technologies (Mohajan, 2019; Tann, 1974). Today, the clothing and textile sector is one of the largest industries globally, manufacturing 100 million metric tonnes of new products annually (Opperskalski et al., 2021). However, the industry relies heavily on natural resources and fossil fuels for generating energy and as a major source of raw material for synthetic fibre production (Karthik & Gopalakrishnan, 2014), causing considerable environmental repercussions. The apparel industry is identified as one of the world's most unsustainable industries and a leading contributor to global warming (Henninger et al., 2016; Ma et al., 2020), responsible for approximately 2.1 billion metric tons of greenhouse gas emissions in 2018 (Wren, 2022). Additionally, the care practices associated with garments, including laundry and dry cleaning, along with the subsequent generation of waste during their disposal, produce substantial levels of greenhouse gases, thereby further augmenting their overall environmental footprint (Bick et al., 2018; Niinimäki et al., 2020).

With the urgent climate crisis, there is a growing demand for sustainability in the clothing and textile industry. Fashion designers face increasing pressure from consumers to consider the environmental impacts of their creations (Gwilt & Rissanen, 2012; Karell & Niinimäki, 2020; Styles, 2019). Designers wield a considerable influence in the garment supply chain, making around 80% of the decisions during product development (Charter & Tischner, 2017). Early choices in design can significantly impact a product's life cycle (Armstrong & LeHew, 2011; Van der Velden, 2016). Thinking about the complete life cycle of a product, from raw material extraction and use to its end-of-life (cradle-to-grave), early at the product development stage can lead to more sustainable outcomes and reduce the garment’s environmental impact (Payne, 2015). A shift towards sustainable design practices has begun with designers seeking environmentally friendly choices such as organic materials, less energy intensive production processes, and offering post sales services such as repairs and alterations (Aakko & Koskennurmi-Sivonen, 2013; Curwen et al., 2013; Hur & Cassidy, 2019). Sustainability-related courses in design schools aim to educate aspiring designers about environmental and social issues, nurturing a new generation of conscious creators (Earley, 2017; Goldsworthy et al., 2018).

Evaluating the cradle-to-grave environmental ramifications of garments during the initial design phase is important in order to identify ways to reduce their impact, which is the first step in designing a more sustainable fashion. Designers must comprehend the current impact of each garment to facilitate the development of environmentally sustainable products (Gwilt, 2012; Muthu, 2020; Van der Velden, 2016). This task is achieved through the application of environmental assessment methods such as life cycle assessment (LCA). LCA examines the environmental impacts of a specific item across its entire life cycle, spanning from the extraction of raw materials to its eventual disposal (ISO 14040, 2006). Employing LCA facilitates the identification of products and processes with the most pronounced impacts, thereby highlighting those areas that have the greatest environmental impact and therefore need to be reviewed (Seuring & Müller, 2008; Wren, 2022). Consequently, LCA is a powerful tool that can be used to gauge the environmental footprint of commodities and has been used extensively in the assessment of fashion items (Choudhury, 2014; Munasinghe et al., 2021; Muthu, 2020). GWP is a measure of the impact of a product or process on climate change. It is particularly relevant across various stages of the garment life cycle, making it a priority in many prominent LCAs in the fashion industry (Bevilacqua et al., 2011; Morita et al., 2020; Wiedemann et al., 2020).

New Zealand has a robust knitwear manufacturing sector, however , many New Zealand designers outsource production to overseas countries, particularly in Asia (Smith & Finn, 2015; Styles, 2019). It is crucial for them to understand the GWP of their creations. Assessing the GWP of their garments will empower them to make informed choices. This thesis assesses the GWP of knitted jumpers consumed in New Zealand and explores how the LCA methodology can be better integrated into fashion practice. By conducting and analysing a comprehensive evaluation of garments using LCA, the study then considers how this approach could be simplified. The primary objective is to develop a simplified LCA approach specifically tailored to the needs of fashion designers in order to enhance the efficacy of existing sustainability measures.

1.1.1 Sustainability and Sustainable Development

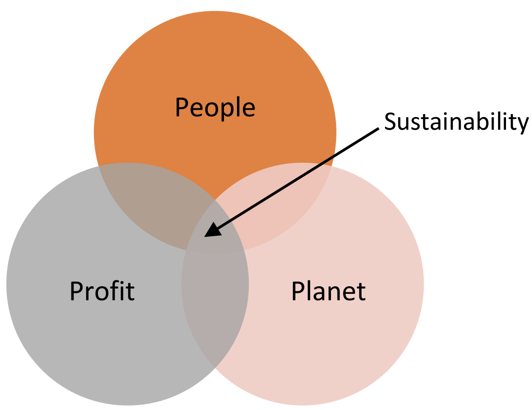
The meaning of sustainability has been the subject of academic inquiry for many decades. Often viewed as a multifaceted and ambiguous concept, the term sustainability has been characterised as "fuzzy" due to its various interpretations (Markusen, 2003). This variability in understanding arises from its inherently subjective nature, making it contingent on personal perspectives and contextual considerations (Gunder, 2006; Henninger et al., 2016). The Oxford English Dictionary provides a range of definitions for sustainability, ranging from its ability to be defended as valid or true to its environmental dimensions by avoiding the depletion of natural resources (Oxford English Dictionary, 2022). However, the concept of sustainability becomes more comprehensive when approached from a long-term perspective, often referred to as *sustainable development.*

The origins of sustainable development can be traced back to historical initiatives of the 17th and 18th centuries such as Europe's Sustainable Forest Management that was established in response to dwindling timber resources (Purvis et al., 2019), highlighting the inextricable link between economic development and environmental well-being (Brundtland, 1987). Over time, the term sustainability has grown to encapsulate the desire for global equilibrium, culminating in the concept of sustainable development introduced by the International Union for Conservation in 1980 (Talbot, 1980). The pivotal Brundtland (1987) report solidified this concept by offering a foundational definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987, p. 37)

Despite some criticism regarding its accuracy, this definition remains one of the most widely accepted and holistic descriptions of sustainable development (Lélé, 1991; Redclift, 2000). This definition underscores the importance of achieving economic progress while safeguarding the environment's long-term value and social well-being (Brundtland, 1987). Sustainable development necessitates the integration of three fundamental dimensions: environmental, social, and economic, also known as the “triple bottom line”(Elkington, 1998, p. 22) (Figure 1). While all three dimensions are integral to achieving sustainability, this study focuses exclusively on the environmental aspect because of its paramount significance in securing the well-being of nature and all its inhabitants.

Figure 1

Triple Bottom Line for Sustainability



Note: Adapted from Elkington (1998)

Numerous studies have underscored the pivotal role of environmental sustainability in sustainable development. Costanza et al. (2014) emphasised the economic value of ecosystem services, while Rockström et al. (2009) stressed the importance of respecting planetary boundaries to avert catastrophic environmental outcomes. Consequently, while acknowledging the importance of all three dimensions of sustainability, this study's exclusive attention to environmental sustainability in the garment industry stems from its crucial role in safeguarding the natural environment for the prosperity of the entire ecosystem.

In conclusion, sustainability and sustainable development represent dynamic concepts that have evolved to encompass environmental, social, and economic dimensions. Since the Industrial Revolution, climate systems have experienced warming. GWP is a reliable measure of the impact of a product or process on climate change. By addressing the GWP of garment production and consumption, this research endeavours to contribute to a more resilient future in which economic growth better harmonises with environmental stewardship and societal progress.

1.1.2 Advancing Sustainable Development in New Zealand

New Zealand has consistently positioned itself as a global leader in the integration of sustainability principles into its policies and laws. As early as the 1960s, the nation demonstrated its commitment to the environmental movement through the emergence of the Values Party, which eventually led to the establishment of the Green Party (Rainbow, 1992). Notably, New Zealand's dedication to environmental protection was solidified by the adoption of sustainability principles in the Resource Management Act (RMA) of 1991, exemplifying a proactive stance toward safeguarding the environment (New Zealand Legislation, 1991). Besides, the nation's active engagement in international organisations such as the United Nations Environment Programme (UNEP) and the Organisation for Economic Cooperation and Development (OECD) underscores its longstanding pursuit of sustainable development (MFAT, 2020).

Central to New Zealand's commitment is its alignment with the United Nations Sustainable Development Goals (SDGs) that were established in 2015. These 17 goals address critical global issues, such as social welfare, inequality reduction, and climate change mitigation, with New Zealand wholeheartedly pledging its commitment to these goals through domestic actions and international leadership (United Nations, 2015; MFAT, 2020). The nation's ambitious pledge to reduce greenhouse gas emissions by 30 percent below the 2005 levels by 2030, alongside its commitment to reporting progress and supporting developing countries in their climate mitigation efforts, further underscores its dedication to achieving sustainable development (MFAT, 2020).

However, amid these significant pledges, critical gaps have emerged one of these is the limited research conducted on the environmental impacts of garments in New Zealand. Thus, even though international research has highlighted the importance of employing scientifically established methods such as life cycle assessment (LCA), carbon footprinting, and water footprinting to mitigate environmental impacts, there is a scarcity of literature specifically concerning clothing items in New Zealand (Engelbrecht et al., 2018; Henry, 2012). This raises concerns about the nation's earnestness to effectively address the environmental consequences of its garment industry, particularly considering its ambitious emission reduction targets.

Aligned with the United Nations 2030 Agenda for Sustainable Development, this study recognises the pivotal role of science, technology, and innovation in attaining development goals. This agenda emphasises the necessity of technological advancements and scientific methodologies to address global challenges, particularly those associated with environmental sustainability (United Nation’s SDG, 2015). The call for increased investments in research and development, along with the promotion of access to information technologies, resonates deeply within the New Zealand context.

Considering these challenges and opportunities, the central aim of this thesis is to advance knowledge in the assessment of the environmental implications of garment production and consumption in New Zealand. Through the application of scientifically rigorous methodologies, notably LCA, within the realm of fashion design, this study strives to provide crucial insights into viable strategies and solutions that align with sustainable development principles. Therefore, this research contributes not only to addressing a dearth of local research on the environmental impacts of garments but also to New Zealand's aspiration for a sustainable and resilient future.

1.1.3 The Environmental Implication of Fashion

The pursuit of economic growth frequently eclipses considerations of an industry's social and environmental well-being (Carvill et al., 2021; Holden et al., 2014). Within the context of the fashion industry, the Triple Bottom Line framework demands a concerted effort to address the environmental impact across the entire life cycle of garments, while simultaneously ensuring social and cultural vitality and upholding economic viability (Gardetti & Torres, 2017; Tham, 2008). The global apparel industry has emerged as a significant contributor to environmental degradation, with production and consumption practices leading to substantial negative environmental impacts (Niinimäki et al., 2020). Of particular concern are the impacts of global warming and climate change, necessitating urgent attention (Fletcher & Tham, 2019). The clothing production sector alone is estimated to emit a staggering 2.1 billion metric tonnes of greenhouse gas emissions annually, exacerbating the critical issue of climate change (Wren, 2022). Additionally, global per capita fibre production has surged, and projections indicate a tripling of garment sales by 2050 (Morlet et al., 2017; Peters et al., 2018), which are likely to have severe environmental repercussions unless processes are changed to more sustainable practices.

The environmental implications of the fashion sector have been primarily attributed to *fast fashion* that encourages a culture of frequent garment replacements and disposability (Anguelov, 2016; Niinimäki et al., 2020). Fast fashion brands produce high volumes of synthetic, petroleum-based garments in developing countries, creating elevated levels of emissions and textile waste (Wren, 2022). This model emphasises the increased production of garments, lower retail prices and shorter lifespans, leading to a substantial decrease in the average use time of clothing (Claxton & Kent, 2020; Morlet et al., 2017). Moreover, when the garments are in use, resource consumption related to clothing care practices is more environmentally intensive for synthetic clothing, requiring more resources for frequent washing and care practices than natural garments (Laitala et al., 2017; McQueen et al., 2020; Muthu, 2015), thus having a bigger environmental footprint. Likewise, the fate of discarded synthetic clothing presents a pressing challenge, with a substantial portion ending up in landfills or incinerated, further exacerbating the resources used for waste management (DeVoy et al., 2021; Morlet et al., 2017).

If these current trends continue unchecked, the environmental consequences will become increasingly severe and contribute further to the irreversible damage to the environment (Wren, 2022). Projections indicate a considerable increase in resource consumption, with demand in the apparel industry projected to rise from 98 to 300 million tons by 2050, accounting for over a quarter of the global budget required to limit global warming to the 2-degree Celsius pathway (Morlet et al., 2017). This trajectory also highlights the need for additional land for fibre production, contributing to deforestation and land-use change, while the anticipated levels of microfiber pollution in oceans are alarming (Eder-Hansen et al., 2017; Morlet et al., 2017).

Given the urgency, it is imperative to recognise and address the environmental implications of fashion. The industry's contribution to environmental degradation coupled with projected growth highlights the urgency for comprehensive evaluation, mitigation, and sustainable practices. In this context, fashion designers play a crucial role as key change agents. Designers bear a compelling responsibility to employ better-informed mitigation strategies in their everyday practices, thereby fostering a transition toward a more environmentally friendly and resilient fashion industry.

1.1.4 Integrating Sustainability into Fashion Practice by 'Reckoning'

Within the field of sustainability and fashion design, a crucial area that deserves attention is the measurement of the environmental impact of clothing items. This study introduces the term *reckoning* to refer to the process of measuring the environmental impact of fashion items and addressing the impacts in order to achieve fashion sustainability. In conjunction with the widely recognised principles of reduce, reuse, and recycle, 'reckon' represents the fourth "r" that serves as a prompt to apply thoughtful considerations regarding the production and consumption practices within the fashion industry.

This study posits that without the ability to accurately reckon the environmental consequences of fashion items, meaningful mitigation efforts cannot be effectively pursued. Therefore, an essential prerequisite for minimising the environmental footprint across the entire life cycle of garments is a comprehensive understanding of the associated impacts. Such knowledge enables designers to identify critical areas of concern, facilitates informed decision-making, and justifies the implementation of alternative materials or processes that may aid mitigation of the garment's environmental footprint.

LCA is a scientifically validated method that evaluates the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle, encompassing stages such as raw material extraction, processing, manufacturing, distribution, use, maintenance, and disposal (ISO 14040, 2006; Wolf et al., 2010). The goal of LCA is to quantify the environmental impact of a product, process, or service, thereby helping stakeholders make informed decisions to minimise negative environmental impacts. It can be conducted by various stakeholders including environmental consultants, research institutions, industry and Government agencies (Zbicinski, 2006).

According to ISO 14040 (2006), the LCA process comprises four essential phases:

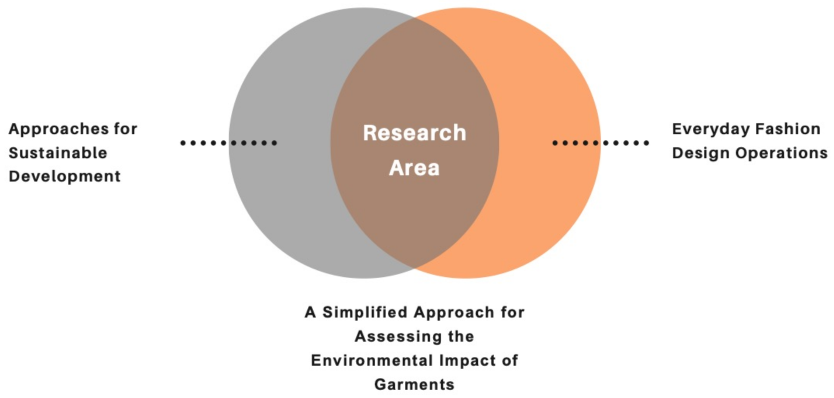
1. **Goal and Scope Definition**: Determines the purpose of the study and establishes the system boundaries.
2. **Life Cycle Inventory Analysis (LCI)**: Involves the collection of data on material inputs, as well as emissions and waste outputs.
3. **Life Cycle Impact Assessment (LCIA)**: Evaluates the potential impacts associated with the inventory data.
4. **Interpretation**: Analyses the results to draw conclusions and make recommendations ISO 14040 (2006).

LCA is instrumental in identifying environmental hotspots and highlighting stages within the life cycle where the environmental impact is most significant and therefore supports businesses, policymakers, and consumers for informed decision-making regarding product design, manufacturing processes, and usage. LCA fosters sustainable design by promoting the development of products with reduced environmental impacts throughout their entire life cycle and thus is a crucial methodology for advancing sustainable development (ISO 14040, 2006; Zbicinski, 2006). However, the complexity and technicality of LCA hinder its practical application, particularly for fashion designers, who seek simplified approaches and assessment methods for attaining environmental sustainability (Hur & Cassidy, 2019; Kozlowski et al., 2019; Vogtländer, 2016).

To support fashion designers in reckoning the environmental profile of the garments they design using LCA, this study focuses on developing practical processes for integrating sustainability into fashion practices. Reckoning the environmental impact of their products allows designers to actively reduce the impacts of the garments they design, thereby ensuring the long-term viability of the fashion industry. Figure 2 shows the research area, which is a simplified LCA method for assessing the environmental impact of garments, that sits at the intersection of the sustainability approaches available to fashion designers and their daily design operations.

Figure 2

Research Area, Sustainable Fashion Design



In conclusion, significant changes are essential in the approach to fashion design, requiring the integration of comprehensive methods for impact assessment as a solution for sustainability. This study bridges the gap between design practices and the evaluation of the environmental impacts of fashion products, demonstrating how reckoning can be incorporated into everyday practices by fashion designers.

1.1.5 Unveiling Sustainability in New Zealand's Fashion Realm

The fashion industry in New Zealand stands at a crossroads, grappling with the challenges of sustainability and global competition. The presence of online retail giants, such as Boohoo and ASOS, as well as the entry of multinational labels into the local market, have posed formidable challenges to the domestic fashion manufacturing sector (Shaw, 2018, April 13). In recent years, there has been a considerable shift towards outsourcing manufacturing to overseas suppliers. Prominent brands such as Macpac, Trelise Cooper, Cotton On, Supré, Factorie, Karen Walker, Breakers, and The

Warehouse rely heavily on globally sourced products (Shaw, 2018, May 10). This has fuelled the availability of cheaper, low-quality clothing, particularly in the form of synthetic substitutes (Jackson, 2011).

The prevalence of cheap imports and the preference for synthetic fibres over natural ones have resulted in a decline in the domestic production of clothing. This has led to a decimation of the local clothing and textile industry (Lewis et al., 2008), and raising concerns about the environmental consequences of cheap synthetic imports retailed in the local markets (Smith & Finn, 2015).

Despite these shifts, knitwear manufacturing still represents a significant sector in New Zealand, producing high-end knitted products for both domestic and international markets (World Bank, 2019). Auckland and Canterbury serve as major hubs for knit production and are supported by regions such as Palmerston North, Dunedin, Bay of Plenty, and Wanganui (Clark, 2020, August 13). The production of luxury textile fibres, such as merino, possum-merino blends, and Cashmere wool constitute a substantial part of New Zealand's knitwear exports (Conforte et al., 2011); however, synthetic fibres are also widely employed in the industry, raising questions about their differential environmental impacts during use and end-of-life disposal (Gonzalez et al., 2023; Jono, 2019, December 5; Moazzem, Wang, et al., 2021; World Bank, 2019).

Despite the country's considerable involvement in natural fibre production, there is a notable lack of recent research on fibre processing, encompassing wet processing and spinning (Cottle & Wood, 2012; Nautiyal et al., 2023a). Mule spinning, employed for finer fibres such as merino, possum, and cashmere, dominates machine knitting, with Woolyarns in the Lower Hutt serving as the sole industrialised mule spinning mill in the country (Khan, 2020). An overarching lack of research exists in understanding the differences between local and global supply chains (Brown, 2022; Larner et al., 2007; McEwan, 2017) and their corresponding environmental impacts in the fashion context of New Zealand.

While knitwear manufacturing is sustained through automated high-end machinery that streamlines production procedures and reduces labour requirements (Smith, 2013), the environmental implications of these technologies remain understudied (Beton et al., 2014). Designers lack adequate knowledge of the associated impacts and the alternative technologies available, necessitating the exploration of sustainable practices within the industry. Additionally, information is scarce regarding how garments, both domestically produced and imported, are used and disposed of in New Zealand (Nautiyal et al., 2023b). Country-specific use phase data are crucial for accurately estimating the potential environmental impacts of clothing items (Nautiyal et al., 2023b; Sandin et al., 2019a).

To address these research gaps, this study employs the LCA methodology to evaluate the cradle-to-grave environmental impact of knitted jumpers in eight different life cycle scenarios. Two varied textile materials- wool and polyester, three flatbed different knitwear manufacturing techniques- cut-and-sew, fully fashioned, and integral knitting, and four distinct supply chain pathways including more localised and international supply chains within New Zealand's fashion realm, will be analysed for their GWP. By illuminating these aspects, this study aims to inform and empower designers with essential insights and knowledge, enabling them to make informed decisions towards fostering sustainable development in the country's fashion sector.

1.2 Research Problem

The magnitude of environmental impacts resulting from clothing production and consumption is unequivocally substantial and therefore demand immediate measures to mitigate adverse effects. It is imperative to adopt evidence-based strategies and methodologies that can lead to tangible and observable improvements. Motivated by the existing gaps within the realm of sustainability in fashion design, this research addresses these notable limitations.

The Lack of Knowledge about Assessing the Environmental Impact of Garments

Clothing manufacturing and usage have numerous adverse environmental impacts that must be addressed (MacArthur, 2015; Niinimäki et al., 2020). However, there is a significant lack of knowledge regarding effective approaches to measuring the environmental consequences of garment production and use (Muthu, 2020; Van der Velden, 2016). Fashion designers tend to avoid scientific methodologies such as LCA because of the complexities involved in gathering the required data and a lack of expertise in the field (Hur & Cassidy, 2019; Kozlowski et al., 2019; Vogtländer, 2016).

As a result, there is a critical need to bridge this knowledge gap and identify appropriate methods for quantifying the impact of clothing throughout its life cycle.

Insufficient Studies on Assessing the Environmental Impact of the Life Cycle of Garments in New Zealand

In New Zealand, studies that measure the life cycle impact of clothing items are lacking (Engelbrecht et al., 2018). Existing research primarily focuses on the environmental implications of wool production (Barber & Pellow, 2006; Henry et al., 2015; McLaren et al., 2012, March 28-29; Wiedemann et al., 2015), neglecting other crucial materials, such as synthetic fibres and their blends. This exclusive focus on wool and its production means there is a large knowledge gap in New Zealand when it comes to the cradle-to-grave consequences of garments made of other textile materials. There is thus an urgent need for comprehensive studies in New Zealand that analyse various materials and consider the entire garment life cycle.

The Dearth of Research on LCA of Natural versus Synthetic Fibres in New Zealand

The New Zealand market is inundated with fast-fashion items, particularly those imported from overseas suppliers, most of which are nearly exclusively made from synthetic fibres and their blends (Jackson, 2011; Lewis et al., 2008). Surprisingly, no study to date has compared the environmental impact of these fibre types with locally available natural fibres such as merino or its natural blends. Given the considerable contribution of synthetic fibres to the overall environmental footprint of clothing items (Gonzalez et al., 2023; Moazzem, Wang, et al., 2021), it is crucial to address this knowledge gap and understand the environmental implications of textile fibres to develop effective mitigation strategies.

Limited Consideration of Use and End-of-Life Phases in LCA Studies

Numerous studies conducted worldwide have employed the LCA to evaluate the environmental impact of several types of clothing. However, many of these studies neglected to consider the critical use and end-of-life phases in the life cycle of clothing (Laitala & Klepp, 2015; Laitala et al., 2018; Laitala et al., 2020). In New Zealand, there is a lack of country-specific data on how garments are used and disposed of, preventing a comprehensive cradle-to-grave LCA analysis (Nautiyal et al., 2023b). Therefore, it is crucial that this research gap is addressed, and country-specific use and end-of-life phases are included in the LCA of garments to obtain a holistic understanding of their environmental impacts.

A Limited Understanding of the Environmental Impact of Clothing Supply Chains

Owing to the limited number of relevant LCA studies conducted in New Zealand, fashion designers lack awareness of the contrasts between producing clothing in a localised versus a globalised supply chain (Brown, 2022; Larner et al., 2007; McEwan, 2017). To enable fashion designers to make better-informed and environmentally sustainable decisions, it is vital to objectively evaluate and compare the impacts of local and global supply chains.

Lack of Research on Simplifying LCA for Everyday Fashion Practice

Despite the recognised benefits of LCA in assessing the environmental impacts of clothing items (Choudhury, 2014; Munasinghe et al., 2021; Muthu, 2020), its practical application in everyday fashion practice is limited because of the complex nature of the LCA process. Conducting LCA requires extensive time for data collection and expertise in inventory and impact assessment, potentially difficult for fashion designers (Hur & Cassidy, 2019; Kozlowski et al., 2019; Vogtländer, 2016). The lack of research on simplified methodologies to integrate LCA into routine fashion practices poses another knowledge gap.

In summary, this study endeavours to address significant gaps in the field of sustainable fashion design. The cradle-to-grave impact of the garment life cycle necessitates a comprehensive evaluation using LCA, which is a complex yet indispensable task for achieving sustainable development. With the idea of reckoning as an important concept for achieving sustainability, this study recognises the need for a simplified approach to LCA that is accessible and applicable to everyday fashion design. By bridging these gaps, the study aims to contribute to a more environmentally conscious and sustainable fashion industry, enabling informed decision-making and fostering a comprehensive approach to mitigating the environmental impact of garments.

1.3 Aims and Objectives of the Study

The primary objective of this study is to develop a simplified approach to employ the LCA methodology for everyday design operations, tailored specifically for fashion designers. This study has three interrelated objectives towards achieving this overarching aim.

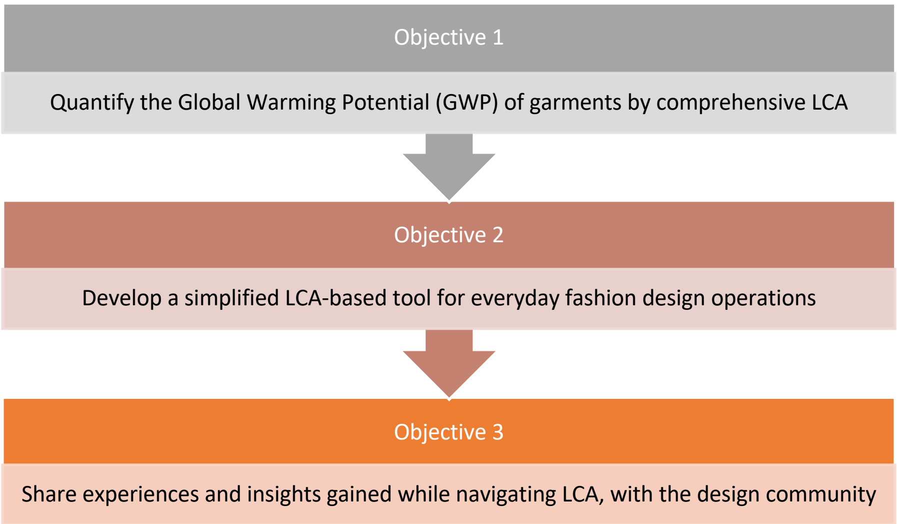
Objective 1: To Explore and Quantify the Global Warming Potential of Garments
The first objective of this study was to employ LCA as a decision-making tool to explore and quantify the environmental impact of garments for their Global Warming Potential (GWP). By conducting a comprehensive LCA evaluation, this objective aims to provide designers with valuable insights into the environmental impact of their material choices, manufacturing techniques, and supply chain decisions.

Objective 2: To Develop a Simplified LCA-based tool for Everyday Design Operations
The second objective of this research endeavour encompasses the simplification of the LCA methodology, culminating in the development of a tool that offers enhanced accessibility and practicability within the realm of daily design operations. Acknowledging the intricacies associated with LCA, this objective primarily revolves around the formulation of a simplified tool that allows fashion designers to seamlessly incorporate sustainability considerations into their decision-making frameworks. Through the LCA-based tool for assessing the environmental impact of garments, designers gain the capacity to make well-informed choices that prioritise sustainability and alleviate the constraints imposed by onerous time and resource demands.

Objective 3: To Share Experiences with the Design Community through this Thesis
The third objective of this study is to share the experiences and distinctive insights, as a designer working in the scientific research realm, specifically navigating the LCA method. Through the dissemination of experiential narratives encompassing encountered challenges and barriers in this thesis, this study endeavours to engender the dissemination of knowledge, foster an exchange of ideas, and encourage further research and innovation at the dynamic intersection of science and fashion design. The visual representation in Figure 3 provides an overview of the three objectives of this study, demonstrating their interconnected nature and emphasising the integrated approach taken to address the research problem.

Figure 3

Objectives of the Study



1.4 Research Questions

This section outlines the research questions that have guided this study in addressing the overarching goal of assisting New Zealand-based fashion designers in evaluating and mitigating the environmental impact of their designed garments. The main research question was:

RQ1. How can the life cycle assessment (LCA) methodology be simplified and effectively implemented in everyday operations to assist fashion designers in mitigating the environmental impact of the garments they design?

The sub-questions were:

RSQ1. What are the environmental implications associated with various phases in the life cycle of a garment?

RSQ2. How can the LCA methodology be simplified to make it practical for fashion designers to integrate sustainability considerations into their decision-making processes?

RSQ3. What are the barriers and challenges faced by designers in implementing LCA in the field of sustainable fashion design and how can they be addressed?

The main research question was designed to explore the adaptation and simplification of LCA for practical implementation in the fashion design industry. The sub-questions narrowed the focus of the study to specific aspects related to the main research question, allowing for a comprehensive investigation into the environmental impact of garments and potential solutions by simplifying the LCA methodology. The experiences and insights gained in implementing LCA will provide valuable lessons for the design community venturing into this scientific realm.

1.5 Significance of the Study

This study holds immense significance in addressing identified research problems and contributing to the field of sustainable fashion design. By effectively addressing the research problems, this research aims to make a meaningful contribution to fostering an environmentally conscious fashion industry. Some of the crucial features of this study are:

Bridging the Knowledge Gap in Measuring the Environmental Impact of Garments

This study addresses the lack of knowledge on how the environmental impact of garments can be measured. By providing appropriate methods for quantifying the environmental impact of clothing throughout its life cycle, it bridges the gap in understanding the environmental implications of the different life cycle phases of a garment and enables fashion designers to make informed decisions when it comes to choices like material, manufacturing technique, and the place of manufacture. This contribution is crucial in fostering an environmentally conscious and sustainable fashion industry.

Comprehensive Evaluation of the Environmental Impact of Garments

Existing research in the assessment of clothing items in New Zealand has primarily focused on fibre production, neglecting other crucial stages of the garment life cycle. This study fills this gap by providing a comprehensive evaluation of the cradle-to-grave environmental impact of garments, i.e., from raw material extraction through to end-of-life disposal in New Zealand, thereby contributing to a more holistic understanding of the consequences associated with their production and use.

Evaluation of Natural versus Synthetic Fibres

This study addresses the absence of research on the environmental impact of natural versus synthetic fibres. Given the prevalence of fast-fashion items made from synthetic fibres, it is essential to understand and compare their environmental implications with locally available natural fibres in New Zealand. Importantly, the study identified a need for New Zealand-specific data on merino wool production. Additionally, it examined the Ecoinvent version 3 database for ethylene, a fundamental raw material for polyester fibre, and discovered inaccuracies in reported CO_2 emissions. This study provides valuable insights for developing effective mitigation strategies and promoting sustainable material choices for textile fibres in the country.

Incorporating Use and End-of-Life Phases in LCA

This study emphasises the importance of considering the impacts of use and end-of-life phases in the garment life cycle. Incorporating them provides a more comprehensive understanding of the environmental impact with the life cycle of a garment. This contribution is crucial for establishing an accurate and holistic evaluation of the cradle-to-grave impact of garments consumed in New Zealand.

Integration of Sustainability into Fashion Practice

Several tools have been developed to assess and minimise the environmental impact of clothing items. The Higg Materials Sustainability Index (Higg MSI) is a prevalent tool that evaluates the environmental performance of various textile materials using a standardised approach (Radhakrishnan, 2015). However, Higg MSI has not gained widespread acceptance in the fashion industry due to its limited accessibility for small and medium-sized enterprises (SMEs), owing to the high cost associated and its opaque methodology (Brad et al., 2018; Kozlowski et al., 2019; Watson & Wiedemann, 2019). To address these issues, this study proposes the methodology for a simplified LCA-based approach for evaluating the environmental impact of garments and a practical flowchart for use by fashion designers. The simplified approach proposed in this thesis has the potential to be developed into a tool which can be a game changer in the field of fashion, allowing designers to quickly analyse the impacts associated with different material types, garment manufacturing techniques, and supply chain pathways, thereby promoting sustainable fashion practices.

Application of LCA for informed decision making

This research provides practical guidance on conducting LCA on clothing items, specifically regarding the four phases of LCA (ISO 14040), which are- goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. Additionally, the study offers specific insights into the environmental performance of knitted jumpers in New Zealand, exploring woollen and polyester material types, three prevalent knitwear manufacturing techniques, and localised and globalised supply chain pathways, enabling fashion designers to make more sustainable decisions based on objective evaluations and comparisons.

Advancing Knowledge by Sharing Insights

By sharing practical insights and experiences related to implementing a scientific methodology, such as LCA, as well as articulating the challenges and barriers encountered throughout the process, this study contributes to advancing knowledge in the field of research on sustainable fashion design. It enhances the understanding of the environmental impact of clothing supply chains and facilitates informed decision-making among fashion designers.

In conclusion, this study contributes to the field of sustainable fashion design by addressing key knowledge gaps and providing practical solutions. By focusing on the cradle-to-grave environmental impact of garments, simplifying LCA for everyday operations, and advancing the understanding to measure and mitigate the environmental impact of garments, this study promotes sustainable practices and fosters an environmentally conscious fashion industry.

1.6 Thesis Overview

This thesis is organised into seven chapters. Chapter 1, the introductory chapter, presents crucial information on the research context, including the research problem of assessing the environmental impact of garments and the lack of simplified methods for their everyday utilisation by fashion designers. It then elucidates the study's aim, objectives, and significance in the field of sustainable fashion design.

Building upon the concepts introduced in the introductory chapter, Chapter 2 provides a comprehensive literature review on the environmental impact through the life cycle of garments, the distinct phases in their life cycle, and the role of fashion designers in integrating sustainability into practice. It then explores the existing literature on LCA as a comprehensive technique for evaluating the environmental impacts of garments, its scope, limitations with its application, and the need for its simplification. Additionally, Chapter 2 investigates the unique contextual factors related to conducting this research in New Zealand, focusing specifically on the country's fashion sector. In conclusion, this chapter identifies and discusses the research gaps in the current literature.

Chapter 3 introduces the exploratory design of this research, which is guided by an ecocentric theoretical perspective. The pragmatic philosophical position justifies an abductive approach to comprehending the complex interactions between design and the use of scientific method such as the LCA for assessment of the environmental impact of garments. A rationale for using LCA is provided, along with details about data collection and analysis methods. This chapter also introduces a comparative and systematic analysis method for developing the simplified LCA-based approach.

Chapter 4 offers a comprehensive account of the data-gathering process for the inventory used in the life cycle of knitted jumpers. It examines data sources and thoroughly assesses the validity of collected data on the various life cycle phases of a garment with regard to fibre production, fibre wet-processing and dyeing, garment manufacturing, supply chain pathways including transportation and packaging, as well as the use and end-of-life disposal.

Chapter 5 presents the research findings. This chapter is structured into three sections, each of which addresses key outcomes. The first section presents the results of a comprehensive LCA analysis of knitted jumpers across eight different life cycle scenarios, analysing the impacts associated with each life cycle phase within the considered scenarios. The second section simplifies the LCA results by focusing on the environmental implications of diverse materials, manufacturing techniques, and supply chain pathways. This section presents a simplified approach to the LCA methodology for assessing the environmental impact of garments and a framework that streamlines the LCA process. The third section in this chapter offers practical insights derived from conducting LCA, drawing upon the expertise of a designer working within the realm of scientific methodology.

Chapter 6 critically discusses the results and scrutinises the insights that have advanced the understanding of sustainable fashion design. Like Chapter 5, this chapter is also divided into three sections according to the three broad areas of research. The first section explores the advancements in knowledge gained through the comprehensive cradle-to-grave LCA of knitted jumpers, providing thorough insights into each life cycle phase, from fibre production to end-of-life considerations. Section two analyses the developed simplified LCA-based approach and framework, delineating its implementation replacing a comprehensive LCA and a SWOT analysis. Section three reflects on the practical aspects and challenges associated with conducting this study.

Chapter 7 concludes the research by presenting a concise summary of how the findings effectively address the research questions and objectives. It then offers an overview of the research contributions, limitations, and the identification of future research opportunities in the field of sustainable fashion design. Subsequently, a concluding note on the researcher's personal growth and learning through this study is presented.

Finally, essential supporting documents are included in a series of eight appendices A to H.

Chapter 2 Literature Review

This chapter addresses the issue of the environmental impact of garments through their life cycle and the ways these impacts can be measured. The initial focus of this chapter is to elucidate the influence of fashion production and consumption on global warming, thereby providing a rationale for the research and a foundation for subsequent discussion. The life cycle of a fashion garment is then expounded and its various stages delineated. This chapter also considers the role of designers in incorporating sustainability practices into fashion design. The literature examines different approaches and tools that facilitate the implementation of life cycle thinking, particularly in assessing the environmental impacts of garments. The challenges encountered by fashion designers in integrating assessment tools into their practice are also discussed.

A sizeable portion of this chapter is dedicated to the examination of the life cycle assessment (LCA) methodology to evaluate the environmental impact of garments. The benefits of an LCA-based tool regarding fashion design are discussed, followed by a review of existing studies in the field of textiles and clothing that have utilised LCA, shedding light on the effectiveness of this approach. Subsequently, the varying scopes of LCA for clothing items are discussed. The literature then focuses on the current limitations in the implementation of the LCA methodology and the need for its simplification for sustainable fashion design.

In addition, this chapter investigates the unique context of New Zealand by reviewing the current state of knowledge regarding LCA in the country. The review also examines current literature about the fashion production and consumption scenario, specifically analysing knitwear throughout the distinct phases of its value chain. This includes a discussion about materials, manufacturing techniques, supply chain pathways, and the influence of materials on the use and end-of-life stages of a knitted garments in New Zealand.

Finally, this chapter addresses the research gaps identified through the literature review and provides a summary of the key issues that this research set out to address.

2.1 Climate Crisis and the Fashion Industry

The fashion industry, which encompasses the production, distribution, and consumption of clothing and accessories, contributes significantly to global warming through its extensive supply chain and resource-intensive practices (Allwood et al., 2015; Hethorn & Ulasewicz, 2015; Karthik & Gopalakrishnan, 2014). The prevalence of the "fast fashion" business model, which promotes excessive production and a throwaway culture, along with the world's growing population, has had a detrimental impact on the environment (Bick et al., 2018; Fletcher & Tham, 2014; Niinimäki et al., 2020). The fashion industry has been widely acknowledged as one of the most polluting sectors worldwide (Henninger et al., 2016; Ma et al., 2020). Projections indicate that the resource consumption in garment manufacture will rise from 98 to 300 million tons between 2015 and 2050, accounting for more than 26 percent of the global budget associated with a 2 °C pathway, which would cause severe and irreversible damage to the planet's environmental systems (Eder-Hansen et al., 2017; Morlet et al., 2017).

Given these circumstances, addressing the environmental implications of clothing is crucial for achieving sustainable development, particularly in line with the United Nations Sustainable Development Goal 12, which aims to promote responsible consumption and production (Gasper et al., 2019; House of Commons, 2019). Several initiatives have been implemented to foster sustainability in the fashion industry. For example, the Sustainable Clothing Action Plan (SCAP) in the UK has garnered commitments from signatories representing 45 percent of retail sales, aiming for reductions in carbon and water footprints, as well as waste to landfill (House of Commons, 2019). Moreover, the UNFCCC and the Fashion Industry Charter for Climate Action, launched in 2018, have brought together stakeholders from the garment industry to pledge climate action and emission reduction targets (Dominish & Sharpe, 2021). Therefore, the fashion industry understands the need to embrace sustainable practices in aid to meet environmental targets; however, there is a lot that needs to be done before there are any measurable improvements.

2.1.1 Sustainability in context to Businesses

As environmental concerns continue to grow worldwide, businesses are facing increasing pressure to adopt sustainable practices to attract customers and align themselves with consumer values. However, it is imperative to recognise that there are no clear cut guidelines for what practices are considered sustainable, necessitating the active participation of regulatory authorities to establish a comprehensive framework (Tharian, 2023). Research conducted by the Sustainable Business Council (2019) in New Zealand has revealed that a large percentage of consumers prioritise sustainability when making purchasing decisions. The study found that 87 percent of consumers consider sustainability a key factor when choosing a brand or product to buy. Additionally, one in every five New Zealanders considers environmental friendliness and low-impact lifestyles to be crucial factors in their buying decisions (Sustainable Business Council, 2019). After quality and price, sustainability is ranked the third most crucial factor in purchase decisions. Consequently, businesses in the country recognise the need to integrate sustainability into their strategies and operations (Sustainable Business Council, 2019).

Moreover, with the increased focus on sustainability, customers are also becoming more aware of the issue of "greenwashing." Greenwashing refers to the practice of misleading customers by providing false or misleading information regarding a company's environmental initiatives (Carvill et al., 2021). Consumers expect brands to be transparent and honest regarding their sustainability actions. Therefore, it is becoming essential for businesses to accurately account for and document their environmental impacts, both in terms of their day-to-day operations and the products they manufacture (Sustainable Business Council, 2019).

A holistic strategy is required to effectively integrate environmental considerations into business operations. Understanding the origins of the raw materials, manufacturing processes, their use and end-of-life disposal options are crucial. This requires collecting data on the environmental aspects of various systems and implementing measurement and benchmarking techniques throughout a product's life cycle (Finnveden & Moberg, 2005). A notable example of a New Zealand-based fashion brand that underlines reporting and documenting sustainability achievements is Allbirds. This company has established environmental reporting standards for businesses worldwide. The company highlights three key priorities: regenerative agriculture, sustainable material, and responsible energy. They believe that "you cannot reduce what you do not measure" (Allbirds, 2021). The company suggests that the collection of data across its supply chain did not only allow them to improve its product design but also to identify hotspots - parts of their production that caused the greatest environmental impact, and subsequently develop strategies to mitigate it.

Moreover, to raise awareness and promote informed decision-making, Allbirds began labelling all their products with its carbon footprint. This transparency serves two purposes: first, to make informed decisions in product design and development, such as identifying hotspots and prioritising efforts to reduce emissions in areas with the most impact, and second, helping customers understand the environmental impact of their purchases. They believe that businesses cannot expect customers to make sustainable choices if they are not provided with relevant information. By prominently displaying the carbon footprint of products, consumers can compare environmental impacts and make more conscious choices. The brand hopes that this practice will inspire other businesses to follow suit, leading to a positive "race to the top" in reducing and eliminating carbon emissions (Allbirds, 2021).

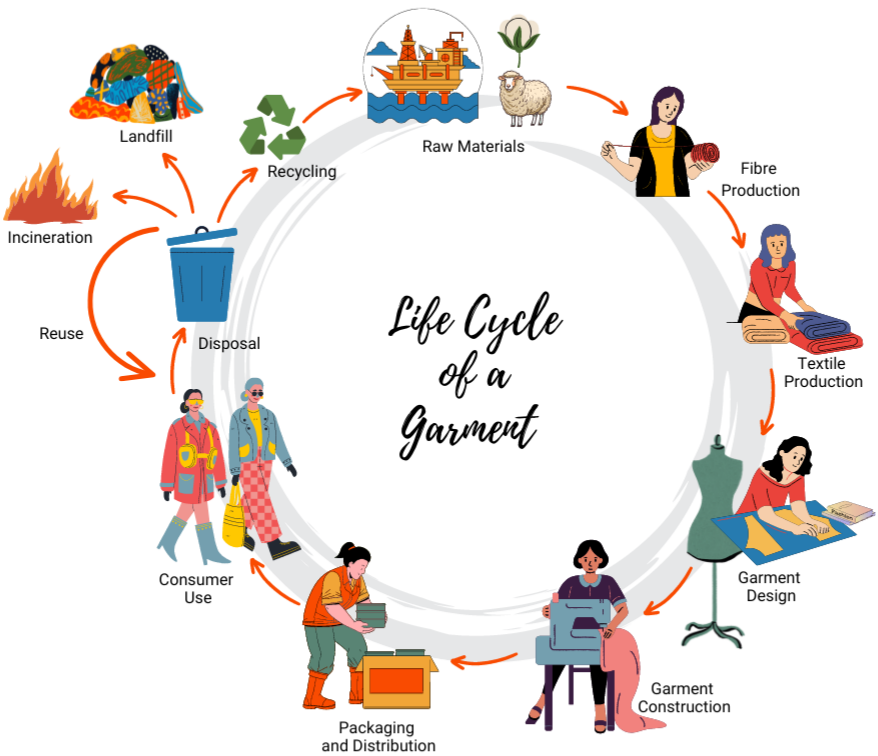
In conclusion, the fashion industry's role in contributing to the climate crisis is apparent, as evidenced by the significant adverse environmental impact linked to garments. Addressing these impacts and finding sustainable solutions are of paramount importance. Consumer awareness of the environmental footprint of products is growing, and there is a strong demand for transparent reporting of these impacts. Thus, businesses are also starting to understand the importance of quantifying the environmental consequences of products in order to reduce their emissions.

2.2 Life Cycle Stages of a Garment

The life cycle of a garment encompasses various stages from resource extraction and production to final disposal. Understanding the distinct phases involved in the garment life cycle is crucial for analysing their environmental impact and implementing sustainable practices. The different stages of a garment life cycle are illustrated in Figure 4 and discussed below.

Figure 4

Life Cycle Stages of a Garment



Note: Adapted from Luján-Ornelas et al. (2020); Payne (2013)

- *Raw material production/extraction:* This phase involves obtaining the raw materials required for garment production. It includes harvesting raw materials obtained from plants, animals, and petroleum, among other sources.
- *Fibre production:* Once the raw materials are obtained, they are transformed into fibres and yarns. This stage involves spinning, twisting, and other manufacturing techniques for creating textile components that can be used in garment production.
- *Textile Production:* In the textile production phase, fibres or yarns are processed to create fabrics. Various techniques such as weaving, knitting, or felting are employed to produce the desired textile structures, textures, and patterns.
- *Garment Design:* This phase sets the foundation for the entire life cycle of a garment. It involves the creative process of conceptualising and developing a garment's aesthetic and functional aspects. Designers draw inspiration, create

sketches, and make decisions regarding fabric, style, construction techniques, and other details.

- *Garment Construction:* The garment construction phase involves the actual construction of a garment. This includes cutting fabric panels, sewing, stitching, and attaching buttons, zippers, or other fasteners. This phase brings together textile components to form the final garment.
- *Packaging and Distribution:* After the garment is assembled, it undergoes packaging to prepare it for transportation and distribution. This phase involves packaging garments and transporting them to retail stores or distribution centres.
- *Consumer Use:* During the consumer use phase, individuals purchase and wear garments. This stage encompasses the entire lifespan of garments, from initial use to potential repairs, alterations, and continued maintenance by consumers.
- *Disposal:* The final phase of the garment life cycle involves its disposal. There are different ways a garment may be disposed of. Discarded garments may end up in landfills or become incinerated. However, the life of a garment could also be increased if it enters the reuse phase or recycled.

Moreover, packaging and transportation may occurs through the life cycle of a garment, as sites for different phases may be situated in various regions of the globe (Luján-Ornelas et al., 2020; Payne, 2013; Zhang et al., 2023).

2.3 Role of Designers in Integrating Sustainability into Fashion Practice

The literature in the field of sustainability in fashion design shows the important role that designers play in shaping the environment through design. Papanek (2005) emphasised that designers should be held more accountable for their creations at social and moral levels. In the garment industry, fashion designers play a pivotal role in pursuing environmental sustainability (Fletcher, 2013; Gwilt, 2012; Gwilt & Rissanen, 2012). Ballie (2012) view designers as change agents with the capacity to modify various interfaces within products and services, extending their influence beyond mere design. Vuletich (2015) considers them connectors, facilitators, quality producers, visualisers, visionaries, and co-producers of change. Consequently, there is growing demand for fashion designers to acquire new skills and competencies to enable sustainable solutions.

The design stage plays a pivotal role in addressing environmental impacts as it exerts influence over more than 80 percent of a product's lifecycle (Charter & Tischner, 2017; Graedel et al., 1995). Decisions made in these early phases significantly shape the environmental consequences associated with both upstream (production-oriented) and downstream (consumption-related) processes, with limited flexibility for modifications once production commences. This underscores the critical importance of integrating environmental considerations into the early stages of design development, as such integration becomes progressively challenging as design progresses, underscoring its far-reaching implications (Hur & Beverley, 2014).

Papanek (2005) argued that designers frequently prioritise visual appeal over environment, overlooking the potential impact their designs may have on nature. He stressed the importance of integrating beauty and function into a successful design. Many designers exhibit a lack of environmental awareness, focusing on product aesthetics without adequately considering the technical aspects of production and its associated consequences (Fletcher & Tham, 2014; Gwilt & Rissanen, 2012).

Incorporating environmental factors into the design phase has proven to be challenging for fashion designers (Bovea & Pérez-Belis, 2012; Connor-Crabb, 2017; Lofthouse, 2006). Designers often face limitations in their roles, such as a lack of suitable tools and inadequate knowledge and insight into the available options for making sustainable decisions (Van der Velden, 2016). Besides, designers often overlook the environmental consequences of using and disposing of garments, considering that aspect of the life cycle to be the consumer’s responsibility (Black, 2008). One solution to help designers integrate sustainability into fashion design is to holistically consider the impacts with entire cradle-to-grave life cycle of a garment, also known as “life cycle thinking” (Gwilt, 2012; Payne, 2013; Van der Velden, 2016; Zbicinski, 2006).

2.3.1 Life Cycle Thinking

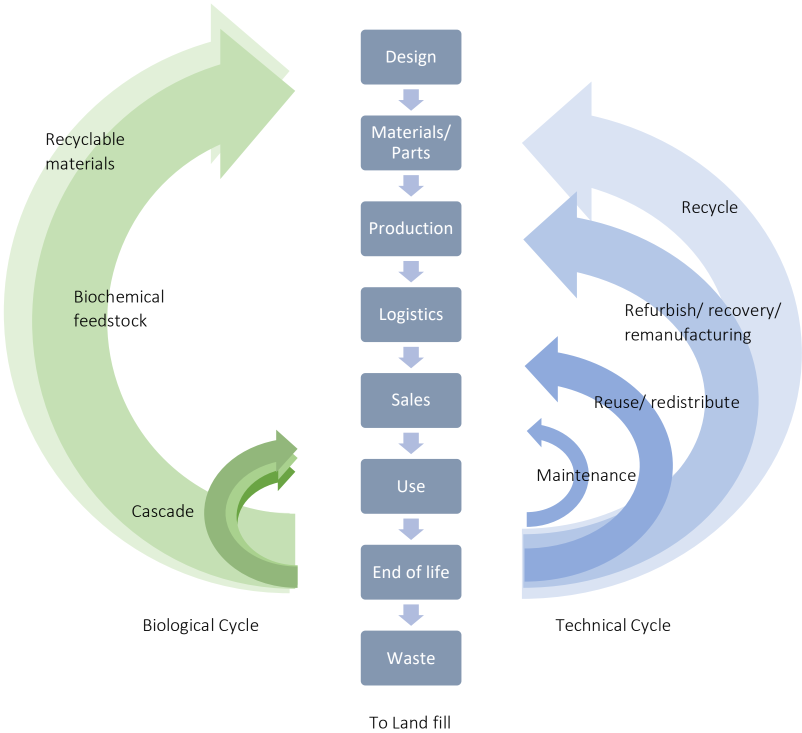
Life cycle thinking (LCT) is an evaluative approach that encompasses the complete life cycle of a product or process, spanning from raw material extraction to end-of-life, to assess and quantify its environmental, economic, social, and cultural impacts (Luján-Ornelas et al., 2020). In the context of environmental sustainability, LCT considers the entire life cycle of a product from its inception to its ultimate disposal. By doing so, it helps prevent the unintended consequence of solving one environmental problem at the expense of exacerbating others, often referred to as the “shifting of burdens”(EU-JRC, 2010).

The "shifting of burdens" occurs when actions taken to reduce the environmental impact at one stage of the product's life cycle inadvertently increase the impact at another stage or in a different environmental category. LCT helps identify and mitigate such situations by providing a comprehensive view of the environmental trade-offs involved. For instance, reducing emissions in one country while outsourcing production to another country with less stringent standards and environmental regulations may cause shifting of burdens. Such reduction in emissions could lead to significant environmental issues in the host country (Kozlowski et al., 2015). Thus, LCT considers all pertinent environmental interactions from a supply chain perspective, seeking to avoid unintended burden shifting between life cycle stages, impact categories, resource efficiency, and geographic regions (Manfredi et al., 2012). Various methodologies, such as life cycle assessment, carbon footprinting, ecological footprinting, environmental input-output analysis, material flows, and life cycle costing, employ the LCT for a comprehensive view of the environmental trade-offs involved (Wolf et al., 2010).

Extending the principles of LCT, the Cradle-to-Cradle (C2C) approach was conceptualised by McDonough and Braungart (2010). C2C extends the principles of LCT by emphasising the creation of systems that are restorative and regenerative by design. According to this concept, a product should be designed in such a way that it can have multiple life cycles or be biodegradable. This approach replaces the traditional end-of-life concept with restoration, promotes the use of renewable energy, and eliminates the use of toxic chemicals that hinder reuse or return to the biosphere. Furthermore, C2C aims to eliminate waste through superior design of materials, products, systems, and business model (MacArthur, 2013). By integrating C2C with LCT, a more robust framework emerges, enabling the development of sustainable solutions that not only minimise negative impacts across the product life cycle but also contribute to the overall health and resilience of environmental and social systems. Figure 5, shows the movement of biological, and technical nutrient-based products and materials throughout the economic system. According to the Ellen MacArthur Foundation, the ability to reintroduce products and materials back into the biosphere through non-toxic, restorative loops should be carried out on the biological nutrient side. On the technical nutrient side, improvements in quality are possible through upcycling. Thus, the circular model builds economic, environmental, and social capital (MacArthur, 2013).

Figure 5

The Circular Economy Model



Note: Adapted from MacArthur (2013)

Aiming for a circular economy is one of the important ways to make the clothing industry more sustainable. Morlet et al. (2017) suggests three focus areas that are critical to this vision:

1. Design out waste and pollution
2. Keep products and materials in use
3. Regenerate natural systems

Therefore in the domain of fashion, there is a need for LCT to establish sustainability practices early in the life cycle of a garment. Including LCT in the design process has the potential to trigger changes that could make the fashion industry more sustainable overall (Gwilt, 2012). Designers must develop an understanding of the interactions between the life cycle of garments and the environment early in the design stage, which entails assessing the environmental impacts of the garments life cycle (Roos, 2016; Sandin et al., 2019a; Van der Velden et al., 2014).

2.3.2 Approaches and Tools for Sustainable Fashion Design

Sustainable design focuses on minimising the environmental impact of products (O'Rourke, 2017). It aims to solve individual problems and minimise harmful activities by developing products with low ecological impact throughout the supply chain (Lofthouse, 2006; Payne, 2013; Van der Velden, 2016). A few design approaches associated with sustainability include increasing the life of garments by the use of quality products, designing for circularity with zero waste, use of renewable resources, resource efficiency, and more (Crawford, 2011; Karaosman et al., 2017). A summary of the key strategies of sustainability in fashion design is presented in Table 1.

Several tools have been developed to assist designers in incorporating sustainable design approaches into their everyday practices. These tools provide designers with reference guides, checklists, and models to facilitate the development of environmentally friendly garments. Their purpose is to present complex information in a concise and accessible manner, allowing designers to identify best practices quickly and effectively (Kozlowski et al., 2019). Scholarly publications have described tools to incorporate sustainable choices into fashion practices (Connor-Crabb, 2017; Gwilt, 2012; Karell & Niinimäki, 2020; Kozlowski et al., 2019). Kozlowski et al. (2019) categorise the these tools into three broad categories: universal, participatory, and assessment. Table 2 presents the available tools for fashion design that aid the integration of sustainability considerations into fashion practices.

Table 1

Key Strategies for Sustainability in Fashion

Strategy	Approach	Reference
Design for longevity	Long-lasting, durable, quality, repairable, reusable	(Cooper et al., 2013; Langley et al., 2013)
Design for trans-seasonality	Trans-seasonal clothing for lowering production volumes	(Gwilt & Rissanen, 2012)
Design seasonless/ timeless design	Never in trend as a design that is never “in” fashion, would never fall “out” of fashion.	(Gwilt & Rissanen, 2012; Karell & Niinimäki, 2020)
Design for multi-functionality/ modularity	Parts can be removed, to allow easy repair, cleaning and replacement	(Connor-Crabb, 2017; Fletcher & Grose, 2012)
Design for alterability/ extend life	Alterable clothing for changing body shapes, guidelines where wearer can unpick and remake	(Claxton & Kent, 2020; Corvellec & Stål, 2017)
Design for physical durability	Clothing that meets specified standards, looks good, withstand prolonged wear	(Cooper et al., 2013; Fletcher & Grose, 2012)
Design for emotional durability	Connecting wearer to the maker/emotional attachment between product and the consumer	(Gwilt & Rissanen, 2012; Payne, 2013)
Considered design	Increasing brand value with customers, understanding needs, preferred styles, and cuts	(Claxton & Kent, 2020; Fletcher, 2013; Harris et al., 2016)
Slow design / Design for endurance	Considering the impact of individual garment in its lifetime/ focussing on user interactions	(Aakko, 2014; DeLong et al., 2013; Štefko & Steffek, 2018)
Design for alternative business model	Clothes having second life, leasing or renting services / clothing libraries, loan services, swap services	(Claxton & Kent, 2020; Payne, 2013)
Design for circularity	No waste generation at the end-of-life	(Aakko & Koskennurmi-Sivonen, 2013)
Design for disassembly	Replacing damaged components from a product	(Gwilt & Rissanen, 2012; Payne, 2013)
Design with recovery in mind	Clothing does not become a waste and can be upcycled to retain its value	(Claxton & Kent, 2020; Earley & Goldsworthy, 2019)
Design for upcycling	Reusing clothing waste to make more valuable new products	(Han et al., 2017; Payne, 2013)
Design for remanufacturing	Supporting material recirculation to reduce land filling of fashion waste.	(Dissanayake & Sinha, 2015)
Design for reuse	Reselling unwanted clothing by take-back services and charity donations	(Cooper et al., 2013; Niinimäki & Hassi, 2011)
Responsible material choice	Natural, recycled, durable, high-quality, certified biodegradable, recyclable materials	(Karaosman et al., 2017; Kozlowski et al., 2015)
Design for minimal use	Reducing the quantity of material used	(Corvellec & Stål, 2017)
Design to reduce waste	Efficient use of patterns in fabric cutting/ zero or minimum waste	(McQuillan, 2011; Rissanen, 2013)
Design to reduce energy	Reducing energy consumption in the use phase extending the need for laundry	(Claxton & Kent, 2020; Fletcher & Grose, 2012)
Design to reduce pollution	Using clean and better technologies. 2D/ 3D printing, 3D knitting, nano-technology, enzyme treatments etc.	(Earley, 2017; Payne, 2013)
Biomimetic design	Taking inspiration from natural world like eliminating the dyeing process	(Payne, 2013)
Design for local	Using only locally sourced materials and manufacturing	(Aakko & Koskennurmi-Sivonen, 2013; DeLong et al., 2013)
Design for activism/ design hacktivism	Projects, partnerships, and schemes to disrupt the traditional fashion system	(Fuad-Luke, 2013; Payne, 2013; Von Busch, 2009)
Life Cycle Assessment (LCA)	Quantitative assessment of garment’s environmental impact in the design phase	(Gwilt & Rissanen, 2012; Karell, 2021)

Table 2

Available Tools for Integrating Sustainability into Fashion Design

Category	Name of Tool	Method	Dimension	Developer	Reference in Literature
UNIVERSAL	The TED's TEN Cards	Cards	Env. & Soc.	Kay Politowicz, Rebecca Earley, and Team at Textiles Environment Design (TED), U.K., 2011	Earley (2017)
	Design with Intent	Cards	Env. & Soc.	Daniel Lockton, Brunel University School of Engineering and Design, 2013	Lockton (2013)
	Considered Take and Return	Open-ended model	Env. & Soc.	Maarit Aakko and Ritva Koskennurmi-Sivonen, Helsinki, Finland, 2013	Aakko and Koskennurmi-Sivonen (2013)
	Sustainability Design Cards	Cards	Env. & Soc.	K.M. Hasling & U. Raebild, 2017, Design School Kolding (DKSD) and Kopenhagen Fur, Denmark, 2017	Hasling and Ræbild (2017)
PARTICIPATORY	Sustainable Fashion Bridges	Cards	Env. & Soc.	Eunsuk Hur, Katharine Beverley, & Thomas Cassidy, U.K. 2013	Hur et al. (2013)
	The Sustainable Fashion Design (FDS)	Visual model	Env. & Soc.	Alison Gwilt, Australia, 2015	Gwilt (2012)
	Redesign Canvas	Chart	Env., Soc. & Eco.	Anika Kozlowski, Cosy Searcy, & Michal Bardecki, Canada, 2018	Kozlowski et al. (2018)
ASSESSMENT	Cradle to Cradle Apparel Design Model	Model	Env.	Hae Jin Gam, Huantian Cao, Cheryl Farr, and Lauren Heine, USA, 2009	Gam et al. (2009)
	Cradle to Cradle Certified Product Standard	Standards, third-party certified	Env. & Soc.	Cradle to Cradle Products Innovation Institute (C2CPII), a non-profit organisation, produced the Cradle to Cradle Certified® trademark	C2CPII (2023)
	Considerate Design Tool	Impact assessment	Env.	Sandy Black and Claudia M Eckert, U.K. 2009.	Black and Eckert (2009)
	Made-By (Environmental Benchmark of Fibres)	Impact assessment	Env. & Soc.	Solidaridad (Dutch-based NGO), Norway. 2013	Brad et al. (2018)
	Nike Material Sustainability Index (NSMI) and Nike's Making app	Impact assessment	Env.	Nike (an apparel and shoe brand), USA, 2003; Making App, 2013	Kozlowski et al. (2019)
	Higg Material Sustainability Index (Higg MSI) and Higg Product Module (PM)	Impact assessment	Env.	Sustainable Apparel Coalition (SAC), USA, 2011	Radhakrishnan (2014)
	Kering Environmental Profit & Loss	Impact assessment	Env. & Soc.	Kering (Global luxuary group- Gucci, Saint Laurent, Bottega Veneta, Balenciaga, Alexander McQueen, Brioni, Boucheron, Pomellato, DoDo, Qeelin, Ginori 1735, Kering Beauté, & Eyewear)	Kering Website (2024)
	European Union's Product Environmental Footprint (EU's PEF)	Impact assessment	Env.	European Commission	European Commission (2024)

Note: Adapted from, Kozlowski et al. (2019); Env.= Environmental, Soc.= Social and Eco.= Economic

Universal tools focus on sustainable design strategies and provide designers with a range of approaches to reduce their environmental impact. Examples of universal tools include Textile and Environment Design's TEN Cards also known as TED TEN (Earley, 2017), Design with Intent by Lockton (2013), Considered Take and Return paradigm by Aakko and Koskennurmi-Sivonen (2013), and Sustainable Design Cards by Hasling and Ræbild (2017). On the other hand, participatory tools involve co-design processes that aim to strengthen consumer experience and emotional attachment with their garments. These tools encourage designers to involve consumers in the design process and consider sustainability. The sustainable fashion bridge framework by Hur et al. (2013) and the Sustainable Fashion Design (FDS) paradigm by Gwilt (2012) are examples of participatory tools.

A third category of tools focuses on assessing the environmental impacts of products and processes. Examples of assessment tools include Nike's Material Sustainability Index (NSMI) (Kozlowski et al., 2019), Higg Material Sustainability Index (Higg MSI) (Radhakrishnan, 2014), Fibre Benchmark's MADE-BY tool (Brad et al., 2018), Considerate Design Tool (Black & Eckert, 2009), Cradle to Cradle Certified Product Standard (C2CPII, 2023), and Cradle to Cradle Apparel Design Model (Gam et al., 2009). Lately, Kering EP& L (Environmental Profit and Loss) and EU's PEF (European Union's Product Environmental Footprint) have been introduced. These tools provide data on the environmental performance of materials and products, considering various life cycle phases.

The various scope of LCA, namely cradle-to-gate (commencing with raw material acquisition and ending upon material preparedness for assembly), cradle-to-grave (starting from raw material extraction to the end of its operational life), and cradle-to-cradle (initiating raw material procurement and concluding upon product disintegration into constituent raw materials for the creation of new products), are explained in the subsequent section 2.4.3.

Among these assessment tools, NSMI and Higg MSI have gained significant popularity in the fashion industry (Radhakrishnan, 2014). The NSMI calculates material scores based on life cycle assessments, whereas Higg MSI assesses the environmental impact of materials from cradle-to-gate. Other tools, such as MADE-BY, the Considerate

Design Tool, and the Cradle-to-Cradle Apparel Design Model, offer specific benchmarks and guidelines for sustainable material selection and design considerations (Brad et al., 2018).

Assessment tools aid in incorporating life cycle thinking early in the design stage, thereby facilitating the identification of environmentally advantageous options (Kozlowski et al., 2018). By quantifying the resources required throughout the garment' life cycle, designers can identify environmental hotspots and implement mitigation measures (Pollini et al., 2020; Van der Velden, 2016). Measuring the environmental impact of garments early in the design stage offers several advantages. The available assessment tools facilitate the use of scientific methodologies such as LCA accessible to fashion designers. LCA evaluates the environmental impacts of products and processes throughout their life cycle from cradle to grave. A more detailed discussion of the LCA method for measuring impacts is presented in Section 2.4. While tools that simplify LCA for inclusion in garment design are beneficial, they also have several limitations, discussed below.

2.3.3 Barriers to the Integration of Assessment Tools in Fashion Design

The successful implementation of assessment tools in the fashion industry is hindered by several barriers that impede their effective adoption in mainstream design processes. The key barriers which prevent the widespread utilisation of these tools in the apparel industry that are relevant to the current study are discussed in the following section:

Financial Barriers and Limited Accessibility to Fashion Designers in SMEs

Certain assessment tools, such as the Higg Material Sustainability Index (Higg MSI), Higg Product Module (Higg PM), Cradle-to-Cradle Certified Apparel Design Module, and Kering Environmental Profit & Loss, have been developed by and for large corporate businesses and come with expensive membership or consultation fees, making them inaccessible to designers in small and medium-sized enterprises (SMEs) (Kozlowski et al., 2019). Conversely, tools that are specifically designed for SMEs often lack the necessary funding for regular updates (Brad et al., 2018). The diverse platforms and spaces in which these tools exist, such as websites and academic journals, also complicate their discovery and accessibility to designers with limited financial resources (Kozlowski et al., 2019). Overcoming these barriers and improving the accessibility of assessment tools, specifically to designers working in SMEs are crucial for ensuring equitable sustainability adoption across the fashion industry.

Usability and Appeal of Assessment Tools

Fashion designers often perceive technical and scientific assessment tools, for example the Higg Index as an unappealing and cumbersome task (Kozlowski et al., 2019; Kozlowski et al., 2018). Tools, such as the Making App from Nike have been reported more usable by designers owing to its visual display (Kozlowski et al., 2018). Kozlowski et al. (2019) reports that requirement to purchase the assessment tool and invest time in learning its use is off-putting to fashion designers. The cost of training needed to learn its use is a burden for designers in SMEs, and may also significantly increase their workload. Thus, the learning curve, resource requirements, and specialised knowledge necessary to utilise these tools add to the demanding nature of designers' job (Kozlowski et al., 2018). To overcome this barrier, assessment tools should have more user-friendly designs to facilitate their application and integration into designers' everyday workflow.

Inconsistencies in Evaluating Life Cycle Impacts

Many existing assessment tools, including the Cradle to Cradle Apparel Design Model, Made-By (Environmental Benchmark of Fibres), Nike’s Making App, and Higg MSI, primarily focus on material or production processes, neglecting the use and disposal phases of the garment life cycle (Brad et al., 2018; Laitala et al., 2018). According to Watson and Wiedemann (2019), the inclusion of a full lifecycle is an urgent priority in an LCA evaluation tool such as the Higg MSI. They emphasised on evidence-based approach reflecting actual garment use and end-of-life by consumers for consistency in LCA. To overcome this barrier, it is crucial to develop holistic tools that consider each phase of the garment lifecycle and provide a comprehensive assessment of a garment’s impact (Watson & Wiedemann, 2019). Lately, the Higg Product Module offers users the ability to a complete cradle-to-grave impact assessment, from the point of resource extraction, material production, finished product manufacturing, packaging, distribution and sale, product care, and product end-of-life (Sustainable Apparel Coalition, 2021). However, its relative novelty precludes a thorough analysis of its effectiveness.

Lack of Transparency and Reliance on Self-Assessment

The lack of transparency in the methodologies used by certain evaluation tools, such as Higg MSI, has been a significant barrier that undermines trust among users (Brad et al., 2018) (Laitala et al., 2018). Watson and Wiedemann (2019) recommended the inclusion of quantitative uncertainty analysis and confidence intervals with all Higg MSI results, along with a full justification of the use of proxy data in it. Transparency is crucial for ensuring scientifically valid comparisons and enhancing credibility. So, evaluation tools should be transparent about their methodologies and provide clear explanations of how assessments are conducted (Watson & Wiedemann, 2019). Without transparency, there is a risk of bias, rendering the assessments akin to self-evaluation (Brad et al., 2018).

Consequently, to overcome the barriers hindering the integration of assessment tools into fashion practice, it is essential to develop financially accessible, user-friendly, and comprehensive tools which are reliable with transparent methodologies. Addressing these barriers and equipping designers with the necessary tools to effectively assess and mitigate the environmental impact of garments is crucial to fostering sustainability practices.

2.4 Measuring the Environmental Impact of Garments

Measuring environmental impacts is a critical approach for mitigating the negative consequences of industrial processes, and governments worldwide have recognised its importance. For instance, in the European Union and the United States of America, businesses are mandated to report inventories of chemical substances used in their operations (Muthu, 2020). The REACH directive (EC 1907/2006) in the European Union and the Toxic Substances Control Act in the United States require producers and importers of chemicals to gather data they consume and register information in centralised databases (REACH EC, 2006; USEPA, 1976). These regulations highlight the significance of measuring indicators to regulate the use of harmful substances for both the environment and human health.

Over the past few decades, a wide range of techniques has emerged to identify and quantify environmental impacts, driven by a greater emphasis on improving the environmental performance of products and services. These techniques include environmental risk assessment, environmental auditing, environmental performance evaluation, strategic environmental assessment, environmental impact assessment, life cycle assessment, material flow analysis, cost-benefit analysis, substance flow analysis, energy flow analysis, and the ecological footprint approach (Finnveden et al., 2009; O'Rourke, 2017).

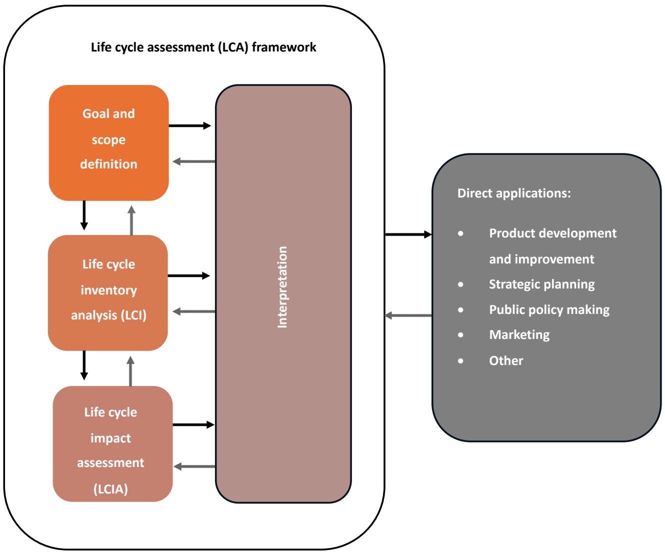
In the context of textiles and clothing and their impact on global warming, the utilisation of quantitative evaluation methods, such as the product carbon footprint (PCF), ecological footprint (EF), and life cycle assessment (LCA), have gained prominence (Muthu, 2020). Among these, LCA stands out because of its comprehensive approach which considers environmental impacts at each stage of a product's life cycle (Finnveden et al., 2009), and thus is used extensively for promoting sustainable practices in the fashion industry.

2.4.1 The LCA Methodology

LCA is a systematic scientific methodology to examine the environmental impacts of the entire life cycle of a product or service. These include all stages of a product's life cycle from raw material extraction, through material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling (Choudhury, 2014). It is used to give better assessment of environmental impact by identifying total material inputs, energy used, and waste generated from the point raw materials are obtained up to final disposal (Rana et al., 2015). LCA helps to identify environmental hotspots, points in the life cycle of a product, or process where the environmental impact is greatest, thereby helping stakeholders make informed decisions to minimise them. It supports businesses, policymakers, and consumers to make more informed decisions regarding product design, manufacturing processes, and usage (ISO 14040, 2006; Zbicinski, 2006). Thus, LCAs are the most comprehensive approach to assessing the environmental impact. The LCA methodology comprises four interconnected phases- goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and Interpretation of results. Figure 6 depicts the four phases of LCA and demonstrates its iterative nature, which is mainly used for product development and improvement, strategies planning, public policy making, and marketing among others (ISO 14040, 2006).

Figure 6

Relationship Between the Four Phases in LCA Framework



Note: Source: ISO 14040 (2006)

Goal and Scope Definition

The goal and scope phase in LCA involves identifying the product under study, specifying the purpose of the assessment, and determining the intended use of the results. Critical components include defining system boundaries, establishing functional units, and selecting relevant impact categories (ISO 14040, 2006). For instance, the goal of this study was to assess and compare the environmental impacts of woollen and polyester-knitted jumpers produced using different knitting techniques within New Zealand's supply chains.

Functional units: Establishing a functional unit is essential for comparative LCA studies. This ensured that comparisons were made on an equivalent basis (ISO 14040, 2006). In the current study, the functional unit was defined as a knitted jumper intended for lifetime use, weighing 385 g and coloured black (Pantone 19-1619 TPX).

System Boundary: The system boundary determines which processes are included in the LCA (ISO 14040, 2006). Different scopes of LCA can be applied to clothing items, including cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle (ISO 14040, 2006). The different scope of LCA are discussed in the following section 2.4.2. A cradle-to-grave boundary was employed in this study, capturing all the stages from raw material extraction to end-of-life disposal. This comprehensive approach provides a complete picture of the environmental impacts associated with a jumper's lifecycle.

Life Cycle Inventory Analysis (LCI)

The phase of Life Cycle Inventory Analysis (LCI) involves the meticulous development of a comprehensive inventory that encompasses crucial inflows, such as energy, water, materials, and land area, and outflows, including emissions and waste for each process within the life cycle of the product (Finnveden et al., 2009; Ramani et al., 2010).

Numerous software tools facilitate the calculation of impacts in a product's life cycle providing LCI and impact assessment (LCIA) datasets using specified analysis methods (Zbicinski, 2006). Pollini et al. (2020) presented some of the principal software available for conducting LCA in fashion and textile industries (Table 3). These tools can be divided into two main categories: Software such as SimaPro, Umberto, GaBi Software, and OpenLCA provide comprehensive environmental analyses. The key feature of the comprehensive assessment software are their customisability. It allows users to select database libraries, input data (including primary data), and impact categories according to their specific requirements. However, the use of comprehensive software tools requires advanced knowledge in the understanding of the LCA methodology and is typically employed post-production owing to the need for comprehensive data for making assessment (Pollini et al., 2020).

On the other hand, there are simplified LCA software tools, such as Eco-concept, IdeamatLight LCA, Sustainability, and CES EduPack, which offer simplified or partial analysis of products and processes. Simplified LCA software can be used in the preliminary phase of product development to perform partial analyses and aid in validating design decisions (Pollini et al., 2020).

Table 3

Available LCA-based Software Tools for Clothing and Textile Items

	Software	Developer	Database	LCA Phases	Environmental Impact factors	Website
Comprehensive LCA. analysis	SimaPro	PRé Sustainability	Includes various databases including Ecoinvent database	Cradle-to-grave / gate-to-gate	Many and customisable	https://simapro.com/
	Umberto	ifu Hamburg GmbH	Includes various databases Ecoinvent and GaBi databases among others	Cradle-to-grave / gate-to-gate	Many and customisable	https://www.ifu.com/umberto/
	GaBi Software	thinkstep, Sphera Company	GaBi database, Ecoinvent, U.S. LCI, Ecological Footprints (EF) database v2.0	Cradle-to-grave / gate-to-gate	Many and customisable	https://gabi.sphera.com/new-zealand/index/
	Open LCA	GreenDelta	Includes various databases including Ecoinvent and GaBi databases	Cradle-to-grave / gate-to-gate	Many and customisable	https://www.openlca.org/
Simplified LCA	Eco-Concept	Sustainable Minds	U.S. EPA, NIST (North American Normalization & Weighting)	Simplified LCA cradle-to-grave	10 impact factors, including mPts and global warming	http://www.sustainableminds.com/software
	IdeamatLight LCA	TU Delft University	Ideamat 2015 developed by TU Delft	Simplified LCA cradle-to-grave and cradle-to-cradle	Eco-cost (Resource depletion, Eco-toxicity, Human health, CO_2); Carbon Footprint	http://idematapp.com/#home
	Sustainability	Dassault Systems Solid Works Corp.	GaBi database	Simplified LCA cradle-to-grave; Find similar material function	Carbon, Energy, air (SO2), Water (eutrophication)	https://www.3ds.com/sustainability/lifecycle-assessment
	CES Edu Pack	Grantadesign	Granta database	Simplified LCA cradle-to-grave with Eco Audit Tool; material selection with CES Selector	Energy and CO_2	https://www.ansys.com/products/materials/granta-edupack/

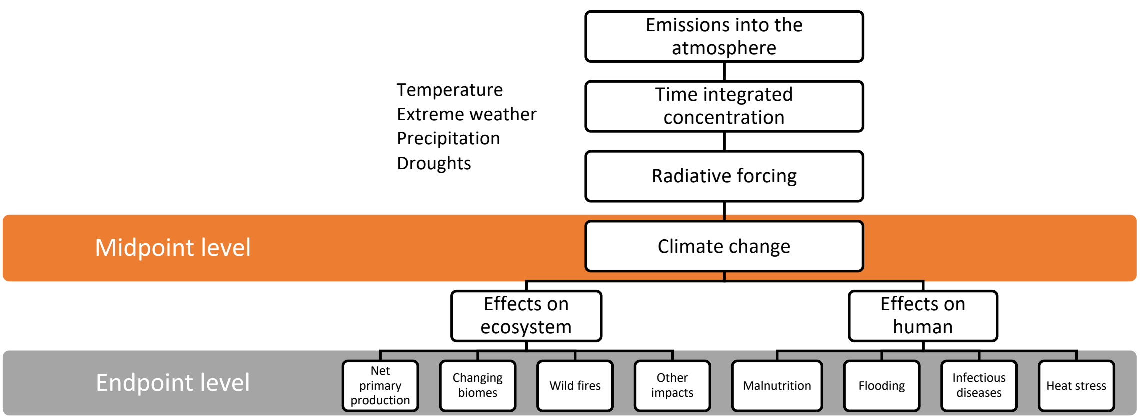
Note: Adapted from Pollini et al. (2020)

Life Cycle Impact Assessment (LCIA)

In LCA, the Life Cycle Impact Assessment (LCIA) phase is designed to evaluate and understand the magnitude and significance of potential environmental impacts associated with a product system. This phase converts the inventory results into potential impacts on Areas of Protection (AoPs) (Beton et al., 2014). The LCIA framework, endorsed by UNEP/Setac, identifies three primary AoPs, also referred to as endpoint characterisation factors, which are- human beings, ecosystems, and resources. However, prior to reaching the endpoints, there are approximately 18 midpoint characterisation factors that represent impacts through indicators situated along the environmental mechanism (Beton et al., 2014; Wolf et al., 2010). For example, the emission of greenhouse gases results in radiative forcing and climate change, a midpoint characterisation factor that eventually affects ecosystems and human health at the endpoint level (see Figure 7).

Figure 7

Relative Impact of GHG Emissions at Midpoint and Endpoint Levels



Note: Adapted from Beton et al. (2014); Wolf et al. (2010)

According to ISO 14044, an impact category indicator can be chosen at any stage along the pathway linking inventory data to impact on AoPs. Although endpoint characterisation factors are easy to understand, as they are few, they introduce additional uncertainty with each aggregated step (Beton et al., 2014; Huijbregts et al., 2016). Midpoint characterization factors, on the other hand, are generally more robust, as the environmental impacts are modelled further in the environmental chain (Beton et al., 2014; Wolf et al., 2010).

According to literature, the most common impact categories in fashion include global climate change, water use, chemical use, eutrophication, and freshwater toxicity (Baydar et al., 2015; Manda et al., 2015; Yacout et al., 2016; Zhang et al., 2015). These impact categories are crucial for identifying and mitigating the most significant environmental burdens associated with textile production and use, thereby supporting informed decision-making within the industry. Global Warming Potential (GWP), a midpoint impact category and a shorthand indicator for climate change impact, was chosen for assessment in the current study.

ReCiPe is a widely accepted methodology for conducting impact assessment. Developed by Mark A.J. Huijbregts and his team at Radboud University in the Netherlands, ReCiPe offers a structured framework for assessing multiple environmental impact categories simultaneously, allowing for a comprehensive understanding of the environmental performance of a system (Beton et al., 2014). It employs characterisation factors to translate emissions and resource extractions into environmental impact scores, offering both midpoint and endpoint indicators to evaluate environmental impacts (PRé Sustainability, 2023).

The ReCiPe Method calculates 18 midpoint indicators that address specific environmental issues such as climate change, acidification, eutrophication, ozone depletion, human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, photochemical ozone formation, and resource depletion (Huijbregts et al., 2016). Additionally, it computes three endpoint indicators that represent the environmental impact on human health, biodiversity, and resource scarcity. Due to the extensive use of the ReCiPe methodology for assessing the impact assessment for textiles and clothing items, it was chosen for the current study (Beton et al., 2014; Manda et al., 2015; Roos, Posner, et al., 2015; Roos, Sandin, et al., 2015).

Interpretation

The interpretation phase of the LCA plays a vital role in deriving meaningful insights and drawing conclusions from the results obtained for both LCI and LCIA. It involves not only summarising and discussing the outcomes of the assessment but also evaluating the level of confidence in the findings (ISO 14040, 2006). The Monte Carlo method is a statistical simulation technique used extensively in LCA to address and quantify uncertainties in the results (Goedkoop et al., 2016).

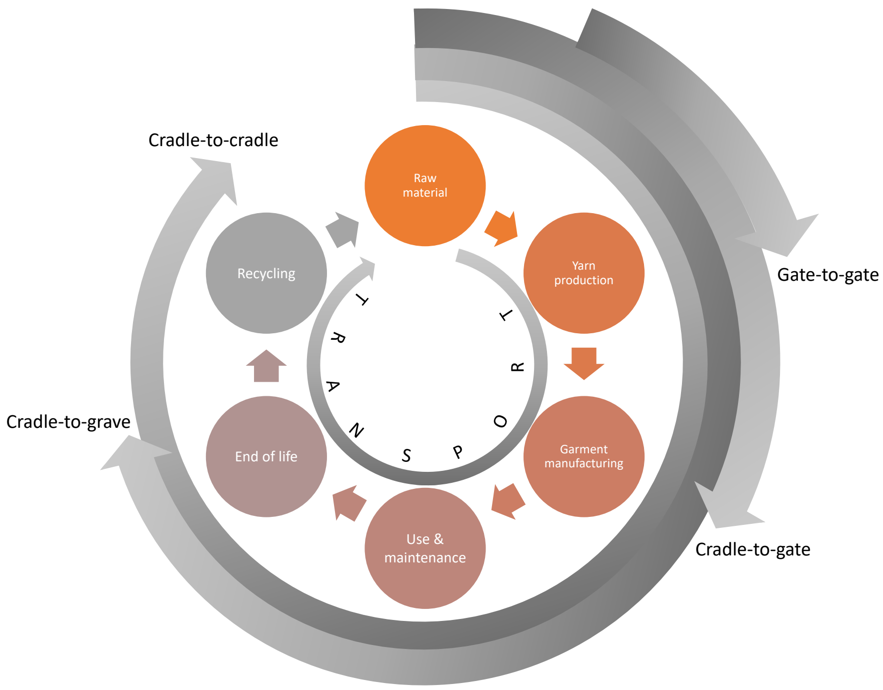
These simulations are particularly useful in LCA due to their ability to incorporate a wide range of uncertainties and complex dependencies among variables. This makes the technique a powerful tool for improving the accuracy and reliability of LCA results, especially in studies where data variability and uncertainty are significant concerns (Goedkoop et al., 2016). The Monte Carlo method was employed for uncertainty analysis in this study.

2.4.2 Different Scope of LCA

Different scopes of LCA can be applied to clothing items, including cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle (ISO 14040, 2006). Figure 8 shows the different scopes of LCA in the garment life cycle.

Figure 8

Different Scope of LCA in a Garment Life Cycle



Cradle-to-gate LCA focuses on the partial life cycle assessment of a product, starting from raw material acquisition and ending when the material is ready for assembly into a final product. It does not include the consumption and end-of-life phases of a garment life cycle. Thus, the examination of the environmental impacts of cotton yarn production from cultivation to fabric formation would fall into the cradle-to-gate category LCA (Bevilacqua et al., 2014).

Gate-to-gate LCA analyses a single value-adding process in the supply chain as it only calculates the environmental impact of raw material leaving the production facility until it is converted into the final product, such as fabric or garment (Muthukumarana et al., 2018).

Cradle-to-grave LCA encompasses the full life cycle assessment of a product, including the use and end-of-life phases. This scope is crucial for comprehensively analysing the environmental impact of a garment. Studies have applied the cradle-to-grave scope to evaluate the environmental impact of garments in various countries, considering fibre production, yarn production, fabric production, wet treatment, confectioning, transportation, use phase, and end-of-life treatment (Sandin et al., 2019a). Cradle-to-grave represents the most commonly applied scope for studies on the clothing and textile industries.

Cradle-to-cradle LCA incorporates recycling in the product life cycle, starting with raw material acquisition and ending when the product is disintegrated into raw materials to create new products. A cradle-to-cradle LCA approach was used to identify sustainability hotspots in the life cycle of a cotton t-shirt which included yarn recycling, for closing the loop once the garment was discarded (Khan et al., 2018).

2.4.3 Benefits of LCA-based Assessment Tool in Fashion Design

LCA is a valuable tool for determining and evaluating the environmental impacts of a product or process throughout its life cycle, from the extraction of raw materials to its disposal at the end of its useful life (Klöpffer, 2006). It considers the inputs and outputs associated with each stage of a product's life cycle, including raw material extraction, energy and water use, emissions, and waste generation. By quantifying these factors, LCA provides a comprehensive evaluation of the environmental implications of a product. The international standard for LCA, ISO 14040 (2006) outlines the consideration of environmental impacts under categories, such as resource use, human health, and ecological consequences.

The use of LCA as an assessment tool in fashion design offers numerous benefits to the fashion industry's sustainability efforts. The literature that highlights its significance in fashion broadly outlines the following benefits:

Key Strategy for Sustainability

The significance of LCA for developing sustainability strategies has been recognised at the global level. The United Nations acknowledges LCA as a key strategy to achieve sustainability goals (UNEP, 2011). European research initiatives, such as the Horizon 2020 program, advocate the use of quantitative techniques such as LCA to develop environmentally sustainable technologies (Argentati & Cusumano, 2015). The European Eco-design Directive and Product Environmental Footprint (PEF) initiative (Finkbeiner, 2014; Roos, 2016) were built on the foundations of LCA. The influence of the LCA methodology is evident from its application in a variety of impact assessment techniques, including the Environmental Design of Industrial Products (EDIP) (Wenzel et al., 1997), the CML method of environmental classification (Heijungs et al., 1992), the Eco-Indicator95 (Goedkoop & Spriensma, 1995), and its current update Eco-Indicator99 (Goedkoop, 2007), which further underscores its importance in promoting sustainability in the fashion industry.

Identifying Environmental Hotspots

LCA serves as a powerful means of identifying environmental hotspots associated with the life cycle of garments. This identification enables fashion designers to focus on critical areas that have the most significant implications (Glavič & Lukman, 2007; Hertwich, 2005). In comparing short and long-life garments, Peters et al. (2018) reported that extending the life of a polyester garment by passing it between several owners and regularly changing it to maintain its appeal by a transfer sublimation overprint three times and later joining it to a jacket using laser technology, does not substantially impact the overall environmental performance of the extended long-life garment when compared to a short-life standard t-shirt. Thus, the information obtained from LCA studies facilitates the development of effective strategies to reduce the environmental burden of fashion products.

Informed Decision Making

By providing comprehensive environmental impact assessments, LCA enables fashion designers to make informed decisions during the product-design phase. Bech et al. (2019) highlighted how LCA supports comparative analysis, allowing designers to evaluate the environmental performance of one product to others. The cradle-to-grave comparison of an antibacterial coated t-shirt showed 20-30 percent lower impacts in environmental categories, such as climate change, as compared to non-antibacterial coated t-shirts (Manda et al., 2015). This reduction in impact is primarily attributed to the antibacterial properties of the t-shirt, which reduces the frequency of washing cycles, thereby lowering energy and water consumption during the use phase. Such comparisons aid in the understanding of the relative sustainability of unique design alternatives. This informed decision-making process helps to align fashion design practices with environmental goals and fosters sustainable design choices.

Justifying Product Claims and Environmental Declarations

LCA offers a robust scientific basis for justifying environmental claims and declarations of fashion products to consumers (Watson & Wiedemann, 2019). As pointed out by Chen and Chang (2013) and Hertwich (2005), the data obtained from LCA can be used to substantiate claims of reduced environmental impacts, eco-friendly materials, or sustainable production processes. This transparency enables consumers to make environmentally conscious choices when purchasing garments.

Strategic Planning and Design

The integration of LCA into fashion design practices aids decision makers in industry, government, and non-government organisations in strategic planning and priority setting. ISO 14040 (2006) emphasises the role of LCA in advising on product or process design and redesign to improve a product's overall environmental performance. By considering the life cycle impacts of fashion products, stakeholders can identify areas for improvement, invest in sustainable practices, and optimise resource utilisation.

Comprehensive Assessment of Environmental Challenges

LCA methodology is highly regarded for its ability to comprehensively address all associated environmental challenges in the fashion industry. By considering factors such as global warming, water use, and chemical pollution, LCA provides a holistic understanding of the environmental impacts throughout the life cycle of a garment. Sandin et al. (2019a) and Esteve-Turrillas and De La Guardia (2017) have applied LCA to analyse the complete cradle-to-grave and cradle-to-cradle life cycle of garments, respectively, further highlighting its comprehensive approach.

Thus, LCA plays a pivotal role in promoting sustainable practices in the fashion industry. Its recognised importance at the global level and its comprehensive assessment through various scope make LCA a valuable methodology in the fashion industry's pursuit of sustainability. By integrating LCA into fashion design practices, designers can align their products with environmental goals, promote sustainable choices, and contribute to a more sustainable fashion industry.

2.4.4 Life Cycle Assessment of Garments

LCA has been widely employed as a methodology to measure and evaluate the environmental impacts of garments throughout their supply chains. Major clothing companies, such as Levi Strauss, Marks & Spencer, and Patagonia, have utilised LCA to reveal the environmental impacts associated with the life cycle of garments they develop (Gwilt & Rissanen, 2012). The incorporation of LCA into fashion research aims to compare different production systems and make informed decisions regarding impact mitigation. Several LCA studies within the clothing and textile sectors have been conducted, focusing on the following objectives:

Assessing the environmental impact of garments using LCA

- Evaluate the environmental impacts of chemicals used in textile production (Roos, 2016).
- Assess the effects of naturally dyed cotton fabrics on the environment (Linhares & de Amorim, 2017).
- Examine the associated greenhouse gas emissions, fossil fuel, energy, and water usage in the life cycle of a wool sweater (Wiedemann et al., 2020).
- Quantify the ecological consequences of energy used in garment production by the Sri Lankan garment manufacturing industry (Muthukumarana et al., 2018).
- Evaluate the environmental impacts of cotton, wool, and polyester clothing used in Australia, providing insights into the entire supply chain (Moazzem et al.,

2018) and assess the impact of garment consumption in Australia (Moazzem, Crossin, et al., 2021b).

Identifying ways to mitigate environmental impacts using LCA

- Identify the supply chain hotspots and implement strategies for mitigating natural resource consumption while aiming for zero emissions (Moazzem, Crossin, et al., 2021a; Rana et al., 2015; Roos, 2016; Woolridge et al., 2006).
- Explore opportunities for impact reduction by promoting increased garment use and best garment care practices (Wiedemann et al., 2021).
- Evaluate the environmental benefits of self-cleaning textile finishes to reduce resource consumption during the usage phase (Busi et al., 2016).
- Assess the environmental impact of landfilling and recycling of clothing during the end-of-life phase (Moazzem, Wang, et al., 2021).

Comparison of alternative supply chain processes using LCA

- Compare the environmental performance of assorted products or processes, such as various Australian wool production scenarios (Russell, 2009), polysaccharides (viscose) versus conventional cotton (Shen & Patel, 2008), conventionally produced t-shirts versus organic t-shirts (Baydar et al., 2015), and different supply system models for synthetic t-shirts versus merino wool t-shirts (Bech et al., 2019).

Hence, the LCA methodology plays a pivotal role in evaluating the environmental impacts of garments within the clothing and textile industry. This technique enables researchers and companies to gain a comprehensive understanding of the environmental consequences associated with various stages of a garment's life cycle, identify areas of significant environmental impact, and facilitate informed comparisons between assorted products and processes. By employing LCA to assess the environmental implications of garments, fashion designers can make informed decisions, track their environmental performance, and develop targeted strategies to mitigate them. LCA serves as a valuable tool for promoting sustainable practices and driving positive changes in the fashion industry.

2.4.5 Limited Application of LCA into Fashion Practice

The fashion industry increasingly acknowledges the significance of sustainability and environmental considerations in its operations. While LCA is a useful tool to achieve greater sustainability, various issues have limited its application with fashion designers.

Complexity and Scientific Nature of LCA

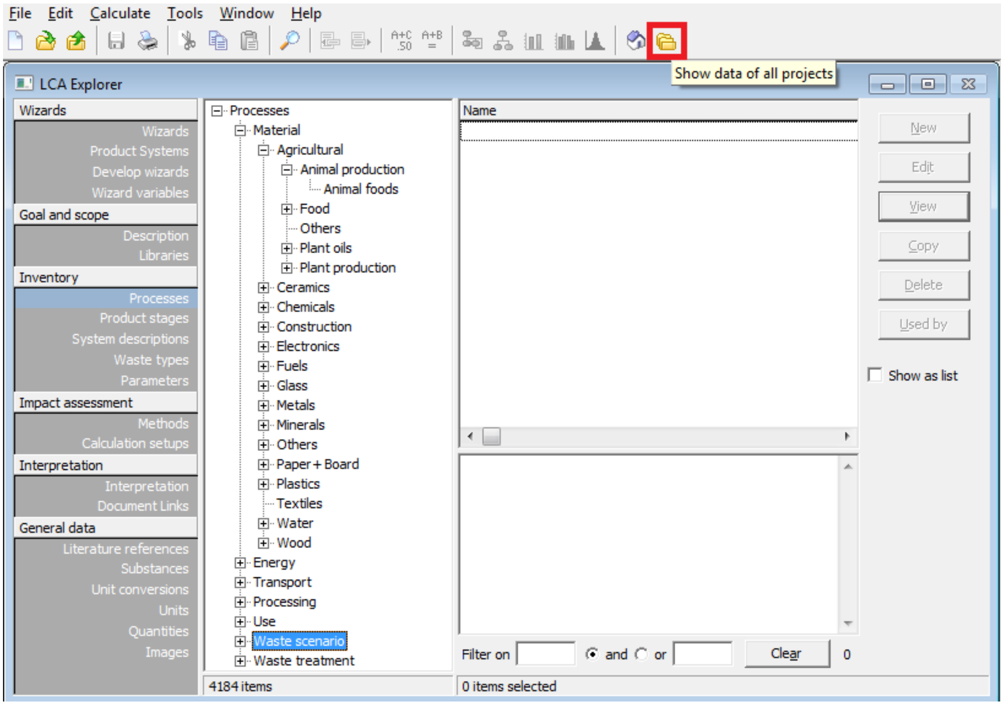
Fashion designers encounter challenges owing to the complexity and scientific nature of LCA, rendering it excessively sophisticated and arduous to comprehend. The specialised terminology and technical concepts associated with LCA prevent non-specialists such as fashion designers from fully understanding and utilising it (Gwilt, 2012; Kozlowski et al., 2018; Vogtländer, 2016). Table 3 provided information on the software interfaces in LCA investigations. These software are equipped with extensive data libraries for various processes, aiding the calculation of impacts throughout a product's lifetime (Finnveden et al., 2009).

Although user-friendly, these software interfaces require extensive knowledge of inputs, such as raw materials, energy, and water, as well as outputs in production, such as emissions to air, water, and soil. The tools for comprehensive LCA assessments often extend beyond the expertise of designers to include in everyday operations (Gwilt, 2012; Vogtländer, 2016). The screenshot in Figure 9 shows the LCA Explorer in SimaPro software, emphasising the complex and the technically challenging nature of the LCA methodology for designers.

This complexity often renders LCA beyond the practical reach of fashion designers, necessitating specialised training and support (Hur & Cassidy, 2019; Kozlowski et al., 2019). Consequently, designers often rely on independent specialists and consultants, which is often costly, impractical and unfeasible, particularly for those in SMEs, and considering the variety of assessments that are required on an everyday basis in the fashion sector (Gwilt, 2012).

Figure 9

A Screenshot of the LCA Explorer in SimaPro Software



Complex Supply Chain and Collaboration Requirements

The intricate and dispersed nature of the fashion industry's supply chain presents an additional obstacle to the implementation of LCA by fashion designers. Conducting comprehensive assessments requires collaboration with various stakeholders involved in the supply chain, including fabric suppliers, trim suppliers, and factories. The extensive and globally distributed nature of the fashion supply chain poses challenges for data collection and environmental impact monitoring (Kozlowski et al., 2019). However, new technological developments such as blockchain and digital product passports offer potential improvements by enhancing the transparency and reliability of data, thereby facilitating more effective collaboration across the industry.

Extensive Data Collection Requirements

Extensive data collection is considered a significant requirement in LCA, posing resource-intensive challenges in terms of data acquisition and analysis (Ramani et al., 2010; Rebitzer et al., 2004).

Subjectivity and Methodological Judgments

Subjectivity presents a challenge in LCA because numerous value-based decisions must be made during the evaluation process (Heijungs, 1997). Choices related to system boundaries and functional units have a substantial influence on LCA outcomes (ISO 14040, 2006). Thus different LCA studies that compare equivalent products but adopt distinct functional units or system boundaries may yield inconsistent results (Rebitzer et al., 2004). This subjectivity and lack of standardisation hinder direct comparisons between studies and products and this makes the application of LCA difficult for fashion designers to comprehend.

Limited Predictive Capability

LCA does not forecast a product's actual environmental impact. The results of LCA are ambiguous since the possible consequences are calculated relative to the functional unit and system boundaries (ISO 14040, 2006). However, experts contend that the primary goal of an LCA is to learn about environmental impacts to allow more environmentally conscious design or purchase decisions (O'Rourke, 2017). As a result, LCA practitioners present it as an environmental systems analysis tool (Finnveden, 2000), or a decision-making tool (Hertwich, 2005), however, very little has been done to look for its simplified application as a ready reckoner.

Incomparability in results of LCA Studies

Due to the subjective nature of LCA and variations in methodological judgments, comparing LCA studies or applying their results to similar issues often proves to be challenging (Finnveden, 2000). Meaningful comparisons require equivalent assumptions and contexts that are frequently unattainable in practice (Khasreen et al., 2009). This lack of comparability restricts the ability to determine the environmental friendliness of a product based solely on LCA results.

Uncertainties in LCA Results

LCA requires extensive input data for modelling the life cycle of products, introducing uncertainties and imprecision (O'Rourke, 2017). Model imprecision, input uncertainty, and data variability can affect the reliability of LCA results (Hertwich, 2005; O'Rourke, 2017). These uncertainties may stem from information gaps that significantly influence the conclusions and recommendations of an LCA study (Finnveden et al., 2009).

Despite these limitations and challenges associated with implementing LCA to assess the environmental impact, it remains an invaluable tool for supporting decisions. LCA can identify potential negative hotspots in the supply chain, allow the design to explore alternative options, and quantify the overall environmental costs of garments. Moreover, advancements in software solutions and comprehensive databases have improved the management of data for LCA studies, making it more feasible to implement. For example, the development of software such as SimaPro by PRé Sustainability in the early 1990s has been instrumental in streamlining LCA processes by providing extensive databases and user-friendly interfaces, thereby enhancing the accuracy and accessibility of LCA for various industries, including fashion (PRé Sustainability, 2023).

Several studies have highlighted the need for simplification of LCA. A simplified data platform would facilitate the integration of LCA into design operations. Efforts should be made to streamline collaboration and data collection within fashion supply chains. Establishing standardised processes and frameworks for data sharing and cooperation could facilitate the integration of LCA into fashion design (Kozlowski et al., 2019). Suggestions for simplification, such as removing those elements that are considered irreverent by the stakeholders, using generic data, and developing simplified analyses have been made (DEAT, 2004; Zbicinski, 2006). The "fast track" LCA which focuses on design alternatives rather than enabling a detailed analysis, have been presented (Vogtländer, 2016).

Ensuring comparability and reliability requires the harmonisation of methodological judgments and transparency in reporting LCA studies. Standardising system boundaries and functional units along with consistent reporting practices can enhance the credibility and meaningfulness of LCA results. Thus, the development of streamlined frameworks capable of comparing products and processes within uniform system boundaries and functional units would be advantageous (Finnveden, 2000; Khasreen et al., 2009).

Therefore, simplifying LCA by addressing collaboration challenges and promoting standardisation and transparency would enable its implementation into fashion practice. This study aims to address the limitations posed by the application of LCA into fashion design and proposes the development of a simplified approach to LCA methodology for assessing the environmental impact of garments early in the design stage.

2.4.6 Simplifying LCA for Sustainable Fashion Practices

The complexity of LCA poses challenges for fashion designers, limiting its widespread integration into daily operations. The previous subsection identified the barriers associated with the application of LCA and emphasised the need to simplify the methodology to make it more accessible and feasible for fashion designers.

Researchers have proposed simplified frameworks and methods to make LCA more user friendly for fashion designers. For instance, Clarke-Sather and Cobb (2019) developed a simplified prospective sustainability LCA method that focuses on social aspects to compare onshoring and offshoring legging production. This approach utilises representative sustainability indicators normalised to a unit scale, allowing for percentage-based comparisons and informed decision-making during the design phase.

The Sustainable Apparel Coalition's (SACs) Higg Material Sustainability Index (MSI) is based on the LCA methodology and is widely used by fashion brands and NGOs to improve the sector's environmental performance. The Higg MSI aims to measure the environmental and social performance of clothing and footwear products (Radhakrishnan, 2014). Md. Islam and Md. Khan (2014) and Cao et al. (2015), both used the Higg MSI 1.0 tool to evaluate the environmental performance of cotton t-shirts and sustainable automotive employee uniforms, respectively.

However, the Higg MSI has been subject to criticism for various shortcomings, notably a lack of transparency and the exclusion of the use and end-of-life phases from the garment life cycle (Watson & Wiedemann, 2019). Despite SACs promise of full transparency by 2020, concerns persist regarding the thoroughness of this commitment (Brad et al., 2018). Researchers have identified issues with the Higg MSI, including incomplete system boundaries, the choice of functional units, and limited data quality assurance (Watson & Wiedemann, 2019). The omission of crucial life cycle stages, such as the use and end-of-life phases, raises significant concerns about the completeness of the assessment and the potential for misleading conclusions (Laitala et al., 2018). Although the Higg Product Module (PM), released in 2021, offers assessments that include product care and end-of-life stages, its accessibility is largely limited to larger corporate firms. Furthermore, its relative novelty precludes a thorough analysis of its effectiveness.

Additionally, the Higg Index has faced criticism for allegedly favouring synthetic materials over natural fibres. Critics argue that the index gives higher sustainability ratings to synthetic fabrics such as polyester, which are derived from fossil fuels, while natural fibres such as wool, silk, and cotton receive lower ratings. This controversy stems from concerns that the data used by the Higg Index may be biased or inconsistent, particularly because some of it is sponsored by synthetic fabric producers and focuses on production in regions with stricter environmental regulations (Evans 2022, Nov 7; SGB Media, 2022 June 17,). In addition, Dutch and Norwegian consumer authorities have recently issued joint guidance to the textile industry for their use of the Higg MSI in marketing. This guidance emphasizes the need for accuracy and transparency in environmental claims made based on Higg MSI, reflecting ongoing concerns about its use and potential to mislead consumers (Forbrukertilsynet, 2022, Oct 11).

Despite efforts to simplify LCA, scant publication is available on methodologies applied for simplification in the fashion industry. Thus, there is a need for further research to enhance the accessibility and usability of LCA-based assessment tools. To effectively integrate sustainability into fashion practices, it is crucial to simplify the LCA methodology and address the shortcomings of existing tools. By enhancing transparency and making a complete life cycle assessment of products, fashion designers can make informed decisions early in the design phase.

The subsequent sections examine the specific context of New Zealand, first understanding the current state of LCA knowledge in the country and subsequently looking into various aspects of garment production and consumption such as the materials employed, manufacturing scenario, supply chain pathways, and practices related to their use and disposal. The purpose of such a close examination of the various aspects is to paint a detailed picture of the factors that influence the life cycle of garments in New Zealand.

2.5 New Zealand's Context

New Zealand, comprising a group of islands located southeast of Australia, has a temperate and subtropical climate, fostering the cultivation of abundant arable land (Mackintosh, 2001). Over the past three decades, the country's manufacturing sector, including garment production, has undergone a considerable transformation. In the apparel manufacturing industry, there has been a shift towards value-based products, wherein items are distinguished based on better qualities, brand name, enhanced performance, innovation, and fulfilling specific functional or service niches (MBIE, 2018). Currently, the textile, leather, clothing, and footwear industries contribute approximately 25 percent of the non-primary output exported from the country (MFAT, 2020). While a few large companies in New Zealand operate multiple stores, most retailers are small, independent enterprises (MarketLine, 2021 August).

Globalisation and the outsourcing of manufacturing have created significant challenges in terms of environmental sustainability (Eder-Hansen et al., 2017; Farrer, 2012; Morlet et al., 2017). In pursuit of cost-effective production, numerous New Zealand fashion brands have turned to offshore manufacturing in countries such as China and Southeast Asia (Styles, 2019). This shift has not only resulted in the closure of many local manufacturing facilities, but has also placed huge challenges in terms of the overall quality of the garments consumed (Smith & Finn, 2015). Large retailers such as The Warehouse rely heavily on synthetic materials, with 38% of their clothing made from polyester and other synthetics, and an additional 36% composed of cotton blended with synthetics (Styles, 2019).

The dominance of imports in the market has several environmental implications because of the extensive distance covered during distribution and the waste generated when these items are discarded. Polyester, a commonly used synthetic fibre, accounts for approximately 60% of the clothing consumed globally (Klepp et al., 2022). It is derived from non-renewable petroleum resources, releasing microfibres into waterbodies during laundry (Henry et al., 2019; Klepp et al., 2022; Stone et al., 2020).

Disposal of polyester material also poses several serious environmental consequences (DeVoy et al., 2021; Niinimäki & Karell, 2020). The disposal of synthetic clothing in landfills worsens the environmental implications associated with the fashion industry, with one of the key concerns being its contribution to global warming. Synthetic garments that end up in landfills decompose and release greenhouse gases including carbon dioxide and methane, which are major contributors to the greenhouse effect and therefore to climate change (Chen et al., 2021; DeVoy et al., 2021).

Although individuals in New Zealand majorly donate used clothing to charity shops, approximately 20% of the donated stock usually ends up in landfills (Nørup, 2019). Despite efforts by organisations, such as the Red Cross, to mend and repurpose garments, there are still items that cannot be salvaged, contributing to landfill waste (Casey & Brian, 2021; Styles, 2019). The prevalence of fast fashion and its emphasis on low-cost production and quick consumption exacerbates this issue as it means an increase in the volume of discarded garments (Bick et al., 2018; Peters et al., 2018). The inability to recycle synthetic textiles economically leads to a cycle of waste generation, as it is often more cost-effective to produce new synthetic materials than to recycle them (Styles, 2019).

Although premium designers and ethical fashion brands continue to uphold local production, the prospects for a substantial revival of domestic manufacturing in New Zealand seem bleak (MBIE, 2018). Local companies engaged in manufacturing often resort to importing fabric or raw materials for production (Sanders & Mawson, 2019). Consequently, the environmental implications associated with the transportation of products from overseas suppliers have become a prominent concern given the prevailing reliance on global supply chains (MBIE, 2018). The substantial distances travelled underscore the urgent need to address the environmental impacts of this system, which has replaced local manufacturers and locally grown natural fibres. Thus, the environmental consequences of long-distance transportation from overseas suppliers and the waste generated when these items are disposed of have emerged as an urgent concern for the environment in the country.

2.5.1 Current State of Knowledge on LCA in New Zealand

The field of LCA in New Zealand has undergone some noteworthy developments in recent years. Nebel (2011) noted the rapid development of the LCA sector, particularly since 2004, when LCA work in the country was largely unknown. The Life Cycle Association New Zealand (LCANZ) was established in 2009 to promote networking and knowledge sharing in LCA among specialists and raise awareness of Life Cycle Thinking among the public and businesses. LCANZ also seeks to coordinate national activities and provide advice to policymakers on Life Cycle Thinking-related matters (Nebel, 2011).

In New Zealand, the pivotal role of LCA in achieving sustainability has been acknowledged. This cognisance is frequently conjoined with the fundamental tenets of the Circular Economy, serving to amplify endeavours towards sustainability. Institutions rooted in New Zealand, such as Mindful Fashion New Zealand, the Life Cycle Association of New Zealand (LCANZ), and 3R, among others, seek to combine LCA and Circular Economy principles in their pursuit of sustainability objectives (3R Group Limited, 2023; LCANZ, 2023; Mindful Fashion New Zealand, 2019). While the prospective dividends of this paradigmatic transition encompass reduced environmental impacts, employment generation, and localised economic proliferation, the imperative is focused on effecting waste mitigation via enhanced design practices (McLaren, 2023, March 30).

Engelbrecht et al. (2018) conducted a comprehensive review of the availability of environmental LCAs in New Zealand. They conducted online searches using various search engines and identified 14 LCA studies, 13 on carbon footprint, and eight on water footprint. Notably, the majority of the LCAs found were focused on industrial and agricultural businesses. In the context of textiles and clothing items, existing literature on evaluating their environmental impact within the country is sparse. Their study highlights the dearth of quantitative data for LCA and carbon and water footprint evaluations in textiles domain. Only a few publicly available references regarding the assessment of garments in New Zealand (Table 4) were identified.

While the focus of LCA research in New Zealand has primarily been on sectors other than fashion, some influential studies have explored the environmental impacts of various industries. For example, Ghose et al. (2019) investigated the environmental impacts of the increase in demand for building refurbishments. Dani et al. (2022) conducted a comprehensive LCA study to quantify and compare the carbon emissions from houses built from light timber and light steel in the Auckland region. These studies demonstrate the versatility of LCA in assessing environmental impacts across various sectors in the country.

Table 4

Assessment Studies in the Field of Textiles and Clothing in New Zealand

	Product	Year	Availability	Document Type	Document Title	Reference
1.	A pair of wool socks and a men's long-sleeved woollen base layer shirt (cradle-to-grave)	2015	Public	Book chapter	LCA of wool textiles and clothing	Henry et al. (2015)
2.	Merino wool from production to fabric formation (cradle-to-gate)	2006	Public	Conference paper	Life Cycle Assessment: New Zealand Merino Industry, Merino Wool Total Energy Use and Carbon Dioxide Emissions	Barber and Pellow (2006)
3.	Merino wool industry	2012	Not available	Conference proceeding	Greenhouse gas, energy, eutrophication, and water footprint assessment of the New Zealand merino industry	McLaren et al. (2012, March 28-29)
4.	Wool production	2015	Public	Journal article	Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers	Wiedemann et al. (2015)
5.	A review of LCA studies of wool	2012	Public	Report	Understanding the environmental impacts of wool: a review of life cycle assessment studies understanding the environmental impacts of studies	Henry (2012)

Note: Sourced from Engelbrecht et al. (2018)

Thus, the state of knowledge of LCA in New Zealand has seen considerable progress in recent years. However, there is limited amount of data publicly available for commercial purposes on the environmental impact assessment of textile and clothing items. While some influential studies have explored environmental impacts in other sectors, further research and more extensive studies are needed to enhance the understanding of LCA in the context of fashion design and the better integration of sustainability in fashion practices.

2.5.2 Material Composition of Garments: Wool versus Polyester

The choice of raw materials in the fashion industry can substantially impact the environmental sustainability of garments (Arshad & Mujahid, 2011; Klepp et al., 2022). The textile materials fall into three categories: natural fibres such as wool, cotton, and silk; man-made fibres such as viscose derived from cellulose; and synthetic fibres such as nylon, acrylic, and polyester sourced from crude oil (Allwood et al., 2015).

The production volume of different fibres varies globally, with oil-based synthetic fibres dominating at more than 60%, followed by cotton at 30%, man-made cellulose fabrics at 6.8%, and wool at 1.3% (Dransfeld, 2015). The choice of fibre impact on the carbon footprint due to the variation in energy use. The embodied energy which is the total energy used in the fibre creation process, differs for natural fibres and includes activities such as planting, field operations, harvesting, and yield (Athalye, 2012; Eady et al., 2012). According to research conducted by the New Zealand Merino Wool Association, the energy consumption during the production of natural fibres is substantially lower than the energy consumed in the production of synthetic fibres (Barber & Pellow, 2006).

Luxury natural fibres such as merino and possum-merino wool blends play a significant role in New Zealand's knitwear exports (Baxter & Wear, 2022; Mitchell et al., 2009). Wool production in New Zealand is rich in heritage and renowned for its quality. It is globally known for its colour purity, low contamination levels, and high tensile strength (Lonsdale, 1996). Wool, being a natural fibre, possesses several environmental benefits over synthetic materials such as polyesters. Its unique properties and characteristics make it an attractive choice for garment production, particularly in New Zealand where sheep farming has played an important role in the country's history and economy (Briggs, 2003; De Pont, 2018). However, despite the significance of wool and its potential environmental advantages, there is a lack of comprehensive research on the environmental impact of natural versus synthetic textile materials in the country (Henry, 2012).

The fibre thickness, or fibre diameter, is a critical aspect of wool that influences its properties and applications. The thickness of the wool fibres plays an important role in determining the overall quality, texture, and suitability of wool products (Conforte et al., 2011). Finer wool fibres with lower micron values are highly desired because of their softness, comfort, and suitability for next-to-skin garments. On the other hand, coarser fibres offer enhanced durability and strength for heavier applications. The diversity of wool exports from New Zealand is attributed to the different thickness ranges of wool fibres, with coarse or strong wool, mainly used for making upholstery, comprising a considerable proportion, followed by medium and fine wool, used for making garments (Conforte et al., 2011).

From an environmental perspective, wool offers several advantages over other synthetic materials. Wool acts as a natural carbon store because it is derived from sustainable grassland systems that can sequester carbon (Peri et al., 2020). Wool is biodegradable but requires specific conditions for effective degradation in soil. For wool to decompose, it should be undyed and free from chemical finishes, as these treatments can inhibit biodegradation. Under optimal conditions, such as warm and moist environments, wool can decompose within a few months, releasing essential nutrients back into soil. It is also recyclable. Additionally, wool is highly recyclable. Wool yarns can be easily converted into new yarns and fabrics, making them a key component of the circular economy. This process supports sustainability by reducing waste and promoting the reuse of materials (Baxter & Wear, 2022; Broda et al., 2016; Henry et al., 2017; Petek & Marinšek Logar, 2021).

In terms of thermal regulation, wool demonstrates excellent performance. It is a breathable material that can absorb and release water vapour, allowing it to adapt to the surrounding environment. This property enables wool garments to keep wearers warm in winter and cool in summer, thus enhancing comfort and reducing the need for additional heating or cooling (Erdogan et al., 2020). Additionally, the durability of wool contributes to its environmental advantages. Wool garments can maintain their shape and structure even after repeated use and washing, resulting in products that are less likely to be worn out or require frequent replacements (Erdogan et al., 2020). Thus, wool plays a significant role in the slow fashion movement, emphasising quality over quantity, encouraging the production of garments that last longer and have minimal environmental impact (Joy & Peña, 2017; Klepp et al., 2022).

Although, polyesters are considered more sustainable than natural fibres such as wool or cotton (Beton et al., 2014; Sandin et al., 2019b; Van der Velden et al., 2014). The Higg MSI scores polyesters as having lower carbon footprint than natural fibres (Brad et al., 2018). Synthetic fibres are derived from non-renewable fossil fuels, having high energy requirements during production and release carbon dioxide at the end of their life cycle (Barber & Pellow, 2006; Shen & Patel, 2008). The extraction of crude oil, a key component of polyester production, has been underestimated in terms of its energy intensity and contribution to global warming (Gervet, 2007; Klepp et al., 2022). This discrepancy raises questions about how polyesters have been calculated to be more environmentally sustainable.

Data flaws in ethylene production- a basic raw material for polyester have been reported earlier. Hischier et al. (2005) indicated that the ethylene dataset in the Ecoinvent is mainly derived from just one source- APME (The Association of the Plastics Manufacturers in Europe). This dataset does not account for the major geographical regions and is an aggregated inventory data, reducing its reliability compared with the data available for other materials in the Ecoinvent library. Despite Hischier's reports in 2005, there have been no updates to the database as of 2020; yet, many studies and government policies have relied on this dataset, particularly in the textile and apparel sector (Watson & Wiedemann, 2019).

Moreover, polyester garments accumulate odour faster than natural fibres (McQueen et al., 2020), necessitating more frequent washing, which leads to excessive microfibre shedding into water bodies (Henry et al., 2019; Klepp et al., 2022). In addition, the disposal of polyester clothing further exacerbates environmental concerns. The incineration of polyester textiles generates high emissions and air pollutants, whereas landfilling non-biodegradable polyester textile materials can lead to long-term environmental contamination (DeVoy et al., 2021; Niinimäki & Karell, 2020). The increasing production of polyester has led to substantial carbon dioxide emissions, contributing to global warming and exacerbating the issue of plastic waste (Kirchain et al., 2015). Although polyester recycling offers some environmental benefits, the quality of recycled fibres is lower than that of virgin fibres (Karthik & Gopalakrishnan, 2014) and rarely recycled. It should be noted that garment recycling globally occurs only on a limited scale (Morlet et al., 2017).

Given the pressing need for sustainable practices, it is imperative to address the environmental sustainability of textile fibre production, including the comparison between natural and synthetic fibres. Moreover, there is a lack of comprehensive research specifically focused on the impact of these textile materials in the context of New Zealand. Conducting a thorough study on the environmental implications of wool versus polyester would fill this research gap and provide valuable information to enable informed decision making by designers on what materials to use. Table 5 summarises key differences between wool and polyester fibres, emphasising their distinct environmental profiles.

Table 5

Difference between Wool and Polyester Fibres

Aspect	Wool	Polyester
Source	Natural fibre from sheep (e.g., Merino wool)	Synthetic fibre derived from crude oil
Energy Consumption in Production	Lower energy consumption (includes field operations, harvesting)	High energy requirements
Carbon Footprint	Acts as a natural carbon store (carbon sequestration)	High CO_2 emissions during production and disposal
Biodegradability	Biodegradable under specific conditions (undyed and chemical-free)	Non-biodegradable, leads to long-term environmental contamination
Thermal Regulation	Excellent (breathable, absorbs and releases water vapor, keeps warm in winter and cool in summer)	Poorer thermal regulation, less breathable
Durability	Maintains shape and structure after repeated use and washing	Prone to wear and tear, requires frequent replacement
Odor Accumulation	Less prone to odour accumulation	Accumulates odour easily
Impact on Fast Fashion	Promotes slow fashion (emphasises quality, longevity, and minimal environmental impact)	Contributes to fast fashion (often lower quality and frequent replacements)
Environmental Impact of Disposal	Decomposes under optimal conditions, releasing nutrients back into the soil	High emissions if incinerated, long-term contamination if landfilled
Recyclability	Highly recyclable (can be converted into new yarns and fabrics)	Recyclable, but with lower quality of recycled fibres
Contribution to Climate Change	Helps mitigate climate change through carbon sequestration	Significant contributor to global warming due to fossil fuel use
Historical and Economic Significance	Rich heritage, particularly significant in New Zealand's economy and culture	Less historical significance, economically driven by industrial use

2.5.3 Knitwear Manufacturing Techniques Employed

New Zealand's garment manufacturing industry, although small on an international scale, plays an important role in the country's economy (MBIE, 2018). Many small and medium-sized businesses are involved in garment manufacturing, with knitwear being the largest sector (Lewis et al., 2008; Smith, 2013).

Worldwide, knitting is the second most used fabric formation process after weaving. It involves intermeshing individually formed loops (Black, 2012). Depending on the direction of loop formation, knitting can be classified as warp knitting or weft knitting. Warp knitting involves the generation of loops in the vertical direction, whereas weft knitting in the horizontal direction (Smith & Finn, 2015; Underwood, 2009). Among the various knitwear manufacturing methods, flatbed knit technologies are employed in New Zealand for the production of garments such as jumpers and sweaters. Approaches include cut-and-sew, fully fashioned, and integral-knitting garment construction technologies (Smith, 2013; Underwood, 2009).

The cut-and-sew method of garment construction uses flatbed knitting machines to create fabric panels that are then cut and sewn into garments, resulting in fabric waste due to the shaping and cutting process (Beton et al., 2014). Fully fashioned knitting, on the other hand, shapes garment pieces on a machine, eliminating the need for cutting fabric and reducing material waste. Integral knitting, with its computer-aided design process, allows the production of partial or complete garments with little or no seams, reducing fabric waste and the need for stitching (Peterson et al., 2008).

In New Zealand, the knitting industry has been sustained owing to investment in advanced machinery and automated devices that require less labour and enhanced production procedures. The fully fashioned knitting technique, introduced in the late 19th century, allows garments to be shaped on a machine. In the early 2000s, the country began importing integral knit technology, which gained increasing demand (Smith, 2013). Advanced knitting machinery companies, such as Shima Seiki and Stoll, have made significant contributions in the field of integral knitting, introducing technologies such as Wholegarment® and Knitwear® that can knit the entire garment on the machine without the need of cutting and stitching (Ramsay, 2013).

Integral knitting has the potential to remove seams during production, resulting in reduced fabric waste, lower manufacturing costs, and enhanced garment comfort and quality (Beton et al., 2014; Ramsay, 2013; Smith & Finn, 2015). However, the environmental implications of integral knitting technology have received limited attention compared to traditional knitwear construction methods, such as cutting, sewing, and fully fashioned (Beton et al., 2014). Understanding the environmental impacts of these alternative manufacturing technologies is crucial for implementing the best practices in garment construction. Table 6 provides a summary of the three alternative flatbed knitwear manufacturing technologies available to designers in New Zealand.

Table 6

Environmental Implications of the Three Flatbed Knitting Techniques

Knitting Technique	Method	Differences in manufacturing	Skills required
Cut-and-sew/ Cut Stitched Shape Knitwear	Fabric blank is knitted according to the required width of the garment, plus a small seam allowance to cut and shape the garment. Parts of the garments are then stitched together.	Can be carried out on all flat knitting machines, including old models & without computer processing systems. Wastes up to 30 percent of the original fabric as cut-loss (Peterson & Ekwall, 2007).	Fabric cutting and garment stitching
Fully Fashioned Knitwear	Blanks are shaped entirely on the knitting machine by decreasing or increasing the number of stitches across the width of the blank. Cutting is not required.	Uses electronic flatbed knitting machines and Computer-Aided Design (CAD) packages for production. Minimum cutting and low material consumption	Garment stitching
Integral Knitwear/ Whole/ Complete Garment	A full garment can be knitted entirely on the knitting machine with little or no seams.	There is no yarn wastage. It saves material which is otherwise lost in the cutting and sewing process. Saves energy that would otherwise be used for cutting and stitching garment parts.	-

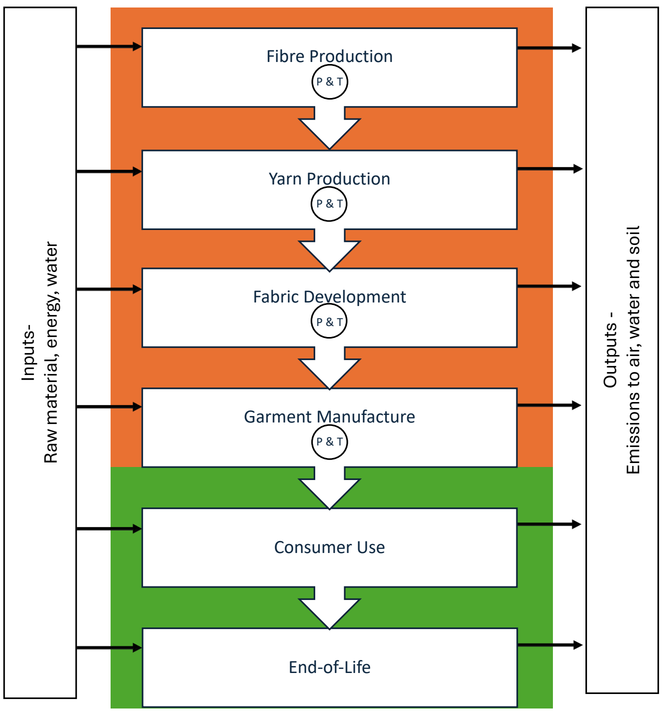
When comparing the environmental profiles of these alternative knitwear technologies, integral knitting appears to be the most efficient in terms of waste reduction but it has a high energy use (Beton et al., 2014). Therefore, more research is needed to examine how these techniques impact the entire life cycle of a garment. Such an investigation would provide valuable insights for fashion designers when selecting the most appropriate technology for minimising the environmental impact of knitwear construction. Understanding the environmental implications of different knitwear manufacturing techniques in New Zealand is essential for promoting locally manufactured products and making sustainable decisions on garment construction.

2.5.4 Supply Chain Impact for Garments

A supply chain refers to a collective of three or more entities, such as organisations or individuals, that are directly involved in the upstream and downstream movements of products from a source to a customer (Mentzer et al., 2001). The upstream stages occur before manufacturing and involve processes such as raw material extraction and fibre production to produce the final garment. Conversely, downstream stages occur after the point of manufacturing and encompass garment use and end-of-life considerations (Curwen et al., 2013; Zbicinski, 2006). The fashion industry's supply chain is characterised by an extensive network of suppliers spanning multiple countries (Eder-Hansen et al., 2017; Strähle & Müller, 2017). Following the flow of materials and products, it encompasses various stages including procurement, production, storage, distribution, and disposal (Rushton & Walker, 2007). Figure 10 depicts a typical apparel supply chain in a linear, cradle to grave model showing upstream and downstream processes.

Figure 10

A Typical Apparel Supply Chain



Note: P & T refers to Packaging and Transport; Orange Block shows upstream activities; Green Block shows downstream activities.

Over the past few decades, the apparel industry's supply chain has experienced major changes due to globalisation (Curwen et al., 2013; Nath et al., 2021). Global-purchasing firms have played a key role in reducing costs by outsourcing production to manufacturers, with most of them based in developing countries. While this has created job opportunities in these countries, it has also resulted in a higher level of associated environmental pollution (Arrigo, 2020). The garment supply chain consumes substantial resources, energy, and water while generating toxic waste in both upstream and downstream processes (Abbate et al., 2023; Nayak et al., 2020).

Awareness of the environmental consequences of global supply chains is crucial for both consumers and local fashion designers. Gwilt and Rissanen (2012) mentioned studies, such as those conducted by Farrer and Parr (2008), which shed light on the carbon emissions associated with clothing transportation. Farrer and Fraser (2009) identified that for garments manufactured offshore, the distribution phase often requires transportation over several thousand kilometres via sea or air freight, which has considerable environmental consequences. Local production, on the other hand, were found to have shorter distribution channels and use lighter vehicles, which likely means a smaller environmental burden (Allwood, 2014; Bocken & Short, 2016). However, more recent and comparable studies are needed to further raise awareness and understand the environmental impacts linked to local and global supply chains in the context of New Zealand.

In addition, within the supply chain, the consumption of resources and the generation of waste are linked to packaging. Packaging serves several essential functions including containment, protection, preservation, transportation, information dissemination, and product promotion (Choudhury, 2014). The choice of packaging material and quantity used depends on several factors, such as the weight of the materials being transported and the distances they will cover (Muthu, 2020; Shen & Patel, 2008). Commonly used packaging materials include plastic, paper, metal, aluminium, cotton, hemp, and biodegradable materials (Choudhury, 2014).

However, addressing the issue of packaging waste is of utmost importance for mitigating environmental impacts within the life cycle of a product. Specific requirements about packaging and packaging waste targets for recycling and imposition of maximum thresholds for heavy-metal content have been set up by many governments globally (Choudhury, 2014). In New Zealand, the Packaging Accord (2004-2009) was signed between the packaging industry, local and central governments, and the recycling industry to reduce packaging waste (Michael-Agwuoke, 2017).

The complex network of suppliers, outsourcing trends, and distribution processes contribute to the impacts of the complete life cycle of garments. Therefore, understanding the environmental impact of the supply chain is crucial. By gaining a better understanding of the environmental consequences of transportation and packaging, fashion designers can make informed decisions and implement sustainable practices to minimise their impact.

2.5.5 Influence of Material on the Use and End-of-Life Practices

The use phase of the garment life cycle often has a greater impact than garment production (Moazzem et al., 2018; Sohn et al., 2021), partly because the garment is produced once but can be used repeatedly (Laitala et al., 2018). The frequency of wear and wash, laundry behaviour, and overall garment lifespan all play critical roles in determining a garment's overall environmental impact (Moazzem et al., 2018). Varied materials require different care levels and vary with regard to how long they tend to be worn before washing (Cooper et al., 2013).

The use stage is regarded as one of the most crucial stages for generating negative environmental impacts, particularly in terms of wearing and washing frequency (Laitala et al., 2017; Laitala et al., 2018). However, many cradle-to-grave LCA studies have overlooked the crucial role of materials in shaping the environmental impact of the usage phase (Cooper et al., 2013; McQueen et al., 2020). They often assume a standard washing frequency, regardless of the material type. Field studies have shown that different textile materials have different washing criteria and wear frequencies. For example, a woollen sweater is typically worn for 10 days before washing, whereas a cotton sweater is worn on average for five days (Laitala et al., 2017). These variations in clothing maintenance substantially impact the resources consumed and the emissions released during laundering operations, such as washing, drying, and ironing (Zhang et al., 2023). It is essential to consider material-specific wear frequencies when simulating the use phase in garment LCA.

The number of times a garment is worn, or the wearing frequency, is also crucial in evaluating its overall environmental impact as it divides the impacts over the garment's lifespan (Klepp et al., 2020). However, this concept again has received little consideration in many cradle-to-grave LCA studies. For example, a study by Roos, Sandin, et al. (2015) evaluated clothing made of varied materials but based their assessments on the same frequency of use for all garment types. In contrast, another study by Sandin et al. (2019a) modelled the use phase inventory over one year, estimating the number of times different garments would be worn based on the average number of new clothes purchased in Sweden annually. Their assumptions regarding the number of uses per year were based on consumer surveys, highlighting a need to model the material-specific wear frequency of garments.

Additionally, several LCA studies have demonstrated that the geographical region in which a garment is used has a considerable impact on its maintenance (Daystar et al., 2019; Sohn et al., 2021). Factors such as the climate and weather influence local consumer wardrobe maintenance practices. Evaluating the environmental performance of t-shirts, for example, revealed variations in the environmental impacts during the use phase, depending on the geographical region and weather conditions. The number of days before laundry, a t-shirt is worn 2.4 times in China, 1.9 times in Germany and The United Kingdom, 2.0 times in Italy, 1.8 times in Japan and 1.6 times in The United States of America (Daystar et al., 2019). Country-specific use phase data are crucial for accurately estimating the environmental impacts of clothing items (Nautiyal et al., 2023b; Sandin et al., 2019a).

Specific end-of-life scenarios for garments also play a crucial role and should be considered in LCA studies. Previous consumer studies on clothing disposal practices have focused on the reasons for disposal but have not examined if consumers dispose of garments differently depending on the materials used (Laitala et al., 2018). It has been observed that a higher proportion of consumers prefer to donate for reuse their woollen garments than synthetic (Laitala et al., 2017).

The discussion presented above indicates that, the material content of a garment has a significant impact on its use, including how frequently it is worn and washed and how it is disposed of. This suggests that accurately evaluating a garment's environmental impact requires modelling its use and end-of-life strategies based on its material content. Therefore, to enable a more comprehensive LCA of clothing items in New Zealand, there is a need for more specific modelling of the use and end-of-life of garments consumed in the country.

2.6 Research Gaps

In the realm of sustainable fashion design, numerous studies have extensively examined the environmental impact associated with the cradle-to-grave life cycle of clothing items (Munasinghe et al., 2021). However, despite the significance of LCA as a robust methodology (Watson & Wiedemann, 2019), it is perceived as complex, expensive, and time-consuming in the context of fashion practice, leading to its limited adoption by designers in everyday practice (Gwilt, 2012; Kozlowski et al., 2018; Vogtländer, 2016).

While LCA is widely recognised as a scientific method for assessing the life cycle impacts of products and processes (ISO 14040, 2006), the literature indicates that available LCA-based tools for evaluating the environmental profile of textile and clothing items are often inaccessible to fashion designers working in small and medium-sized enterprises (SMEs). The cost and opacity of these tools pose major barriers to their adoption (Brad et al., 2018; Kozlowski et al., 2019). Consequently, there is a substantial research gap regarding simplified LCA-based tools that are readily available and user-friendly for everyday design operations. It is crucial to ensure that sustainability becomes an integral part of fashion design, allowing for mitigation of the life cycle impacts of garments through well-informed decisions that positively contribute to the environmental system.

In addition, the literature review shows that there are lots of different factors that need to be considered for understanding the environmental impacts of textile materials (Arshad & Mujahid, 2011; Klepp et al., 2022), knitwear production techniques (Beton et al., 2014; Peterson et al., 2008), supply chain impacts of local and global production (Abbate et al., 2023; Nayak et al., 2020), and practices related to garment use and disposal (Laitala et al., 2017; Laitala et al., 2018). This research seeks to fill these knowledge gaps as it aims to enhance the comprehension of LCA and its implementation in fashion practice, particularly in New Zealand.

2.7 Chapter Summary

This chapter presented a comprehensive literature review of sustainable fashion design, addressing various key aspects related to the integration of LCA methodology into fashion design.

The chapter began by highlighting the pressing issue of the climate crisis and its considerable impact on the fashion industry. The life cycle stages of fashion garments were explored, emphasising the importance of understanding the entire supply chain from production to disposal. The role of designers in promoting sustainability in fashion practice was then discussed, covering the application of life cycle thinking (LCT), available sustainability approaches, tools, and barriers to implementing them by fashion designers in the industry.

The chapter then examined methods for measuring the environmental impact of garments, specifically highlighting the benefits of LCA-based tools in fashion design. Subsequently, the literature on LCA of garments is explored along with its different scopes and the reason why it is not commonly used in fashion design yet. Consequently, the study explored the potential of simplifying LCA to facilitate fashion practices.

The focus of this chapter then shifted to the context of New Zealand and the current state of LCA knowledge within the country. The literature found gaps in the information currently available on the material composition of garments, particularly comparing wool and synthetics, the prevalent knitwear manufacturing techniques, the impact of the supply chain on garments, and the influence of material choice on the use and end-of-life practices.

Finally, the chapter identified many research gaps in the existing literature, particularly areas requiring further investigation to advance sustainable fashion design.

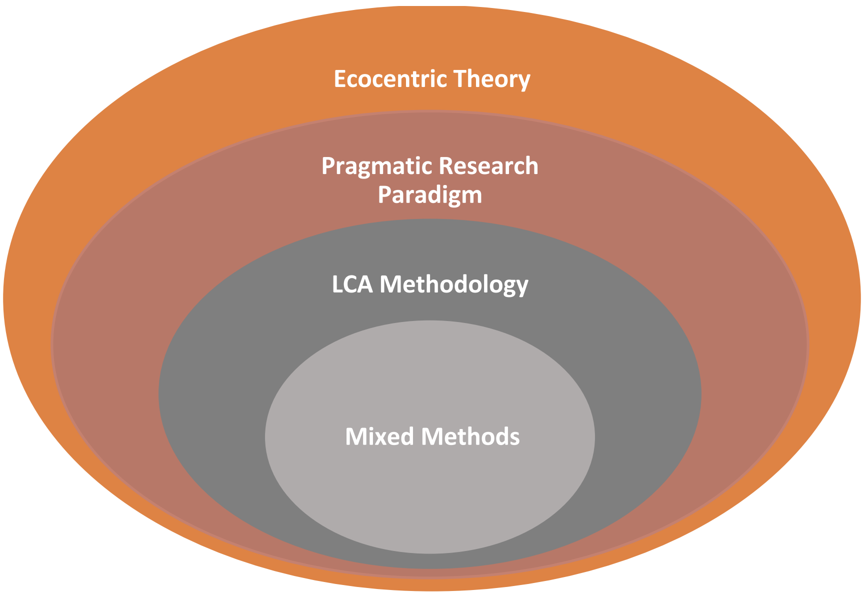
The next chapter reviews the research methodology employed, elucidating the research approach taken and the methodologies and methods used in doing LCA and its simplification.

Chapter 3 Research Methodology

This chapter describes the systematic approach used to address the research problems and frames the logic of the research process. The research methodology is formulated and justified, revealing a deeper understanding of the intricacies involved. This chapter is organised into two sections, with the first section describing the theoretical and philosophical stance of this study. The second section investigates the research methodology and methods employed. By exploring the interrelation between the four levels within the structure of this study: the ecocentric theory, the pragmatic research paradigm, the life cycle assessment (LCA) methodology, and the application of mixed methods, this research manifests its intrinsic approach in shaping and guiding this investigation (Figure 11).

Figure 11

The Research Approach



The initial section of the study presents the exploratory research design and the underlying rationale for its selection. Then the research process is outlined, which consist of four distinct phases: 1. Problem identification and development of research question, 2. Identification of the target product, 3. Comprehensive Life Cycle Assessment of garments, 4. Formulation of a simplified LCA-based approach and reflecting on the experiences gained. Subsequently, the eco-centric theoretical perspective, which serves as an overarching ontological framework, is introduced. This leads to a discussion of the pragmatic research paradigm as an epistemological framing that seeks to unearth solutions to the research problems and questions. The first part of the chapter concludes with an analysis of the rationale for adopting an abductive approach, which supports mixed methods, a key component of pragmatism.

The second section ventures into an in-depth description of the chosen research methodology and methods. The rationale behind selecting the LCA methodology for evaluating the environmental impact of garments in this research endeavour is clarified. The four distinct phases of the LCA were examined, providing a comprehensive understanding of the research process. This chapter subsequently explores the specific research methods employed.

Primary data collection methods, including laboratory experimentation and survey methods, are discussed, highlighting a judicious selection process. Valuable insights into the secondary data collection method are provided, affirming the thoroughness of the research design. Notably, the selected ReCiPe methods for data analysis within the LCA study are closely examined, along with the use of the Monte Carlo Method for uncertainty analysis, further solidifying the methodological rigour of this research endeavour.

The final section of this chapter sheds light on the comparative and systematic analysis method, that aided the simplification of the LCA methodology and the subsequent formulation of the simplified LCA-based approach for fashion design. This innovative approach takes a different perspective on simplifying the LCA methodology, allowing for novel insights and potential advancements in the field of sustainable fashion design.

Section 1

Research Design

This section provides a comprehensive overview of the exploratory research design employed in this study. The choice of an exploratory research design is discussed, including the specific research process undertaken. This study embraced an ecocentric theoretical perspective that serves as the foundation for its environmental beliefs and values. The study utilised a pragmatic research approach, allowing for flexibility in selecting the research methodology and methods. A pragmatic framework allowed for the use of diverse methods through an abductive approach, aiming to identify the most effective strategies for addressing the research questions. Integrating these theoretical and philosophical perspectives, this study set out to explore and uncover practical solutions to the identified research problems.

3.1 The Exploratory Research Design

This study adopted an exploratory research design to understand the environmental impact of clothing in the context of New Zealand's fashion industry. The study aims to develop a simplified approach to using LCA specifically for practical implementation by fashion designers, allowing future research in the field of sustainable fashion design to build on the insights gained here. Chapter 2 focussed on exploring the environmental consequences associated with garment production and consumption, emphasising the importance of quantifying these impacts to implement effective mitigation strategies. Additionally, the chapter highlighted the obstacles hindering the widespread adoption of the scientifically validated and robust LCA methodology for assessing the life cycle impacts of products and processes in the fashion industry. To overcome the challenges identified in Chapter 2, the research approach discussed in this chapter was developed to closely examine and then streamline LCA, turning it into a practical tool that can be used in everyday fashion practices.

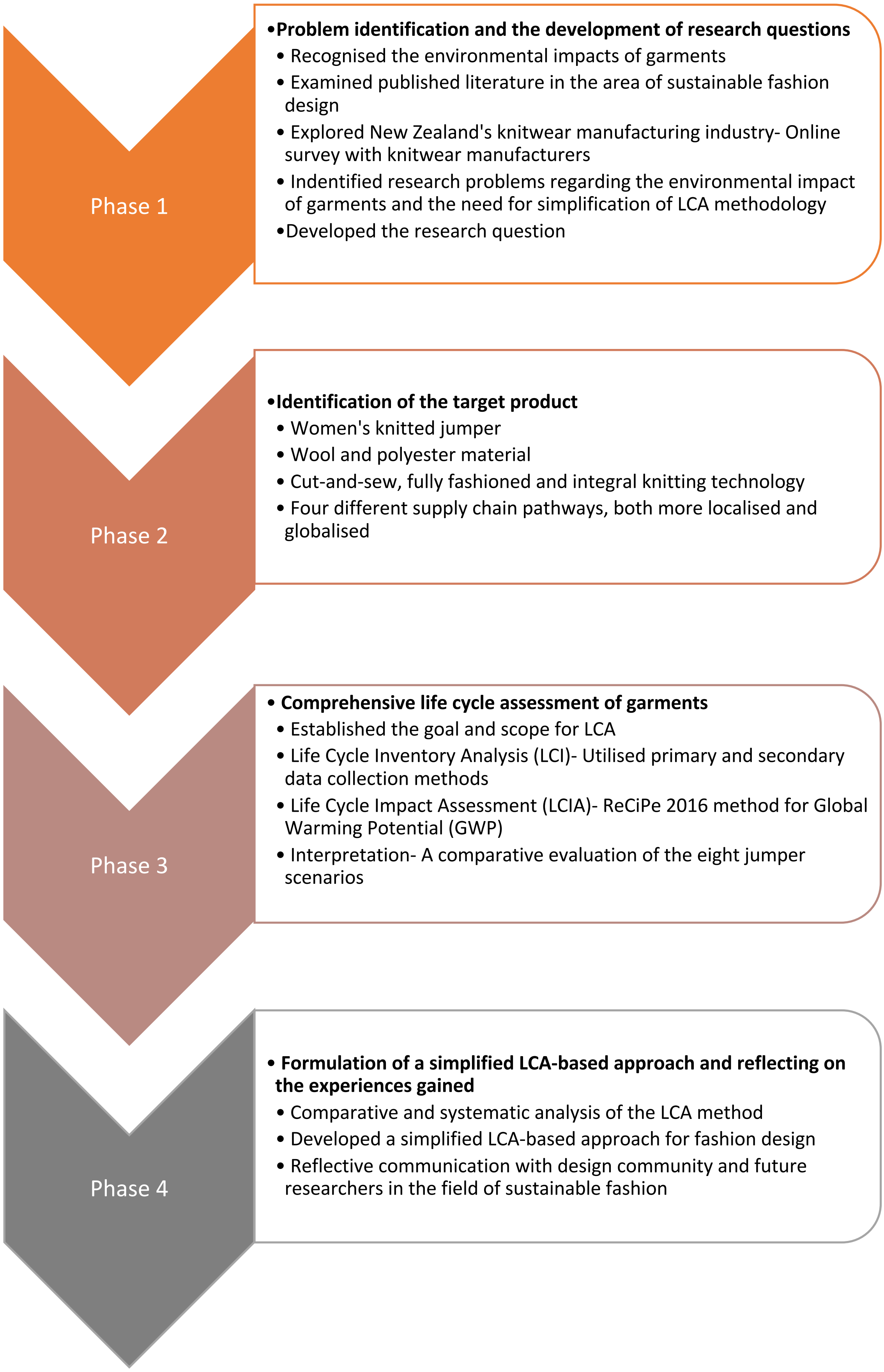
Exploratory research designs are particularly valuable when the subject area is novel or when limited prior knowledge exists on the topic (Babbie, 2020; Kumar, 2018). Such studies aim to enhance understanding, develop measurement instruments, and validate techniques (Kumar, 2018). The decision to employ an exploratory research design was based on numerous factors. First, the exploratory approach facilitates a comprehensive understanding of the research problem, allowing for a more profound and nuanced exploration of the phenomenon (Babbie, 2020; Creswell & Clark, 2011; Kothari, 2004). This can unearth previously unknown facts and insights. Furthermore, exploratory research provides researchers with a broader range of viable choices to address research objectives (Creswell & Clark, 2011; Kothari, 2004). Owing to their unstructured and adaptable nature, numerous qualitative and quantitative methods can be employed to gather research data, enabling researchers to discover potential solutions more effectively (Teddlie & Tashakkori, 2010). Exploratory research aids in the identification of new research problems and contributes to the creation of methods that can be used by future researchers in the field (Babbie, 2020; Kothari, 2004).

However, it is important to acknowledge the inherent limitations of exploratory research. The conclusions drawn from exploratory studies tend to be broad and general, and some may perceive the lack of explicit results as impractical. Furthermore, for exploratory research that relies primarily on qualitative data, interpretation may be susceptible to bias (Kothari, 2004). Nevertheless, these limitations were not of concern for the present study as it did not seek explicit qualitative results but a combination of qualitative and quantitative methods, leading to more robust research findings.

Considering the imperative need for a comprehensive understanding of the research problem and the limited availability of information on the New Zealand context, an exploratory research design was deemed the most appropriate for this study. The flexibility of the exploratory research design meant that different approaches could be used to explore the LCA methodology in-depth, and flexibility to employ different avenues of data collection. The subsequent subsection examines the specific process that was undertaken in conducting this research exploration.

Figure 12

The Research Process



3.1.1 Research Process

The research consisted of four distinct phases involving sequential steps. The sequential flow of activities and their interconnectedness are outlined in Figure 12, which presents the design of the exploratory research process.

Phase 1: Problem identification and development of research question

The initial stage of this research focused on exploring the environmental impacts related to the life cycle of garments as well as reviewing literature on sustainable fashion design. During this phase, a comprehensive understanding of New Zealand's knitwear manufacturing industry was acquired. The investigation also encompassed an exploration of the circumstances surrounding wool production and processing in New Zealand and the considerable imports of synthetic clothing. However, owing to the global impact of the COVID-19 pandemic during this stage of research, the information collection process had to be adapted. An online poll was used to collect industry-specific information instead of in-person interviews as originally planned. Questions about the effects of the pandemic on knitwear manufacturers in the country were also included in the survey.

The survey sought to comprehend the companies' supply networks, revenue-generating strategies, and the ramifications of the support the New Zealand government offered to businesses to help them survive amid lockdowns and other restrictions that were put in place during the pandemic. This was done to acquire a nuanced understanding of the present status of the knitwear industry, discern its trajectory, and gain valuable insights into the strategies employed by industry participants. Furthermore, this survey sought to serve as an initial exploration, aiming to assemble contemporary data and wisdom emanating from manufacturers' experience. The intent was to harness these insights to forge innovative solutions and unearth prospective opportunities for the sustained growth and resilience of the knitwear manufacturing sector in New Zealand.

An online survey was used to gain insights on the impact of the COVID-19 pandemic on knitwear manufacturers in New Zealand (see Appendix A for ethical approval, Appendix B for the copy of the survey questionnaire, and Appendix C for the survey results). The survey outcomes were published in the form of an article in the journal

Fashion Practice (Nautiyal et al., 2023a) (see Appendix D for a copy of the publishing). Based on insights gained from this research phase, the research problems were defined, and the main research question and three sub-questions were developed (see Chapter 1, section 1.4).

Phase 2: Identification of the target product

The decision which product to focus on was based on a systematic selection process that considered a wide range of garment types used in the fashion industry in New Zealand. The rationale behind selecting knitted jumpers as the specific garment type for this study is underpinned by the recognition that knitwear manufacturing is a substantial sector of New Zealand's economy (MBIE, 2018). In 2020, clothing and footwear manufacturing together constituted 2% ($ 0.6 billion) of the country’s manufacturing GDP (MBIE, 2020). Numerous small and medium-sized enterprises actively engage in garment manufacturing (Lewis et al., 2008; Smith, 2013). Knitted jumpers, as prominent products, frequently occupy dominant positions in fashion showrooms throughout the nation and are manufactured by a diverse array of small and medium-sized units within the country (Drought & Mellor, 2020; Gover, 2011).

Based on a field study conducted in July 2020, the prevalence of women's jumpers in New Zealand's fashion market is evident (Nautiyal, M., 2020. Unpublished report on women’s knitwear clothing in New Zealand). The survey encompassed nine garment stores, ranging from boutiques to fast fashion retailers, located in the New Market region of Auckland. The primary categories of women's knitwear observed included jumpers, cardigans, long dresses, tops, and lingerie items. Among these, knitted jumpers attracted considerable interest from fashion-conscious young women, warranting further analysis. To understand the variety of women’s jumpers available in New Zealand retail, data was collected and is summarized in Table 7.

Table 7

Women's Jumper Brand and Varieties Observed in New Zealand's Fashion Retail Market

Retail store	Brand names	Price range in NZD	Common material compositions	Place of manufacture
Farmers	Zest, North South Merino, Whistle, Mineral	$59.99 - $159.99	Cotton, Merino, Synthetic blends	China
Glassons	Own branded jumpers	$39.99 - $49.99	Acrylic, Polyester, Spandex blends	China
Max	Assorted knitwear brands	$84.99 - $199.99	Recycled Cashmere, Merino, Mohair blends	China
Kate Sylvester	Own branded jumpers	$205.00 - $389.00	Merino, Cotton, Nylon	NZ/China
Taylor	Own branded jumpers	$387.00 - $467.00	Mohair, Merino, Synthetic blends	China
Elle Riley	Own branded jumpers	$599.00 - $898.00	Cashmere, Possum, Silk blends	NZ/Nepal
Kowtow	Own branded jumpers	$399.00 - $649.00	Organic Cotton, Merino, Mohair blends	India
Trelise Cooper	Own branded jumpers	$399.00 - $499.00	Acrylic, Wool, Alpaca blends	NZ/China/India /etc.
Optimum	Own branded jumpers	$250.00 - $375.00	Baby Alpaca, Merino	NZ/Peru

Key observations from the field study:

- **Variety:** Jumpers are prevalent across all surveyed stores, indicating high market presence.
- **Price Range:** Prices vary significantly from affordable ($39.99) to high-end ($898.00), catering to a wide range of customers.
- **Material:** A mix of natural fibres (wool, merino, and cashmere) and synthetic blends (polyester, acrylic and nylon) is common.
- **Manufacture:** Most jumpers are manufactured in China; however, some are also made in other Asian countries and New Zealand.

These findings underscore the significant presence and variety of women's jumpers in New Zealand's fashion market spanning different price points and material compositions.

The deliberate focus on this particular garment type in this research endeavours to elucidate the distinct environmental implications of its production, particularly when employing various textile materials and knitwear manufacturing techniques. This emphasis facilitates a nuanced examination of the environmental impact associated with knitted jumper production, contributing to a more comprehensive understanding of the environmental dimensions of the knitwear industry.

New Zealand, the world's third-largest producer of wool, has a strong association with merino wool production (Baxter & Wear, 2022). It is worth noting that merino wool fibre used in garment production is locally produced (Mitchell et al., 2009). Synthetic garments present a substantial competitive challenge for the dominance of merino wool garments in New Zealand. The annual importation of over 13,000 tons of synthetic textiles in the country raises concerns regarding the negative environmental impact associated with their use and disposal (Jono, 2019, December 5). Synthetic materials, including polyester blends, have been shown to contribute to greenhouse gas emissions (Kirchain et al., 2015).

Moreover, this study acknowledges the potential differences in the environmental impacts between local and overseas manufacturing. Looking at the environmental consequences associated with garment production in Asia, a major garment production hub for New Zealand (Biswas, 2018), and the choices made by fashion designers in the country can be achieved by comparing local and overseas garment production scenarios. The profiling and information-gathering of the target product is presented in Table 8.

Table 8

Profiling the Information Gathered of the Target Product

Key location	New Zealand
Targeted market	Fast fashion clothing
Focus group /stakeholders	Fashion designers
Product type	Women's knitted jumper
Materials	1. Merino wool 2. Polyester
Garment manufacturing techniques	1. Cut-and-sew 2. Fully fashioned 3. Integral knitting
Supply chain scenarios	1. Locally manufactured in New Zealand for consumption in New Zealand 2. Manufactured in Asia for consumption in New Zealand
Environmental assessment method	Life cycle assessment (LCA) method based on ISO 14040/44
Environmental impact factor	Climate Change/ Global Warming Potential (GWP)

Phase 3: Comprehensive life cycle assessment of garments

To address the research questions and develop a simplified method for assessing the environmental impact of garments, this study involved a comprehensive LCA of knitted jumpers. These jumpers were assumed to be made in many alternative life cycle scenarios. The women's knitted jumpers considered two distinct textile materials, wool, and polyester; three different knitwear manufacturing technologies; cut-and-sew, fully fashioned, and integral knitting; and implementing local and offshore supply chain pathways. This resulted in eight different life cycle scenarios being modelled to evaluate their respective environmental impacts.

5. Woollen jumper made with cut-and-sew technology in New Zealand.
6. Woollen jumper made with fully fashioned technology in New Zealand.
7. Woollen jumper made with integral knitting technology in New Zealand.
8. Polyester jumper made with cut-and-sew technology in Bangladesh.
9. Polyester jumper made with fully fashioned technology in Bangladesh.
10. Polyester jumper made with integral knitting technology in Bangladesh.
11. Woollen jumper made with integral knitting technology in Bangladesh.
12. Polyester jumper made with integral knitting technology in New Zealand.

For the collection of information on fibre production, standardised datasets such as Ecoinvent were utilised, providing secondary data from established sources. Information regarding fibre pre-processing and dyeing was obtained from the published literature. However, owing to the absence of published information on the subsequent phases of the life cycle, namely garment manufacturing, the use, and end-of-life, primary data were acquired. Laboratory experiments were conducted to gather information on garment manufacturing, and a questionnaire survey was administered to residents of New Zealand to acquire information on the use and end-of-life phases of knitted jumpers. All the eight jumper scenarios were intended for consumption in New Zealand.

In this study, Global Warming Potential (GWP), a midpoint impact category and a shorthand indicator for climate change impact, was chosen for assessment. To provide characterization factors at midpoint levels, the ReCiPe egalitarian perspective (E) for a 1000 years' time horizon was considered (Goedkoop et al., 2009). The ReCiPe method is discussed more in detail later in this chapter, section 3.5.4. The ReCiPe method allowed for a comprehensive and reliable comparison of the climate change impacts associated with the eight jumper scenarios considered in this study.

Phase 4: Formulation of a simplified LCA-based approach and reflecting on the experiences gained

In the concluding phase of the study, the LCA results were examined and scrutinised to devise a practical approach for routine use by fashion designers. By integrating the insights gained from the comprehensive analysis of the eight jumper scenarios, a comparative and systematic analysis method was developed that simplifies the complexities of the LCA methodology. A simplified data table was created which informed the creation of a "Simplified LCA framework for Fashion Design," listing ten foundational processes for assessing the environmental impact of garments.

The simplified framework developed in this study facilitated objective evaluation and comparison of the environmental implications associated with various garment production choices. These ten processes in this framework serve as a blueprint for programming the envisioned tool, custom-tailored to the unique requirements of fashion designers. The tool aims to foster a more conscientious and environmentally responsible approach to fashion design by equipping designers with practical means to reckon, compare, and mitigate the environmental performance of their designs.

While the development and testing of a tool for simplified LCA was the initial aim of the research, the focus of the project shifted as the study delved deeper into the complexities of the LCA model and the challenges of accessing relevant data. As a result, the scope and focus of the study underwent a change. Rather than concentrating on creating a digital tool that could be utilised by fashion designers, the project became increasingly focused on knitwear and the development of a conceptual prototype. Developing and testing the tool with fashion designers will serve as the next stage of the project.

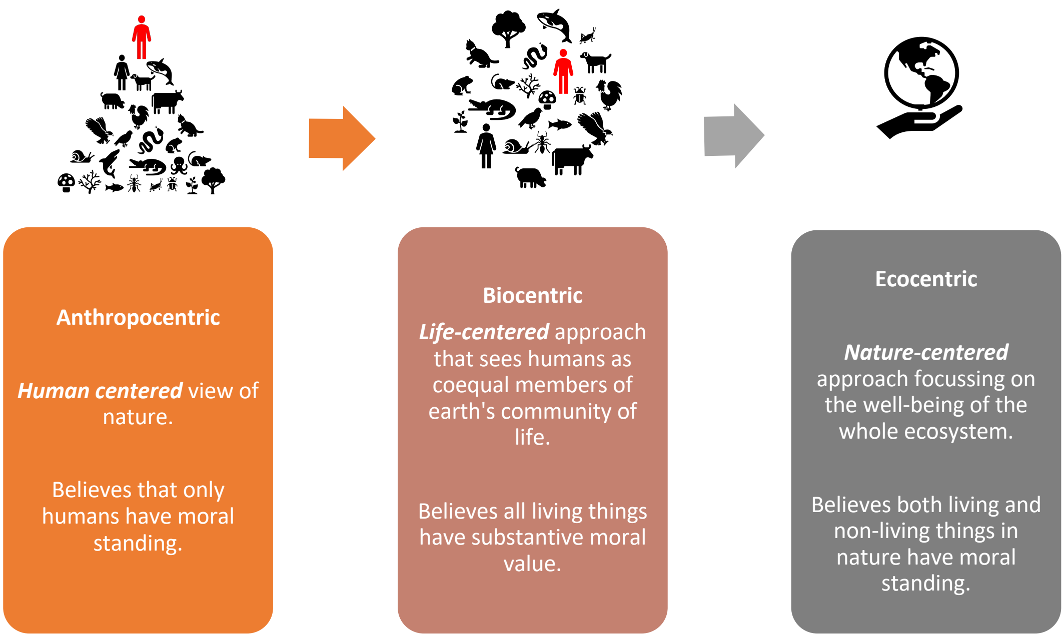
3.2 The Ecocentric Theoretical Perspective

This exploratory study was grounded in the ecocentric perspective of environmental psychology. The ecocentric approach recognises the intrinsic value of the environment and emphasises the interdependence of all living beings within it. It rejects anthropocentrism - a human centered view, and prioritises the well-being of the natural world (Taylor, 2003). Adopting an ecocentric perspective entails considering the long-term ecological implications of human actions and promoting harmonious coexistence with nature (Zimmerman et al., 1993).

Understanding the relationship between humans and nature is crucial for sustainability and sustainable development. Human ecology, a field of study that explores the interactions between humans and their environment, provides insights into the principles of sustainable development (Bubolz & Sontag, 2009). Ecology, derived from the Greek word "oikos," meaning "household," initially focused on studying the relationships between living organisms and their environments (McIntosh, 2016). Over time, human ecology has shifted from an anthropocentric (human-centered) perspective to biocentric (life-centered) and then to an ecocentric (nature-centered) viewpoint, that recognises the intrinsic value of nature and consider humans as interconnected elements within a larger living system (Bassham, 2020; Light & Rolston, 2007). An ecocentric perspective is based on the belief that both living and non-living things in nature have moral standing. Figure 13 displays the three prominent ecological perspectives, anthropocentrism, biocentrism and ecocentrism, along with their underlying moral convictions.

Figure 13

Ecological Perspectives and Their Underlying Moral Convictions



Note: Adapted from Taylor (2003)

In this study, motivation stems from an ecocentric philosophy that advocates a balanced ecological perspective. Prominent figures like Aldo Leopold have contributed to the development of ecocentrism with concepts such as "the land ethic," which emphasises moral obligations to the land itself and the need for human stewardship (Taylor, 2003). This perspective also resonates with Māori culture in New Zealand, where the principle of “kaitiakitanga” reflects the recognition of humans as integral parts of the natural order and highlights the importance of environmental guardianship (Royal, 2007).

The reciprocal relationship between humans and nature is fundamental to sustainable development, to meet current needs without compromising the well-being of future generations (Brundtland, 1987). While this research focuses on assessing the environmental impacts of garments, it acknowledges that these impacts extend to the entire ecological system, affecting both human life and the broader web of living and non-living entities. Consequently, effective solutions must be sought to mitigate the collective impacts on the environment. The adoption of LCA for measuring the environmental impact of garments aligns with the concept of ecocentrism and underscores its holistic methodology which looks at the cradle-to-grave environmental impacts associated with products and processes that is required to address sustainability challenges.

By embracing an ecocentric viewpoint, this study acknowledges the interconnectedness of ecological systems and the importance of preserving and protecting the environment for future generations. It recognises the significance of sustainable practices in the field of fashion design and aims to contribute to the exploration of environmentally conscious approaches to clothing production and consumption. The ecocentric theoretical perspective serves as the foundational framework within the pragmatic research paradigm that shapes the epistemological orientation of this study. Pragmatism also facilitates the integration of mixed-methods approaches, thereby allowing the combination of different elements of investigation in a systematic and harmonious manner, making it easier to conduct research and draw meaningful conclusions.

3.3 The Pragmatic Research Paradigm

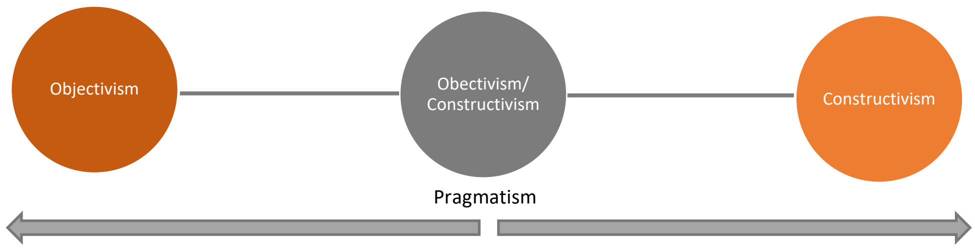
In the realm of research, it is paramount for researchers to explicitly articulate their philosophical stance, as it forms the bedrock of their understanding of the world and shapes their decision-making processes. Philosophy, with its inquiries into profound questions regarding meaning, value, and the nature of reality, extends beyond the confines of scientific inquiry and sensory observation (Bassham, 2020). Each researcher harbours a unique philosophical stance that encompasses personal interpretations and influences their perspectives and actions (Cohen et al., 2017). Consequently, researchers must conscientiously acknowledge and communicate the facts, ideas, beliefs, and assumptions that underpin their research endeavours (Jonker & Pennink, 2010).

Against the backdrop of an ecocentric theoretical perspective and a deep-seated recognition of the urgency to instigate change for the sustainability of the entire ecosystem, the present study was founded upon a pragmatic strategy chosen to enhance its practicality and flexibility. Pragmatism seeks to find better ways of providing answers to research questions (Amolo et al., 2018). It is particularly useful for studies that explore new territories and do not have established data collection methods (Saunders et al., 2019), which is the case for this study. Therefore, the adoption of a pragmatic research approach was followed in selecting suitable methods and techniques for finding answers to the complex research questions considered in this study.

Pragmatism, as a research paradigm, offers a practical and adaptable approach to research by harmoniously blending the insights of objectivism and constructivism (Figure 14). Traditionally, these two theoretical philosophies have embodied opposing views on reality and the process by which knowledge is constructed (Bell et al., 2022; Crotty, 2015). Objectivism, rooted in the conviction that realities can be observed and scientifically tested, concentrates on discerning relationships, patterns, and logical explanations (Pring, 2004). It postulates that social phenomena exist independent of social actors. Conversely, constructivism posits that social phenomena and their meanings are not fixed but continually revised and shaped by social actors (Bell et al., 2022). Constructivism recognises the role of individuals in ascribing meaning to social phenomena and emphasises the contingent nature of reality (Cohen et al., 2017).

Figure 14

The Ontological Placement of Pragmatism



Source: Adapted from Crotty (2015)

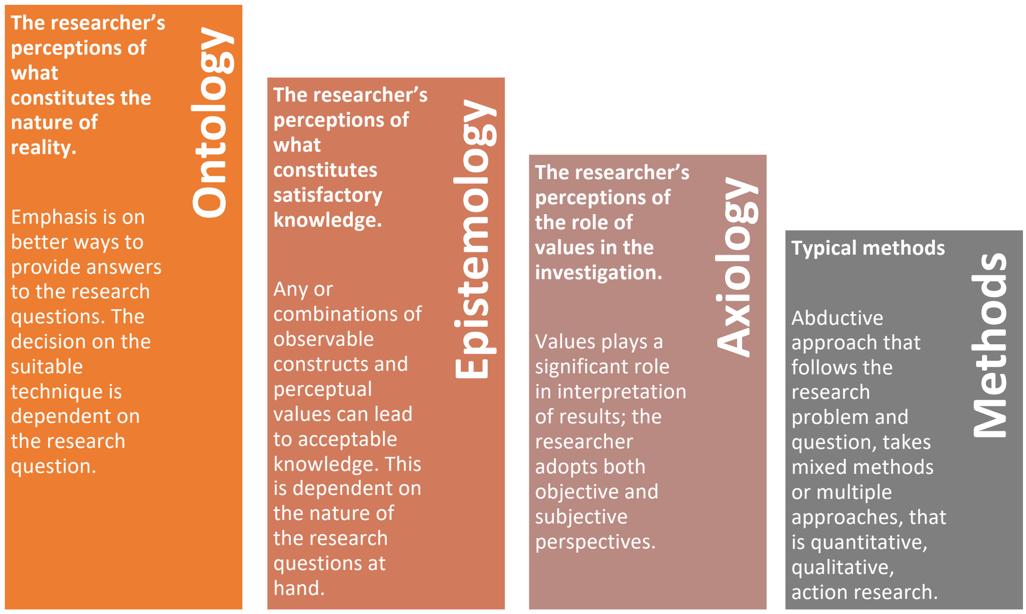
Given the philosophical tensions between objectivism and constructivism, researchers embrace the pragmatic paradigm as it transcends this binary opposition. Pragmatism consciously rejects the notion of a singular "reality" or "truth" and instead concentrates on determining "what works" in addressing research questions (Teddlie

& Tashakkori, 2010). This perspective allows for the amalgamation of different philosophical assumptions required to effectively solve a problem (Crotty, 2015; Morgan, 2013).

The roots of pragmatism can be traced back to eminent American philosophers, such as Charles Pierce, William James, Josiah Royce, John Dewey, and George Herbert, who sought to derive purpose in life through the application of science and philosophy (Katz & Light, 2013). Their contributions extend beyond the realm of philosophy and profoundly influence various domains, including social, political, and educational advancements (Wakkary, 2009). Figure 15 illustrates the ontology, epistemology, axiology, and the methods that support the pragmatic research paradigm.

Figure 15

The Pragmatic Research Paradigm



Note: Adapted from Saunders et al. (2019)

This pragmatic research paradigm confers several advantages to research endeavours. It endows researchers with the freedom to select from a diverse array of methods and methodologies, thereby fostering flexibility in addressing research problems (Greene & Caracelli, 1997). It draws upon the complementary insights of both objectivism and constructivism while recognising their limitations, thereby striving to achieve a more comprehensive understanding of research topics (Tolich & Davidson, 2011). It integrates facts, values, accurate information, and contextualised experiences and considers them valuable tools for thought and action in specific situations (Saunders et al., 2019). Researchers can employ multiple methods and seamlessly integrate quantitative and qualitative data, enabling a more holistic comprehension of the subject matter (Saunders et al., 2019).

However, this pragmatic research paradigm has inherent limitations. Its reliance on a flexible and outcome-driven research strategy, as opposed to a predefined strategy, can potentially extend the research timeline, as the formulation of procedures and methodologies is contingent upon the findings of previous investigations (Saunders et al., 2019). This may pose challenges to achieving swift research completion. Nonetheless, given the novel and exploratory nature of this study within the research domain, a heightened demand for adaptability in the pursuit of innovative solutions warrants the adoption of the pragmatic approach as the most appropriate choice.

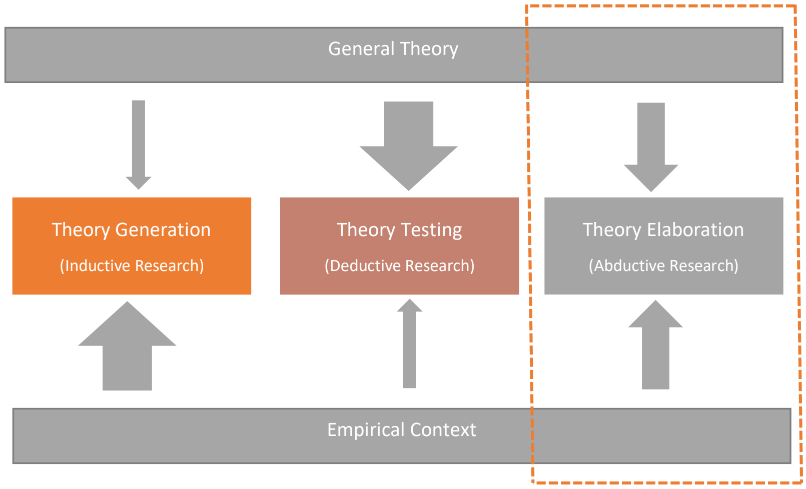
Thus, pragmatism serves as a valuable philosophical framework to navigate the complexities of a research problem, empowering researchers to adapt and refine their methods as needed, contributing to a more nuanced understanding of the subject matter at hand. By embracing a pragmatic research paradigm, this study aims to amalgamate disparate perspectives and approaches, thereby enhancing the practical and comprehensive nature of its investigation. It endeavours to bridge the gap between ecocentrism and fashion practice, offering relevant and valuable insights to address real-life challenges in the field of sustainable fashion design.

3.3.1 Abductive Approach: Mixed Methods

This study adopted an exploratory research design to first comprehend the environmental impacts associated with garments and consequently develop a simplified LCA-based approach for evaluating them. Saunders et al. (2019) explained three approaches to finding answers to research questions and theory development: inductive, deductive, and abductive. As noted by Ketokivi and Choi (2014), these approaches correspond to the dynamic interplay between theory and practice, as shown in Figure 16. The three dimensions outlined therein encompass theory generation, characterised by inductive research; theory testing, exemplified by deductive research; and theory elaboration, typifying abductive research. This study adopted an abductive research approach, signifying a methodological orientation that combines elements of induction and deduction to facilitate a nuanced exploration of the research question.

Figure 16

Three Approaches in Research



Note: Adapted from Ketokivi and Choi (2014) and Costa et al. (2017)

The utilisation of an abductive approach underpinned by the pragmatic paradigm holds considerable significance within this study as it facilitates the exploration of unanticipated complexities and the discovery of novel insights. By integrating deductive and inductive reasoning, this approach enables the interpretation, recontextualization, and integration of diverse knowledge sources (Bell et al., 2022; Kovács & Spens, 2005; Taylor, 2003). Given the multifaceted nature of the research problems addressed in this study, involving the inter-relationships of environmental sustainability, fashion practice, and assessment of impacts, the abductive approach offered the freedom to select from various available methods.

The abductive approach aligns with a pragmatic perspective, granting researchers the flexibility to select methods based on their suitability for investigating specific research problems (Crotty, 2015; Johnson et al., 2016). Researchers can employ multiple approaches within a single investigation, delve deeper into datasets to enhance understanding, or use just one methodology to validate findings (Onwuegbuzie & Leech, 2005).

The LCA methodology also lends itself to the application of mixed methods. The evaluation of the environmental impacts of clothing items through LCA necessitates both quantitative research outcomes and subjective value settings (Scholz & Tietje, 2002). Uncertainties, which are often challenging to measure quantitatively, are frequently explored qualitatively (Sandin et al., 2019a). Notably, an analysis of methodologies employed in studies examining the environmental impact of garments reveals that the majority have employed mixed methods (Beton et al., 2014; Roos, Sandin, et al., 2015; Sandin et al., 2019a). Besides, the uncertainty regarding the methods to be employed for simplifying the LCA methodology, the flexibility offered by the mixed methods approach proved to be highly advantageous. Thus, the use of mixed methods, empowered the exploration of knowledge gaps, the development of practical solutions, and the integration of multiple perspectives in this study.

However, it is essential to acknowledge that the abductive approach holds certain inherent biases, the most significant one being the potential lack of reliability and validity of the research findings (Danermark et al., 2005). Nonetheless, such limitations can be mitigated by transparently reporting the research procedures and acknowledging the inherent limitations of this study.

The pursuit of developing a simplified LCA-based approach for everyday use in fashion design operations aligns with pragmatic epistemology by prioritising practical and actionable knowledge. Pragmatic epistemology emphasises the value of knowledge that is grounded in real-world applications and problem-solving, making it well suited for the goal of providing fashion designers with a user-friendly tool to assess the environmental impact of garments in their practical design work. Consequently, this study embraces a pragmatic research paradigm, aiming to bridge the gap between ecocentric theory for sustainable development and the realities of fashion practice.

Section 2

Research Methodology and Methods

This section expounds on the research methodology employed and describes the specific methods used. Commencing with a comprehensive explanation of the LCA methodology, it explores the execution of the four distinct phases of LCA. The subsequent subsections provide an in-depth analysis of the research methods, encompassing a comprehensive elucidation of data collection, impact assessment and uncertainty analysis methods applied within the LCA methodology. It then justifies the use of the comparative and systematic analysis method applied in simplifying the LCA methodology.

3.4 The LCA Methodology for Assessing the Environmental Impacts

LCA has emerged as a significant approach for evaluating the environmental performance of goods and services. LCA offers several advantages, including its capability to identify the most environmentally impactful aspects of a product and to facilitate targeted mitigation strategies. It supports informed decision-making, assists in product claims and labelling, and provides guidance for strategic planning and design. Chapter 2, Section 2.4, emphasised that LCA is a methodology that is recognised and used by several international organisations, research frameworks, regulations, and sustainability initiatives (Glavič & Lukman, 2007; Hertwich, 2005; ISO 14040, 2006; Laurenti et al., 2014; United Nation's SDG, 2015).

LCA involves the comprehensive compilation, evaluation, and assessment of a product's inputs, outputs, and any other relevant environmental impacts across its entire life cycle, encompassing stages from raw material extraction to end-of-life disposal or recycling. This thorough assessment accounts for resource consumption and emissions throughout the product life cycle (ISO 14040, 2006; Manfredi et al., 2012). A comprehensive examination of the garment supply chain and the considerations regarding inputs and outputs for their environmental impacts have been discussed in Chapter 2, Section 2.5.4 of this thesis.

In the context of this study, the adoption of LCA proved pivotal in appraising the GWP associated with the cradle-to-grave life cycle analysis of knitted jumpers consumed in New Zealand. This feature was facilitated by the utilisation of sophisticated computerised tools such as SimaPro and databases such as Ecoinvent, which played a pivotal role in successfully executing the LCA methodology. In Chapter 2, Section 2.4.1 , we discussed the four interconnected phases of the LCA methodology. The subsequent subsections 3.4.1 to 3.4.4 describe each of these LCA phases, in context to this study.

3.4.1 Phase 1: Goal and Scope Definition

The initial step in conducting an LCA involves a comprehensive process of goal and scope definition, which entails identifying the subject of analysis, specifying the purpose of the assessment, and determining the intended application of the results (ISO 14040, 2006). This crucial phase also encompasses defining the system boundaries, establishing the functional unit, selecting impact categories, and specifying the desired level of analysis detail (Finnveden et al., 2009; Rebitzer et al., 2004).

For this study, the goal and scope of this LCA study were first outlined to assess and compare the overall environmental impact of knitted jumpers made using two distinct materials- wool and a polyester. The assessment considered various knitting techniques- cut-and-sew, fully fashioned, and integral knitting, within specific supply chain pathways in New Zealand. The primary target audience for this study comprises fashion designers who possess limited familiarity with LCA methodologies but seek simplified approaches to evaluate and compare of the environmental implications of their designs.

Functional unit

The functional unit was defined as one jumper intended for lifetime use, weighing 385 g upon and featuring a black colour (Pantone 19-1619 TPX). Accessories or labels were excluded from the scope of the analysis.

System boundary

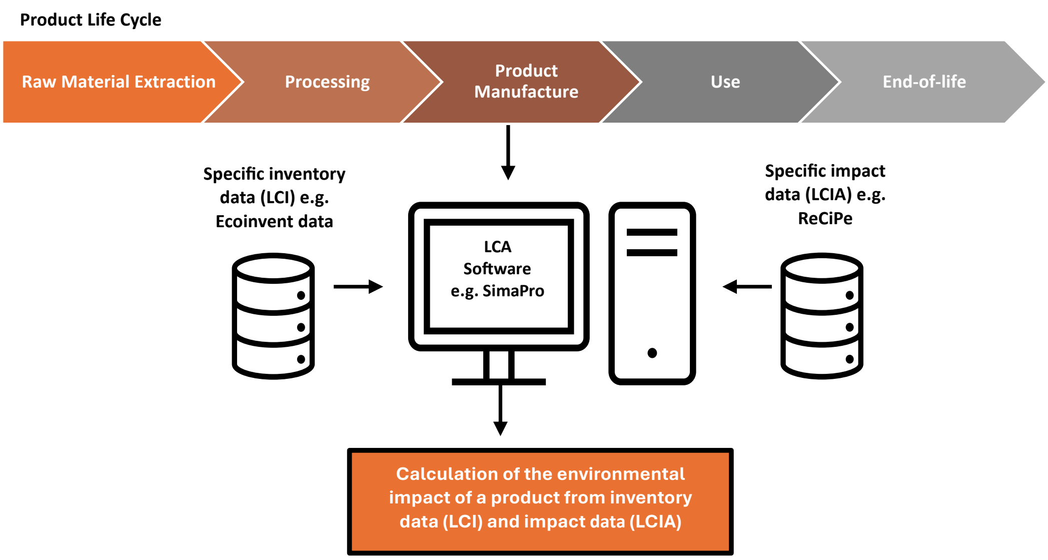
The system boundary for this study was comprehensively defined as a cradle-to-grave boundary, encompassing the entire life cycle of the garments from raw material extraction to the final disposal, including end-of-life considerations. A comprehensive elucidation of the goal and scope of this study is presented in Chapter 5, Section 5.2 of this thesis.

3.4.2 Phase 2: Life Cycle Inventory Analysis

The phase of Life Cycle Inventory Analysis (LCI) involves the meticulous development of a comprehensive inventory that encompasses crucial inflows (such as energy, water, materials, and land area) and outflows (including emissions and waste) for each process within the life cycle of the product (Finnveden et al., 2009; Ramani et al., 2010). The LCI model can be developed using data from specific processes inventoried for the study or generic data from LCI databases such as the Ecoinvent, IDEMAT or GaBi that contain pre-made LCI data for various processes (Roos, 2016). These databases include information on the use of inputs in production. The Ecoinvent database that features more than 20,000 datasets, crucial for doing comprehensive LCA was chosen for modelling inventory in this study (Ecoinvent Website, 2024). This study employed SimaPro software for comprehensive LCA on knitted jumpers in eight life cycle scenarios. The connection between LCI and LCIA database, the Ecoinvent and the ReCiPe respectively, in SimaPro software are illustrated in Figure 17.

Figure 17

Overview of LCI and LCIA in Comprehensive LCA using SimaPro Software



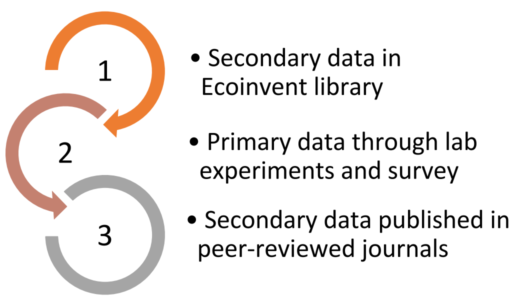
Note: Adapted from Roos (2016)

In this study, LCI modelling, and impact assessment was conducted using SimaPro 9.0, developed by PRé Consultants and employing the Ecoinvent v.3 database. SimaPro provided the necessary capabilities for performing comprehensive calculations related to the global warming implications of the jumper's life cycle. The software's ability to model and analyse complex life cycles systematically and transparently was particularly useful for this study. It allowed for the measurement of the environmental impact of the jumpers across all life cycle stages and the identification of hotspots in the supply chain, from raw material extraction to use and disposal. The software also offered an uncertainty assessment through the Monte Carlo analysis, employing one thousand iterations to provide a 95% confidence interval for the results. This study presented results using the mean, allowing for a comprehensive understanding of the GWP of jumpers in the eight life cycle scenarios identified (Goedkoop et al., 2016).

For the foreground inventory data in this study, a combination of primary and secondary data collection methods was employed. The choice between primary and secondary methods depends on the specific data requirements and quality standards of any study (Wolf et al., 2010). This research encountered several challenges owing to the disruptive impact of the COVID-19 pandemic, which hindered the comprehensive acquisition of primary data for all life cycle phases of the jumper scenarios examined. Therefore, the utilisation of primary or secondary data collection in this study was influenced by the availability of resources. However, the inclusion of data for modelling the inventory at each life cycle stage played a pivotal role in influencing the outcomes of this study and is discussed in detail in Chapter 4. The hierarchy applied in sourcing foreground inventory for LCA is depicted in Figure 18.

Figure 18

The Hierarchy Applied in Sourcing Foreground inventory data



Given the study's objective to develop a simplified approach of the LCA methodology tailored specifically for fashion designers, the hierarchy applied for sourcing inventory data in the current study followed these steps:

1. The Ecoinvent database holds the highest priority as a globally standardised and reliable source of secondary data (de Souza et al., 2021). It serves as the fundamental basis for the intended simplified LCA framework, with the understanding that the database undergoes regular updates, ensuring the accuracy and relevance of the proposed simplified methodology (Frischknecht et al., 2005).
2. The second technique for modelling the inventory involved laboratory experiments and surveys to gather primary data when adequate data from the Ecoinvent database were unavailable.
3. Considering that the study was conducted during the restrictive period of the COVID-19 pandemic, when gathering primary data proved challenging, secondary literature from peer-reviewed journals, which had previously been applied in similar studies and underwent rigorous review processes, was employed as a reliable inventory data source.

The Ecoinvent v.3 library datasets provided data on the production of both polyester and woollen fibres, making them applicable to this LCA investigation (Wernet et al., 2016). Secondary data from peer-reviewed, published sources were collected pertaining to the pre-processing of wool fibres (Wiedemann et al., 2019) as well as the dyeing processes for both wool and polyester fibres (Rosa et al., 2019). For garment manufacturing, data were primarily obtained through laboratory experiments conducted on the three most prevalent knitwear manufacturing techniques. The details of the laboratory experiment method employed for data collection are given in subsection 3.5.1.

The study also examined four distinct transportation scenarios, referred to as supply chain pathways, based on the routes taken by raw materials from production to retail of the finished product. The inventory for both road and sea transportation were sourced from the Ecoinvent v.3 database and subsequently used to model the four supply chain pathways (Wernet et al., 2016). Packaging was accounted for separately within each of the four transportation pathways and the inventory for packaging was based on assumptions gathered from speaking with merchandisers in the industry.

To address the use and end-of-life phases of the jumpers, an extensive survey was conducted to gather information on wool and synthetic blend jumper consumption in New Zealand, including laundry practices, garment lifespan, and end-of-life scenarios. More details about the survey method for the use and end-of-life phases are provided in subsection 3.5.2. Thus, to gather data for LCA analysis and address the research questions, a combination of primary and secondary data collection methods was employed.

3.4.3 Phase 3: Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) phase served to establish a link between the inventory data generated in the LCI and potential environmental damage. It involves translating the inputs and outputs of elementary flows collected and reported in the inventory into impact indicator results related to human health, natural environment, and resource depletion (EU-JRC, 2010). The LCIA model can be constructed using pre-made LCIA packages such as the IMPACT 2000+, USAE tox, and ReCiPe that contain data on various emissions and resources (see Figure 17). It can also be developed with specific impact data from the study by employing an impact assessment method to create new characterization factors, although this is rarely done (Roos, 2016). The ReCiPe method was chosen for this study owing to its extensive use for assessment in the field of fashion and textiles (Beton et al., 2014; Manda et al., 2015; Roos, Posner, et al., 2015; Roos, Sandin, et al., 2015). This study examined climate change as a midpoint impact category, specifically referring to it as the Global Warming Potential (GWP). GWP is a widely recognized metric used to quantify the impact of various greenhouse gases on global warming, expressed in kilograms of CO_2 equivalents (kg CO_2 eq.).

3.4.4 Phase 4: Interpretation

The interpretation phase of the LCA plays a vital role in deriving meaningful insights and drawing conclusions from the results obtained for both LCI and LCIA. It involves not only summarising and discussing the outcomes of the assessment but also evaluating the level of confidence in the findings (ISO 14040, 2006). In this study, the

LCA results were interpreted by comparing the environmental impact of jumpers across eight different life cycle scenarios. To account for data uncertainty in the LCA results, the Monte Carlo method was employed.

The study focused on eight jumper scenarios, assessing the impacts associated with various stages of their life cycles, including fibre production, wet-processing and dyeing, garment manufacturing, transportation and packaging, lifetime use, and end-of-life considerations. Each scenario was evaluated based on its anticipated lifetime, with woollen jumper scenarios expected to have a 237 wears per lifetime, and polyester jumper scenarios expected to have a lifetime of 171 wears per lifetime (Nautiyal et al., 2023b). By considering the cradle-to-grave life cycle of jumpers, this study provides a comprehensive assessment of their environmental impacts.

Furthermore, the study examined the potential benefits of reusing and downcycling jumpers to quantify the advantages associated with circular economy principles in sustainable fashion design. By analysing the avoided impacts through circular economy practices, this study highlighted the potential for reducing environmental burdens and promoting more sustainable consumption and production patterns in the fashion industry. However, recycling material was not considered due to its absence in New Zealand (Casey & Brian, 2021; Cleveland, 2018).

In addition to considering the life cycle impacts, this study also examined the impacts associated with care for each wear of the jumper. By assessing the per-wear impacts, this study aimed to quantify the reduction in environmental burdens achieved when garments were used for a longer duration. This analysis aligns with the principles of longevity and durability in sustainable fashion design, emphasising the importance of extending the lifespan of garments to minimise their overall environmental footprint.

The interpretation of the LCA results, presented in Chapter 5, encompassed a comprehensive analysis of the environmental consequences, circular economic benefits, and per-wear impacts of the jumper scenarios. By examining these various dimensions, this study provides valuable insights into the environmental performance of different life cycle scenarios, enabling others to engage in a more informed decision-making and offering guidance for the development of sustainable fashion practices.

3.5 Research Methods

The present study employed a mixed-methods approach, and this section elucidates the specific methods. First, a comprehensive explanation is provided of the methods employed for collecting primary data, including laboratory experimentation and survey methods, as well as the collection of secondary data for the LCI. Subsequently, a detailed discussion on the ReCiPe (2016) and Monte Carlo methods employed in LCIA is presented. Transitioning from LCA, this section examines the methods employed to simplify it. The comparative and systematic analysis method is explained, highlighting its pivotal role in achieving the research aim to develop a simplified LCA-based tool tailored specifically for fashion designers.

3.5.1 Laboratory Experiment for Garment Manufacturing Inventory

The primary data collection method employed for obtaining the inventory regarding garment manufacturing in the three flatbed knitwear manufacturing scenarios involved conducting laboratory experiments. These experiments aimed to evaluate the environmental impact of varied garment manufacturing techniques that are commonly used in the knitwear industry. By constructing jumpers and measuring the inventory utilised in a controlled setting, precise and consistent observation and measurement methods could be employed that allowed for the close control of variables and the isolation of random influences (Denscombe, 2017). The Textile Design Lab (TDL) at the Auckland University of Technology provided the necessary experimental space for this work.

Garment manufacturing is a critical stage that involves numerous factors including the manufacturer, machine efficiency, product design, and fabric type (Peterson & Ekwall, 2007; Rahman & Haque, 2016). Three variations of a jumper were created using cut-and-sew, fully fashioned, and integral knitwear manufacturing techniques. The physical features of the jumpers, such as yarn quality, garment size and style, knit pattern, and needle gauge were consistent across all three construction methods. Table 9 presents the manufacturing details for the three knitwear construction techniques. The process involved using CAD software to develop the designs and create multiple samples for each knitwear construction method. The size specifications for ready jumpers in all three styles are presented in Figure 19.

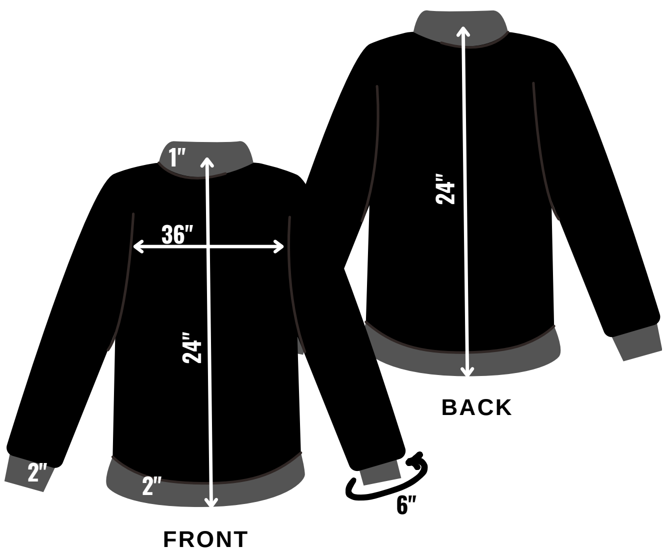
Table 9

Manufacturing Details for the Three Flatbed Knitting Techniques

Details	Cut-and-sew, Fully Fashioned and Integral Knitting Techniques
Yarn quality	1. Merino wool 2. Polyester
Yarn diameter	28/2 Nm
Knitting machine	Shima Seiki Wholegarment ®
Needle Gauge	Half gauge
Number of Ends	2
Style	Round neck, full sleeves
Knit pattern for bodice	Rib stitch
Knit pattern for collar, waistband and wristband	1 X 1 Rib stitch
Knit pattern for bodice and sleeves	2 X 2 Rib stitch
Garment size	New Zealand Size- 14 (Medium)

Figure 19

Size Specifications for Garment Manufacturing



During laboratory experiments, the electrical energy used to construct each garment was recorded along with the waste generated in the process. The power consumption of the machines was calculated using the following formula:

Power of a Machine (Watts) = I(Ampere) × V(Volts)

Where, I is the current in amperes and V is the voltage

To determine the total energy consumed, the power of the machine is multiplied by the duration of its use. The formula for energy consumption is as follows:

Energy Consumed (Watthours, Wh) = Power of a Machine (Watts) × Time of use (hours)

This approach allowed for precise calculation of the electrical energy required to produce each garment, providing a detailed insight into the energy efficiency and sustainability of the manufacturing process. The averages for each manufacturing technique were consequently calculated. The inventory data collected for garment manufacturing are reported in Chapter 4, section 4.4. where detailed information on the quantities of materials and energy used as well as the emissions and waste generated during the various stages of manufacturing are provided. The experimental findings contribute to LCI for garment manufacturing, enabling the assessment of the environmental impacts associated with this process.

The selection of laboratory experiments as the primary data collection method was advantageous for this study because of the limited availability of information on the three knitwear manufacturing techniques in existing literature (Beton et al., 2014). Conducting experimental sampling using the three techniques provided the specific inventory required for LCA. Moreover, gathering comparable data from fields such as garment manufacturing factories would not have provided precise statistics.

To address concerns about the representativeness of laboratory conditions compared with real-world scenarios, the project employed the same knitting equipment and CAD programming employed by knitwear manufacturers globally. Knitwear panels were produced using Shima Seiki knitting machines, which are widely utilised across the industry (Ramsay, 2013), and garment stitching was done with Juki machines, which are also commonly used in garment factories worldwide (Sarkar et al., 2023). Garment panels were joined during the fully fashioned construction process using overlocking machines typically used in industrial settings. The finishing applied to the garments matched the practices employed in factories, further minimising discrepancies between the laboratory and real-world conditions.

3.5.2 Survey for Inventory on Garment Use and End-of-Life

This study identified the importance of considering the use and end-of-life disposal phases in the garment life cycle to achieve better estimations of consumer practices and accurately assess the cradle-to-grave environmental impact of knitted garments. However, there is a dearth of information on the use and disposal habits of knitted clothing, particularly in the context of New Zealand. Therefore, a nationwide online survey titled ‘A Consumer Survey on Woollen and Synthetic Knitted Jumpers’ was conducted. Although similar surveys have been conducted in other countries, none were found in New Zealand (Daystar et al., 2019; Laitala et al., 2018).

The survey method was employed as the primary data collection approach to gather information on jumpers in New Zealand. Online surveys were preferred because of their higher response rates and ability to reach niche groups, thereby expanding the survey's reach (Van Selm & Jankowski, 2006). Web-based questionnaire platforms were chosen because of their user-friendly nature, cost-effectiveness, and accessibility, which have contributed to their popularity in research (Denscombe, 2017; Dillman et al., 2014). Consequently, a survey questionnaire was deemed appropriate for collecting data on washing, wearing, and disposing of knitted garments from each respondent, offering ease of participation, and data analysis (Denscombe, 2017; Hoxley, 2008).

It is important to acknowledge the limitations of online surveys. One significant limitation is the potential for non-response bias, as individuals without internet access have been excluded. However, this bias was mitigated by New Zealand's high internet penetration rate (Hughes, 2023, January 3). The survey was geographically distributed to cover both urban and rural areas, ensuring representation across the country. Although many respondents were women, this gender bias has been considered to have minimal impact on the study's aim, as it may be attributed to factors such as women's higher involvement in laundry practices or their greater comfort in responding to laundry-related questions.

Survey Design

Questionnaires are considered the most suitable method for gathering research data for quantitative analysis (Creswell, 2018). In this survey, 30 closed-ended questions were asked, with the initial 10 questions focussing on the demographic information of the participants. The remaining 20 questions were divided equally between woollen and synthetic blend jumpers, to enquire about their laundry practices, lifetime wears and disposal methods. Participants who washed both wool and synthetic jumpers in the same manner, were presented with an alternative set of questions on laundry practices.

Ethical Consideration

Ethical considerations were carefully addressed throughout all stages of the study. To ensure adherence to ethical principles, an ethics application was submitted to AUTEC, which was subsequently approved and updated by the committee on the 8th of December 2021 (see Appendix E). The ethics application encompassed comprehensive information about the research objectives, the rationale behind conducting the study, procedures of data collection, and the process of obtaining participants' information and consent before they participated in the survey. To maintain confidentiality and fulfil the responsibility of safeguarding identifiable information, the survey was designed to be anonymous. Participants were duly informed about the voluntary nature of their involvement in the research and granted the right to withdraw from the survey at any given point. All the details were meticulously incorporated into the participants’ information sheet which along with the survey questionnaire can be found in Appendix F. The results of the survey are included in Appendix G and Appendix H presents the survey outcomes in the form of a published paper: “Examining practices of garment use and end-of-life in New Zealand,” in the journal Sustainability (Nautiyal et al., 2023b).

Questionnaire Distribution

The survey was conducted anonymously, and the online distribution of the questionnaire took place from December 10, 2021, to January 31, 2022. The survey was administered through the Qualtrics software program, chosen for its user-friendliness and widespread usage among researchers (Barnhoorn et al., 2015; Miller et al., 2020). Sample size calculations were based on a confidence level of 95% and a margin of error of +/-3%, considering New Zealand's population of five million in 2019 (StatsNZ, 2020). The optimal sample size was determined according to the calculation depicted in Table 10 (Qualtrics, 2020).

Table 10

Calculating the Required Sample Size for New Zealand's 5 million Population in 2019

Required Sample Size = $\frac{(\text{Z-score})^2 \times \text{Standard Deviation} \times (1 - \text{Standard Deviation})}{(\text{margin of error})^2}$	
Where, Z score for 95%= 1.96; Standard Deviation= 0.5; Margin of error= 0.03)	
Hence, the required sample size	= $(1.96)^2$ X (0.5) X (1-0.5) / $(0.03)^2$
	= 1066.66
	= 1067 respondents were required

Note: Sourced from (Nautiyal et al., 2023b)

The questionnaire was distributed across popular social media platforms through personal networks, such as Facebook, LinkedIn, and Neighbourly, with invitations extended to interested individuals. Social groups with demonstrated awareness of fashion and textiles were specifically targeted. This selection criterion was essential because the survey required participants to discern differences between natural clothing materials such as woollen jumpers and synthetic blend jumpers. Therefore, targeting these knowledgeable social groups ensured that participants had the requisite understanding to provide informed responses. Various communities, including knitting circles, Weavers of New Zealand, Spinning and Art Yarn Communities, Upcycled Clothing and Creations, New Zealand Women's Discussion Group, Buy and Sell Clothing, Off-Grid Living, as well as neighbourly communities in Auckland such as the Blockhouse Bay, Avondale, Sandringham, Lynnfield, New Lynn, and university student groups, were contacted to encourage participation. A total 1097 participants took up the survey and their data was retrieved and analysed.

Data Retrieval

The Qualtrics tool facilitated the retrieval of the survey data from each completed questionnaire. Additionally, graphs and charts were generated based on the survey data to analyse the variations between the two types of jumpers in terms of laundry practices, longevity, and end-of-life practices. Arithmetic means were calculated based on earlier studies conducted by Wiedemann et al. (2020) in the UK and Germany as well as on other significant studies in the field reported by Laitala et al. (2017).

The inventory data collected through the survey method are reported in Chapter 4, sections 4.6 and 4.7, which specifically address the inventory for the use and end-of-life of jumpers. The survey has provided valuable insight into consumer practices and behaviours related to garment wear and care, contributing to a comprehensive understanding of their environmental implications.

3.5.3 Secondary Data Collection Method

The collection of inventory data using secondary sources such as the Ecoinvent database and published literature is a crucial component of this study. To ensure a robust theoretical foundation and align the research with existing knowledge and best practices, a comprehensive review of the relevant literature, academic research papers, industry reports, and other pertinent publications was conducted.

The data for wool fibre pre-processing were obtained from the secondary literature published by Wiedemann et al. (2019), while data for wool fibre spinning were sourced from the Ecoinvent v.3 libraries. The dyeing processes for both wool and polyester fibres, employing reactive and disperse dyeing methods, respectively, were sourced from Rosa et al. (2019).

3.5.4 ReCiPe 2016 Assessment Method

The conversion of midpoint indicators to endpoint indicators simplifies the interpretation of the LCIA results, although it introduces additional uncertainty with each aggregation step (Huijbregts et al., 2016). In this study, emphasis was placed on the Global Warming Potential (GWP), a midpoint characterisation factor that quantifies the integrated infrared radiative forcing increase of a greenhouse gas (GHG). GWP is expressed in kilogrammes of Carbon Dioxide equivalent (kg CO_2 eq.) emissions (Stocker et al., 2014). This study was based on an ecocentric theoretical perspective, believing that the negative impacts of garment production and consumption extend beyond human life to the entire ecological system, affecting a broader web of living and non-living entities. Aligned with this perspective, this study employed the ReCiPe 2016 v1.1 midpoint method, specifically utilising the egalitarian perspective technique (E) for impact assessment. The egalitarian perspective accounts emissions for a 1000 years' time horizon (Stocker et al., 2014).

However, it is important to acknowledge the limitations of conducting an LCIA in this study. First, the ReCiPe method adopts a global scope approach for GWP, which may overlook region-specific or context-specific impacts that can substantially influence assessment results (Huijbregts et al., 2016). In addition, as this study primarily focused on GWP, it limited the comprehensive assessment of other significant environmental impacts relevant to garment production and consumption. These limitations, however, do not undermine the focus of this study, which is to develop of a simplified method for assessing the environmental impact of garments. Notably, the ReCiPe Method, along with GWP, is widely utilised for assessing textile and clothing products, as indicated earlier in section 3.4.3. This study employed the ReCiPe Method for conducting LCIA in the analysis of jumpers.

3.5.5 Monte Carlo Uncertainty Analysis Method

The Monte Carlo method is a statistical simulation technique used extensively in LCA to address and quantify uncertainties in the results (Goedkoop et al., 2016). These simulations are particularly useful in LCA due to their ability to incorporate a wide range of uncertainties and complex dependencies among variables. This makes the technique a powerful tool for improving the accuracy and reliability of LCA results, especially in studies where data variability and uncertainty are significant concerns (Goedkoop et al., 2016).

The Monte Carlo method involves running simulations using random values within the specified uncertainty ranges for each input parameter. By performing multiple iterations, typically on the order of thousands, it generates a distribution of possible outcomes that provides a comprehensive view of the variability and potential range of results for the study. Each iteration of the Monte Carlo simulation randomly sampled values from predefined probability distributions for the input parameters. These distributions reflect the uncertainties associated with various factors such as process efficiency, emission rate, and resource consumption (Goedkoop et al., 2016).

Performing 1000 iterations resulted in 1000 different potential outcomes, allowing the construction of a probability distribution of the LCA results. This distribution provides critical insights into the potential variability of impacts, enabling informed decision-making and risk assessment. By analysing this range of outcomes, one can identify not only the most likely impacts but also the potential extremes, thereby ensuring a more comprehensive understanding of the environmental implications (Goedkoop et al., 2016).

In this study, the integration of Monte Carlo simulations into the LCA framework enabled a detailed uncertainty analysis and the generation of robust environmental impact assessments for knitted jumpers across eight life cycle scenarios. These simulations provided a comprehensive understanding of the potential variability in the environmental impacts, thereby enhancing the reliability and robustness of the LCA findings.

3.5.6 Comparative and Systematic Analysis Method for Simplifying LCA

This study aims to develop a methodology for simplifying LCA in the context of fashion design. The research methodology employed a comparative and systematic analysis of two materials in eight different life cycle scenarios, considering various manufacturing techniques and supply chain pathways. The goal was to assess differences in environmental impacts, particularly in terms of their GWP, and to formulate a simplified method applicable to other products within the fashion industry. The following outlines the research methodology used to achieve this aim of the study.

Step 1. Comparative Analysis of the Global Warming Potential (GWP) of Woollen and Polyester Jumpers

The initial phase of this study involved a comprehensive analysis of knitted jumpers in eight different life cycle scenarios. This analysis examined the GWP associated with material production, material wet processing and dyeing, garment manufacturing, transportation and packaging, use, and end-of-life. A comparative analysis was made, drawing upon established LCA methodologies like the ReCiPe 2006 (ISO 14040, 2006) to quantify the environmental impacts and highlight variations between the eight jumper scenarios considered.

Step 2. Development of a Simplified LCA-based Approach

Based on the findings of the comparative analysis and the assessment of the GWP, a systematic approach was adopted to develop a simplified methodology for future LCA applications. The identified factors influencing environmental impacts were synthesised and consolidated to formulate a simplified approach applicable to other textile products within the fashion category. This involved generalising the impacts and considering the similarities and commonalities in material production and processing, manufacturing techniques, and supply chain pathways of the scenarios compared.

Step 3. Validation and Applicability

The developed simplified approach was validated by comparing the results generated by it with those from the comprehensive LCA done in Step 1. The methodology was applied to assess the environmental impacts of not just jumpers but several other garments, considering their unique characteristics and life cycle stages. This validation process was aimed at ensuring the applicability and robustness of the simplified methodology for capturing key environmental factors across a broader range of textile items.

Step 4. Development of the "Simplified LCA Framework for Fashion Design"

The study culminated in the development of a framework that serve as a process flowchart for simplified LCA-based approach for evaluating the environmental impact of garments without extensive calculations. The processes involved in the simplified framework serve as a blueprint for programming a tool custom-tailored to the unique requirements of fashion designers with the potential to integrate LCA into the early design decision-making phase.

In conclusion, the research methods employed in this study encompassed a comparative and systematic analysis of woollen and polyester jumpers in various life cycle scenarios. These findings were used to develop a simplified approach, also applicable to other textile products within the fashion industry. This method integrates established LCA methodologies (ISO 14040, 2006) and the environmental impact assessment framework ReCiPe, 2016, ensuring scientific rigour and reliability.

3.6 Chapter Summary

This exploratory study has adopted an ecocentric viewpoint, acknowledging the interconnectedness of ecological systems and emphasising their preservation and protection for future generations. Grounded in a pragmatic research paradigm, the study rejected the idea of a singular reality or truth and instead recognised the significance of determining "what works" in finding practical solutions to the research's problems. Given the complex nature of the research, which integrates environmental sustainability, fashion design, and life cycle assessment methodology for clothing items, an abductive approach provided the necessary flexibility to effectively reason and employ a mixed methods approach to data collection.

The target audience for this study are fashion designers who are keen on a simplified LCA-based tool to objectively evaluate the environmental implications of their designs. The investigation initially focused on assessing and comparing the environmental impacts of knitted jumpers in eight different life cycle scenarios. It utilised a combination of primary and secondary data collection methods for the life cycle inventory (LCI), employing the Ecoinvent database. The life cycle impact assessment (LCIA) was done using the ReCiPe method and the uncertainty in the results was analysed using the Monte Carlo method. Subsequently, a simplified LCA-based approach was developed that led to the design of the Simplified LCA Framework for Fashion Design which will serve as a blueprint for programming a rapid assessment tool, specifically for fashion designers. This framework introduced novel perspective and offered meaningful advancements in sustainable fashion design. By adopting this approach, the methodology aimed to enhance the accessibility and manageability of the LCA process for fashion designers, enabling them to effectively integrate sustainability considerations into everyday design practices.

Consequently, this study employed rigorous research methodologies to investigate the environmental impacts of knitted jumpers and simplify the LCA process. The subsequent chapter focuses on the inventory data collection sources used and their validity, further contributing to the overarching goal of enhancing sustainability in the fashion industry.

Chapter 4 Data Collection and Validity Analysis

This chapter discusses how the data needed for Life Cycle Assessment (LCA) was collected for assessing the global warming impacts of two knitted jumpers—one made of wool and the other of polyester—both intended for use and disposal in New Zealand. As discussed in the during the problem identification phase of this study (see Chapter 3, Section 3.1.1), conducting a full scale LCA of knitted jumpers in New Zealand is a vital first step in the process of developing a simplified approach for assessing the environmental impact of garments.

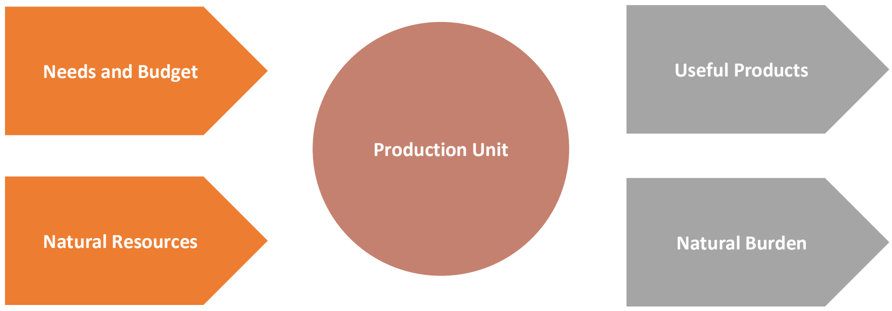
This chapter begins by delineating the fundamental components of the Life Cycle Inventory (LCI) data and discussing the parameters for assessing its quality. It subsequently examines specific details of the data used for modelling the inventory required for LCA analysis. Section 4.1 identifies the data sources used for modelling the inventory for various life cycle phases. The following sections (4.2 to 4.7) provide a comprehensive account of data acquisition and validate its relevance for each life cycle phase of the jumper within the scope of this LCA study. The final section 4.8 analyses the inventory used for making a cleaning cloth from polyester fibres, a process employed to offset environmental burdens by downcycling jumpers at the end of their useful lifespan. The purpose of this chapter is to give a detailed account of how the data used for the LCA methodology were sourced in order to establish a robust foundation for the comprehensive assessment presented in Chapter 5. In short, this chapter provides a detailed account of the decisions made when compiling the data used in the comprehensive LCA presented in Chapter 5 (Sections 5.1 and 5.2), thereby increasing the dependability of the findings.

4.1 Life Cycle Inventory (LCI) data

The Life Cycle Inventory (LCI) is a key phase of LCA involving the compilation and quantification of inputs and outputs of a product through its life cycle (see Chapter 2, Figure 6) (ISO 14040, 2006). It outlines the environmental inflows and outflows of a given technological system by quantifying material and energy flows. For example, the functional unit to produce a certain item may include significant inflows such as raw materials, energy, and natural resources. Products, by-products, waste, and emissions into the air, water, and soil are all considered relevant outflows. Decisions made during the modelling process, such as determining the system's boundaries and content, can considerably influence the outcomes of a study. In an LCA, impacts are calculated using environmentally relevant inflow and outflow (Zbicinski, 2006). The key components of the LCI used in modelling an LCA are shown in Figure 20.

Figure 20

Elements of Life Cycle Inventory (LCI)

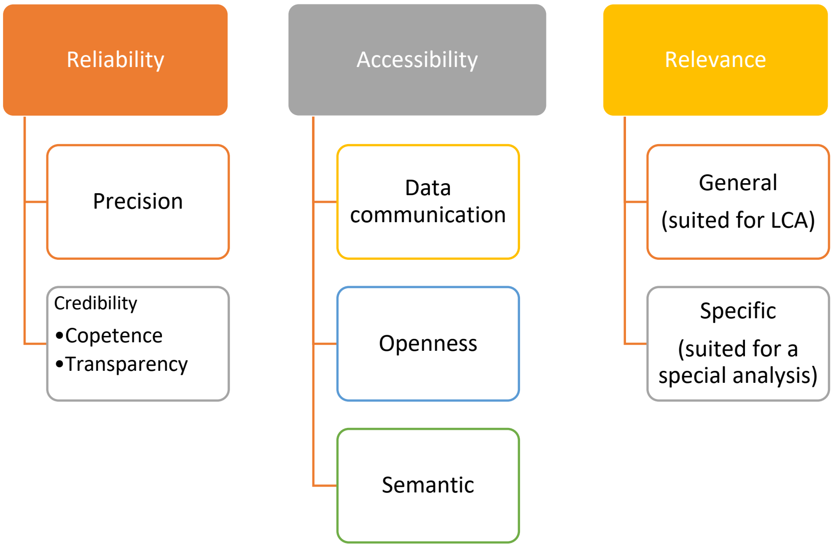


Note: Source: Zbicinski (2006)

The data for the LCI model were derived from various sources, depending on the goal of the study and the requirements for data quality. These sources include statistically analysed measured data, theoretical models, and estimations. The evaluation of data quality involves considering both qualitative and quantitative factors such as reliability, accessibility, and relevance. The reliability of data is determined by the accuracy and credibility of its source. Accessibility is strengthened by communicating data, its openness to public and transparency. Additionally, the data must be relevant to the LCA study; data that are not applicable to the product examined by the LCA have no value and will be ignored. These factors should be considered when assessing data quality (Figure 21)(Zbicinski, 2006).

Figure 21

Data Quality Requirement in LCA



Note: Source, Zbicinski (2006)

Two crucial aspects require careful attention when assessing the data quality. The first aspect concerns the input-output inventory, also known as foreground data, which includes the quantities of materials and energy used or emitted in modelling a particular product system. The second aspect pertains to Life Cycle Inventory (LCI) data, or background data, which includes emissions and energy related to the production of generic materials, energy, transport, and waste management (Goedkoop et al., 2016). Various software tools are available to assist in the LCA of clothing and textiles. Chapter 2, Table 3 introduces available software for assessing the environmental impact of textile and clothing items. The software which are extensively used for comprehensive LCAs in the fashion and textile sector are SimaPro and GaBi (Herrmann & Moltesen, 2015; Speck et al., 2016).

In This study, SimaPro was employed to do a cradle-to-grave life cycle analysis of knitted jumpers in New Zealand. SimaPro offer the Ecoinvent database, providing users with access to extensive life cycle inventory data (LCI) that supports comprehensive sustainability assessments. This database features more than 20,000 datasets covering various human activities and processes, which are crucial for comprehensive LCAs. Users can also download additional datasets, such as Allocation at the Point of Substitution (APOS) and Consequential data libraries, for more specialised analyses (PRé Sustainability, 2023). The relationship between SimaPro and the Ecoinvent dataset has been earlier explained in Chapter 3, section 3.4.2

According to Goedkoop et al. (2016), users of the SimaPro software package have access to six different dataset types.

1. Allocation default, unit processes
2. Allocation default, system processes
3. Allocation recycled content, unit processes
4. Allocation recycled content, system processes
5. Consequential, unit processes
6. Consequential, system processes

The allocation datasets adhere to the fundamentals of attributional modelling, where the environmental impact of a product or a comparison between two products with the same functional unit is sought. Consequential datasets, on the other hand, follow the fundamentals of consequential modelling, where the implications of a change are measured against a baseline situation. With certain exceptions, the term default designates the sort of allocation used, which is often an economic allocation. The difference between allocation default, system model, allocation, and recycled content does not account for any recycling-related benefits (Goedkoop et al., 2016). This study employs attributional modelling to determine the impacts associated with the life cycle of a knitted jumper, rather than the impacts resulting from any changes made.

A unit process type includes references to inputs from other unit processes, as well as details on the emissions and resource inputs of a particular process step. Additionally, it provides details on statistical analysis and uncertainty using the Monte Carlo technique. However, the system process type does not reveal information about the inputs and outputs of certain supply chain processes within the production system. Faster computations are provided, but no information on its uncertainty can be sought in the system processes (Goedkoop et al., 2016). To comprehend the impacts associated with each individual process in the life cycle of knitted jumpers, this study focused on unit processes, which also facilitated an uncertainty analysis using the Monte Carlo method.

In the context of the current investigation, the inventory data encompassed a combination of primary and secondary data, which were gathered for the six life cycle phases of the woollen and polyester jumpers: fibre production, fibre pre-processing and dyeing, garment manufacture, transport and packaging, garment use, and end-of-life. All six of the selected stages in the system boundary of the knitted jumpers were based on background inventory gathered from the Ecoinvent Version 3.7.1 (allocation at point of substitution-unit) library datasets.

4.1.1 Identification of Data Sources

The inclusion of data for the modelling inventory for each stage in the LCA of woollen and polyester jumpers played a pivotal role in influencing the outcomes of this study. Given the study's objective of developing a simplified tool, the initial approach was to seek foreground data from the Ecoinvent dataset. In cases where Ecoinvent data were unavailable, the life cycle phases were modelled using data primarily obtained from laboratory experiments and surveys. In cases where both Ecoinvent and primary data were unavailable or challenging to obtain, the published literature in the field was used to model the inventory employed. Details of the hierarchy involved in selecting the data collection method were previously discussed (see Chapter 3, Section 3.4.2). Care was taken to select comparable data sources for each phase in the life cycles of the woollen and polyester jumper types. Table 11 presents the data sources for modelling the inventory in the six life cycle phases studied.

Table 11

Data Sources for Modelling Input-Output Inventory

	Primary Data (Lab experiment & Survey)		Secondary Data (Ecoinvent dataset & published literature)	
	Wool Jumper	Polyester Jumper	Wool Jumper	Polyester Jumper
Fibre Production	-	-	X	X
Fibre processing and dyeing	-	-	X	X
Garment manufacture	X	X	-	-
Transportation and Packaging	X	X	-	-
Use phase	X	X	-	-
End-of-life	X	X	-	-

The subsequent subsections offer an intricate exposition of the inventory for each distinct life cycle phase of knitted jumpers. Including these sections provides comprehensive information regarding the selection process employed. Additionally, this study acknowledges instances in which substitute data had to be utilised owing to the unavailability of precise inventory records within the Ecoinvent library.

4.2 Data for Fibre Production

The validation of datasets utilised in LCA is paramount for ensuring the integrity and reliability of findings. In the context of this study, which explores the environmental impacts associated with wool and polyester fibre jumpers, validating the datasets for fibre production is essential. Given the constraints of time and resources inherent in PhD research, collecting primary data for fibre production was deemed impractical and beyond the scope of this study. Consequently, reliance on existing data sources has become imperative, leading to the utilisation of the Ecoinvent v.3 library. The Ecoinvent database is widely recognised for its comprehensive coverage of global environmental impacts across various sectors, underpinned by rigorous methodology and adherence to established standards and guidelines for data collection and analysis (Ecoinvent Website, 2024).

Notably, the availability of wool and polyester fibre production datasets within the Ecoinvent library renders it a practical and reliable resource for addressing the research objectives, owing to its international scope and credibility. Thus, this section aims to validate the utilisation of the Ecoinvent v.3 dataset for wool and polyester fibre production, highlighting its suitability within the context of this study's objectives. The following sections 4.2.1 and 4.2.2 present the validity of the Ecoinvent datasets for wool and polyester fibre production, respectively.

4.2.1 Analysis of Data for Wool Fibre Production

Wool is a natural fibre derived from animal. Sheep produce wool annually from proteins, lipids, and minerals that are absorbed through their diet and environmental factors. Every part of the wool fleece is utilised, leaving nothing to waste. When disposed of, the wool fibres decompose in the soil, slowly releasing valuable nutrients that improve soil health and enhance plant growth (McNeil et al., 2007; The Woolmark Company, 2022).

However, the assessment of the environmental impacts of wool production is complicated because of the differences in resource categories among various production methods. Farmers around the world have different approaches to managing sheep farms, ensuring that animals receive proper nourishment and health care. Agricultural practices, including fertiliser application and irrigation, are employed to boost meadow productivity. To supplement grass, feedstuffs, such as grain or silage, may be imported or locally produced. One sheep typically yields 4 to 5 kilogrammes of wool and 40 to 60 kilogrammes of meat annually (Biswas et al., 2010; Eady et al., 2012; Nemecek & Kägi, 2007).

Wool production is also associated with greenhouse gas emissions resulting from enteric fermentation and manure remaining on pastures. Enteric methane produced by microorganisms in the rumen of sheep contributes significantly to methane gas emissions (Gavrilova et al., 2019). The shearing process, which occurs once a year in spring, requires energy and is typically manually performed (Cardoso, 2013). All these processes and allocation methodologies must be considered when collecting inventory for wool fibre production.

On-farm production, where co-products such as meat, milk, and cereals are produced with wool, may be substantially different from other farms from an environmental, economic or social standpoint (Eady et al., 2012; Henry et al., 2015). Recent studies have proposed economic and protein mass allocation strategies to cope with wool co-products. Based on biophysical allocation on protein yields for fine merino wool and its co-product live weight sheep meat, Wiedemann et al. (2020) allocated 46% to wool and the remaining to meat for their LCA analysis, which included wool production on Australian farms in the New South Wales region.

New Zealand provides specialised farm assurance programmes, exemplified by organisations such as Oritain and NZFAP, which focus on verifying the quality of agricultural products based on their origin. Oritain's methodology emphasises precise identification of the exact sources of organic materials. Concurrently, the New Zealand Farm Assurance Programmes (NZFAP and NZFAP Plus) play a vital role in guaranteeing the authenticity, safety, and excellence of wool derived from sheep in the country. These programmes aim to instil confidence among consumers, both domestically and globally, by ensuring that products originating in New Zealand adhere to stringent standards of integrity and traceability (oritain.com; nzfap.com).

Though New Zealand prides itself on the quality of its wool production, there is a significant gap in the availability of inventory data concerning wool in the country. Furthermore, while the Ecoinvent database offers comprehensive information on worldwide wool and meat production along with transportation details in the supply chain, it lacks localised data specific to wool production in New Zealand. This reliance on global data raises concerns regarding the suitability of the dataset for certain types of studies pertaining to a region's wool industry. Despite providing substantial information on wool production worldwide, the limitations of the Ecoinvent dataset necessitate caution when applying it to address specific concerns related to New Zealand’s wool production.

The first reason why the data provided by the Ecoinvent database needs to be critically examined is that the dataset may not be valid to analyse the production of high-quality merino wool fibres, which this study intends to do. This is because it does not contain information on the quality of the wool produced. Secondly, it lacks a regional breakdown of wool production, for instance, merino wool production in Australasia, which limits its applicability for analysing specific geographic regions. Regional datasets for Australasia, such as those provided by Wiedemann et al. (2020), offer thorough inventories but have restrictions on data quality. Table 12 provides the data inventories included in the Ecoinvent and New South Wales (NSW) farms as presented by Wiedemann et al. (2020), for 1 kg wool production.

Table 12

Comparing 1 kg Wool Production Inventory between Ecoinvent and Wiedemann et al. (2020)

Inventory from Ecoinvent database - RoW sheep production for wool	Amount used in 1 year	Inventory from Wiedemann et al. (2020)- Wool production in NSW region in Australia	Amount used in 1 year
Lime	2.1 kg	Lime	0.04 kg
Maize grain	4.4 kg	Protein grains	0.55 tons
Irrigation	0.08 m3	Veterinary products ($ yearly expenditure)	$ 8651
Inorganic phosphorus fertiliser	0.084 kg	Herbicides ($ yearly expenditure)	$391
		Administrative expenditure ($ yearly expenditure)	$ 4579
Ammonium nitrate	0.18 kg	Superphosphate	0.29 tons
Fertilising, by broadcaster	0.06 kg	Electricity	0.11 kWh
Potassium chloride	0.11 kg	Diesel	0.03 kg
Shed	0.004 m2	Petrol	0.02 kg
Sodium chloride powder	0.4 kg		
Soya bean meal	2.9 kg	Transport of farm inputs	41 tkm
Tillage rolling	0.001 Ha		
Occupation, pasture manmade	86.94 m^2a	Pastureland utilised for sheep	100 m^2
Transformation from pasture	86.94 m^2		
Transformation to pasture	86.94 m^2	Drinking water including losses	6.1 ML

Note: RoW= Rest-of-world; kWh = Kilowatts per hour; ML= Mega Litre; tkm= tons kilometre

Discrepancies in datasets

A comparison of the two datasets presented in Table 12 above reveals disparities in material inventories, including lime, maize grain, irrigation, fertilisers, and farm expenditures, indicating the need for further examination of the data sources and methodologies employed. However, comprehending the extensive scope of inventories is beyond the scope of the present study. A comparison of the dataset scopes indicated that Wiedemann et al. (2020) focused specifically on merino wool production with diameters less than 20 µm, whereas the Ecoinvent dataset did not provide specific information regarding the quality of the wool fibre produced. Wiedemann et al. presented a five-year dataset from an annual sheep sale involving 52,173 kg live weight (LW) and 12,454 kg of greasy wool production, sourced from 34 farms in the New South Wales region of Australia. In contrast, the Ecoinvent dataset, covering a period of nine years from 2011 to 2020, includes a production volume of approximately 2 billion kg of wool, significantly surpassing the production volume reported by Wiedemann et al. (2020).

Regarding the allocation of impacts between wool and meat, Wiedemann et al. (2020) applied a 46 percent biophysical allocation for wool production to live weight sheep, whereas within the Ecoinvent dataset 0.22 kg is designated for meat production and 0.77 kg for wool production. Additionally, the dataset included 0.74 tkm of lorry-transported freight. Both these datasets underscore the importance of considering farm inputs and their impact on the environmental assessment of wool fibre production. Inputs, such as fertilisers, feedstuffs, pesticides, and irrigation, play a critical role in determining the environmental footprint of wool production. Furthermore, it is possible that the wool production dataset in the Ecoinvent database may contain some chemicals which may be prohibited in Australia. These are just examples of information gaps noticed in the Ecoinvent database for wool production. However, since this study did not provide a precise identification of such errors, further investigations are necessary to systematically identify other areas where vital information are missing. Accurate quantification and analysis of these inputs are essential for understanding the environmental impacts associated with the production of wool fibres.

Consequently, though the Ecoinvent database offers valuable insights into global wool production, certain limitations should be acknowledged. The absence of wool quality specifications and regional breakdowns of merino wool in regions such as Australia and New Zealand is a notable concern. Nevertheless, Ecoinvent's commitment to transparency and quality assurance instils confidence in the reliability of the data despite potential variations in environmental implications across regions. Given the constraints of time and resources inherent in PhD research, the decision to utilise the Ecoinvent dataset for wool production aligns with the pragmatic approach of leveraging existing resources to effectively address research objectives. While acknowledging the inherent limitations and potential variations in environmental impacts, the utilisation of Ecoinvent data represents a methodologically sound and pragmatic choice within the scope of this study.

4.2.2 Analysis of Data for Polyester Fibre Production

Polyethylene terephthalate (PET) is a hydrocarbon compound that serves as a basic raw material to produce polyester fibres. The life cycle of PET begins with the extraction of crude oil, followed by the cracking process and production of resin. The associated gases are transformed into ethylene, naphtha into benzene and ethylene oxide, and ethylene oxide into ethylene glycol, and eventually PET granules are formed (Singh et al., 2021). This method of producing PET has been used since the 1970s (Tamoor et al., 2022); thus, as an established industrial process, it will be further investigated in this study. After the production of PET granulates, polyester yarns are produced by the melt-spinning process, where PET is transformed into yarn filaments by drawing and texturing according to the intended use (Periyasamy & Militky, 2020). The process flowchart for polyester yarn production is shown in Figure 22.

Figure 22

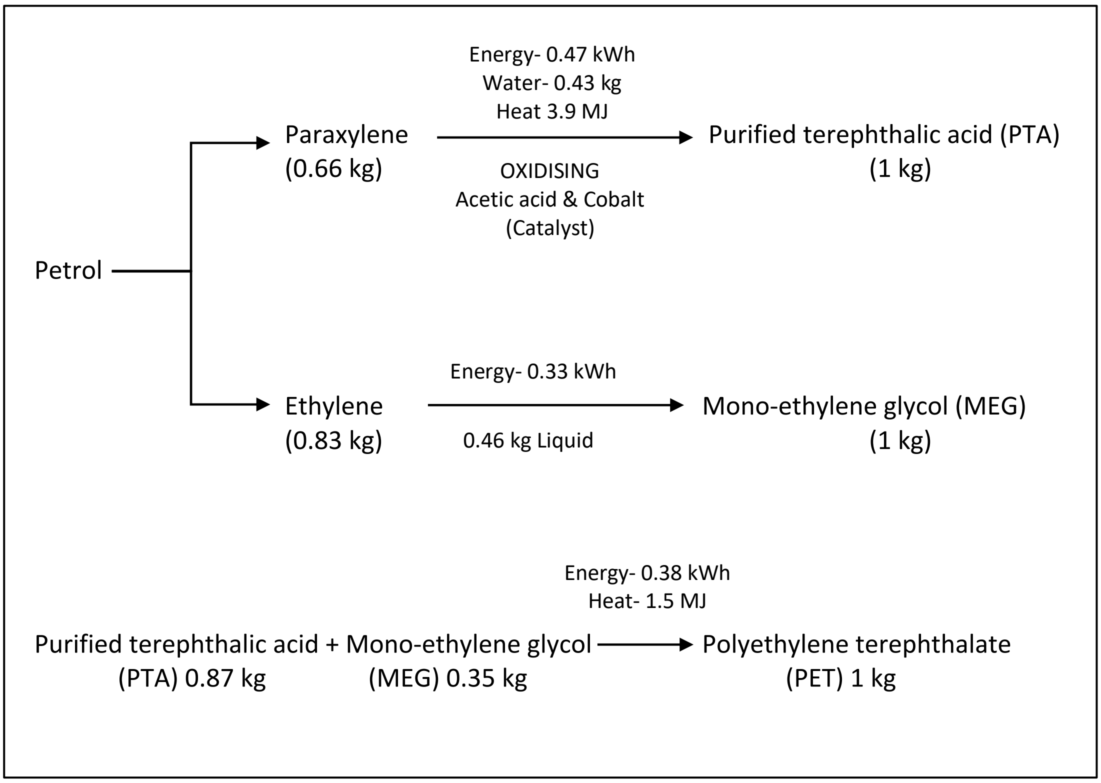
Cradle-to-Gate Flowchart for Polyester Yarn Production

Note: Adapted from Madival et al. (2009)

Crude oil extraction is the first step in the cradle-to-gate life cycle of polyester fibre. According to Gervet (2007), 0.9 kg of crude oil produces 1 litre or 0.76 kg of petrol, with one kilogramme of crude oil equalling 44 MJ of energy. The plastic-to-petroleum ratio in kilogrammes per litre is a result of this. When crude oil is mined or drilled out of the earth for the purpose of making PET, it is broken down into two substances: paraxylene and ethylene. Pure terephthalic acid (PTA) is then formed from paraxylene and mono-ethylene glycol (MEG) is formed from ethylene (Tamoor et al., 2022). Figure 23 illustrates the major steps and reactants involved in the production of 1 kg PET.

Figure 23

Chemical Reactions in PET Production



One kilogramme of PTA is created by oxidising 0.66 kg of paraxylene with 0.43 kg of water, 0.47 kWh of energy, and 3.9 MJ of heat using acetic acid and cobalt as the catalyst. Besides, one kg of MEG is produced when 0.83 kg of ethylene is oxidised using water, 0.46 kg of liquid oxygen, and 0.33 kWh of energy. PTA and MEG, in the presence of a catalyst, react with each other to create the PET resin.

To produce 1 kg PET resin, 0.87 kg PTA, 0.35 kg MEG, 0.38 kWh of energy and 6.3 MJ of heat are utilised (Tamoor et al., 2022). PET granulates are then transformed into polyester fibre strands that may be spun (Radhakrishnan et al., 2020). According to Ecoinvent database, 1.01 kilogrammes of PET granulates are utilised to create 1 kg of polyester yarn through the process of melt spinning. The Ecoinvent v.3 dataset includes the production of polyester fibre using melt spinning and inputs of PET granulates, electricity, heat, and water.

Viability of the Ecoinvent dataset for polyester fibre production

The Ecoinvent dataset (version 3.7.1) used in this study has a cradle-to-gate data inventory to produce polyester fibre that was modelled for a rest-of-world (RoW) scenario. The database was produced in December 2007 and is valid through December 2022. This dataset, which was last updated in 2018, deals with the manufacturing of polyester using PET granulates through melt spinning operations. The techniques for manufacturing polyester and melt-spinning are based on global statistics. Modelling of these processes was performed using global data and adjusted for the electricity mix. It is assumed that about 3.5% of the input PET granulates are recycled back into the manufacturing process as textile waste during spinning.

The input inventory for producing one kilogramme of polyester fibre in the Ecoinvent dataset under the rest-of-world (RoW) scenario is presented in Table 13. Given that it was outside the purview of this study to include all facets of fibre production, only the input data have been given provided, but the output emissions as well as waste management have been excluded from the table. This study investigated whether the production of polyester fibres from cradle-to-gate considered the extraction of crude oil from the ground.

Table 13

Inventory for Polyester Fibre Production in Ecoinvent

Input	Amount
Natural water	0.006 m^3
Lubricating oil	0.01 kg
PET granulate, amorphous (Global market)	1.01 kg
Tap water for melt spinning process	22.7 kg
Electricity, medium voltage (Global market)	1.01 kWh
Heat, district, or industrial, natural gas (Europe without Switzerland and RoW)	1.9 MJ

Note: Sourced from Ecoinvent; RoW= Rest-of-world; kWh= Kilo watts per hour; MJ= Mega Joules

Ethylene serves as the primary raw material for making PET, the basic element in the production of polyester yarn. Ethylene was examined in the Ecoinvent dataset's input inventory. The Ecoinvent dataset includes average statistics for RoW for ethylene manufacturing, which was generated from the Eco-profiles of the European plastics industry. As per Ecoinvent v.3, the dataset for ethylene production is an aggregate of all processes, from the extraction of raw materials to the delivery of ethylene to the plant. The steam cracking of naphtha is a key component of the ethylene synthesis process. This information in the Ecoinvent v.3 library was first created in July 2010 and was last updated in October 2018, valid through December 2020. The dataset was already included in the Ecoinvent v.2 and was not individually modified during transfer to the Ecoinvent v.3. According to the documentation that goes with the dataset in the SimaPro v.3 software, the dataset was generated following the database's quality guidelines for version 2.

No unit process inventory was discovered when analysing the manufacturing of ethylene in the Ecoinvent v.3 database. There was no separate mention of the materials or fuels, power, or heat used in the process. The uncertainty of the LCI could also not be determined for the production of ethylene owing to this lack of unit process data. It is essential that the ethylene inventory in one of the most reliable databases, Ecoinvent, provides sufficient information as it is the most significant raw material in the production of PET, which has been extensively searched and published for many product categories. Therefore, the current study has noticed serious gaps in the amount of detail provided for ethylene production within the Ecoinvent database, which raises concerns regarding the quality of the dataset and its usefulness for research inquiries. The primary concerns raised by this study, some of which have also been corroborated by earlier researchers in the field, are as follows.

Aggregated information hinders uncertainty analysis

Ethylene production dataset in the Ecoinvent relies on aggregated data, which is challenging because it lacks precision. According to (Frischknecht et al., 2005), there is little information available about the manufacture of fine chemicals, such as ethylene, needed to make PET. The lack of information available on ethylene production was supported by Hischier et al. (2005), who confirmed that the ethylene production data in Ecoinvent v.2 comes exclusively from the European Plastic Industry (also known as APME - The Association of the Plastic Manufacturers in Europe), and that it is not available at a unit process level but only at a general level that merely captures the cumulative LCI results. Thus, ecoinvent library provides a general estimate of the inventory in use in ethylene production.

Aggregated data also make it difficult to perform an uncertainty analysis, which is essential to test the robustness for any dataset. It is exceedingly challenging to construct quantifiable data uncertainty when the precise history behind the final figures is unknown. Hischier et al. (2005) reported that the ethylene production dataset by the European Plastic Industry represents a so-called horizontal average, meaning the weighted average of the last production step, while the preceding process steps back to the resources are calculated separately for each production chain involved. Therefore, contrary to the other datasets in the Ecoinvent library, the ethylene production dataset could not be used to quantify the degree of uncertainty associated with the LCI results.

Lack of transparency

The Ecoinvent dataset for ethylene production lacks transparency and as a result, the reliability of the dataset is also compromised. It has been claimed that Ecoinvent has hidden crucial information under the pretext of confidentiality of fine chemical production (Frischknecht et al., 2005; Hischier et al., 2005). The transition from Ecoinvent dataset v.2 to v.3 for ethylene production without any modifications (Ecoinvent v.3.7, 2022) implies that any discrepancies or inaccuracies present in the data during the 2005 period may continue to persist. Therefore, scholarly investigations that previously identified issues with v.2 remain relevant in shedding light on similar concerns within the new version and maintain their importance in evaluating data integrity and reliability. Considerable discrepancies between the Ecoinvent dataset and a dataset from 1992 from the Tellus Institute in the United States were discovered in a comparative analysis done by Hischier et al. (2005). However, because the Ecoinvent dataset is opaque, the cause for these differences in impact between the two inventories could not be determined (Hischier et al., 2005). This undermines the data reliability requirements for a credible database, such as Ecoinvent.

Many scholars have questioned the validity of statistics for PET manufacturing. Gironi and Piemonte (2011) used Ecoinvent v.2.0 database to compare PET with Polylactic Acid (PLA) bottles and concluded that the PET dataset was unreliable so the results could not be used as a benchmark for the market adoption of PET over PLA bottles, or the other way around. According to Hischier et al. (2005), ethylene production data should only be employed when no other data are available because it is a translation of aggregated industry data. This is concerning because all information pertaining to the manufacturing of PET in the Ecoinvent library is linked to ethylene production.

Missing process information

When considering the entire life cycle, such as the environmental impact of polyester fibre production, it is impossible to identify environmental hotspots because of a lack of knowledge about the many intermediate processes, such as the production of ethylene. Because the manufacture of ethylene does not demonstrate the inclusion of impacts related to the mining of crude oil, it is unclear whether it was considered. This is vital when comparing the environmental impacts of multiple fibre types, such as the manufacture of polyester fibres versus natural replacements such as wool.

Studies comparing polyesters with natural fibres have found that polyesters are preferable. Due to the inclusion of water and land use, as well as the consequences of the use of fertilisers and pesticides in farming crops such as cotton, the environmental implications for natural fibres are frequently found to be higher (Chen et al., 2016). A substantial number of LCA studies comparing polyester to natural fibres such as wool or cotton rely on production data from Ecoinvent datasets, revealing polyester to be lower on global warming than natural fibres (Beton et al., 2014; Sandin et al., 2019b; Van der Velden et al., 2014). Van der Velden et al. (2014) used the Ecoinvent v.2.2 database for a cradle-to-gate analysis as part of their LCA benchmarking study for six textile materials. Their investigation utilised the CO_2 indicator at the midpoint level, which indicated larger emissions (3.474 kg CO_2 per kg) from cotton fibre production, whereas they were substantially lower (2.698 kg CO_2 per kg) from the manufacture of polyester. Relying on flawed data can lead to misleading conclusions, especially in studies that provide benchmarks for textile fibres. Such benchmarks can influence manufacturers' and consumers' choices of clothing materials. Therefore, ensuring the accuracy and reliability of data is crucial for informed decision making.

Europe specific dataset

The Ecoinvent database on PET production includes information from several European production sites but excludes information from other nations that produce polyester. A lack of data on PET production for jackets in China was reported by Steinberger et al. (2009). Their LCA study used data on polyester fibre production from

Franklin Associates from the year 1993, an American source. The study showed 7.66 kg of CO_2 emissions from the production of polyester fibre for a kilogramme of polyester jackets. This was high considering that the polyester fibre manufacturing data from Ecoinvent that was used by Van der Velden et al. (2014) showed only 2.69 kg CO_2 emissions per kilogramme of polyester fibre. This could be due to differences in the way PET is produced in between the two nations or due to an error in one of the datasets.

There are few databases on PET production using statistics from the United States, Asia, and Africa (Gomes et al., 2019), which are the major hubs for plastic production globally. China (32 percent) and North America (18 percent) are the world's top producers of plastics (Plastics Europe and EPRO, 2022). China, along with India and Southeast Asia, produces 86 percent of all polyester fibre globally (Cassidy & Goswami, 2017); and so, if the production inventory data from these significant industrial regions are not included, there is a substantial gap in the dataset.

Outdated dataset

Other key methodological assumptions affect the relevance of PET production statistics for climate change. The PET production data in Ecoinvent v.3 were adapted from Ecoinvent v.2; however, as the PET market has expanded over the past two decades, PET is no longer an avoided by-product of petroleum production but rather a significant co-product. Therefore, careful consideration should be given to its allocation in the LCI. When dividing the environmental cost of producing co-products, their environmental implications are either allocated based on mass, where the heavy co-product is seen as responsible for most environmental impacts, or based on market price, where the most valuable co-product is held accountable for a large share of environmental impacts (Sandin et al., 2019b). As PET materials and polyester yarns are more expensive than gasoline, their allocation should be carefully considered in the Ecoinvent dataset. The relevance of Ecoinvent in the current context is questioned because it does not include the allocation processes for the environmental impact of PET and petroleum extraction.

Non-compliance with other inventory datasets in Ecoinvent

The PET manufacturing data source did not adhere to Ecoinvent's data specifications. The Eco-profiles of the European plastics industry in Ecoinvent were not based on the same preceding process steps as the other data in the dataset. For example, PET production has a specific electricity mix model that does not correspond to the electricity mix of other processes in the Ecoinvent library (Hischier et al., 2005). This does not make for a fair comparison with other processes. From a scientific standpoint, it is not recommended to compare PET production with any other material because their inventories have not been produced using the same methodologies and boundaries. Therefore, this study claims that scientific studies on the LCA of PET and polyester fibres using the Ecoinvent datasets have significantly underestimated the environmental impact.

Consequently, given the impact of crude oil extraction on global warming, the ambiguity surrounding mining to produce PET in the Ecoinvent database cannot be overlooked. This is an aggregated dataset from the Eco-profiles of the European plastics industry, which lacks unit process-level information and transparency. This dataset should not be used for comparative evaluations as it is also non-compliant with other processes in the Ecoinvent library. This dataset should not be used in LCA studies owing to its lack of reliability, low accessibility, and redundant data quality.

It is crucial to invest in research that improves the quality of the datasets used to measure the impact of crude oil extraction on PET production. Researchers must gather more data, particularly at the unit process level, to enable a more accurate analysis of PET production. This data must be open and available for examination to guarantee that all components in the supply chain have been included and that their results are viable. Additionally, to ensure that the LCI data for ethylene production comply with Ecoinvent's requirements and methods, more efforts must be made to harmonise it.

An assessment of the credibility of wool fibre production in Section 4.2.1 and polyester fibre production in Section 4.2.2 revealed a lack of alternative data sources for the latter. Consequently, the present study proceeded with the utilisation of the Ecoinvent database for both material types. It should be noted that the primary focus of this study revolves around the development of a comprehensive approach for evaluating the environmental ramifications associated with clothing items, using the LCA methodology. The study deemed it prudent to work with the information available on the database. Table 14 provides the inventory data sources used for this study, serving as the fundamental basis for examining the environmental impacts arising from the production of wool and polyester fibres in this investigation.

Table 14

Inventory for Fibre Production in Ecoinvent

	Inventory from Ecoinvent dataset	Amo- -unt in kg	Allocation	Waste type	Process type	Date of data creation
Wool Fibre Production	Market for sheep fleece in grease GLO	1	100%	Compost	Unit process	02/08/2011
Polyester Fibre Production	Market for polyethylene terephthalate, granulate, amorphous RoW	1	100%	PET	Unit Process	28/07/2010
	Polyester fibre production, finished RoW	1	100%	PET	Unit process	20/03/2018

Note: Sourced from Ecoinvent; RoW= Rest-of-world; GLO= Global

4.3 Data for Fibre Processing and Dyeing

The production of wool fibre necessitates a pre-processing stage which in polyester yarn is not required. Before dyeing, wool is subject to undergo scouring process to eliminate impurities and residual grease that may be present on the fibres. During production at the farm, wool fibres accumulate various natural secretions, such as suint (sweat) and grease, particularly in the case of finer fibres such as merino wool, which can contain substantial proportions of suint (8–10%) and grease (30%). These impurities, along with other undesired elements such as kemp (dead fibres), insects, dirt, and vegetable matter, are also removed during the blending or carding processes after scouring (Cassidy & Goswami, 2017).

The scouring process involves a series of three to five tanks or bowls containing warm water mixed with soap and alkali, accompanied by forks or rakes that facilitate wool movement through these tanks. In each subsequent tank, the concentrations of soap and alkali are gradually reduced, and the final tank typically contains only water for rinsing the wool before it is dried. The suint, which is extracted during scouring, is a natural form of lanolin and is often sold to cosmetic companies. Subsequently, conventional hot-air dryers are employed to dry the scoured fibres (Cassidy & Goswami, 2017). These activities consume considerable amounts of material and energy resources, thereby exerting a substantial environmental impact. Therefore, the inventory used in these processes should be thoroughly examined and considered when conducting an LCA.

The following subsections encompass the evaluation of the inventory sources and their reliability concerning the pre-processing of wool fibres via scouring (section 4.3.1) as well as the subsequent spinning of wool fibres (section 4.3.2). The final subsection (section 4.3.3) provides an inventory analysis pertaining to the dyeing processes employed for both wool and polyester yarns, specifically focusing on reactive dyeing for wool and disperse dyeing method for polyester fibres.

4.3.1 Analysis of Data for Wool Fibre Scouring/ Pre-Processing

The scouring operation is important when assessing the impact of processing wool fibres because it requires a large amount of energy and chemical inputs to ensure thorough cleaning of the fibres. However, it was found that the Ecoinvent library lacks inventory records on wool scouring, and gathering source data became challenging due to the COVID-19 pandemic during the course of this study. Furthermore, despite its significance in wool production, large-scale scouring operations are limited in the Australasian region (Wiedemann et al., 2019). It is worth highlighting that the absence of extensive scouring facilities in New Zealand and Australia leads to most wool being exported in its greasy state to Asian countries for further processing (Wiedemann et al., 2019). Consequently, to obtain data on wool scouring within the confines of New Zealand, it is imperative to identify and examine the available scouring facilities that operate within the country's boundaries.

To collect primary data from wool scourers in New Zealand, this study initially focused on investigating the scouring processes at *Jumbuck Carding*, a small-scale scouring plant located in West Auckland region of the country. The unavailability of commercial scouring facilities in New Zealand has compelled individuals to undertake scouring activities on a small scale, utilising the available resources at hand. Figure 24 depicts the modest shed of *Jumbuck Carding*, where wool processing, including scouring, bleaching, dyeing, and subsequent activities such as drying, blending, and spinning of yarn takes place. The data gathered from this facility sheds light on the intricacies of the scouring process and elucidates the associated environmental inputs and outputs.

Figure 24

A Small-Scale Wool Fibre Processing Unit in New Zealand

However, as small scale processing operations were not comparable to large scale production and limited availability of data from a single small-scale supplier, this study sought alternative sources of information from secondary literature to obtain an inventory of data pertaining to large-scale scouring operations, which are commonly carried out on the merino wool produced in Australia and New Zealand. The most recent and comprehensive datasets on the scouring of merino wool were identified in the research conducted by Wiedemann et al. (2019). These datasets were meticulously compiled over a period of 12 months, spanning 2016 and 2017, encompassing the activities of eight wool scouring operators located in China and India. The dataset offers averaged values, ensuring a robust representation of scouring processes.

LCI was modelled in the Ecoinvent v.3 dataset. In instances where the inventories were not as precise as those given by Wiedemann et al. (2019), suitable substitute were applied. Table 15 present the life cycle inventory for wool scouring that was utilised in this investigation.

Table 15

Inventory for Wool Scouring from Wiedemann et al. (2019)

Inventory from Ecoinvent dataset	Amount	Substituted inventory
Australian greasy wool	1.390 kg	
Diesel production, petrol refinery operation RoW	0.00021 kg	
Liquefied petroleum gas production, petroleum refinery operation ROW	0.00051 kg	
Non-ionic surfactant production, fatty acid derivate GLO	0.00130 kg	Surfactant
Sodium bicarbonate, soda production, Solvay process RoW	0.00509 kg	
Sodium chloride production, powder RoW	0.00384 kg	
Soap production RoW	0.00425 kg	Detergent
Aluminium sulfate production, powder RoW	0.00039 kg	Focculent
Market for copper sulfate GLO	0.00374 kg	Metal salt
For packaging bales- market for nylon 6 RoW	0.00063 kg	
For packaging bales- market for steel, low alloyed GLO	0.00068 kg	
Steam production, as energy carrier, in chemical industry RoW	0.013 MJ	
Market group for tap water GLO	17.843 kg	
Market group for electricity, high voltage CN	0.209 kWh	
Heat and power co-generation, natural gas, combined cycle power plant, 400MW electricity	6.266 MJ	
Outputs to technosphere		
Clean wool scoured	1 kg	
Lanolin	0.077 kg	
Direct disposal of wastewater from textile production	15.444 litres	
Treatment of biowaste, industrial composting	0.318 kg	Wool recovery & wool waste
Outputs to nature		
Water lost to evaporation	2.399 kg	

Note: RoW= Rest-of-world; GLO= Global; CN= China

4.3.2 Analysis of Data for Wool Fibre Spinning

The wool yarn production typically involves opening, carding, pre-bending, stretching, roving, and spinning fibres. According to Laursen et al. (2007), it is critical to evaluate aspects such as energy use, fibre waste, spindle oil use, and dust when considering the environmental impact of spinning fibres to yarn. The energy consumption in yarn spinning varies depending on factors such as the intended use of the yarn as finer yarns require higher energy (Koç & Kaplan, 2007). The amount of material lost during the spinning process also varies depending on the fibre type. Polyester experiences a material loss of only 2-3% while spinning, whereas wool incurs a 10% and cotton losses 13–16% of material during spinning (Strand, 2015).

The wool spinning process employs two distinct drafting methods: ring spinning and mule spinning. In ring spinning, the yarn is twisted using a revolving traveller that moves around a ring. The yarn is then wound onto a spinning tube, which rotates at a faster speed than the traveller, spinning the fibres. Mule spinning, on the other hand, is an intermittent process where drafting, twist insertion, and winding-on steps alternate. Mule spinning machines are specifically used for delicate yarn types, such as merino, cashmere, lambswool, and vicuna. Despite its slower production rates, smaller package sizes, and larger floor space requirements compared to ring frames, mule spinning is renowned for producing more uniform and finer yarns as well as superior quality yarns made from shorter blends (Cassidy & Goswami, 2017; Cottle & Wood, 2012). The production process for manufacturing merino wool yarns used in jumper production involves mule spinning, specifically employing 28/2 nm wool yarns. However, upon searching for inventory data pertaining to the mule spinning process, a notable scarcity of information was observed.

Due to the unavailability of specific inventory for mule spinning, the dataset provided for ring spinning of cotton fibres from the Ecoinvent library was deemed a suitable substitute for the purpose of this study. Moreover, considering the reported high material loss in both wool and cotton spinning (Cottle & Wood, 2012), the inventory originally employed for ring-spinning cotton fibres was utilised without any modifications. However, this study suggest that future investigations should focus on further exploring the mule spinning process and collecting inventory data to ensure more accurate LCA of knitted garments made using finer yarns. Table 16 presents the input inventory utilised for spinning wool fibres, which was derived from the Ecoinvent library database.

Table 16

Inventory for Wool Fibre Spinning in Ecoinvent

Inventory from Ecoinvent dataset	Amount	Allocation	Waste type	Process type	Date of data creation
Yarn production, cotton, ring spinning, for knitting GLO	1 kg	100%	Compost	Unit process	20/12/2018

Note: Sourced from Ecoinvent; RoW= Rest-of-world

4.3.3 Analysis of Data for Wool and Polyester Fibre Dyeing

Textile wet processing, particularly dyeing, plays a crucial role in enhancing the value of clothing items. However, it is important to recognise that these processes have the potential to cause considerable environmental impacts. Dyeing can be performed at various stages in the textile chain, including dyeing of staple fibres (stock dyeing), yarn dyeing before weaving or knitting, and dyeing of ready fabric or garments (Terinte et al., 2014). Yarn dyeing encompasses numerous requirements that are specific to each type of fibre. Various process parameters, such as pH, temperature, and time, must be carefully controlled for each fibre type. In addition, the operation of machinery requires electricity, and steam is employed for heating the dye bath. The machinery employed also varies depending on the fibre grade and scale of the industrial setup (Terinte et al., 2014). As each fibre requires a specific dyeing system and a distinct combination of chemicals, it is necessary to consider their specific environmental impact.

Dyes can be classified in several ways, such as according to their chemical constitution, application class, or end use. The two main criteria for categorising dyes are the types of fibres they can be applied to and their chemical makeup (OECD, 2015). Reactive dyes are commonly used to dye wool fibres. These dyes react with wool fibre molecules to form chemical bonds. A variety of auxiliary chemicals may be employed during the dyeing process to aid dye absorption and fixation into the fibres. This facilitates the achievement of desired shades by adhering to the substrate at a certain fixation rate (OECD, 2015).

Disperse dyes are typically used for dyeing oleophilic fibres such as polyesters and other synthetics. These dyes have low water solubility and are used as finely ground powders dispersed in a dye bath. The particles dissolve in the aqueous dyeing medium at low concentrations and penetrate the synthetic fibres because of their higher solubility in the substrate. High temperatures and super-atmospheric pressures may be employed to facilitate dye applications, reducing the need for chemical accelerants used at lower temperatures (OECD, 2015).

Owing to the inherent differences between wool and polyester fibres in terms of their dyeing requirements, it was necessary to obtain separate dyeing inventories for these fibre types. The available Ecoinvent datasets only include dyeing inventories for cotton fibres using reactive dyes, rendering uncertainty regarding their applicability to wool. Furthermore, Ecoinvent lacked datasets for conducting disperse dyeing of polyester fibres. Consequently, a comprehensive literature search was conducted to identify suitable data inventories for dye categories for both wool and polyester fibres.

Rosa et al. (2019) proved to be a valuable resource as they presented a detailed inventory for dyeing knitted fabric using both reactive and disperse dyes. Their data provided inventory information based on the material weight, which aligned with the requirements of the current study. Notably, all fibres were dyed in a specific Pantone 19-1619, a dark black colour that was also a requirement for the current research investigation. The dataset includes a comprehensive breakdown of the chemicals and auxiliaries employed in the dyeing process. Table 17 presents a chemical list for dyeing wool and polyester yarns using reactive and disperse dyes. In instances where the specific inventory provided by Rosa et al. (2019) was not available, an alternative inventory was applied and appropriate acknowledgement is provided in the last column of the table.

Table 17

Inventory for Fibre Dying from Rosa et al. (2019)

Inventory from Ecoinvent dataset	Reactive dying for woollen yarns	Disperse dying for polyester yarns	Substituted inventory
	Amount	Amount	
Fibre for dyeing	1.1 kg	1.1 kg	
Petroleum gas production, off-shore RoW	0.000163 litres	0.000133 litres	Natural gas
Sodium tripolyphosphate production RoW	0.011 kg	0.011 kg	Sequestering agent
Non-ionic surfactant production, fatty acid derivate GLO	0.011 kg	0.011 kg	Non-ionic detergent
Sodium percarbonate production, powder RoW	0.055 kg	0.055 kg	Sodium carbonate
Chlor-alkali electrolysis, mercury cell RoW	0.0154 kg	0.011 kg	Sodium hydroxide
Market for sodium metasilicate pentahydrate, 58% active substance, powder RoW	0.0055 kg	-	Sodium metasilicate
Sodium chloride production, powder RoW	0.55 kg	-	-
Ethoxylated alcohol (AE7) production, petrochemical RoW	0.011 kg	0.011 kg	Dispersant
Sulfuric acid production RoW	0.00154 kg	-	-
Hydrogen peroxide production, product in 50% solution state RoW	0.022 kg	-	Hydrogen peroxide
Market for acetic acid, without water, in 98% solution state GLO	0.0055 kg	0.0055 kg	-
Enzymes production RoW	0.0055 kg	-	-
Fatty alcohol production, petrochemical RoW	0.0134 kg	-	-
Market group for tap water GLO	70 kg	40 kg	-
Market group for electricity, high voltage CN	2580000 J	1640000 J	-
Heat production, natural gas, at industrial furnace. 100kW RoW	7730 J	6270 J	-
Outputs to Technosphere-			
Dyed fibre/ yarn	1 kg	1 kg	-
Direct disposal of wastewater from textile production GLO	56 litres	32 litres	-
Treatment of biowaste, industrial composting	0.1 kg	-	-
Market for waste polyethylene treatment	-	0.1 kg	-
Outputs to nature-			-
Water lost to evaporation	14 litres	8 litres	-

Note: RoW= Rest-of-world; GLO= Global; CN= China

4.4 Data for Garment Manufacturing

Garment manufacturing represents the final stage before a product is released from the factory and reaches consumers. This process involves several sequential stages that require the use of energy and steam and may also result in fabric loss occurring at any given point. The quantity of energy consumed depends on factors such as manufacturer, machine efficiency, product design, and fabric composition (Md. Islam & Md. Khan, 2014).

Three distinct flatbed knitting technologies are commonly employed to create knitted jumpers: cut-and-sew, fully fashioned, and integral knitting. These techniques differ from one another in terms of their construction methods, utilising diverse machine types and patterning approaches. Consequently, the application of these three processes leads to varying energy consumption levels and waste generation outcomes (Choi & Powell, 2005; Peterson et al., 2008).

The Ecoinvent library does not provide access to the data inventory of the specific knitwear manufacturing processes examined in this study. Furthermore, no existing literature has adequately elucidated the disparities between the different methods of garment construction. Given the specific nature of the garments under investigation, this study aimed to gather primary data. However, because of the ongoing pandemic, most garment manufacturing factories in New Zealand were either closed for a good portion of the study's duration or implemented stringent protocols to limit access to their premises. To obtain information for modelling the input-output inventory of different garment manufacturing techniques, the research relied on the support and facilities of the Textile Design Lab located at the Auckland University of Technology (AUT), where the study was conducted.

The Textile Design Lab at AUT is equipped with state-of-the-art machinery for knitwear production. Conducting garment manufacturing within this controlled laboratory setting facilitated the convenient collection of data for inventory modelling across three construction methods: cut-and-sew, fully fashioned, and integral knitting. This experiment also indicated that such controlled environments could be advantageous when designers seek to gather data for garment manufacturing before large-scale production. A sampling unit, where fashion designers construct the initial prototypes of their intended garments, can serve the purpose of collecting the requisite data to assess the environmental impact of manufacturing. In this context, designers can estimate the materials utilised and wasted during construction, as well as record the energy requirements. Using research conducted within the confines of the laboratory setting presents a novel approach to inventory data collection for LCA.

In a controlled laboratory environment, 12 jumpers were constructed, comprising six with merino wool yarn and six with polyester yarn. Both had yarn diameters of 28/2 nm. The physical features such as yarn quality, garment size and style, knit pattern, and needle gauge remained the same for all three forms of knit construction. Figures 25 to 27 depict the CAD involved in the construction of the three types of knitwear. The study collected data on energy usage and material loss for each sample produced in a laboratory setting, and then averaged the results. Table 18 lists the average energy inputs and fabric losses considered in this study for the three flatbed knitwear manufacturing techniques. The data obtained from this experiment served as the basis for establishing an input-output inventory related to garment manufacturing.

Figure 25

CAD for Constructing Knitted Panels in Cut-and-Sew Method

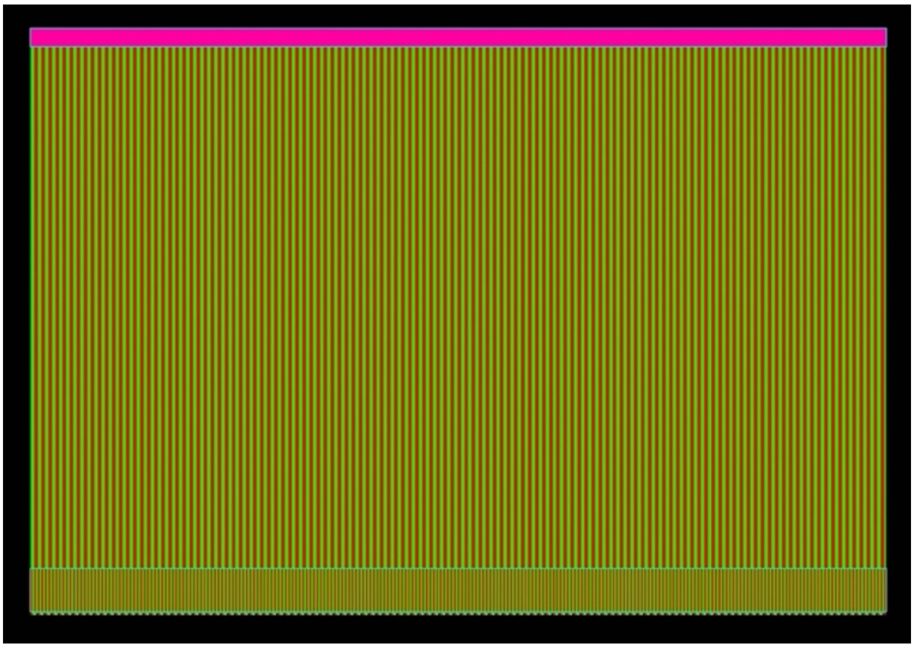


Figure 26

CAD for Constructing Shaped Bodice in Fully Fashioned Method

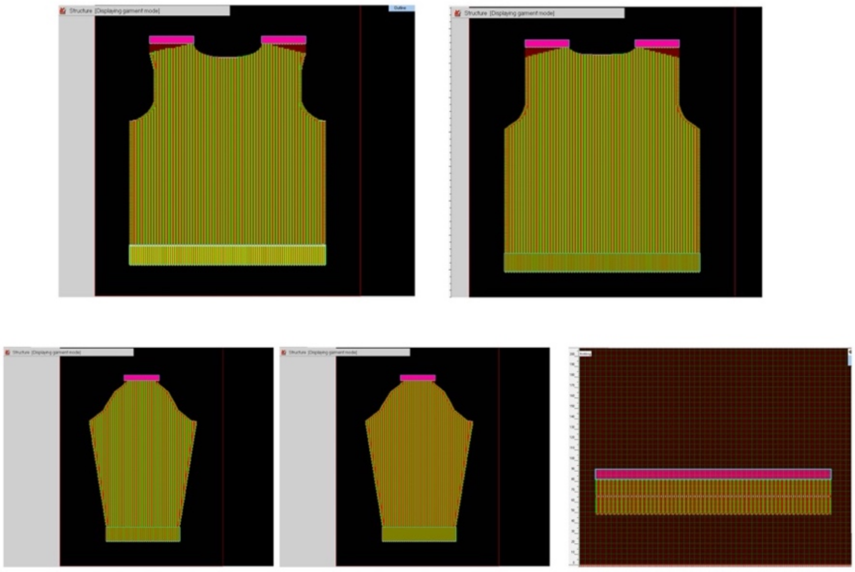


Figure 27

CAD for Constructing Whole Jumper in Integral Knitting Method

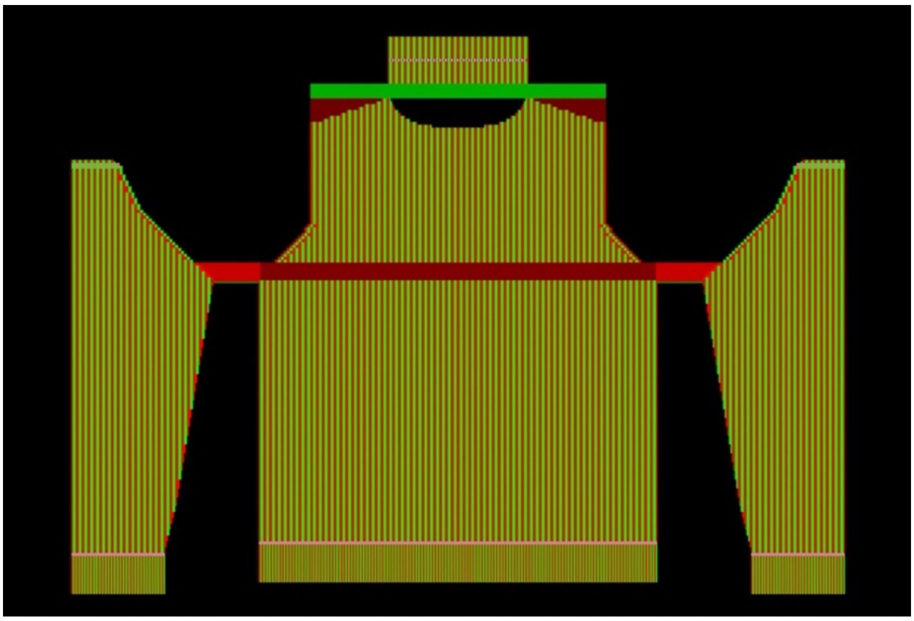


Table 18

Energy Inputs and Fabric Loss in Three Flatbed Manufacturing Scenarios

Breakdown of data for each garment manufacturing stage		Cut-and-sew	Fully Fashioned	Integral Knitting
Knitting	Energy (Wh)	623	1831	2530
	Fabric losses (%)	3.2	4.6	2.1
Steaming	Energy (Wh)	100	93	140
	Fabric loss (%)	-	-	-
Cutting	Energy (Wh)	-	-	-
	Fabric losses (%)	23	-	-
Overlocking	Energy (Wh)	354	-	-
	Fabric losses (%)	-	-	-
Linking Neck	Energy (Wh)	29	158	-
	Fabric losses (%)	-	-	-
Stitching	Energy (Wh)	83	83	-
(Bar tacks at sleeves & sides)	Fabric losses (%)	-	-	-
Ironing/ finishing	Energy (Wh)	40	40	-
	Fabric losses (%)	-	-	-
Total Energy Consumed		1,229 Wh	2205 Wh	2670 Wh
Total Fabric lost		26.2%	4.6%	2.1%

Formulas: Power of a Machine (Watts) = I (Ampere) X V (Volts);

Energy Consumed (Watts per Hour/ Wh) = Power of a Machine X Time of use in hours

Notably, despite the utilisation of different manufacturing processes, the final product remained consistent for all three techniques. Specifically, a rib-stitched, full-sleeved jumper with a high collar and identical dimensions is produced. The input-output data, which encompass the production modelling of both woollen and polyester jumpers utilising cut-and-sew, fully fashioned, and integral knitting technologies, are presented in Table 19.

Table 19

Inventory for Garment Manufacturing (Based on Lab Experiment)

	Inventory from Ecoinvent database	Cut-and-sew	Fully Fashioned	Integral Knitting
Wool jumper manufacturing	*Inputs from Technosphere*	Amount	Amount	Amount
	Dyed woollen yarn	0.521 kg	0.403 kg	0.393 kg
	Market electricity, high voltage BD/NZ	1229 Wh	2205 Wh	2670 Wh
	Market for heat, from steam, in chemical industry RoW	6000 J	6000 J	6000 J
	Market group for tap water GLO	0.08 kg	0.08 kg	0.08 kg
	Outputs to Technosphere-			
	Knitted jumper	0.385 kg	0.385 kg	0.385 kg
	Treatment of biowaste, industrial composting RoW	0.136 kg	0.018 kg	0.008 kg
	Outputs to Nature -			
	Water lost to evaporation	0.08 litres	0.08 litres	0.08 litres
Polyester jumper manufacturing	*Inputs from Technosphere*	Amount	Amount	Amount
	Dyed woollen yarn	0.521 kg	0.403 kg	0.393 kg
	Market electricity, high voltage BD/NZ	1229 Wh	2205 Wh	2670 Wh
	Market for heat, from steam, in chemical industry RoW	6000 J	6000 J	6000 J
	Market group for tap water GLO	0.08 kg	0.08 kg	0.08 kg
	Outputs to Technosphere-			
	Knitted jumper	0.385 kg	0.385 kg	0.385 kg
	Market for waste polyethylene treatment	0.136 kg	0.018 kg	0.008 kg
	Outputs to Nature			
	Water lost to evaporation	0.08 litres	0.08 litres	0.08 litres

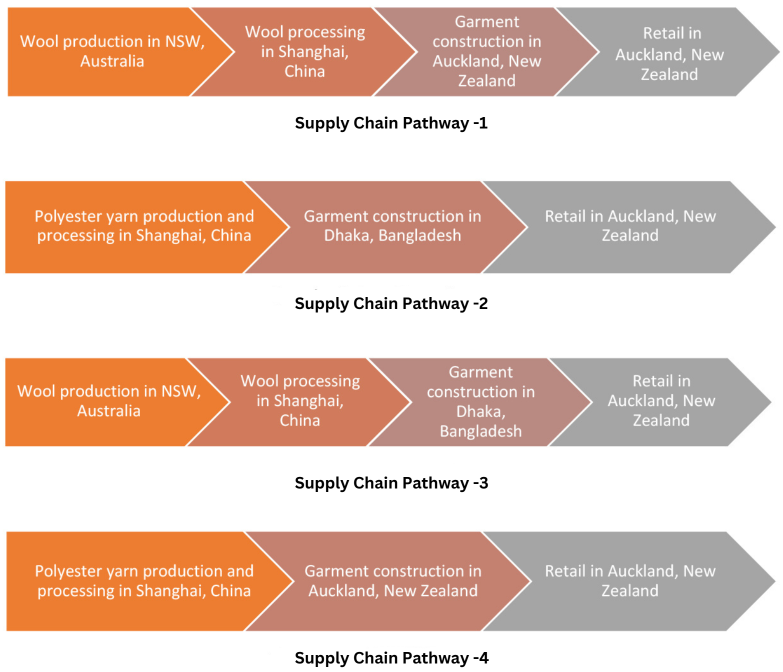
Note: RoW= Rest-of-world; Wh= Watts per hour; J= Joules; kg= kilogram; GLO= Global; BD= Bangladesh; NZ= New Zealand

4.5 Data for Transport and Packaging

The apparel industry operates as a global enterprise, with various stakeholders, such as raw material suppliers, manufacturers, and retailers, dispersed across different regions of the world (Karthik & Gopalakrishnan, 2014). Throughout the life cycle of a clothing item, from the cradle to the grave, the transportation of supplies plays a crucial role in building its environmental profile. Within the garment supply chain, transportation involves the application of different modes, including roads, water, and air. Each mode of transportation introduces varying levels of environmental pollution. Decision makers who possess the authority to determine the mode of transportation in the supply chain, can assess their impacts to make environmentally friendly selections through a range of choices and strategies. This study examined four distinct transportation scenarios, also referred to as supply chain pathways, based on the routes taken by raw materials from production to finished products. Figure 28 presents the four supply chain pathways investigated in this study.

Figure 28

Four Supply Chain Pathways Investigated in this Study



The analysis focused on road transport via lorries and sea transport via container ships. The distances associated were estimated based on assumptions made regarding the production sites. For the purpose of this study, it was assumed that the same type of vehicles were used so the values used for the calculation remained constant. All land transportation was carried out using a EURO-4 lorry weighing more than 32 metric tons, and all sea transportation was conducted through container ships. To convert shipping distances from nautical miles (nm) to kilometres (km), a standard conversion factor of 1.852 was applied. The inventory for both road and sea transportation were sourced from the Ecoinvent database and was subsequently used to model the four pathways. Detailed information regarding the mode of transportation and the Ecoinvent inventory applied in each supply chain pathway are presented in Tables 20 to 23.

Table 20

Inventory Modelled for Supply Chain Pathway 1

Transport route		Mode	Input inventory from Ecoinvent database	Amt. in kg	Distance in nautical miles (nm)	Distance in kg km
From	To					
NSW Farm, Australia	Port of Sydney, Australia (via wool auction centre)	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	200
Port of Sydney, Australia	Port of Shanghai, China	Sea	Transport, freight, sea, container ship GLO	1	5215	9658.18
Port of Shanghai, China	Wool processing unit, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Wool processing unit, Shanghai, China	Port of Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Port of Shanghai, China	Port of Auckland, New Zealand	Sea	Transport, freight, sea, container ship GLO	1	6252	11578.70
Port of Auckland, New Zealand	Knitwear manufacturer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Knitwear manufacturer, Auckland, New Zealand	Garments retailer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50

Note: RoW= Rest-of-world; GLO= Global; NSW= New South Wales

Table 21

Inventory Modelled for Supply Chain Pathway 2

Transport route		Mode	Input inventory from Ecoinvent database	Amt. in kg	Distance in nautical miles (nm)	Distance in kg km
From	To					
PET producer Shanghai China	Yarn manufacturer, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Yarn manufacturer, Shanghai, China	Yarn wet processor, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Yarn wet processor, Shanghai, China	Port of Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	100
Port of Shanghai, China	Port of Chittagong, Bangladesh	Sea	Transport, freight, sea, container ship GLO	1	4522	8374.74
Port of Chittagong, Bangladesh	Knitwear manufacturer, Dhaka, Bangladesh	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	260
Knitwear manufacturer, Dhaka, Bangladesh	Port of Chittagong, Bangladesh	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	260
Port of Chittagong, Bangladesh	Port of Auckland, New Zealand	Sea	Transport, freight, sea, container ship GLO	1	7304	13527.01
Port of Auckland, New Zealand	Garments retailer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50

Note: RoW= Rest-of-world; GLO= Global

Table 22

Inventory Modelled for Supply Chain Pathway 3

Transport route		Mode	Input inventory from Ecoinvent database	Amt. in kg	Distance in nautical miles (nm)	Distance in kg km
From	To					
NSW Farm, Australia	Port of Sydney, Australia (via wool auction centre)	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	200
Port of Sydney, Australia	Port of Shanghai, China	Sea	Transport, freight, sea, container ship GLO	1	5215	9658.18
Port of Shanghai, China	Wool processing unit, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Wool processing unit, Shanghai, China	Port of Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Port of Shanghai, China	Port of Chittagong, Bangladesh	Sea	Transport, freight, sea, container ship GLO	1	4522	8374.74
Port of Chittagong, Bangladesh	Knitwear manufacturer, Dhaka, Bangladesh	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	260
Knitwear manufacturer, Dhaka, Bangladesh	Port of Chittagong, Bangladesh	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	260
Port of Chittagong, Bangladesh	Port of Auckland, New Zealand	Sea	Transport, freight, sea, container ship GLO	1	7304	13527.01
Port of Auckland, New Zealand	Garments retailer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50

Note: RoW= Rest-of-world; GLO= Global

Table 23

Inventory Modelled for Supply Chain Pathway 4

Transport route		Mode	Input inventory from Ecoinvent database	Amt. in kg	Distance in nautical miles (nm)	Distance in kg km
From	To					
PET producer Shanghai China	Yarn manufacturer, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Yarn manufacturer, Shanghai, China	Yarn wet processor, Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Yarn wet processor, Shanghai, China	Port of Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	100
Port of Shanghai, China	Port of Auckland, New Zealand	Sea	Transport, freight, sea, container ship GLO	1	6252	11578.70
Port of Auckland, New Zealand	Knitwear manufacturer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Knitwear manufacturer, Auckland, New Zealand	Garments retailer, Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50

Note: RoW= Rest-of-world; GLO= Global

Packaging

The role of packaging is of paramount importance and should not be underestimated within the life cycle of a sales commodity such as the jumper under investigation. However, it is also crucial to acknowledge the environmental burden associated with packaging throughout the journey from production to waste, as it is inseparable from the garment itself. Packaging is used at various stages of the garment life cycle, ranging from the distribution of raw materials to the disposal of garments (Choudhury, 2014). However, identifying the specific packaging involved in each step of the garment life cycle and each ancillary material within the supply chain can be challenging.

The study accounted for packaging separately for each of the four transportation pathways. Two stages were identified where the packaging was considered: first, during the transportation of yarn cones from yarn processors to knitwear manufacturers, and second, during the shipping of finished jumpers from knitwear manufacturers to garment retailers. Data regarding the input and output of packaging were obtained through direct conversations with garment merchandisers in Bangladesh, and the packaging inventory in each supply chain scenario was modelled using the Ecoinvent datasets.

For the purposes of this study, it was assumed that a total of 20 yarn cones weighing 500 g each were individually packed in polyethylene bags and shipped together in one cardboard carton box (no stuffing in the boxes will be required for shipping jumpers). Similarly, 20 jumpers, weighing 385 g each, were individually packed in polyethylene bags, consolidated, and placed inside a single cardboard box during transit. It is important to note that the packaging involved in transporting raw wool from farms to wool processors was not categorised here but rather included in the impacts associated with scouring greasy wool. The inventory source for packaging in the four supply chain pathways can be found in Tables 24 to 27.

Table 24

Packaging Inventory Per kg Transport in Supply Chain Pathway 1

	Input inventory from Ecoinvent database	Amount	Output inventory from Ecoinvent database	Amount
Packaging 1 kg yarn from Shanghai, China to Auckland, New Zealand	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh	-	-

Note: RoW= Rest-of-world; GLO= Global; Wh= Watts per hour

Table 25

Packaging Inventory Per kg Transport in Supply Chain Pathway 2

	Input inventory from Ecoinvent database	Amount	Output inventory from Ecoinvent database	Amount.
Packaging 1 kg yarn from Shanghai, China to Dhaka, Bangladesh	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh		
Packaging 1 kg ready garment from Dhaka, Bangladesh to Auckland, New Zealand	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh	-	-

Note: RoW= Rest-of-world; Wh= Watts per hour

Table 26

Packaging Inventory Per kg Transport in Supply Chain Pathway 3

	Input inventory from Ecoinvent database	Amount	Output inventory from Ecoinvent database	Amount
Packaging 1 kg yarn from Shanghai, China to Dhaka, Bangladesh	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh		
Packaging 1 kg ready garment from Dhaka, Bangladesh to Auckland, New Zealand	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh	-	-

Note: RoW= Rest-of-world; Wh= Watts per hour

Table 27

Packaging Inventory Per kg Transport in Supply Chain Pathway 4

	Input inventory from Ecoinvent database	Amount	Output inventory from Ecoinvent database	Amount
Packaging 1 kg yarn from Shanghai, China to Auckland, New Zealand	Packaging film production, low density polyethylene RoW	0.01 kg	Market for waste polyethylene RoW	0.01 kg
	Corrugated board box production RoW	0.1 kg	Treatment of waste paperboard, unsorted, sorting RoW	0.1 kg
	Electricity voltage transformation from high to medium voltage RoW	40 Wh	-	-

Note: RoW= Rest-of-world; Wh= Watts per hour

4.6 Data for Garment Use

Garment use, which encompasses wear and care, is a pivotal element with substantial environmental consequences in its life cycle. This phase involves critical determinants such as laundering, drying, maintenance, and duration of active usage. Consumers have the power to make decisions concerning the care of their garments, including choices related to washing frequency, wash temperature, drying methods, and duration of usage, among others. It has been discussed earlier in the literature (see Chapter 2, Section 2.5.5), how these behaviours demonstrate substantial diversity and notable variations across different countries and cultures (Daystar et al., 2019; Laitala et al., 2017).

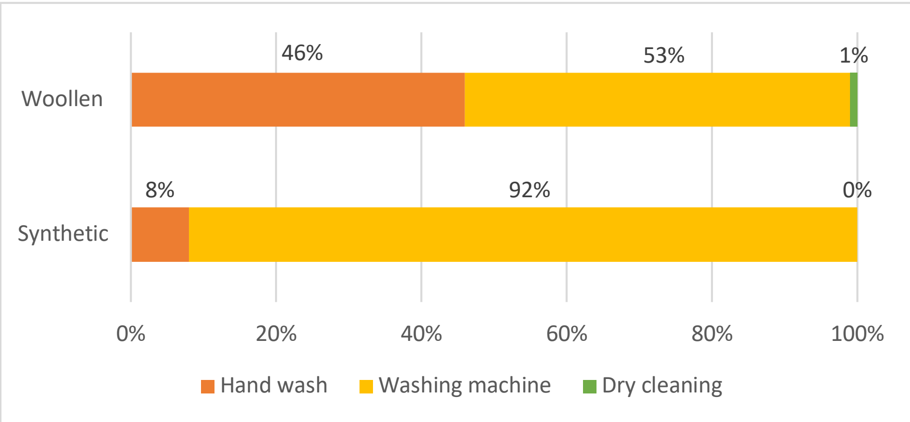
Effectively addressing the uncertainties stemming from a wide range of practices and consumer behaviours poses a significant obstacle for LCA investigations. Assumptions made regarding washing, drying, lifespan, and end-of-use scenarios can disproportionately influence the comparative performance outcomes of garments made from various materials, potentially resulting in misleading information. Given the paramount importance of the use phase in the overall life cycle of garments, relying on primary data to the greatest extent possible is crucial for achieving more accurate inventory modelling (Laitala et al., 2017; Nautiyal et al., 2023b).

Garment usage patterns in New Zealand differ from those observed in other countries and can substantially influence its overall environmental footprint (Nautiyal et al., 2023b). Although previous studies have been conducted in this field, they have not provided the specific data required for modelling the inventory necessary for wool and polyester jumper use in New Zealand. Consequently, a primary survey was undertaken to gather information on laundry practices for garment use, along with an estimation of the lifespan of wool and polyester jumper types. The detailed survey questionnaire and findings are provided in Appendix F and G of this thesis. This survey was used to determine the inventory required for washing and drying wool and polyester jumpers (see Figure 29 – 32), and the laundry frequency and estimated garment lifespan (see Figure 33 - 34).

The survey outcomes indicated that the laundering practices for the two types of jumpers are noticeably different. Approximately 46% of New Zealanders washed their woollen garments by hand, while 53% used washing machines. On the other hand, a majority of 92% machine washed their synthetic clothing, with the remaining 8% opting for hand washing. Only a small number of respondents (1%) chose to dry-clean woollen jumpers (see Figure 29). When looking at the washing machine setting, approximately 88% New Zealanders strongly favoured a delicate wash program and 8% a normal wash. For synthetic jumpers, 57% opted for a normal wash cycle and 33% chose a delicate cycle (see Figure 30) (Nautiyal et al., 2023b).

Figure 29

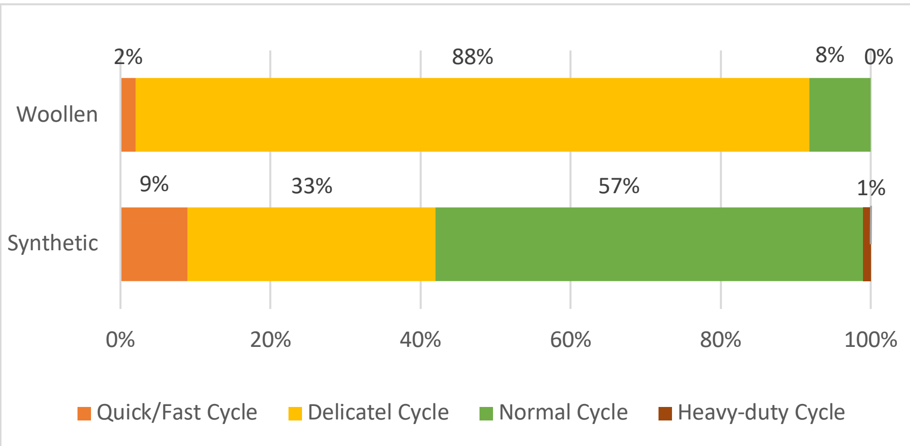
Washing method for Woollen and Synthetic Jumpers in New Zealand



Note: Sourced from Nautiyal et al. (2023b)

Figure 30

Washing machine setting for Woollen and Synthetic Jumpers in New Zealand

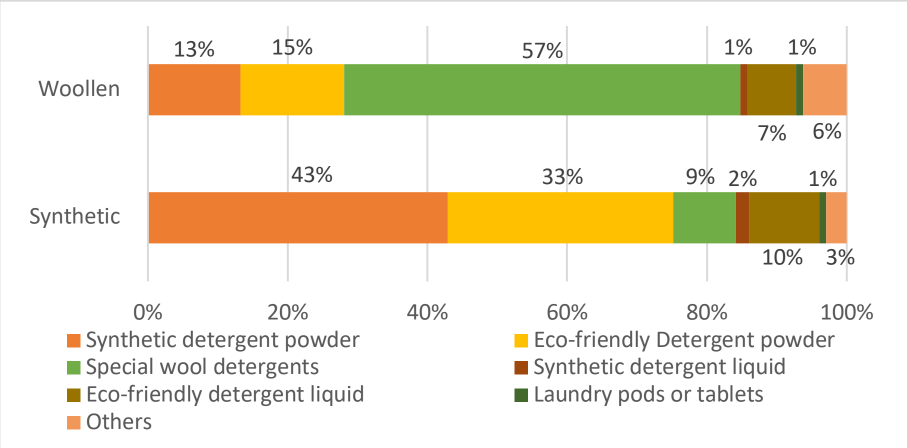


Note: Sourced from Nautiyal et al. (2023b)

In New Zealand, a majority of woollen sweaters (57%) are washed with detergents that specifically contain lanolin. Synthetic jumpers, on the other hand, are washed with either chemical-intensive synthetic detergent powders (43%) or milder eco-friendly detergent powders (32%). Other types of detergents are also used for both material types, but the percentages are small (see Figure 31). Majority of participants, 99% woollen and 88% of synthetic, air-dried their jumpers. The remaining participants used a tumble dryer (see Figure 32) (Nautiyal et al., 2023b).

Figure 31

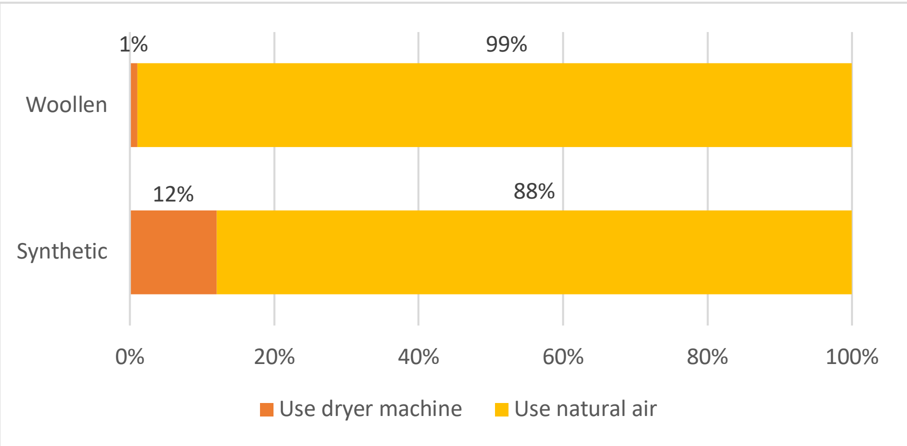
Detergent Used for Woollen and Synthetic Jumpers in New Zealand



Note: Sourced from Nautiyal et al. (2023b)

Figure 32

Drying method for Woollen and Synthetic Jumpers in New Zealand

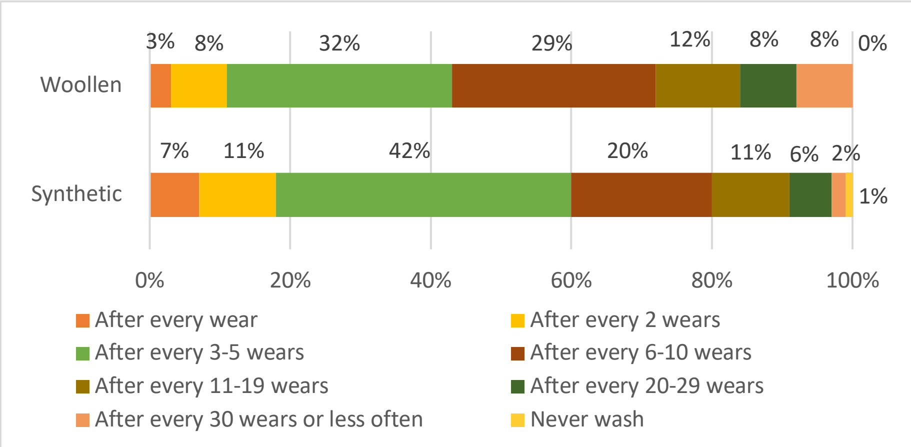


Note: Sourced from Nautiyal et al. (2023b)

When looking at the laundry frequency, woollen jumpers are used twice as long as synthetic ones before needing to be laundered. On average, a woollen jumper was worn 11.5 times, and a synthetic jumper was worn 6.4 times before being laundered (see Figure 33) (Nautiyal et al., 2023b).

Figure 33

Laundry Frequency for Woollen and Synthetic Jumpers in New Zealand

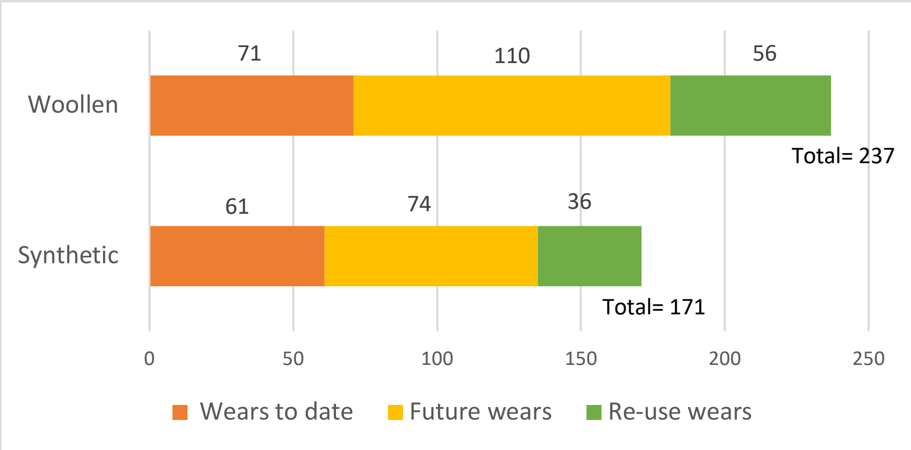


Note: Sourced from Nautiyal et al. (2023b)

According to the survey, woollen jumpers had a higher lifespan than synthetic. On average, woollen jumpers had been worn 71 times, while synthetic jumpers were worn 61 times by the first user. In the future, participants estimated that they would wear woollen jumpers 110 times and synthetic jumpers 74 times. A significant portion of the survey respondents indicated their willingness to donate used jumpers to charity, family, friends, or resell them. Reuse was projected for 83% of woollen and 72% of synthetic jumpers. However, not all clothing designated for reuse gets acquired by a subsequent user, with approximately 25% remaining unused (Nørup, 2019) . Hence, the survey reuse rates were adjusted to 62% for woollen jumpers and 54% for synthetic jumpers. Using the formula $U = L1 + (L2 \times R)$, where L1 is the first life of the jumper, L2 is the second life of the jumper, and total lifespan is estimated. Woolen jumpers are estimated to be worn 237 times, while the total use of synthetic-blend jumpers was estimated to be 171 times in their lifetime (see Figure 34) (Nautiyal et al., 2023b).

Figure 34

Estimated Lifespan for Woollen and Synthetic Jumpers in New Zealand



Note: Sourced from Nautiyal et al. (2023b)

The analysis revealed that woollen jumpers typically undergo 21 washes, whereas polyester jumpers undergo 27 washes during their entire lifespan including reuse. To calculate the amount of soap needed for each wash, a study conducted by Strand (2015) was referenced, which indicated a detergent requirement of 15.6 grams per wash per kilogramme of garments. (Nautiyal et al., 2023b). Table 28 presents a summary of the garment use and end-of-life statistics for wool and synthetic blend jumper types in New Zealand. The inventory employed to evaluate the environmental profile during the use phase of both woollen and polyester jumpers is presented in Table 29. Further details regarding the detergents employed for washing the wool and polyester jumpers are provided in Table 30.

Table 28

Summary of Survey Results for Use and End-of-Life

	Woollen Jumper	Synthetic blend Jumper
Washing methods	More people handwash	Washed primarily using a machine
Washing machine settings	A delicate wash cycle. However, there is uncertainty regarding the load size as woollens may be washed with only half of the machine's capacity (Laitala et al., 2017).	A normal wash cycle.
Washing detergents	By detergents made specifically for wool that contain lanolin	Equally by chemical based and eco-friendly detergent powders
Drying methods	Both are primarily dried naturally	
Laundry frequency	Worn more often before washing. 11.5 times before washing.	Worn less often before each wash. 5.2 times before washing.
Estimated lifespan	237 wears in total, including reuse	171 wears in total, including reuse
Wash per lifespan	21 washes	27 washes
Reuse rate	62%	54%
Downcycling rate	6.5%	5%
Landfilling rate	35.5%	41%

Note: Sourced from Nautiyal et al. (2023b)

Table 29

Inventory for Lifetime Maintenance of 1 Jumper (Based on Survey Results)

Inventory from Ecoinvent dataset	Wool Jumper	Polyester Jumper
Inputs from Technosphere	*Amount*	*Amount*
Soap for washing (as per the material kind)	0.327 kg	0.421 kg
Tap water production, conventional treatment RoW	330.75 kg	357.75 kg
Electricity voltage transformation from high to medium voltage NZ	1.522 kWh	6.3 kWh
Outputs to Technosphere		
Market for wastewater for residence RoW	317.55 litres	343.45 litres
Outputs to nature		
Water lost to evaporation	13.2 litres	14.3 litres

Note: RoW= Rest-of-world; kWh= Kilo watts per hour; NZ= New Zealand

Table 30

Inventory for 1 kg Soap Employed in Maintenance (Based on Detergent Labels)

	Inventory from Ecoinvent dataset	
Lanolin-based soap for washing woollen jumpers	*Inputs from Technosphere*	Amount in kg
	Non-ionic surfactant production, ethylene oxide derivate GLO	0.15
	Ethoxylated alcohol (AE3) production, palm kernel oil RoW	0.05
	Palm oil refinery operation GLO	0.30
	Tap water production, conventional treatment RoW	0.15
	Market for glycerine RoW	0.05
	Lanolin extracted during scouring	0.30
Detergent for washing polyester jumpers	*Inputs from Technosphere*	Amount in kg
	Zeolite production, powder RoW	0.25
	Market for non-ionic surfactant GLO	0.25
	Market for sodium perborate, monohydrate, powder GLO	0.10
	Carboxymethyl cellulose production, powder RoW	0.10
	Market for foaming agent GLO	0.10
	Market for soap GLO	0.20

Note: RoW= Rest-of-world; GLO= Global

4.7 Data for Garment End-of-Life

The management of garments at the end of their life cycle may vary across countries and clothing types. The responsibility for determining how consumers dispose of their clothing lies solely with the individual considering the options available to them (Daystar et al., 2019). Consumers tend to opt for reusing clothing items by giving them to charity, family, or friends, rather than discarding them in a municipal bin, although convenience plays a major role in this decision-making process (Laitala et al., 2017).

Recycling serves as an alternative approach for managing garments that have reached the end of their useful lives. The recycling of clothing products can be achieved through two methods: upcycling, where the material is recycled to the quality of virgin material as in fibre-to-fibre recycling, and downcycling, where a product is used for or in something of lower value (Vogtländer, 2016), for example, the main use of jumpers at the end of their life is a cleaning cloth at home (Nautiyal et al., 2023b). However, fibre recycling has not yet been widely adopted globally because of various challenges, such as the separation of fibres of different composition, blending issues, colour separation, and other complexities associated with it (Sandvik & Stubbs, 2019). In New Zealand, for instance, fibre-to-fibre recycling facilities have not yet been implemented (Casey & Brian, 2021; Cleveland, 2018).

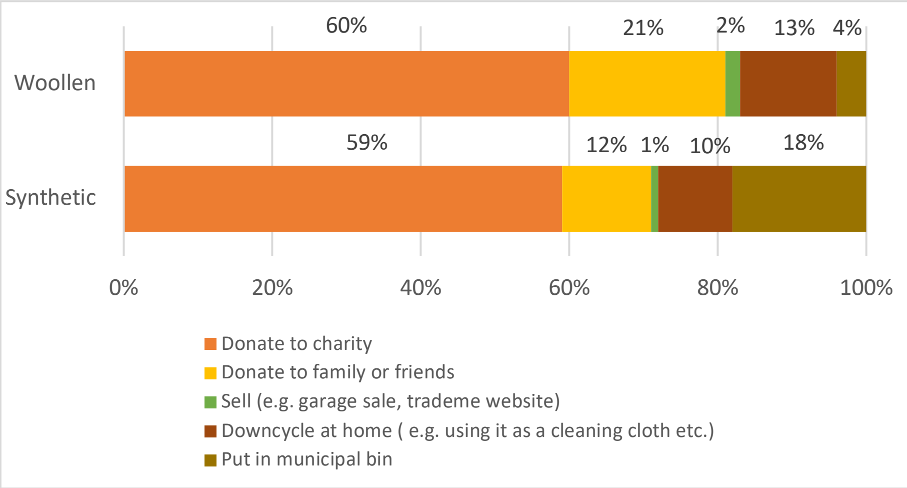
In New Zealand, when initial users no longer desire clothing, several disposal options are available. Charitable donations were the primary destination, with 83% of woollen and 72% of synthetic jumpers donated to charity, friends, family, or resold. However, as discussed earlier in the lifespan of jumper, not all garments for reuse are picked up by a second user and approximately 25% is never worn again (Nørup, 2019). Therefore, 62% of woollen and 54% of synthetic blend jumpers are estimated to be reused (Nautiyal et al., 2023b).

In addition, the survey suggested that 13% of woollen and 10% of synthetic jumpers are downcycled at home and mainly used as cleaning cloths. However, as not all parts of the jumper are downcycled, and many parts, such as the neck and sleeves, are cut off before use, it is assumed that 50% of the downcycled jumpers are discarded in municipal trash. Consequently, 6.5% of the woollen and 5% of the synthetic blend jumpers in New Zealand are downcycled at home for uses like a cleaning cloth (Nautiyal et al., 2023b). Figure 35 illustrates the disposal method for woollen and synthetic blend jumpers in New Zealand. Table 28 presented the percentage breakdown in the end-of-life of woollen and polyester jumpers.

Engaging in practices such as reuse, recycling, or downcycling not only reduces the overall waste associated with the disposal of a garment, but also diminishes the environmental impacts linked to the use of resources used in the production of a new product. This phenomenon is commonly known as "avoided burden," wherein the production of a new product is avoided, thus mitigating the associated environmental impacts (Finnveden et al., 2009). When a second user reuses a jumper, it obviates the need to produce a new jumper. This reuse process, as part of the end-of-life scenario, is therefore considered to be an avoided burden resulting from the production of a jumper. The impacts associated with reuse were calculated using a formula adapted from PAS 2050:2011 (Figure 36) (Henry et al., 2017).

Figure 35

Disposal method for Woollen and Synthetic Jumpers in New Zealand



Note: Sourced from Nautiyal et al. (2023b)

Figure 36

Formula to Calculate the Environmental Impacts when Reusing

$$\text{GW impact} = \frac{A + F}{B} + C + D + E$$

Where:
A = total life cycle impact of product, excluding use-phase
B = the anticipated number of reuse instances for a given product
C = impacts arising from refurbishment of the product
D = impacts arising from use-phase
E =impacts arising from transport returning the product for reuse
F =impacts arising from disposal

Note: Sourced from Henry et al. (2017)

When a jumper is downcycled at home, the impacts associated with manufacturing, packaging, and transporting a new cleaning cloth are eliminated by introducing an additional life cycle, such as a cleaning cloth. Section 4.8 will look at the avoided burden in further detail, specifically focusing on the substitution of data inventory for manufacturing a cleaning cloth with the practice of downcycling sweaters as homemade cleaning cloths.

Unfortunately, regardless of whether the jumpers are reused or downcycled, they will end up in landfills because of the absence of fibre recycling facilities in New Zealand (Casey & Brian, 2021; Cleveland, 2018); therefore, at the end of life, woollen and polyester jumpers both were modelled to be disposed of in landfills. Because specific data differentiating between landfilling wool and polyester material types were not found in the Ecoinvent database, information on the industrial composting method was used for calculating the environmental cost of disposing of wool jumpers. For polyester jumpers, the waste scenario was assumed to be a 50-50 split between PET waste and the treatment of municipal solid waste as noted on Ecoinvent for a global scenario. Refer to Table 31, for details on the waste scenarios considered in the LCA study for the woollen and polyester jumper types.

Table 31

Waste Scenarios for Woollen and Polyester Jumpers

	Inventory from Ecoinvent dataset (materials and/or waste types separated from the waste stream)	Amo- -unt in kg	Percent	Category	Process type	Date of data creation
Woollen jumpers	Treatment of biowaste, industrial composting	1	100%	Landfill	Unit process	11/01/2016
Polyester jumpers	Market for waste polyethylene terephthalate RoW	1	50%	Landfill	Unit process	02/08/2011
	Treatment of municipal solid waste, unsanitary landfill, very wet infiltration class (1000 mm)		50%	Landfill	Unit process	23/03/2002

Note: Sourced from Ecoinvent; RoW= Rest-of-world

It is important to acknowledge that the inventory data employed for the end-of-life fate of wool and polyester jumpers in New Zealand may not represent the most precise landfill waste scenario. However, it was utilised because no other more accurate alternative was found. This highlights the need for more precise waste management scenarios, specifically for those tailored to clothing products. Moreover, the Ecoinvent database offers disposal scenarios for various regions worldwide, such as North America and Europe, but lacks waste management data for New Zealand.

4.8 Data for a Cleaning Cloth as 'Avoided Burden' for Downcycling

A central aspect within the LCA framework is the concept of "avoided burden," which examines the environmental savings achieved through the repurposing or reuse of existing resources, thereby obviating the necessity of manufacturing new products. This approach is designed to minimise resource consumption, encompassing both raw materials and energy, while simultaneously mitigating pollution and curbing waste generation (Finnveden et al., 2009; Tamoor et al., 2022). A survey conducted in New Zealand by Nautiyal et al. (2023b) investigating the usage and disposal patterns of jumpers identified various potential downcycling options for the jumper's end-of-life fate. For example, jumpers were found to be utilised for gardening purposes, as fillers for cushions, and for a few other applications such as making soft toys. However, in this study the end use of a downcycled jumper was assumed to be a cleaning cloth and incorporated in the LCA study to account for the resources saved through their avoidance.

To ascertain the environmental savings or avoided burden related to downcycling woollen and polyester jumper types, a comprehensive assessment was conducted to quantify the resources required to produce cleaning cloth, which would otherwise have been manufactured anew. The quantification of these saved resources contributes to a comprehensive understanding of the environmental benefits associated with the avoided burden in LCA, highlighting the potential of repurposing materials to minimise resource consumption and waste generation while fostering sustainable practices.

The inventory analysis conducted for cleaning cloths involved examining its production process, which specifically encompassed the manufacturing of a nonwoven textile. Nonwoven textiles are characterised as sheets or web of fibres that are bonded together by mechanical, thermal, or chemical means. They differ from traditional textiles in that they do not involve weaving or knitting processes, and do not require fibre-to-yarn conversion.

Based on these guidelines, the production process of the nonwoven polypropylene spun bound fabric was examined within the Ecoinvent library dataset. This process entailed the delivery of the polypropylene (PP) granules to the factory, followed by the manufacturing of the spun bound fabric, cutting, and packaging stages. It was assumed that the all-purpose cleaning cloth was produced in Shanghai, China, implying that the associated inventory originated from China. Tables 32 to 34 provide relevant information pertaining to the inventory employed in the modelling of the life cycle of the cleaning cloth.

Table 32

Inventory for Producing 1 kg All-Purpose Cleaning Cloth, Including Cutting and Packaging

Input inventory from Ecoinvent dataset	Amount in kg	Allocation	Waste type	Process type	Date created
Textile production for non-woven polypropylene, spun bound RoW	1	100%	PET	Unit process	05/12/2017

Note: RoW= Rest-of-world

Table 33

Inventory for Transporting 1 kg All-Purpose Cleaning Cloth

Transport route		Mode	Input inventory from Ecoinvent database	Amount in kg	Distance in nautical miles (nm)	Distance in kg km
Manufacturer in Shanghai, China	Port of Shanghai, China	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50
Port of Shanghai, China	Port of Auckland, New Zealand	Sea	Transport, freight, sea, container ship GLO	1	6252	11578.70
Port of Auckland, New Zealand	Retail outlets in Auckland, New Zealand	Road	Transport, freight, lorry >32 metric ton, EURO4 RoW	1	-	50

Note: RoW= Rest-of-world

Table 34

Waste Scenario for All-Purpose Cleaning Cloth

Inventory from Ecoinvent dataset (materials and/or waste types separated from the waste stream)	Amount in kg	Percent	Category	Process type	Date of data creation
Market for waste polyethylene terephthalate RoW	1	50%	Landfill	Unit process	02/08/2011
Treatment of municipal solid waste, unsanitary landfill, very wet infiltration class (1000 mm)		50%	Landfill	Unit process	23/03/2002

Note: RoW= Rest-of-world

Considering the downcycling rates of 6.5% for woollen jumpers and 5% for synthetic jumpers in New Zealand (Table 28) established by the survey (Nautiyal et al., 2023b), the weight of a cleaning cloth that would substitute a single jumper was derived. Consequently, the environmental impacts connected to the life cycle of a cleaning cloth were evaluated based on the assumption that a 25.02 g cleaning cloth replaced one woollen jumper, while a 19.25 g cleaning cloth replaced one polyester jumper, considering the weight of a single jumper as 385 g. These values were deducted from the environmental impact of the production of the jumpers.

4.9 Conclusion

This chapter focused on the collection of LCI data to assess the environmental impacts associated with the cradle-to-grave life cycles of woollen and polyester jumpers. It discussed the challenges encountered during the data collection phase and emphasised the scarcity of data for textile products in New Zealand. Significant issues regarding sourcing data and their validity for each stage of the product life cycle, including fibre production, fibre pre-processing and processing, garment manufacture, transportation and packing, garment use, and end-of-life, were thoroughly addressed.

The use of the Ecoinvent database has provided insights into global wool production; however, certain limitations have been identified. These limitations included the absence of wool quality specifications and regional breakdowns, particularly concerning merino wool production in Australasia. Additionally, the dataset related to crude oil extraction in polyester fibre production lacked transparency and information at the unit process level was missing, rendering it unsuitable for comparative evaluations and non-compliance with other processes in the Ecoinvent library. Nevertheless, these datasets were utilised as the primary objective of this study was not a comparison of impacts but to establish a methodology for an LCA-based tool for assessing the GWP of a garment, specifically for use by fashion designers. However, this study underscores the need for higher-quality datasets that are more reliable, accessible, and pertinent to textile fibre production.

The lack of extensive fibre pre-processing (scouring) facilities in New Zealand results in most wool being exported in its greasy state. Although primary data were collected from a small-scale wool processor in Auckland, it was inadequate to meet the comprehensive data requirements for LCA. Consequently, a more comprehensive and reliable inventory data for fibre wet processing is lacking in New Zealand, which necessitated the employment of secondary data from published literature for this aspect of the clothing supply chain. Garment manufacturing data could not be obtained from secondary sources and were primarily obtained through laboratory experiments. Controlled environments, such as textile design labs, are advantageous for gathering data on garment-manufacturing techniques. This study found that sampling units, where designers create prototypes for their designs, can provide valuable data on material utilisation, waste, and energy requirements. The transportation and packaging datasets relied on estimations based on four selected supply chain pathways and incorporated an inventory from the Ecoinvent library. Extensive surveys were conducted to gather data on garment use and end-of-life, revealing considerable differences in washing practices, lifetime wear events, and disposal methods between woollen and synthetic garments in New Zealand. The results were used to model the inventory of garment consumption. These findings could prove important for future LCAs in the garment industry.

This chapter provided a comprehensive inventory of all life cycle phases of woollen and polyester jumpers, enabling a valid comparison of their environmental impacts and thereby to facilitate the development of the intended tool to assess the environmental implications of clothing items. The next chapter conducts a comprehensive cradle-to-grave assessment of the environmental impact of these jumpers across eight different life cycle scenarios.

Chapter 5 Results

This chapter presents the findings of the LCA investigation and discusses the steps taken to develop a simplified approach to assess the environmental impact of garments, specifically for fashion designers. The chapter is structured into the following three sections:

- Section One: Comprehensive LCA of Knitted Jumpers
- Section Two: Simplification of the LCA Methodology
- Section Three: Communication with the Design Community

Section one, which comprises sub-sections 5.1 and 5.2, discusses the LCA study conducted as part of this research investigation. Sub-section 5.1 details the background information for the LCA undertaken that includes the goal and scope of the study detailing functional unit, system boundaries, the supply chain pathway considered, and the location of events in the supply chain. Chapter 4 discussed in detail how the Life Cycle Inventory (LCI) is used for the LCA as sourced from the Ecoinvent datasets where possible. Sub-section 5.2 presents the findings for the comprehensive LCA of wool and polyester jumpers, considering the different manufacturing and supply chain pathways.

Section two includes sub-section 5.3, which introduces the simplified LCA-based approach for fashion design. Building upon the comprehensive LCA results obtained from section one, a tool concept was developed to assist fashion designers in assessing the environmental impact of knitted garments in New Zealand. This section outlines the development of the simplified LCA-based approach and the method employed to create it.

Section three, which includes sub-section 5.4, gives a first-hand account of the challenges encountered as a designer researching in the scientific field of LCA, and the strategies used to overcome those barriers. The purpose of sharing this discussion is to enable others to learn from the mistakes made and gain valuable insights into the research process. It aims to improve approaches taken by researchers in future working in the field of fashion practice and sustainability.

Section 1

Comprehensive LCA of Knitted Jumpers

Evaluating the environmental repercussions of a specific garment type is complex because of the multitude of scenarios that can influence the environment throughout its life cycle. Some of the critical decisions a designer makes while considering sustainability approaches in mitigating the environmental impact of their garment designs are the choice of the material, garment manufacturing technique and the place of its production. Figure 37 illustrates the significant life cycle phases of both woollen and polyester jumpers, from the initial fibre production to the end of its useful life, investigated in this study.

Figure 37

Cradle-to-Grave Life Cycle of Woollen and Polyester Jumper

5.1 Goal and Scope of the LCA

This LCA study aimed to conduct a comparative assessment of the overall environmental impacts of a woollen and a polyester jumper. Woollen jumpers were made from merino wool, sourced from New South Wales (NSW) in Australia and the polyester jumper yarn was sourced from China. For this study, it is assumed that the jumpers were produced using cut-and-sew, fully fashioned, and integral knitting techniques of flatbed knitwear manufacturing across various supply chain pathways for consumption and disposal in New Zealand. The intended target audience for this study was fashion designers without an LCA background who seek simplified methods to objectively assess and compare the environmental implications of the garments they designed.

Eight Jumper Scenario Modelled

Eight distinct jumper scenarios which represent typical choices encountered by fashion designers in New Zealand during the garment design phase were formulated and assessed. These scenarios are identified by their respective acronyms: WJCSNZ, WJFFNZ, WJIKNZ, PJCSAS, PJFFAS, PJIKAS, WJIKAS, and PJIKNZ. The first two letters in each acronym denote the material used in the jumper: 'WJ' denotes woollen jumper, while 'PJ' indicates the polyester jumper. The following pairs of letters signify the garment construction method used: 'CS' for cut-and-sew, 'FF' for fully fashioned, and 'IK' for integral knitting. The final pair of letters in each acronym indicates the country of manufacture, with 'NZ' representing that the jumper was locally made in New Zealand and 'AS' representing overseas production in Asia. For this comparative LCA study, all overseas production was assumed to take place in Dhaka, Bangladesh, and local production took place in Auckland, New Zealand.

1. WJCSNZ: Woollen jumper made using cut-and-sew knitwear technology in Auckland, New Zealand.
2. WJFFNZ: Woollen jumper made using fully fashioned knitwear technology in Auckland, New Zealand.
3. WJIKNZ: Woollen jumper made using integral knitting technology in Auckland, New Zealand.
4. PJCSAS: Polyester jumper made using cut-and-sew knitwear technology in Dhaka, Bangladesh.
5. PJFFAS: Polyester jumper made using fully fashioned knitwear technology in Dhaka, Bangladesh.
6. PJIKAS: Polyester jumper made using integral knitting technology in Dhaka, Bangladesh.
7. WJIKAS: Woollen jumper made using integral knitting technology in Dhaka, Bangladesh.

8. PJIKNZ: Polyester jumper made using integral knitting technology in Auckland, New Zealand.

Polyester jumpers produced using cut-and-sew and fully fashioned techniques were not considered in New Zealand. This decision stemmed from the notion that the environmental consequences associated with manufacturing would remain equivalent, and wool was considered for garment manufacturing impacts in New Zealand. Similarly, woollen jumpers using the cut-and-sew and fully fashioned technique were not considered for construction in Asia as their manufacturing impacts would remain equivalent to polyester jumpers manufactured in Asia.

The scope of this study provides a comprehensive description of the investigated system under the following headings: functional unit, system boundary, supply chain pathway, location of events, impact assessment methods and categories, and assumptions made.

5.1.1 Functional Unit

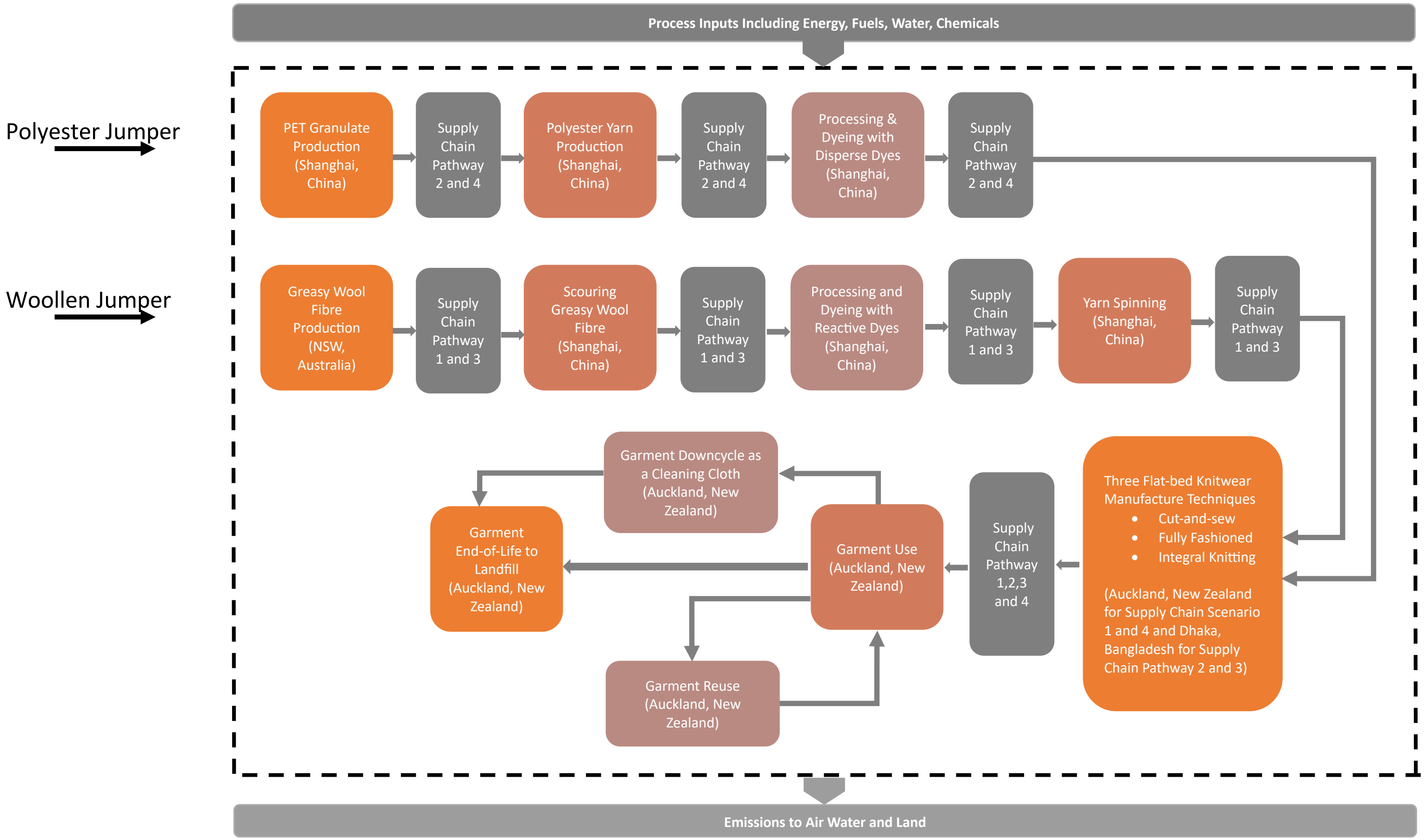
The functional unit for this study was a black (Pantone 19-1619 TPX) knitted jumper intended for lifetime use, weighing 385 g when completed, and made without any accessories or labels.

5.1.2 System Boundary

The system boundary for this study is defined as a cradle-to-grave boundary; that is, it extends from raw material extraction and processing until end-of-life disposal. Figure 38 depicts the system boundary for the woollen and polyester jumper scenarios examined in this LCA.

Figure 38

System Boundary for the Two Jumper Scenarios Examined



5.1.3 Supply Chain Pathway (SCP)

To analyse the impact of multiple transportation modes and the supply chain for garments in New Zealand, four different supply chain routes were considered. These routes were created based on presumptions regarding the location of raw material production and the locations of the hubs that undertake the subsequent processing of these materials. This section includes a description of the four supply chain pathways (SCP) and how they apply to the eight jumper scenarios.

Supply Chain Pathway 1: SCP 1 was considered for the first three jumper scenarios WJCSNZ, WJFFNZ, and WJIKNZ. In this scenario, the production of wool fibre occurred on merino sheep farms in the Australian state of New South Wales; the processing and development of yarn in Shanghai, China; and garment manufacture, use, and disposal in New Zealand. Refer to Supply Chain Pathway 1 in Figure 39.

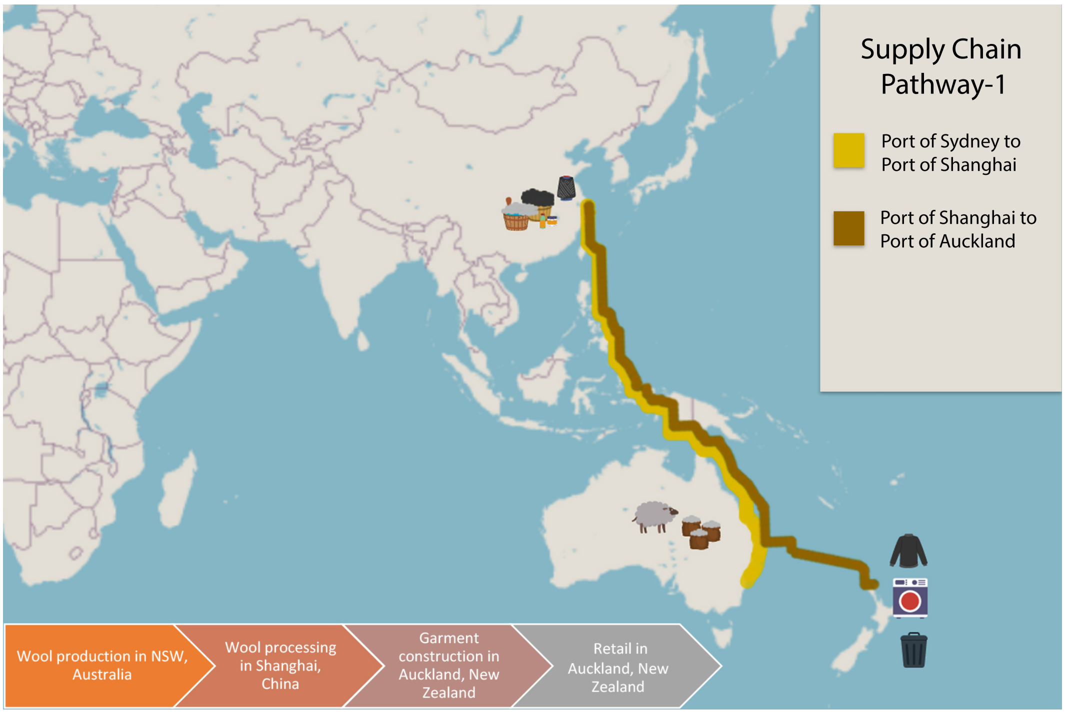
Supply Chain Pathway 2: For the three jumper scenario PJCSAS, PJFFAS, and PJIKAS SCP 2 was employed where the polyester yarn was produced and processed in Shanghai, China; garments were made in Dhaka, Bangladesh; and use and disposal occurred in New Zealand. Refer to Supply Chain Pathway 2 in Figure 40.

Supply Chain Pathway 3: For jumper WJIKAS, SCP 3 was employed, where wool was produced on merino sheep farms in the Australian state of New South Wales, the yarn was processed and developed in Shanghai, China; the garment was constructed in Dhaka, Bangladesh, and its use and disposal occurred in New Zealand. Refer to Supply Chain Pathway 3 in Figure 41.

Supply Chain Pathway 4: In the last jumper scenario, PJIKNZ, SCP 4 captures a pathway where the polyester yarn was produced and processed in Shanghai, China, while the garment was manufactured, used, and disposed of in New Zealand. Refer to Supply Chain Pathway 4 in Figure 42.

Figure 39

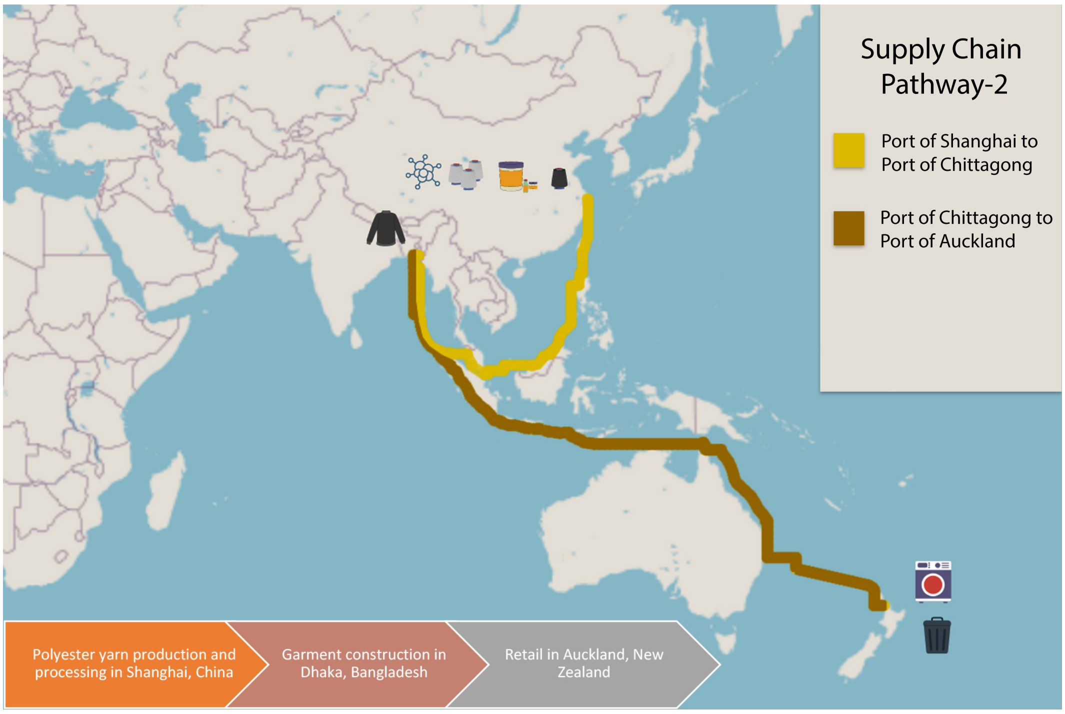
Supply Chain Pathway 1 for WJCSNZ, WJFFNZ, WJIKNZ



Note: Route map source, (Ports.com, 2023)

Figure 40

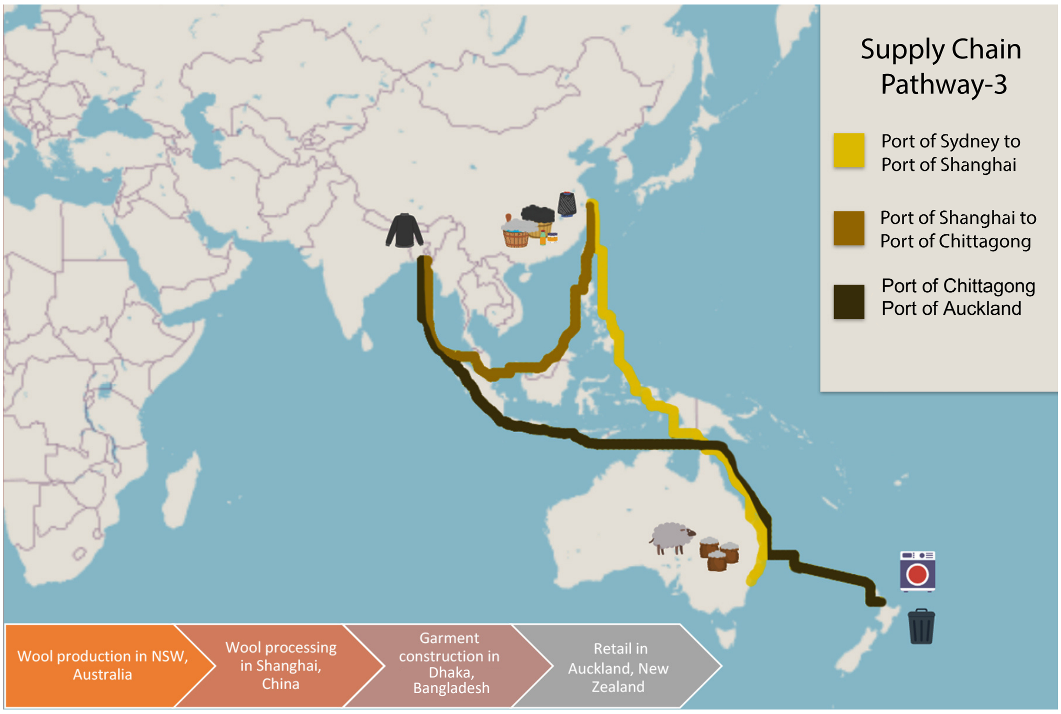
Supply Chain Pathway 2 for PJCSAS, PJFFAS, PJIKAS



Note: Route map source, Ports.com (2023)

Figure 41

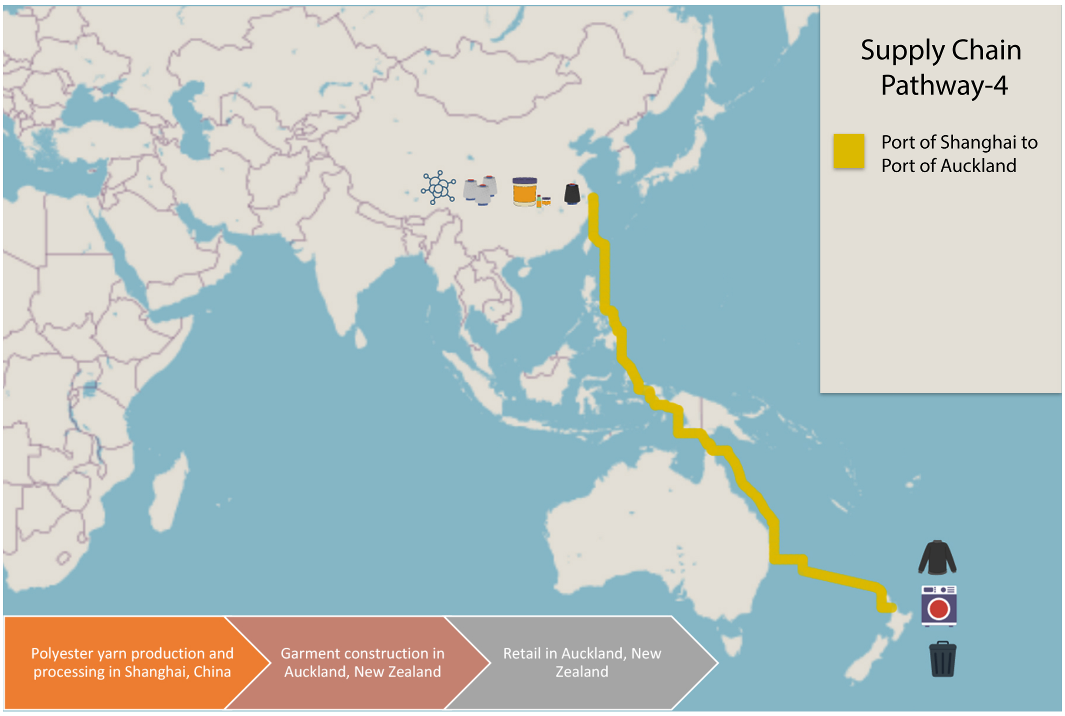
Supply Chain Pathway 3 for WJIKAS



Note: Route map source, Ports.com (2023)

Figure 42

Supply Chain Pathway 4 for PJIKNZ



Note: Route map source, Ports.com (2023)

5.1.4 Location of Events

For this LCA model, it is assumed that merino wool was sourced from Australia's NSW for all four wool related scenarios WJCSNZ, WJFFNZ, WJIKNZ, and WJIKAS. For the remaining polyester jumper scenarios (PJCSAS, PJFFAS, PJIKAS, and PJIKNZ), it was assumed that the polyester fibre used was both produced and converted into yarn in China. Wet processing of all woollen and polyester jumpers occurred in Shanghai, China.

The knitting, cutting, stitching, and finishing operations involved in jumper construction were performed locally in Auckland, New Zealand, for the WJCSNZ, WJFFNZ, WJIKNZ, and PJIKNZ scenarios. For WJIKAS, PJCSAS, WJIKAS, and PJIKAS garment construction operations were performed overseas in Dhaka, Bangladesh. Considering both localised and globalised supply chains, transportation and packaging were modelled in four distinct Supply Chain Pathway (SCP).

SCP 1- Australia-China- New Zealand
SCP 2- China- Bangladesh- New Zealand
SCP 3- Australia- China-Bangladesh-New Zealand
SCP 4- China- New Zealand

It was assumed that woollen and polyester jumpers were destined for use in New Zealand and eventually disposed of in landfills, following a linear economic model. This assumption aligns with the current circumstances in New Zealand, where fibre to fibre recycling facilities are scarce and most textile waste is landfilled (Casey & Brian, 2021). However, a preliminary survey on wool and synthetic blend jumper usage and end-of-life practices in New Zealand (Nautiyal et al., 2023b) revealed that a considerable portion of jumpers (62% woollen and 54% synthetic) were reused, with a smaller portion (6.5% woollen and 5% synthetic) subjected to downcycling. To mitigate the negative consequences of the linear economic model for both types of jumpers, these aspects were considered by adopting an avoided burden approach.

Packaging and transportation occurred at each production and manufacturing phase. Key transportation operations during the production phase were considered, although transportation post-consumer acquisition was not addressed because of the difficulty in establishing a standard for all garments. At the end of their useful lives, all eight scenarios assumed landfill disposal; transportation from municipal bins to landfill sites were assumed to be uniform across scenarios and were thus not considered in this study.

5.1.5 Data Quality

Two aspects concerning data quality had to be considered, including the input-output data, that is, quantities of material and energy used and/or emitted during the life cycle phases of the knitted jumpers, and the life cycle inventory data, that is, the emissions and energy required for the production of material or generation of electricity. Chapter 4 provides a thorough list of the input-output data used in this investigation. Inventory data for all processes were obtained from the Ecoinvent library of the SimaPro database. This study used the Ecoinvent Version 3.7.1 library (allocation at point of substitution, as unit processes). Table 35 lists the input/output data sources and the locations where events took place through the life cycle for each of the eight jumper scenarios examined.

5.1.6 Impact Assessment Method and Categories

ReCiPe 2016, a global methodology for evaluating the environmental impact of products and processes, was used in this study. The midpoint category of climate change, the characteristic factor of which is global warming potential (GWP), was considered for evaluation. The GWP calculations were based on the egalitarian perspective (E), which assesses global warming impacts for a 1000 year time horizon (Stocker et al., 2014).

Table 35

Data Source and Location of Events for the Eight Jumper Scenarios

Unit processes	Subprocesses	WJCSNZ data source	WJFFNZ data source	WJIKNZ data source	PJCSAS data source	PJFFAS data source	PJIKAS data source	WJIKAS data source	PJIKNZ data source
Production	Fibre /yarn production	Wool fibre: Ecoinvent	Wool fibre: Ecoinvent	Wool fibre: Ecoinvent	Polyester yarn: Ecoinvent	Polyester yarn: Ecoinvent	Polyester yarn: Ecoinvent	Wool fibre: Ecoinvent	Polyester yarn: Ecoinvent
	Location	NSW Farms, Australia	NSW Farms, Australia	NSW Farms, Australia	Shanghai, China	Shanghai, China	Shanghai, China	NSW Farms, Australia	Shanghai, China
	Fibre processing	Scouring: (Wiedemann et al., 2019)	Scouring: (Wiedemann et al., 2019)	Scouring: (Wiedemann et al., 2019)	-	-	-	Scouring: (Wiedemann et al., 2019)	-
	Location	Shanghai, China	Shanghai, China	Shanghai, China	-	-	-	Shanghai, China	-
	Dyeing of fibre to black colour	Reactive dye: (Rosa et al., 2019)	Reactive dye: (Rosa et al., 2019)	Reactive dye: (Rosa et al., 2019)	Disperse dye: (Rosa et al., 2019)	Disperse dye: (Rosa et al., 2019)	Disperse dye: (Rosa et al., 2019)	Reactive dye: (Rosa et al., 2019)	Disperse dye: (Rosa et al., 2019)
	Location	Shanghai, China	Shanghai, China	Shanghai, China	Shanghai, China	Shanghai, China	Shanghai, China	Shanghai, China	Shanghai, China
	Yarn spinning	Ecoinvent	Ecoinvent	Ecoinvent	-	-	-	Ecoinvent	-
	Location	Shanghai, China	Shanghai, China	Shanghai, China	-	-	-	Shanghai, China	-
Garment Construction	Knit & Manufacture	Lab experiment	Lab experiment	Lab experiment	Lab experiment	Lab experiment	Lab experiment	Lab experiment	Lab experiment
	Location	Auckland, New Zealand	Auckland, New Zealand	Auckland, New Zealand	Dhaka, Bangladesh	Dhaka, Bangladesh	Dhaka, Bangladesh	Dhaka, Bangladesh	Auckland, New Zealand
	Packaging	Personal contacts	Personal contacts	Personal contacts	Personal contacts	Personal contacts	Personal contacts	Personal contacts	Personal contacts
	Location	Auckland, New Zealand	Auckland, New Zealand	Auckland, New Zealand	Dhaka, Bangladesh	Dhaka, Bangladesh	Dhaka, Bangladesh	Dhaka, Bangladesh	Auckland, New Zealand
Use	Maintenance	Survey	Survey	Survey	Survey	Survey	Survey	Survey	Survey
	Location	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand
End-of-life	Waste Scenario	Survey	Survey	Survey	Survey	Survey	Survey	Survey	Survey
	Location	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand

5.1.7 Assumptions Made

Several assumptions were made during LCA modelling; however, the most generic were related to data accuracy. The key notions were:

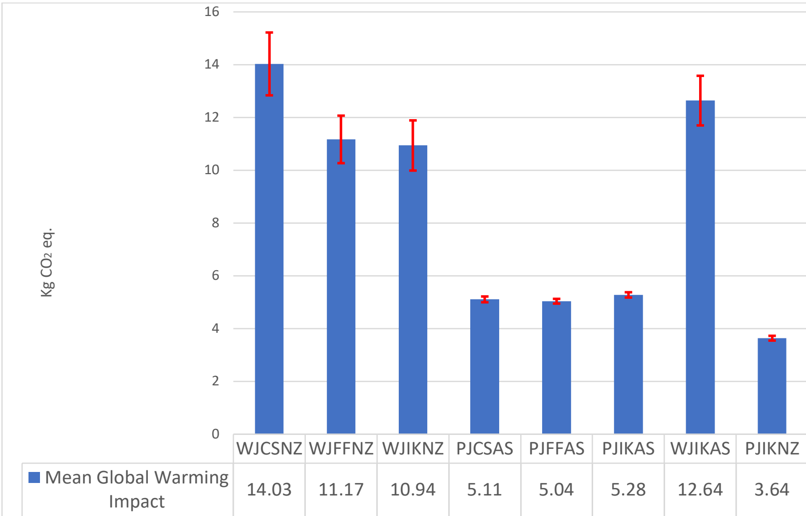
- The Ecoinvent datasets were used to gather information on the production of wool and polyester, which are global data that are not specific to merino wool grown in Australia and polyester yarn produced in China.
- Data on wool scouring were acquired from Wiedemann et al. (2019) and may not be precise.
- The fibre bleaching and dyeing data from Rosa et al. (2019) for reactive and disperse dyes may not apply to the distinct production environments of this study.
- The dyeing information for polyester yarn was taken to be the same as that for polyester fibre.
- In flatbed knitwear technology, yarns with a thickness of 2/28 Nm are produced using the mule-spinning method. Owing to the unavailability of data on mule spinning, data for ring spinning that was available in the Ecoinvent database were employed.
- The data collection on the input inventory for jumper construction may not be accurate as it was collected in a lab environment and therefore may differ from factory conditions. Changes to the equipment could also have an impact on the amount of energy consumed.
- Packaging statistics may vary with manufacturer or retailer preferences or the volume of the jumper and may not be very precise.
- The input data for detergent consumption were based on Strand (2015) on detergent use in Sweden and therefore may not accurately reflect its use in New Zealand.
- The woollen sweater was assigned to the waste scenario of composting, while the polyester jumper was set for the municipal waste scenario. However, this may not be accurate for New Zealand.

5.2 Calculation of the Environmental Impact

In a linear economic model, the impact of the eight jumper scenarios on global warming was evaluated, and the uncertainties in the results were modelled using the Monte Carlo approach. A 95% confidence interval was provided to show the level of absolute uncertainty for each jumper scenario. Figure 43 displays the standard deviation for the global warming impact of the life cycle in the eight jumper scenarios.

Figure 43

Uncertainty Analysis in the Eight Jumper Scenarios Using Monte Carlo



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E, confidence interval: 95%; Uncertainty analysis showing variability within each scenario by Standard Deviation (SD)

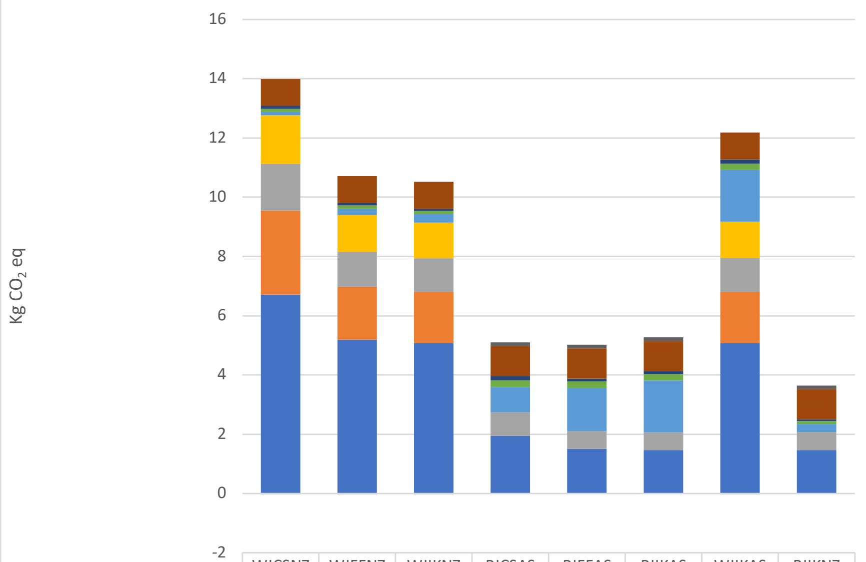
Compared to polyester jumper types PJCSAS, PJFFAS, PJIKAS, and PJIKNZ, the woollen jumpers scenarios WJCSNZ, WJFFNZ, WJIKNZ, and WJIKAS have much greater global warming implications. The woollen jumpers, which were constructed using the cut-and-sew knitwear manufacturing method in SCP 1 (WJCSNZ) had the largest environmental implication (14.03 kg CO_2 eq.), whereas the polyester jumper constructed using integral knitwear technology in SCP 4 (PJIKNZ), had the lowest (3.64 kg CO_2 eq.). Among the woollens, the jumper which was made using the integral knitwear technology in SCP 1 (WJIKNZ), had the least negative impact on global warming (10.94 kg CO_2 eq.).

5.2.1 Comparing Global Warming Impact of Various Life Cycle Phases

The global warming impact of each phase in the garment life cycle was calculated to determine environmental hotspots. In terms of the impact of different life cycle phases, the production and processing of textile fibre had the largest impact on global warming; however, it was proportionally higher for scenarios involving woollen fibres than for polyester. Figure 44 shows the relative impact for each phase of the life cycle of the eight jumper scenarios.

Figure 44

Comparing Impact for Each Life Cycle Phase in Eight Jumper Scenarios



	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
END OF LIFE	-0.02	-0.02	-0.02	0.13	0.13	0.13	-0.02	0.13
LIFETIME USE	0.9	0.9	0.9	1.02	1.02	1.02	0.9	1.02
TRANSPORT	0.11	0.09	0.09	0.14	0.1	0.1	0.14	0.05
PACKAGING	0.11	0.11	0.11	0.22	0.22	0.22	0.22	0.11
GARMENT MANUFACTURE	0.11	0.22	0.27	0.86	1.45	1.75	1.75	0.27
SPINNING WOOL	1.64	1.24	1.21	0	0	0	1.22	0
BLEACHING & DYEING	1.57	1.17	1.14	0.78	0.6	0.59	1.14	0.6
WOOL SCOURING	2.83	1.78	1.73	0	0	0	1.74	0
FIBRE PRODUCTION	6.72	5.2	5.07	1.95	1.51	1.47	5.07	1.47

Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The production of wool fibre, which involves scouring, bleaching, dyeing, and finally spinning the wool fibre into yarn, was responsible for a sizeable portion of the impact in all the woollen jumper scenarios WJCSNZ, WJFFNZ, WJIKNZ, and WJIKAS, which ranged from 5.07 to 6.72 kg CO_2 equivalent emissions. The environmental impacts of polyester fibre production in PJCSAS, PJFFAS, PJIKAS, and PJIKNZ had fewer environmental impacts that ranged from 1.47 to 1.95 kg CO_2 equivalent emissions, which is substantially lower than the values given for the wool. In the polyester jumpers, global warming impact were more evident at the later stages of their life cycles, which included manufacturing, packaging, shipping, use, and eventual disposal which were lower for woollen jumper kinds.

These findings imply that the largest impact in all woollen jumper scenarios (WJCSNZ, WJFFNZ, WJIKNZ, and WJIKAS) primarily occurred in the first four stages of the life cycle from the production of the fibres to the spinning of woollen yarn. In contrast, the manufacturing, lifetime usage, and end-of-life of the garments had a proportionally greater impact on the overall life cycle of the polyester jumper scenario (PJCSAS, PJFFAS, PJIKAS, and PJIKNZ), which were larger than that for woollen.

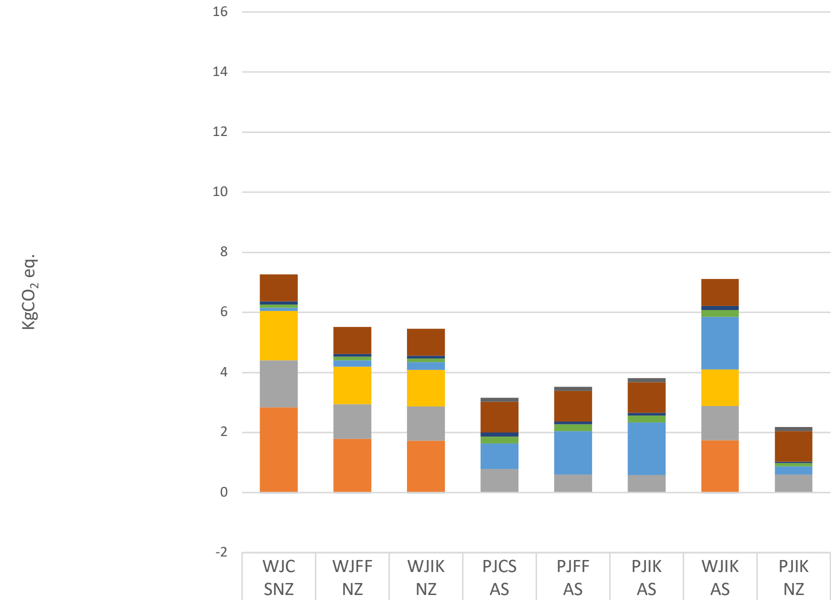
5.2.2 Not Considering the Impacts of Fibre Production

Chapter 4, sub-section 4.2.2 of this thesis extensively discusses the inherent unreliability of the Ecoinvent v. 3. 7.1 datasets concerning polyester fibre production, emphasising that this dataset should not be employed, particularly in the context of comparative assessments. Therefore, to ensure fair comparisons between wool and polyester jumper types, this investigation re-examined the eight scenarios while disregarding the impact of fibre production for both material types. This fact had a transformative effect on the overall impact linked to the life cycle of the eight jumper scenarios, as depicted in Figure 45. The figure vividly illustrates that the impact attributed to wool production was diminished by half in comparison to the previous depiction in Figure 44. The polyester jumper types also exhibited a reduction in their overall impact, although the extent of this reduction was not as pronounced as that observed in the four woollen jumper scenarios.

Table 36 presents the total global warming impact of the eight jumper scenarios with and without considering the impact of fibre production. The table also shows the percentage reduction in impact for all eight scenarios, proving that woollen jumpers exhibited a range of 44–51% reduced impact, whereas, for polyester, it was low at the 28–40% range when excluding the fibre production data.

Figure 45

Comparing Impact for Each Life Cycle Phase Excluding Fibre Production



	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
END OF LIFE	-0.02	-0.02	-0.02	0.13	0.13	0.13	-0.02	0.13
LIFETIME USE	0.9	0.9	0.9	1.02	1.02	1.02	0.9	1.02
TRANSPORT	0.11	0.09	0.09	0.14	0.1	0.1	0.14	0.05
PACKAGING	0.11	0.11	0.11	0.22	0.22	0.22	0.22	0.11
GARMENT MANUFACTURE	0.11	0.22	0.27	0.86	1.45	1.75	1.75	0.27
SPINNING WOOL	1.64	1.24	1.21	0	0	0	1.22	0
BLEACHING & DYEING	1.57	1.17	1.14	0.78	0.6	0.59	1.14	0.6
WOOL SCOURING	2.83	1.78	1.73	0	0	0	1.74	0

Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

Table 36

Global Warming Impact, With and Without Considering Fibre Production

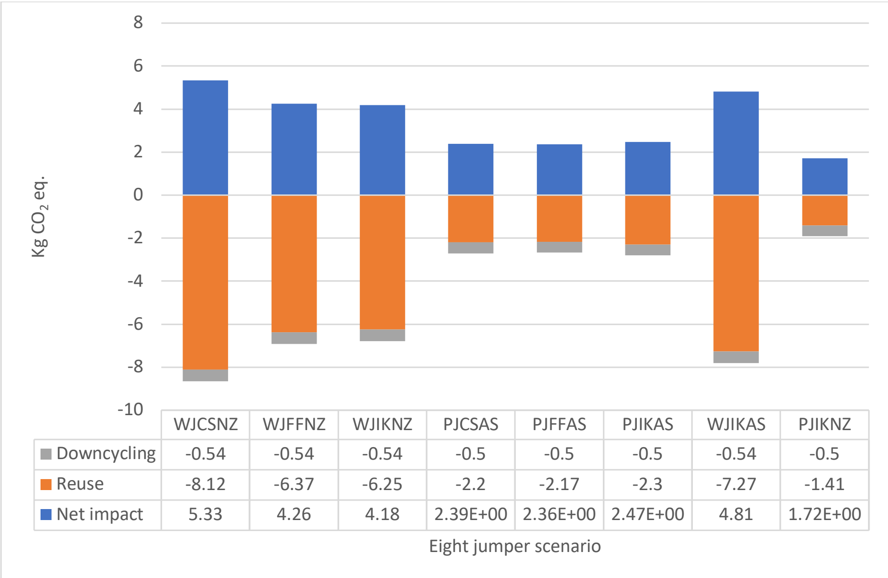
	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
With fibre production	14.03	11.17	10.94	5.11	5.04	5.28	12.64	3.64
Without fibre production	7.25	5.49	5.43	3.15	3.52	3.81	7.09	2.18
Impact reduction	48%	51%	50%	38%	30%	28%	44%	40%

5.2.3 Avoided Impacts by Reuse and Downcycling

When considering reusing and downcycling the jumpers, the negative environmental impacts of producing raw material, processing it, and manufacturing it into a new product were avoided. When the reuse and downcycling percentages for knitted garments in New Zealand were applied, the production of both wool and polyester jumpers showed a significant reduction in their overall environmental consequences. When the reuse percentages were applied to the linear economic model, the environmental impact of making new woollen and polyester jumpers decreased by 62% and 54 %, respectively. Similarly, when downcycling was considered, the environmental impact of the woollen and polyester jumper types was reduced by 6.5% and 5%, respectively. The impact of net global warming on the jumper's life cycle following a circular economic model (considering reuse and downcycling) is shown in Figure 46.

Figure 46

Impact Considering Reuse and Downcycling in the Eight Jumper Scenarios



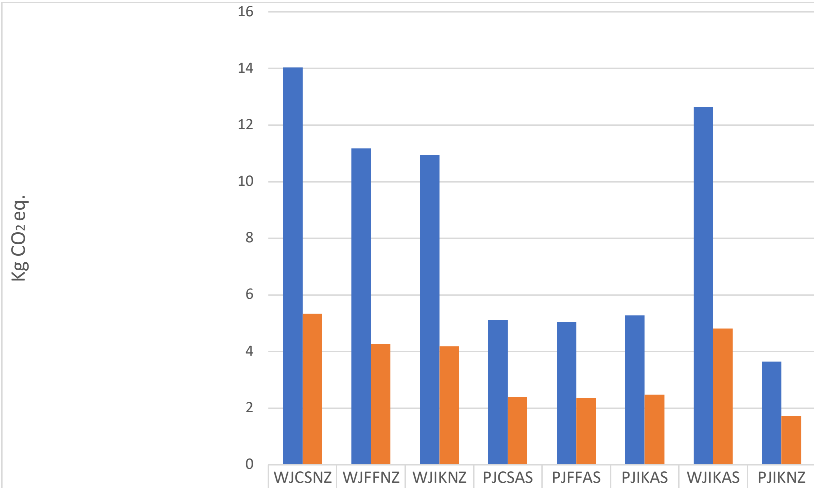
	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
Downcycling	-0.54	-0.54	-0.54	-0.5	-0.5	-0.5	-0.54	-0.5
Reuse	-8.12	-6.37	-6.25	-2.2	-2.17	-2.3	-7.27	-1.41
Net impact	5.33	4.26	4.18	2.39E+00	2.36E+00	2.47E+00	4.81	1.72E+00

Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The global warming impact in all eight jumper scenarios decreased compared to the net impact after reuse and downcycling. Figure 47 shows the reduced impact of global warming for each of the eight jumper scenarios in a circular economy adjacent to the impact on a linear economy.

Figure 47

Comparing Impact in a Linear versus Circular Economy



	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
KgCO2 eq. Impacts in a Linear Economy	14.03	11.17	10.94	5.11	5.04	5.28	12.64	3.64
KgCO2 eq. Impacts after Reuse and Downcycling	5.33	4.26	4.18	2.39E+00	2.36E+00	2.47E+00	4.81	1.72E+00

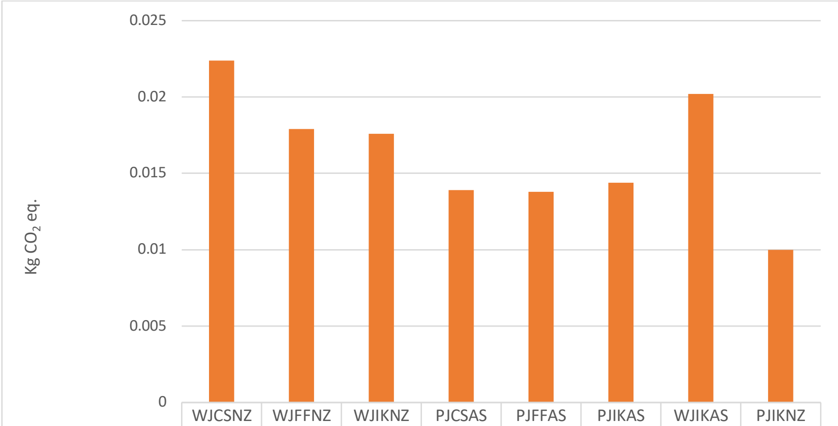
Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

5.2.4 Analysing Impact Per Garment Wear

Considering both the first use and reuse, consumer estimates in New Zealand indicated that woollen jumpers were worn 237 times compared to 171 times for synthetic blend jumpers (Nautiyal et al., 2023b). Consequently, the impact of each wear of the jumper depending on its material type would provide a clearer picture of the impact of the eight jumper scenarios investigated in this study. The global warming impact per wear for both materials were calculated by dividing their total impact by the number of wears per lifetime (including reuse). Figure 48 displays the impact per wear in the eight jumper scenario analysed.

Figure 48

Comparing Impact per Wear in the Eight Jumper Scenario



	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
Impact Per Wear	0.0224	0.0179	0.0176	1.39E-02	1.38E-02	1.44E-02	0.0202	1.00E-02

Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

While the consequences of wearing a woollen jumper per wear ranged from 0.0224 to 0.0176 kg CO_2 eq., those of polyester jumpers ranged from 0.0144 to 0.0100 kg CO_2 eq. Once more, the impact per unit of wear was lowest for PJIKNZ (0.0100 kg CO_2 eq.) and greatest for WJCSNZ (0.0224 kg CO_2 eq.), corresponding to their overall lifetime impact.

5.2.5 Concluding the LCA of Knitted Jumpers

This section successfully employed the LCA methodology to evaluate the environmental consequences of garments produced using various material options, production techniques, and supply chain pathways for consumption in New Zealand. The LCA methodology encompassed goal and scope definition, inventory analysis, impact assessment, and interpretation, ensuring a comprehensive evaluation of the environmental impact of woollen and polyester jumpers.

The study's functional unit was established as a single knitted jumper, weighing 385 g, in black colour, devoid of any accessories or labels, and intended for use and disposal in New Zealand. The system boundary encompasses the entire cradle-to-grave life cycle, spanning from raw material extraction to end-of-life disposal. To assess the environmental impact, the LCA study employed the ReCiPe 2016 methodology for impact assessment, with a specific focus on the midpoint category of climate change and utilising Global Warming Potential (GWP) as the characterisation factor. Furthermore, the study adopted an egalitarian perspective, considering the impact over a 1000-year timeframe.

The results revealed that woollen jumpers have greater global warming implications than polyester jumpers. Notably, the production and processing stages of textile fibres exerted the greatest influence throughout the entire cradle-to-grave life cycle of the jumpers. Wool jumpers displayed a higher impact attributed to wool fibre production, subsequent wet processing involving scouring, bleaching, and dyeing, and the requirement for spinning the fibre after processing.

In conclusion, the obtained results effectively addressed the primary research question by elucidating the LCA methodology employed to evaluate the environmental impact of knitted jumpers consumed in New Zealand. LCA analysis of the eight jumper scenarios provided valuable insights into the global warming impact of clothing items, underscoring the significance of material selection, garment manufacturing techniques, and supply chain pathways in assessing their overall environmental profile. The subsequent section of this chapter leverages the findings from this LCA investigation to develop a simplified method that can be employed for future environmental assessments of garments.

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Section 2

Simplification of the LCA Methodology

Building upon the insights gained from the comprehensive LCA investigation conducted in section one, this section focuses on the development of a simplified approach for the environmental assessment of garments. The results obtained from the LCA analysis of knitted jumpers consumed in New Zealand highlighted the crucial role of material choice, garment manufacturing technique, and supply chain pathway in assessing their overall environmental implications. By leveraging this knowledge, this section proposes a systematic method that can serve as a practical approach for measuring the global warming impact of clothing items. The goal of developing a simplified LCA-based approach is to facilitate the integration of environmental considerations into routine fashion practice.

5.3 Development of an LCA-based Tool for Fashion Design

In order to simplify the LCA methodology it was necessary to provide a more detailed comparison of the different elements involved in the garment life cycle. As a result, comparisons were made between similar jumper scenarios. The following sub-sections compare the eight jumper scenarios, based on the material used (section 5.3.1) garment construction technique (section 5.3.2), supply chain pathway (section 5.3.3) and their use and end-of-life (section 5.3.4). Finally, the most relevant data are extracted from these comparisons to develop a simplified LCA-based approach and subsequently design a process flowchart called "Simplified LCA framework for Fashion Design," that will serve as the blueprint for programming the proposed tool for rapid environmental evaluations (sections 5.3.5 and 5.3.6).

5.3.1 Impact of Material Production and Processing

To compare the impact related to the production of woollen and polyester fibres, two jumper scenarios, WJIKNZ and PJIKNZ, were contrasted, as both were made using the integral knitting technique in New Zealand and required the same quantity of raw material (393 g). The findings showed that manufacturing 393 g of wool yarn (5.07 kg CO_2 eq.) had a much higher environmental impact than producing same amount of polyester yarn (1.47 kg CO_2 eq.). Figure 49 illustrates the difference in impact of the production of fibre for the woollen and polyester jumper types.

Figure 49

Comparing Impact of Wool and Polyester Fibre Production

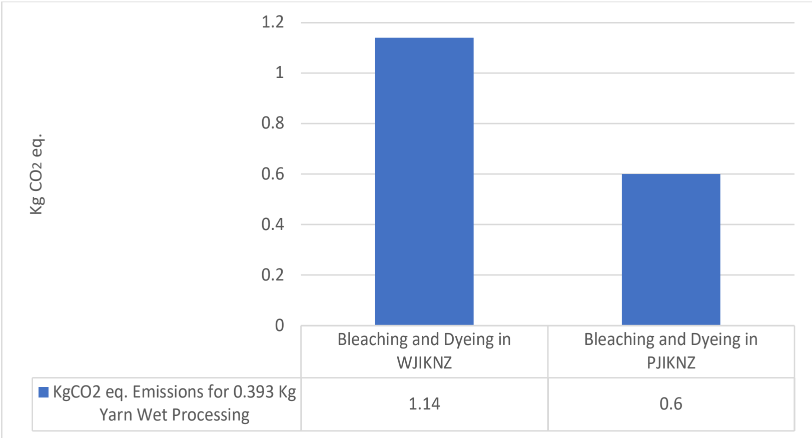
Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

This information was incorporated into the proposed tool to compute the impact of yarn production for polyester and woollen fibre types. As a baseline for estimating the impact of any weight of woollen and polyester material, the impact of manufacturing one kilogramme of material was calculated.

When comparing the wet-processing outcomes, which comprises bleaching and dyeing woollen with reactive dyes and polyester with disperse dyes, as is the requirement for these fibre types, the results showed a larger impact for WJIKNZ (1.14 kg CO_2 eq.) than PJIKNZ (0.6 kg CO_2 eq.). Figure 50 depicts the impact of bleaching and dyeing woollen and polyester fibres, both in a jet-black shade (Pantone 19-1619 TPX).

Figure 50

Comparing Impact of Wool and Polyester Fibre Wet-Processing



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

Woollen fibre requires additional processing before being dyed, which includes scouring the raw fibre or taking the grease out, which is not required in the production of polyester yarn. According to this study, the scouring of the wool fibre produced 1.73 kg CO_2 equivalent for every 393 g of wool used to make a jumper in the WJIKNZ scenario. Furthermore, the environmental impact of the spinning of polyester yarn was also included in the production of fibres, but this was not the case for spinning wool, as it occurred after scouring, bleaching, and dyeing. During the spinning of wool into yarn, a further 1.21 kg of CO_2 equivalent emissions were produced in the WJIKNZ scenario.

Because the above impact was brought on by processing 393 g of each of the two material types, the impact of processing one kilogramme of fibre was required to be estimated for the intended simplified framework. However, it is also important to consider the reduced benefits of reuse and downcycling as it substantially influence global warming by mitigating the amount of material required to produce a new garment. The impact on production and processing was reduced by 62% for reuse and 6.5% for downcycling woollen (62+6.5= 68.5%), and by 54% for reuse and 5% for downcycling polyester jumper (54+ 5= 59%). Based on these calculations, the impact of producing and processing one kilogramme material, was calculated. Table 37 provides the net impacts of producing and processing one kilogramme material after considering the reduction in impacts by reuse and downcycle for both wool and polyester jumpers.

Table 37

Impact of Producing and Processing 1 kg Material, Considering Reuse and Downcycling

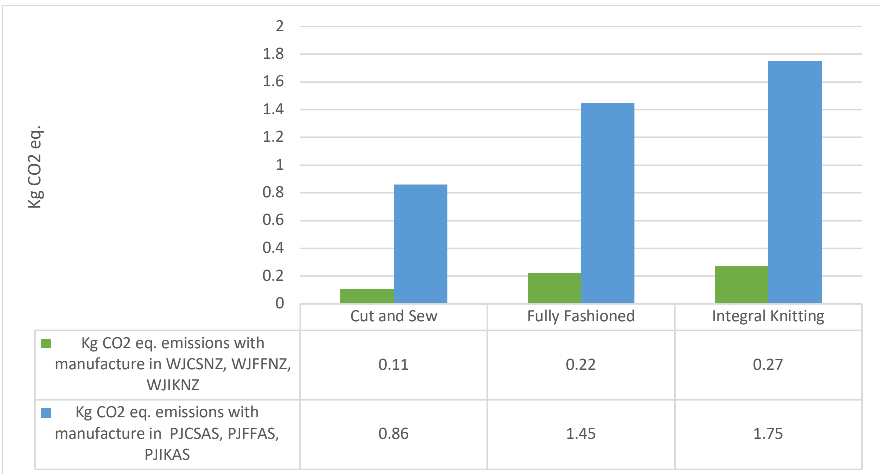
	In 393 g wool fibre (kg CO_2 eq.)	In 1 kg wool fibre (kg CO_2 eq.)	In 393 g polyester fibre (kg CO_2 eq.)	In 1 kg polyester fibre (kg CO_2 eq.)
Production of fibre	5.07	12.90	1.47	3.74
Scouring of fibre	1.73	4.40	-	-
Bleaching and dyeing fibre	1.14	2.90	0.6	1.52
Spinning fibre to yarn	1.21	3.07	-	-
Production and processing impact for 1 kg material in linear economy		23.27		5.26
Avoided impact by reuse and downcycling (68.5% for wool and 59% for polyester)		-15.93		-3.10
The total impact of production and processing material in circular economy		7.34		2.16

5.3.2 Impact of Garment Construction

The findings showed that the cut-and-sew approach had the least negative impact on global warming compared with fully fashioned and integral knitting. Figure 51 presents how the three flatbed knitwear manufacturing techniques for various materials (woollen and polyester) had different global warming impacts.

Figure 51

Comparing Impact of Three Flatbed Manufacturing Techniques



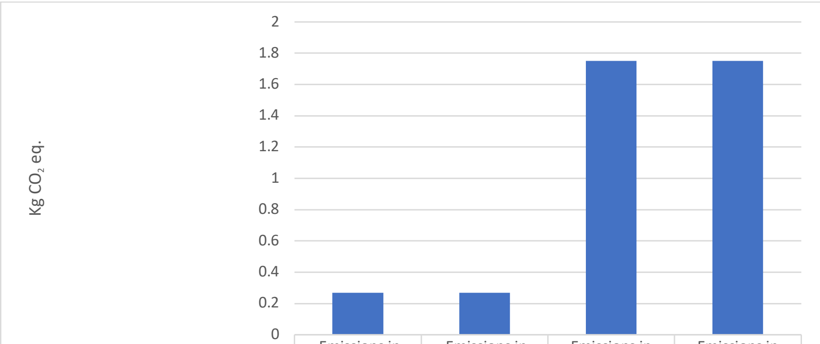
Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The manufacturing of woollen jumper types WJCSNZ, WJFFNZ, and WJIKNZ had lower global warming consequences than polyester jumper manufacturing. Among the woollens, the cut-and-sew jumper WJCSNZ had the lowest impact (0.11 kg CO_2 eq.), while the integral knitted jumpers had the largest (0.27 kg CO_2 eq.). Among the polyester jumpers manufactured through integral knitting, PJIKAS had the highest carbon emissions (1.75 kg CO_2 eq.), whereas PJCSAS had the lowest (0.86 kg CO_2 eq.).

The impact of global warming on the construction of woollen and polyester jumpers differed in terms of the place of manufacture. In this model, the production of woollen jumpers in scenarios WJCSNZ, WJFFNZ, and WJIKNZ was carried out in New Zealand, which relies on hydro-based renewable energy sources, whereas the manufacturing of polyester jumpers PJCSAS, PJFFAS, and PJIKAS was assumed to take place in Dhaka, Bangladesh, which relies on natural gas as its energy source. We can observe the disparities that have developed because of the use of different energy sources in New Zealand and Bangladesh by examining the energy consumption in the four integral knitting scenarios WJIKNZ, PJIKAS, WJIKAS, and PJIKNZ (Figure 52).

Figure 52

Comparing Impact of Integral Knitting in New Zealand and Bangladesh



	Emissions in manufacturing WJIKNZ	Emissions in manufacturing PJIKNZ	Emissions in manufacturing WJIKAS	Emissions in manufacturing PJIKAS
Integral knitting scenarios in Kg CO2 eq.	0.27	0.27	1.75	1.75

Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The findings highlight the significant variations in the impact of manufacturing jumpers in New Zealand and Bangladesh. For the four integral knitting jumper techniques for the construction of one jumper, a standard energy consumption of 2670 Watt Hour of electricity and 6000 Joules of heat from steam was considered. Similarly, the solid waste generated in each of the four scenarios was considered to be the same (8 g). Both jumpers made of wool and polyester in New Zealand, WJIKNZ and PJIKNZ, both displayed a smaller negative impact (0.27 kg CO_2 eq. emissions) than those made of wool and polyester in Bangladesh, WJIKAS and PJIKAS (1.75 kg CO_2 eq. emissions). This highlighted that jumpers made in New Zealand had environmental impacts that were 15% lower than those made in Bangladesh.

For simplification, it was important to separate the manufacturing-related consequences into energy use and material loss to implement the environmental impact of garment construction. For each of the three flatbed knitwear manufacturing techniques, the impact on the energy consumption for one kilogramme of jumper material was considered independently using the SimaPro programme. However, as 62% of woollen and 54% of polyester jumpers were reused, they reduced the energy needed to make new jumpers and were therefore included as an avoided burden. Table 38 shows the global warming impact of the three flatbed knitwear manufacturing techniques in the construction of a one kilogramme jumper, as well as the implications that can be avoided by reuse.

Table 38

Impacts for Energy Consumption in Garment Construction for 1 kg Material, Considering Avoided Burden by Reuse

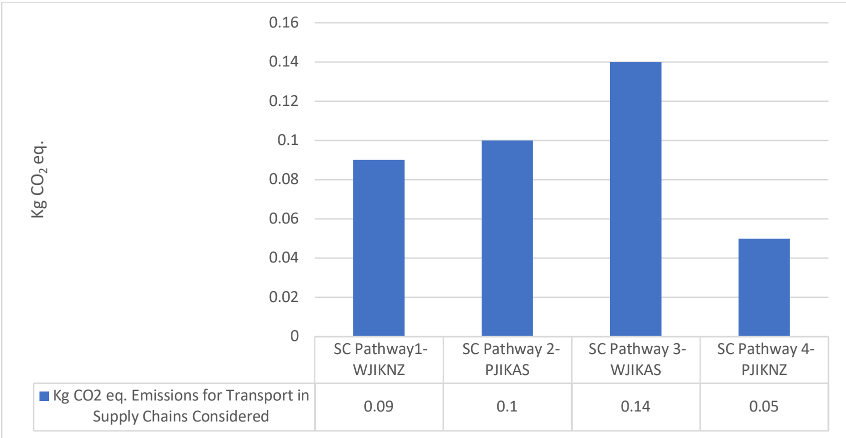
	Cut-and-sew Technique (kg CO_2 eq.)		Fully Fashioned Technique (kg CO_2 eq.)		Integral Knitting Technique (kg CO_2 eq.)	
Impact of energy consumption in manufacturing 1 kg jumper	2.08 in BD/ 0.32 in NZ		3.75 in BD/ 0.58 in NZ		4.53 in BD/ 0.72 in NZ	
	Wool	Polyester	Wool	Polyester	Wool	Polyester
Avoided burden for constructing a new jumper (based on reuse percentage)	-1.28	-1.12	-2.32	-2.02	-2.80	-2.44
Total impact for energy consumption for 1 kg garment in BD. Reduce 15% if manufactured in NZ	0.8	0.96	1.43	1.73	1.73	2.09

5.3.3 Impact of Transportation and Packaging

When comparing the global warming impact for the different supply chain pathways investigated, SCP 3 employed in the life cycle of WJIKAS had the highest environmental repercussions (0.14 kg CO_2 eq. emissions). The environmental impact of SCP 4 was a third of SCP 3, which had the smallest impact on global warming (0.05 kg CO_2 eq.). Figure 53 depicts the differences between the four supply chain pathways considered.

Figure 53

Comparing Impact of Transport for the Four Supply Chain Pathways

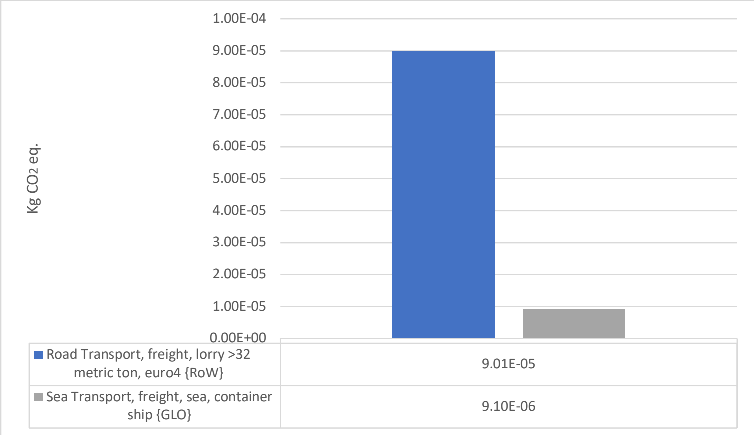


Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

Because numerous modes of transportation could occur and the supply chain pathway could change depending on the situation and availability of materials, for the simplified framework, transportation was divided into two categories: road transportation and sea transportation. Figure 54 illustrates the impact of the mode of transportation by providing the global warming impact of transporting one kilogramme of textile material for one kilometre on a road and across the sea.

Figure 54

Comparing Impact of 1 kg per km Transport through Road and Sea



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

However, as different knitwear manufacturing scenarios call for varied material weights to be transported, their impact on transportation in the simplified framework needed to be altered for each of the chosen methods of garment manufacturing. Thus, an additional transportation impact of 26.2% for cut-and-sew, 4.6% for fully fashioned, and 2.1% for integral knitting operations were added. This was done to accommodate the environmental impact of the waste generated in each of the three knitwear manufacturing techniques. The impact of shipping one kilogramme of material via road and sea in the three flatbed knitwear manufacturing techniques is given in Table 39.

Table 39

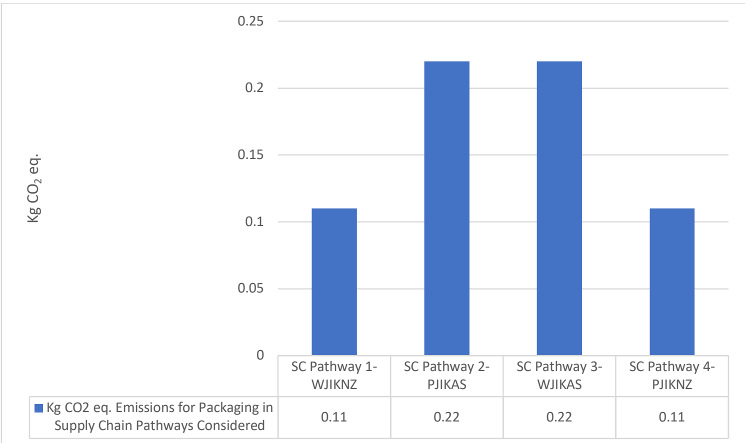
Adjusted Impact of Transportation by Road and Sea for 1 kg Jumper Material in Different Manufacturing Techniques

	Woollen / Polyester jumper		
	Cut-and-sew Technique (kg CO_2 eq.)	Fully Fashioned Technique (kg CO_2 eq.)	Integral Knitting Technique (kg CO_2 eq.)
Impact for transporting by road 1 kg material (when ready) for 1 kilometre	0.00020	0.00016	0.00016
Impact for transporting by sea 1 kg material (when ready) for 1 kilometre	0.000011	0.000009	0.000009

Throughout the lifespan of a jumper, packaging occurs multiple times, and this frequency mostly increases with the frequency of transportation requirements for materials or produced goods. One jumper from each supply chain pathway was chosen and compared with another to understand the impact of packing on global warming. When compared, SCPs 2 and 3 in WJIKAS and PJIKAS scenarios had greater emissions (0.22 kg CO_2 eq.) than SCPs 1 and 4 in scenarios WJIKNZ and PJIKNZ (0.11 kg CO_2 eq. emissions). Figure 55 illustrates the impact of packaging jumpers in each of the four supply chain pathways.

Figure 55

Comparing Impact of Packaging in Four Supply Chain Pathways



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The standardisation of packaging must be included in the proposed simplified method. The LCA revealed that when garments are manufactured overseas, the impact of packaging increases. As in this study, packaging took place twice in SCP 2 and SCP 3, first when yarns were transferred from one country to another and again when a finished garment was moved. Packaging occurred only once to transport the yarns in SCPs 1 and 4. As a result, the simplified LCA framework can make the packaging's impact proportional to the place of garment manufacture, with local production having a lesser impact than global production. Table 40 provide the impact of packaging one kilogramme jumper in three flatbed knitwear manufacturing techniques according to their location of manufacture.

Table 40

Packaging Impact for 1 kg Material, Based on the Location of Garment Manufacture

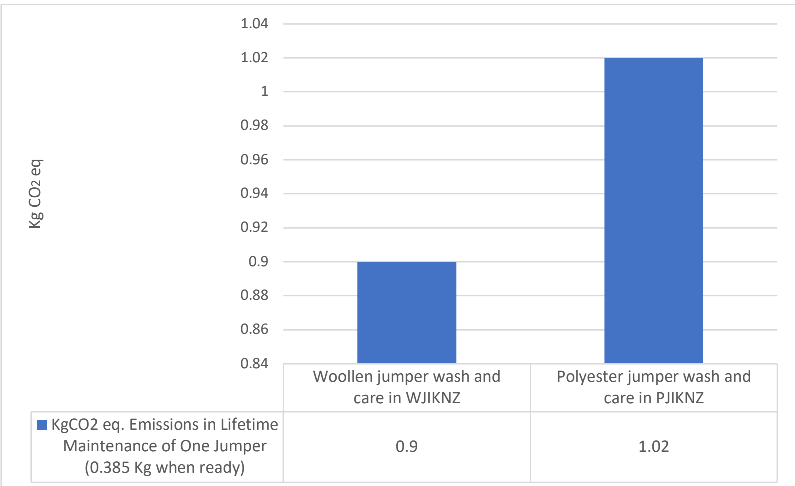
	Woollen and Polyester Jumper					
	Cut-and-Sew (kg CO_2 eq.)		Fully Fashioned (kg CO_2 eq.)		Integral Knitting (kg CO_2 eq.)	
	Packaging 385 g Jumper	Packaging 1 kg Jumper	Packaging 385 g Jumper	Packaging 1 kg Jumper	Packaging 385 g Jumper	Packaging 1 kg Jumper
Impact for 1 kg of a locally manufactured garment (in New Zealand)	0.11	0.28	0.11	0.28	0.11	0.28
Impact for 1 kg of a globally manufactured garment (in Bangladesh)	0.22	0.57	0.22	0.57	0.22	0.57

5.3.4 Impact for Use and End-of-Life (EOL)

Both types of jumpers had different lifetime maintenance impacts during the use phase, with woollen jumpers having slightly less impact than polyester. When comparing the use phase impact for WJIKNZ and PJIKNZ, the findings revealed that one lifetime usage of a woollen jumper would result in 0.9 kg of CO_2 equivalence and a polyester jumper would result in 1.02 kg of CO_2 equivalence global warming impact. The distinction between the impact of the lifetime maintenance of the woollen and polyester jumper types is shown in Figure 56.

Figure 56

Comparing Impact of the Jumper Use Phase



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

As these impacts were established for a 385-gram jumper, the impact on the maintenance of each kilogramme of material was estimated for the projected framework. Table 41 presents the global warming impact linked to the lifetime use of one kilogramme material.

Table 41

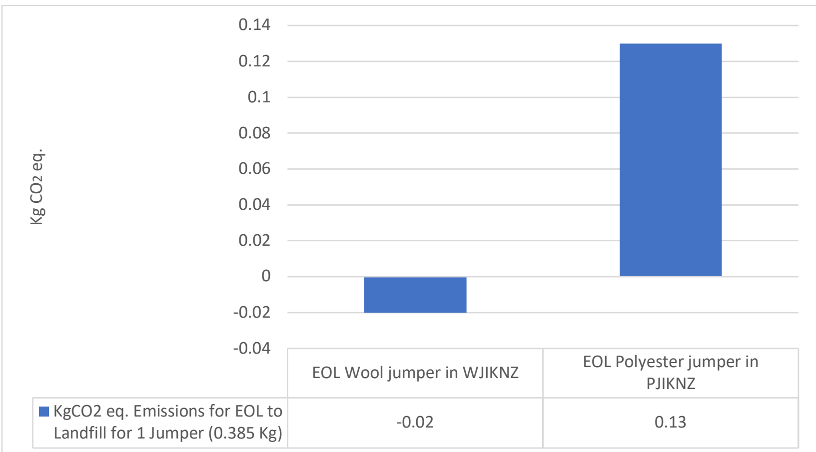
Use Phase Impact for 1 kg material in kg CO_2 eq.

	385 g use of wool jumper (kg CO_2 eq.)	1 kg use of wool jumper (kg CO_2 eq.)	385 g use of polyester jumper (kg CO_2 eq.)	1 kg use of polyester jumper (kg CO_2 eq.)
	0.9	2.33	1.02	2.65
Total impact for lifetime use of 1 kg jumper material		2.33		2.65

Only the landfilling scenario was used to calculate the end-of-life (EOL) impact for both the wool and polyester jumper types in the WJIKNZ and PJIKNZ scenarios. Because wool is completely biodegradable, industrial composting waste treatment was considered; however, for polyester, it was municipal dumping. Therefore, a 385 g wool sweater had global warming emissions of -0.02 kg CO_2 eq., whereas a jumper made of polyester of the same weight had emissions of 0.13 kg CO_2 eq. Figure 57 depicts the impacts related to the EOL of the woollen and polyester jumper types.

Figure 57

Comparing End-of-Life Impact for Wool and Polyester Jumper



Note: Method: ReCiPe 2016 Midpoint (E) V1.05/World (2010) E

The EOL impact was then converted into emissions resulting from the inclusion of one kilogramme of wool and polyester material in the simplified framework. The impact of one kilogramme of material reaching its end-of-life is presented in Table 42.

Table 42

Impact with EOL for 1 kg Material

	In EOL for 385 g of wool jumper (kg CO_2 eq.)	In EOL for 1 kg wool jumper (kg CO_2 eq.)	In EOL for 385 g of polyester jumper (kg CO_2 eq.)	In EOL for 1 kg polyester jumper (kg CO_2 eq.)
Global warming impact	-0.02	-0.05	0.13	0.33
Total impact with 1 kg EOL of material		-0.05		0.33

The material loss for each manufacturing scenario also differed when constructing a jumper weighing 385 g. A jumper was made with 521 g of material in cut-and-sew, 403 g of material in fully fashioned, and 393 g of material in the integral knitting processes. Owing to the incorporation of the three manufacturing scenarios, it was necessary to modify the implications for material consumption in previously given Table 37 and their EOL impact in Table 42. For the cut-and-sew, fully fashioned, and integral knitting processes, increased material intake of 26.2%, 4.6%, and 2.1%, respectively, as well as a corresponding increase in material output at EOL, were therefore accommodated in the table for the simplified framework. Since the energy used to manufacture the jumpers was unaffected by the change in material consumption percentage and the use phase, they remained unchanged. The adjusted global warming consequences from Table 37 and Table 42 for a one kilogramme jumper (when ready) are presented in Table 43 for the three flatbed knitwear manufacturing technologies.

Table 43

Adjusted Impact for Production and Processing Material and Impact for EOL of 1 kg jumper in the Three Manufacturing Scenarios

	Woollen Jumper			Polyester Jumper		
	Cut-and-sew ($kg\ CO_2$ eq.)	Fully Fashioned ($kg\ CO_2$ eq.)	Integral Knitting ($kg\ CO_2$ eq.)	Cut-and-sew ($kg\ CO_2$ eq.)	Fully Fashioned ($kg\ CO_2$ eq.)	Integral knitting ($kg\ CO_2$ eq.)
Adjusted impact for production and processing 1 kg material (when ready)	9.26	7.67	7.49	2.72	2.25	2.20
Adjusted impact for EOL 1 kg material (including waste)	-0.06	-0.05	-0.05	0.41	0.34	0.33

5.3.5 Simplification of data

A method to assess the impact of global warming on the life cycle of knitted jumpers of any weight was developed. A simplified data table for evaluating the global warming impact of one kilogramme of knitted jumpers in New Zealand is presented in Table 44. This simplified approach employed a set of five straightforward queries.

1. The choice of material
2. Selected knitwear manufacturing technique
3. Quantification of road transport throughout the supply chain (from raw-material production to retail)
4. Quantification of sea transport throughout the supply chain
5. Geographical origin of the garment (New Zealand or Asia)

Table 44

Simplified Data Table to Assess Global Warming Potential for 1 kg Knitted Jumper in New Zealand

	Question Prompts	Impact Specification	Cut-and-sew		Fully Fashioned		Integral Knitting	
1.	Which material are you going to use?	Include impact for material (including material loss)	Wool	Polyester	Wool	Polyester	Wool	Polyester
		Material production and processing (Refer to Table 43)	9.26 kg CO_2 eq.	2.72 kg CO_2 eq.	7.67 kg CO_2 eq.	2.25 kg CO_2 eq.	7.49 kg CO_2 eq.	2.20 kg CO_2 eq.
		Use phase impact (Refer to Table 41)	2.33 kg CO_2 eq.	2.65 kg CO_2 eq.	2.33 kg CO_2 eq.	2.65 kg CO_2 eq.	2.33 kg CO_2 eq.	2.65 kg CO_2 eq.
		EOL phase impact (Refer to Table 43)	-0.06 kg CO_2 eq.	0.41 kg CO_2 eq.	-0.05 kg CO_2 eq.	0.34 kg CO_2 eq.	-0.05 kg CO_2 eq.	0.33 kg CO_2 eq.
		+						
2.	Which knitwear manufacturing technique do you intend to employ?	Include energy consumption impact	Cut-and-sew	Cut-and-sew	Fully Fashioned	Fully Fashioned	Integral Knitting	Integral Knitting
		Manufacturing impact in BD (Refer Table 38). Reduce 15% for NZ	0.8 kg CO_2 eq.	0.96 kg CO_2 eq.	1.43 kg CO_2 eq.	1.73 kg CO_2 eq.	1.73 kg CO_2 eq.	2.09 kg CO_2 eq.
		+						
3.	How much road transport will be used across the supply chain (from production of raw material to retail)?	Include impact for road transport for kgkm (Refer to Table 39)	0.00020 kg CO_2 eq.	0.00020 kg CO_2 eq.	0.00016 kg CO_2 eq.	0.00016 kg CO_2 eq.	0.00016 kg CO_2 eq.	0.00016 kg CO_2 eq.
		+						
4.	How much sea transport will be used across the supply chain (from production of raw material to retail)?	Include impact for sea transport for kgkm (Refer to Table 39)	0.000011 kg CO_2 eq.	0.000011 kg CO_2 eq.	0.000009 kg CO_2 eq.	0.000009 kg CO_2 eq.	0.000009 kg CO_2 eq.	0.000009 kg CO_2 eq.
		+						
5.	Is this garment made in New Zealand or abroad?	Packaging for locally manufactured garments (Refer to Table 40)	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.28 kg CO_2 eq
		Packaging for garments manufactured overseas (Refer to Table 40)	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.

Table 44 serves as a comprehensive representation of the methodology employed to simplify the outcomes derived from the comprehensive LCA investigation. This tabular presentation constitutes the fundamental framework upon which has to potential to be converted into a specialised tool, tailored to the specific needs of fashion designers. This novel approach is herein denoted as the "simplified LCA-based approach," representing a pivotal outcome of this exploratory research inquiry.

To validate the efficacy of the simplified approach, an assessment of the environmental impact spanning the entire cradle-to-grave life cycle of knitted jumpers was conducted across the same eight scenarios and 385 g weight as considered for the comprehensive LCA. Table 45 lists each of these eight jumper scenarios, along with the corresponding quantified outcomes pertaining to their life cycle impacts in kg CO_2 eq. emissions. Subsequently, these outcomes were juxtaposed with those emanating from the comprehensive LCA, as reported in section 5.2 of this research investigation.

The outcomes of this comparative analysis indicate a remarkable proximity between the environmental impacts assessed via the simplified LCA-based approach and those determined using the comprehensive LCA methodology. To visually represent this proximity, Figure 58 shows a comparative contrast between the results stemming from the conventional rigorous LCA and those arising from the proposed simplified LCA-based approach, particularly in relation to the GWP associated with the life cycle of the eight distinct jumper scenarios.

Table 45

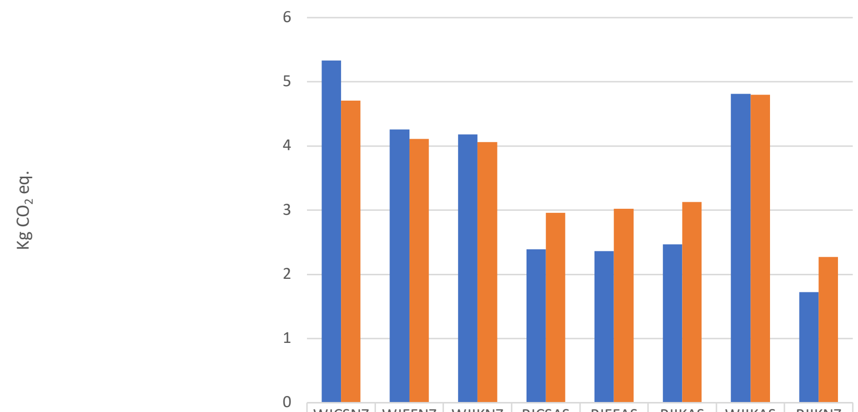
Validating Global Warming Potential of the Eight Jumper Scenarios Studied Using Simplified Data from Table 44

Question prompts	Impact Specification	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
Which material are you going to use for manufacturing?		Wool	Wool	Wool	Polyester	Polyester	Polyester	Wool	Polyester
	Material production and processing impact	9.26 kg CO_2 eq.	7.67 kg CO_2 eq.	7.49 kg CO_2 eq.	2.72 kg CO_2 eq.	2.25 kg CO_2 eq.	2.20 kg CO_2 eq.	7.49 kg CO_2 eq.	2.20 kg CO_2 eq.
	Use phase impact	2.33 kg CO_2 eq.	2.33 kg CO_2 eq.	2.33 kg CO_2 eq.	2.65 kg CO_2 eq.	2.65 kg CO_2 eq.	2.65 kg CO_2 eq.	2.33 kg CO_2 eq.	2.65 kg CO_2 eq.
	EOL phase impact	-0.06 kg CO_2 eq.	-0.05 kg CO_2 eq.	-0.05 kg CO_2 eq.	0.41 kg CO_2 eq.	0.34 kg CO_2 eq.	0.33 kg CO_2 eq.	-0.05 kg CO_2 eq.	0.33 kg CO_2 eq.
				+					
Which knitwear manufacturing technique do you intend to employ?		Cut-and-sew, NZ	Fully Fashioned, NZ	Integral Knitting, NZ	Cut-and-sew, BD	Fully Fashioned, BD	Integral Knitting, BD	Integral Knitting, BD	Integral Knitting, NZ
	Impact of energy consumption	0.12 kg CO_2 eq.	0.21 kg CO_2 eq.	0.26 kg CO_2 eq.	0.96 kg CO_2 eq.	1.73 kg CO_2 eq.	2.09 kg CO_2 eq.	1.73 kg CO_2 eq.	0.31 kg CO_2 eq.
				+					
How much road transport will be used across the supply chain (from production of raw material to retail)?	Road kilometres travelled	400 km	400 km	400 km	770 km	770 km	770 km	870 km	300 km
	Impact for 1 kg Road transport	400 X 0.00020	400 X 0.00016	400 X 0.00016	770 X 0.00020	770 X 0.00016	770 X 0.00016	870 X 0.00016	300 X 0.00016
	Total impact	0.08 kg CO_2 eq.	0.06 kg CO_2 eq.	0.06 kg CO_2 eq.	0.15 kg CO_2 eq.	0.12 kg CO_2 eq.	0.12 kg CO_2 eq.	0.13 kg CO_2 eq.	0.04 kg CO_2 eq.
				+					

How much sea transport will be used across the supply chain (from production of raw material to retail)?	Sea kilometres travelled	21236.88 km	21236.88 km	21236.88 km	21901.75 km	21901.75 km	21901.75 km	31559.93 km	11578.70 km
	Impact for 1 kg Sea transport	21236.88 X 0.000011	21236.88 X 0.000009	21236.88 X 0.000009	21901.75 X 0.000011	21901.75 X 0.000009	21901.75 X 0.000009	31559.93 X 0.000009	11578.70 X 0.000009
	Total impact	0.23 kg CO_2 eq.	0.19 kg CO_2 eq.	0.19 kg CO_2 eq.	0.24 kg CO_2 eq.	0.19 kg CO_2 eq.	0.19 kg CO_2 eq.	0.28 kg CO_2 eq.	0.10 kg CO_2 eq.
			+						
Is this garment made in New Zealand or Asia?		New Zealand	New Zealand	New Zealand	Asia	Asia	Asia	Asia	New Zealand
	Packaging impact	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.28 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.57 kg CO_2 eq.	0.28 kg CO_2 eq.
Total impact for 1 kg garment (when ready)		12.24 kg CO_2 eq.	10.69 kg CO_2 eq.	10.56 kg CO_2 eq.	7.7 kg CO_2 eq.	7.85 kg CO_2 eq.	8.15 kg CO_2 eq.	12.48 kg CO_2 eq.	5.91 kg CO_2 eq.
Total impact for 385 grams of garment (when ready)		4.71 kg CO_2 eq.	4.11 kg CO_2 eq.	4.06 kg CO_2 eq.	2.96 kg CO_2 eq.	3.02 kg CO_2 eq.	3.13 kg CO_2 eq.	4.80 kg CO_2 eq.	2.27 kg CO_2 eq.

Figure 58

Comparing Results of Comprehensive LCA with Simplified LCA-based Approach



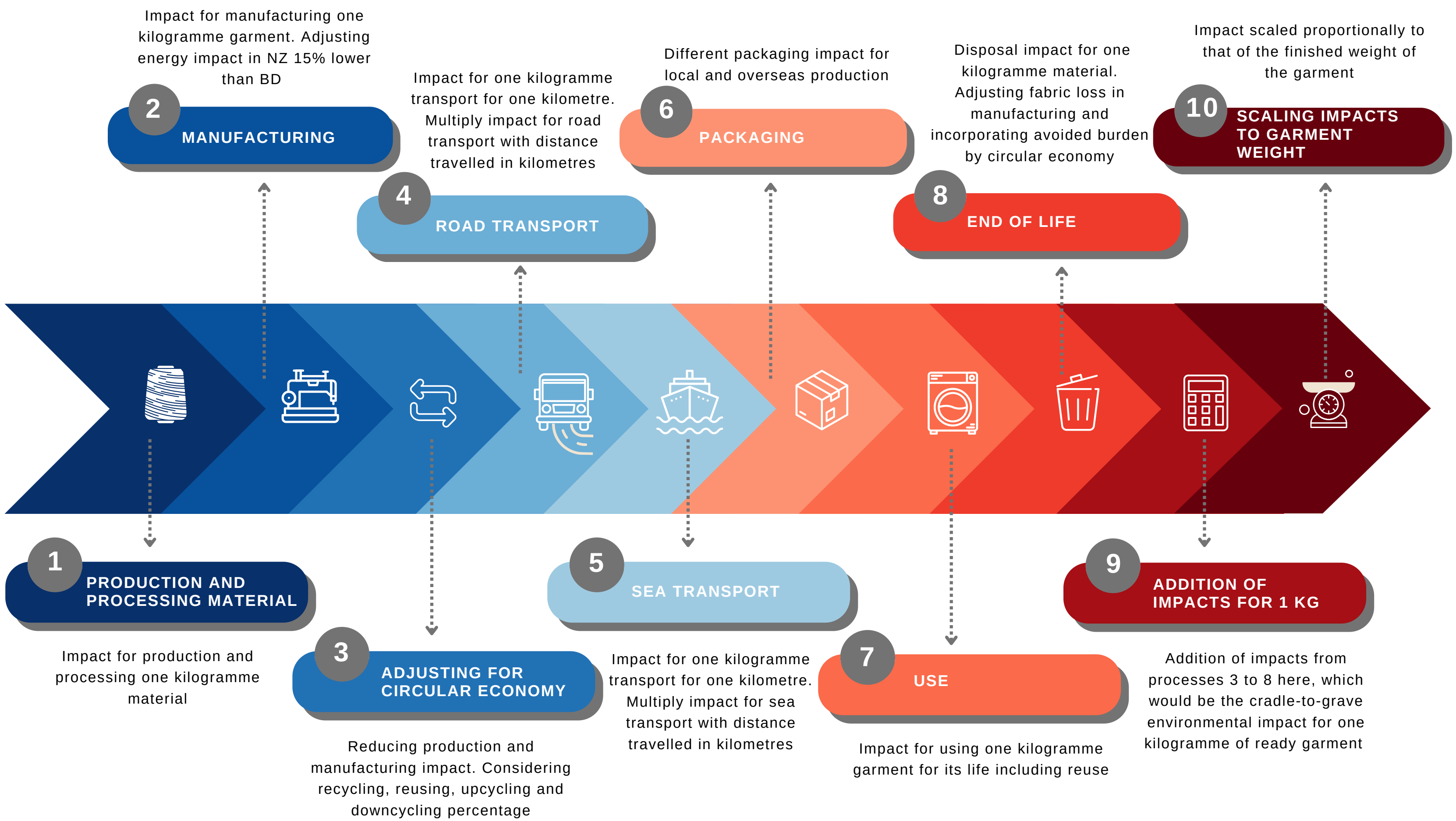
	WJCSNZ	WJFFNZ	WJIKNZ	PJCSAS	PJFFAS	PJIKAS	WJIKAS	PJIKNZ
Rigrous LCA Results using SimaPro (Kg CO2 eq.)	5.33	4.26	4.18	2.39E+00	2.36E+00	2.47E+00	4.81	1.72E+00
Simplified LCA Data Table (Kg CO2 eq.)	4.71	4.11	4.06	2.96	3.02	3.13	4.8	2.27

The figure demonstrates that the simplified LCA-based approach can serve as a benchmark for evaluating garments, given the availability of information regarding the impact of material utilisation, energy consumption during construction, transportation distances by road and sea, manufacturing location (New Zealand or Asia), and the resultant weight of the garment. By incorporating these details, an estimation of the global warming impact can be derived. This concept was further developed into a process flowchart that lays out ten foundational processes to prototype a practical tool for fashion designers.

A graphical representation of this simplified flowchart is shown in Figure 59 which is named as "Simplified LCA Framework for Fashion Design." This framework gleans the key information from Table 44, providing a blueprint for programming the envisioned tool, for rapid environmental assessments. The presentation of the simplified LCA-based approach through this framework aligns with the research objective of streamlining the LCA methodology for practical implementation in everyday fashion design operations, thereby facilitating the integration of sustainability into the field of fashion practice.

Figure 59

Graphical Illustration of the Simplified LCA Framework for Fashion Design



5.3.6 Processes in the Simplified LCA Framework for Fashion Design

This study aimed to simplify the LCA methodology, enabling an easy evaluation of the environmental impact of garments. Through a comprehensive LCA of jumpers in eight different life cycle scenarios, the study successfully extracted essential elements for simplifying the LCA outcomes. As a result, a simplified LCA-based approach along with the Simplified LCA Framework for Fashion Design, that can be translated into a tool to effectively assess the environmental impact of fashion items was devised. To demonstrate the practicality of this simplified framework, this section breaks down the LCA investigation into ten sequential processes that are explained below.

Process 1- Assessing the Environmental Impact of Textile Fibres

The first step in the simplification process involves assessing the environmental impact of the production and processing of textile fibres. When comparing woollen and polyester jumpers, sizeable differences in CO_2 equivalent emissions were observed in fibre production and the subsequent wet processing and dyeing. These impacts were incorporated into the simplified LCA framework in Process 1 that considers the production and processing of one kilogramme of textile material.

Process 2- Variation in Garment Manufacturing Technologies

This study investigated the variations in global warming across different flatbed knitwear technologies for garments constructed in New Zealand and Bangladesh. The findings indicate that knitting operations in New Zealand resulted in substantially lower emissions than those in Bangladesh, and there were marked differences in the energy consumption of the three technologies investigated. Consequently, the impact of energy consumption on the manufacture of a one kilogramme jumper was calculated for the three manufacturing processes and integrated into the simplified LCA framework in Process 2.

Process 3- Consideration of Avoided Burden through Reuse and Downcycling

The study considered the burden avoided through reuse and downcycling, thereby reducing the environmental consequences of different material choices. The impact on fibre production and manufacturing was mitigated by excluding the reuse and downcycling percentages. The adjusted impact was incorporated into the simplified LCA framework in Process 3.

Process 4 and 5- Incorporating Transportation Impact

Different modes of transportation were considered in this study, and their impacts were adjusted based on the material weight per kilometre of transport. Road transportation and sea transportation were divided into separate categories, and their impacts were multiplied by the distances travelled. This process is depicted as Processes 4 and 5 in the simplified LCA framework.

Process 6- Standardisation of Packaging

This study examined a method to standardise packaging and its proportionality to garment manufacturing locations. Local production was emphasised to reduce the packaging impact, and different packaging impacts were considered for local and overseas production. The packaging impact was integrated into the simplified LCA framework in Process 6.

Process 7- Assessing the Use Phase Impact

The impacts of global warming during the use phase of woollen and polyester jumpers were compared. The impact of the use of one kilogramme of garments throughout their cradle-to-grave lifetime was calculated and integrated into the simplified LCA framework in Process 7.

Process 8- End-of-Life Phase Considerations

This study analysed the emissions of waste scenarios for woollen and polyester jumpers, considering fabric loss for different manufacturing techniques- cut-and-sew, fully fashioned and integral knitting. The impact of landfilling one kilogramme of material, along with the adjusted avoided burden and fabric loss for each manufacturing scenarios, was incorporated into the simplified LCA framework in Process 8.

Process 9 and 10- Comprehensive Impact Assessment

In Process 9, the impacts calculated from Processes 3 to 8 were added to calculate the cradle-to-grave impact of a garment. In Process 10, the results from Process 9 of a one kilogramme garment were multiplied or divided according to the intended weight of the ready garment. This comprehensive impact assessment will provide designers with a clear understanding of the environmental consequences of their choices of material, manufacturing technique, and supply chain pathway, based on the final weight of the garment.

5.3.7 Concluding the Simplification of the LCA Methodology

The research objective to develop a simplified method to assess the environmental impact of garments was accomplished. This section demonstrated that it is possible to simplify the application of LCA in fashion design. Through the extraction of critical elements from the comprehensive analysis of knitted jumpers, a simplified data table (Table 44, p.200) and a framework (Figure 59) tailored to fashion design were devised, introducing new possibilities for integrating sustainability considerations into fashion practice. The implementation of this simplified LCA-based approach to fashion design and its strength, weaknesses, opportunities, and threats (SWOT) analysis are presented in Chapter 6, section 6.10. and 6.11, respectively.

The simplified method offers a foundational design for the development of an effective assessment tool to aid fashion designers in evaluating the environmental impact of garments. This tool will enable the incorporation of life cycle thinking during the garment design phase and empower designers to make informed decisions. This advancement sets the stage for a future in which sustainability can seamlessly permeate the fashion industry by fostering an environmentally conscious and responsible approach. The subsequent section in this chapter presents a personal reflection on the journey of undertaking the objective of simplifying LCA and addressing the challenges encountered.

Section 3

Designer's Journey in Scientific Research: Navigating LCA

Recognising the ongoing efforts to integrate sustainability into fashion, this study aims to simplify the LCA methodology for its practical implementation in everyday design operations. However, achieving this breakthrough was not without a fair share of challenges. The journey of this research tested my abilities as a designer and challenged my determination to overcome various hurdles along the way.

Several challenges were encountered throughout this research process and the main ones are discussed in this section. These challenges not only provided invaluable learning experiences but also played a pivotal role in shaping the decision-making process and overall design of this study. By sharing these challenges, this study endeavours to shed light on the broader obstacles faced by fashion designers who, despite their expertise in design, often struggle to incorporate scientific principles such as LCA into their practice.

5.4 Challenges Faced During Research Exploration

Understanding scientific terminology for LCA

This study lies in the nexus between design and technology. Despite falling under the umbrella of art and design, conducting an LCA study requires knowledge of scientific jargon. LCA demands proficiency in quantitative methods to assess the environmental implications of garments. Furthermore, the collection of life cycle inventory data necessitates a sound comprehension of scientific terminology. This requires knowledge of the physics underlying energy conversion processes, such as volts and amperes to watts per hour, as well as the chemistry of chemicals used throughout the many stages of a jumper's life cycle, particularly when choosing substitute chemicals when the original ones are not available in the Ecoinvent library. Although it took some time to become accustomed to these demands, I was eventually able to use scientific principles to fill in data gaps and make informed decisions when acquiring primary data for the study.

Uncertainty in LCA execution

As a fashion designer delving into the realm of LCA, I faced uncertainty regarding my ability to independently execute the assessment. I discovered that textile engineers and academic specialists have undertaken most earlier studies on LCA in the clothing and textile industries. To overcome this challenge, I enrolled in a course at Massey University, New Zealand, called "Introduction to LCA”. Although the course did not provide a comprehensive understanding of LCA execution, it offered guidance on crucial preliminary steps such as setting the LCA goals, establishing system boundaries, and defining functional units.

Finding a critical reviewer for the LCA study

Ensuring the integrity of the LCA study required a critical reviewer well-versed in the ISO 14040-44 standards. However, identifying a certified LCA practitioner as a critical reviewer for garments proved challenging, particularly in New Zealand. The limited availability of such professionals necessitates the exploration of alternatives outside the country. Through the online professional platform LinkedIn, I connected with Dr Chalaka Fernando, an Australia-based certified practitioner (CP), and an LCA expert who provided valuable guidance and reviewed the LCA report.

Collecting extensive data for LCA

The LCA of a jumper, even in its simplest form without attached accessories, entailed gathering an extensive data. This involved mapping out the complex supply chain, including fibre production, pre-processing and dyeing, yarn spinning, garment manufacturing, packaging and transport, garment use, and end-of-life. Collecting inventory data for each life cycle phase introduced a host of complexities, such as accurately reporting the inputs and outputs for each process in the supply chain. A simple dataset on wool production at the farm required the consideration of factors such as yearly sheep feed intake, water consumption, energy and fuel usage on the farm, as well as an understanding of allocating burdens between wool and meat. Similar challenges arose when collecting data for subsequent phases of the life cycles of both wool and polyester jumpers. This complexity gave rise to the notion of a universal repository for future use in LCA. Published LCA literature is required to deposit inventory data in a shared library so that they can be used for future environmental evaluations. Data banks, such as Ecoinvent, should seek to increase their collection of textile-and clothing-related information.

Collaborating with suppliers in the garment supply chain

Engaging with suppliers across the garment supply chain to collect inventory data also proved to be a significant challenge. Despite reaching various yarn suppliers, processors, and garment manufacturers within and outside New Zealand, obtaining confidential information was a hurdle. Concerns about data misuse and the potential negative labelling of their businesses may have discouraged many from sharing the required information. While some information can be gathered from small-scale wool producers and yarn processors in New Zealand, no such data can be collected from large businesses. Therefore, the study had to take advantage of secondary sources to fill these data gaps.

Limited availability of textile research facilities in the country

This study required access to textile research facilities to collect inventory data on different knitwear manufacturing techniques. However, the unavailability of suitable research facilities in the field of clothing and textiles in New Zealand posed a challenge. Although the Textile Design Laboratory at the Auckland University of Technology (AUT), where this research was based, initially provided access to research facilities, it was later completely shut down due to funding issues during the study. The absence of such facilities for further exploration of garment construction limits the scope of the investigation.

Designing surveys for data collection

The use of surveys became essential for gathering data on the use and end-of-life phases of jumpers. The lack of existing data on garment usage and disposal in New Zealand prompted the need for primary data collection. Seeking guidance from experts in the field, such as Dr Kirsi Laitala from Oslo University, Norway, facilitated the design of questionnaires and helped in identifying a suitable strategy to reach out to consumers of wool and synthetic jumpers in the country. In addition, an extensive review of pertinent scholarly articles within the subject domain was conducted, and a methodological approach for executing a comprehensive survey was devised. The primary objective of this survey was to ascertain critical insights into the lifespan, laundering, and disposal behaviours of woollen synthetic jumpers among the New Zealand populace.

Technical challenges with LCA Software

Although SimaPro software simplified the LCA methodology, its usability presented challenges, especially for non-experts. Navigating software requires technical expertise beyond fashion design. Additionally, the limited inventory of textile products in the Ecoinvent database, which focused primarily on cotton materials, was a barrier. The absence of crucial information on various garment manufacturing techniques, home laundry products, and end-of-life strategies made it challenging to conduct a comprehensive assessment.

Technical challenges with formulating the intended tool

A comparative assessment of the environmental impact on the life cycle of wool and polyester jumpers is a crucial aspect of this study. However, formulating a simplified methodology that incorporates the available data presented considerable technical challenges. Although the concept of breaking down the impact for different life cycle phases provided a good starting point, accurately accounting for the avoided burden of reuse and downcycling added another layer of complexity to the calculation of the global warming impact of garments.

To effectively incorporate the avoided burden into the assessment of a garment's environmental impact, a deep understanding of the LCA methodology was required. This involved considering the reduction in impact for material production to incorporate the impact by reusing the jumper for a longer time. A cleaning cloth was created to incorporate the decrease in the environmental burden caused by a downcycled jumper. The complexity of these computations required a thorough understanding of the LCA principles, which could only be acquired through practice and perseverance.

5.5 Chapter Conclusion

This chapter provided a comprehensive examination of how considerations of sustainability can be integrated into fashion design through LCA. By evaluating the environmental consequences for jumpers produced in eight different scenarios, the first section of this chapter successfully employed comprehensive LCA to assess the environmental impact of woollen and polyester jumpers consumed in New Zealand. The results underscored the significance of material selection, garment manufacturing techniques, and supply chain pathways in influencing the global warming implications of clothing items.

The subsequent section presented the development of a simplified approach to assess the environmental impact of garments. This section demonstrated the potential for streamlining LCA through the extraction of critical elements from the comprehensive LCA of knitted jumpers in the eight scenarios conducted in section one. By providing designers with a simplified LCA-based approach and the Simplified LCA Framework for Fashion Design introduced new possibilities for incorporating sustainability into fashion practice. This study proposes a tool which will allow rapid life cycle assessment of garments, empowering fashion designers to make better-informed decisions.

However, it is important to acknowledge the challenges encountered throughout this research, as discussed in the last section of this chapter. As a designer delving into the realm of LCA, this study presented unique obstacles that may provide valuable lessons to others. The interdisciplinary nature of the research, combining scientific concepts with fashion design, exemplifies the importance of collaboration, continuous learning, and adaptability in overcoming challenges in academic endeavours.

In conclusion, this chapter made significant contributions to the integration of sustainability into fashion design through the application of LCA. The findings and results presented here shed light on the environmental implications of clothing production and consumption, emphasising the importance of material choice, manufacturing techniques, and supply chain pathways. The simplified LCA-based approach provides the fundamentals of a tool that aids the integration of life cycle thinking into the design phase and fosters a more environmentally conscious and responsible fashion industry. Building upon these insights, Chapter 6 will examine the practical application of the results and explore how they can inform and guide decision-making in the fashion industry.

Chapter 6 Discussion

This research focused on conducting an LCA of the Global Warming Potential (GWP) of knitted jumpers consumed in New Zealand. Two textile materials (woollen and polyester) and three flatbed knitwear manufacturing technologies (cut-and-sew, fully fashioned, and integral knitting) were examined across four specific supply chain pathways. The geographical scope of consumption and disposal was confined to New Zealand. The LCA findings were examined to develop a simplified system that can form the basis of a tool for fashion designers to use in everyday design operations.

Chapter 5 provided the results of the comparative LCA of knitted jumpers for a total of eight life cycle scenarios and the development of a simplified methodology, along with a discussion of the challenges faced as a designer navigating the scientific realm of the LCA methodology. The current chapter is also structured into three sections based on the research findings. Section one, encompassing subsections 6.1 to 6.9, considers the comprehensive LCA analysis for the knitted jumpers, exploring the environmental implications of various life cycle scenarios, material choices, garment manufacturing technologies, transportation modes, packaging in the supply chain, data requirements, circular economy considerations, and limitations related to the assumptions made.

Section two covers subsections 6.10 and 6.11, and focuses on the advancement and implementation of the simplified LCA-based approach, a core outcome of this research endeavour. It further examines this novel approach through a SWOT analysis outlining its effective integration into fashion practice.

Section three, incorporating subsections 6.12 and 6.13, delineates the adversities encountered during this research inquiry. These issues, previously alluded to in Chapter 5, Section 3, are expounded in greater depth, elucidating the strategies employed to surmount them. This comprehensive discussion aims to provide valuable insights for prospective researchers and the design community to facilitate their endeavours in this field.

Section 1

Discussion on the Comprehensive LCA of Knitted Jumpers

The environmental implications of woollen and polyester jumpers consumed in New Zealand were examined in Chapter 5 (see sections 5.1 and 5.2). The comprehensive comparative assessments revealed that polyester jumpers manufactured using integral knitwear manufacturing technologies, followed by Supply Chain Pathway 4, where the polyester yarn was produced in China and the garment manufactured and consumed in New Zealand, produced the least carbon dioxide emissions throughout its cradle-to-grave life cycle. Conversely, a woollen jumper produced using the cut-and-sew knitwear manufacturing technology in Supply Chain Pathway 1, where the woollen yarn was produced in Australia, processed in China, manufactured in Bangladesh, and consumed in New Zealand, demonstrated the maximum carbon dioxide emissions in its life cycle from cradle-to-grave. However, it is acknowledged that the reliability of these comparative assessments is compromised due to the assumptions made regarding global wool production and limitations associated with data validity for polyester fibre production (see Chapter 4, sections 4.2.1 and 4.2.2). Nonetheless, these findings enable us to understand the different life cycle phases of garments and their varied environmental impacts. The following subsections, 6.1 to 6.9, discuss the key findings from this comprehensive LCA of knitted jumpers consumed in New Zealand.

6.1 Exploring the Impact of Natural versus Synthetic Fibres

The choice of material substantially influence the environmental impact of the garment throughout its life cycle. The literature review (see Chapter 2, section 2.5.2) highlighted a dearth of comprehensive research specifically focused on the environmental impact of different textile materials in the context of New Zealand (Engelbrecht et al., 2018). This study aimed to evaluate and compare the environmental implications of natural versus synthetic fibres in jumpers consumed in New Zealand. By considering the distinct phases of the life cycle of woollen and polyester jumpers, including fibre production, processing, use, and end-of-life scenarios, this study provides holistic insights into the sustainability implications of material choices for fashion designers. LCA was employed to quantify the environmental impacts at each stage of the garment life cycle, to inform and enable designers to make better choices towards increasing sustainability in the fashion industry.

Substantial disparities were observed between the environmental implications of woollen and polyester fibre production. The production of wool for a jumper made using the integral knitting technology was associated with 5.07 kg CO_2 eq. emissions, whereas the corresponding value for the polyester was only 1.47 kg CO_2 eq. (see Chapter 5, section 5.2.1). However, as discussed earlier, owing to the lack of reliable inventory data for polyester fibre production and the unavailability of local datasets for wool production in New Zealand, the validity of these findings is limited (see Chapter 4, sections 4.2.1 and 4.2.2). To provide a comprehensive assessment, a reliable dataset for polyester fibre production should consider the impacts associated with crude oil extraction through mining processes, while local data for merino wool production in New Zealand needs to be made available. Until these data gaps are addressed, a fair comparison between wool and polyester fibre production cannot be conducted.

In the wet-processing phase, the carbon dioxide emissions with wool were greater, primarily because of the resource-intensive processes involved in the scouring, bleaching, and dyeing, whereas polyester primarily required dyeing without extensive additional processes. Moreover, wool processing is mostly carried out in Asia. Although this study could not definitively state that local wool processing in New Zealand would consume fewer resources, it was worth noting the difference in the energy mix between Asia and New Zealand, with the latter showing a 15% reduction in environmental implications from the energy mix in Bangladesh (see section 5.4.2). The study revealed that wool had environmental impacts of 1.14 kg CO_2 eq. emissions, whereas polyester exhibited lower impacts at 0.6 kg CO_2 eq. during bleaching and dyeing processes. Moreover, wool encountered an additional 1.73 kg CO_2 eq. emissions while scouring the greasy raw fibre (see section 5.2.1). Therefore, the choice of material plays a crucial role in differentiating the environmental impact of the material processing stages.

Type of material, also influence several other factors. Assessing the environmental footprint of a garment requires an understanding of its lifespan, which can be estimated based on years of use, number of wears, and number of users (Klepp et al., 2020). Natural fibres, such as wool, have demonstrated exceptional longevity and resilience, resulting in higher wear events, and longer estimated lifespans (Laitala et al., 2018). In New Zealand, woollen jumpers were estimated to have a total lifetime wear of 237 times, whereas synthetic jumpers are estimated to be worn 171 times (Nautiyal et al., 2023b). These statistics highlight the sustainable approach to consumption, as woollen garments exhibits higher garment usage and durability (Erdogan et al., 2020). Conversely, synthetic blends often fall short in terms of durability, necessitating more frequent replacements (McQueen et al., 2020; McQueen & Vaezafshar, 2020). By selecting more durable materials such as wool, the need for frequent replacement would be reduced, resulting in lower resource consumption associated with manufacturing new garments (Erdogan et al., 2020). Additionally, the extended lifespan and higher wear events of woollen jumpers helped distribute the environmental impacts of production over a longer period, thereby reducing the overall environmental footprint (Niinimäki et al., 2020; Stenton et al., 2021).

In addition to lifespan, the frequency of garment washing during the use phase was also influenced by material type (Laitala et al., 2017; Nautiyal et al., 2023b). Synthetic materials, such as polyester tend to accumulate odours more quickly and require more frequent cleaning compared to natural fibres such as wool (McQueen et al., 2020). In New Zealand, survey data indicate that woollen jumpers are worn twice as often (11.5 wears) as synthetic jumpers (5.2 wears) before being washed (Nautiyal et al., 2023b). This disparity translated into lower resource consumption and reduced global warming emissions associated with the use phase, with woollen jumpers contributing 0.9 kg CO_2 eq. emissions and polyester jumpers generating 1.02 kg CO_2 eq. emissions (see section 5.2.1). Therefore, a reduced laundering frequency was found to result in a more sustainable use phase.

According to the New Zealand based survey conducted as part of this study suggested that a large percentage of woollen (62%) and synthetic jumpers (54%) are reused. Additionally, a small portion of woollen (6.5%) and synthetic jumpers (5%) were downcycled for purposes such as cleaning cloth, whereas the remaining were discarded in municipal bins and eventually ended up in landfills (Nautiyal et al., 2023b).

Consequently, wool exhibited a lower disposal-to-landfill ratio than synthetic clothing. The full biodegradability of wool fibres contrasts with the hundreds of years required for polyester to decompose, releasing microplastic fibres, harmful gases, and leachate that contribute to environmental pollution (DeVoy et al., 2021; Niinimäki et al., 2020). The study revealed that woollen jumpers that were composted using the industrial composting method had emissions of -0.02 kg CO_2 eq., while polyester jumpers that had the same waste scenario as PET, contributed 0.13 kg CO_2 eq. emissions during the end-of-life stage (see section 5.2.1).

However, specific data differentiating between the environmental impact of wool and polyester that have been disposed of in landfills were not found in the Ecoinvent database (see Chapter 4, section 4.7). Hence, in this study, the industrial composting method was applied to disposing of woollen jumpers. For polyester jumpers, the waste scenario was assumed to be a 50-50 split between the PET waste and the treatment of municipal solid waste set up in Ecoinvent as a global scenario. Consequently, the choice of materials not only influences the production and use phases in the garment life cycle but also contributes to significant carbon dioxide emissions at the end-of-life.

Consequently, the selection of materials for garment production plays a pivotal role in shaping the environmental profiles of garments. The inherent durability and maintenance characteristics of materials such as wool positively influence lifespan and therefore reduce the need for frequent replacements. The choice of materials at the end of a garment's life cycle is crucial, as wool is fully biodegradable, whereas polyester poses environmental risks. Thus, informed material choices are necessary to reduce environmental impacts and boost sustainability in the fashion industry.

6.2 Analysis of the Three Flatbed Knitwear Construction Techniques

Garment construction methods were also found to greatly influence the sustainability of garments, affecting energy usage and fabric wastage. This study compared three prevalent flatbed knitting technologies: cut-and-sew, fully fashioned, and integral knitting. By examining energy consumption, material waste, and environmental impacts during the garment manufacturing phase, the most sustainable approaches for jumper manufacturing could be identified.

Using the LCA methodology, the global warming emissions associated with different knitwear manufacturing techniques were evaluated. Wool jumpers produced in New Zealand through the cut-and-sew method showed emissions of 0.11 kg CO_2 eq., while fully fashioned and integral knitting techniques resulted in emissions of 0.22 kg CO_2 eq. and 0.27 kg CO_2 eq., respectively. For polyester jumpers produced in Bangladesh, the cut-and-sew method yielded emissions of 0.86 kg CO_2 eq., while fully fashioned and integral knitting techniques resulted in emissions of 1.45 kg CO_2 eq. and 1.75 kg CO_2 eq., respectively (see section 5.2.1 for further details). These findings highlight the fewer global warming impacts associated with the cut-and-sew method for both wool and polyester jumper manufacturing.

Local disparities in the energy mix play a crucial role in the environmental impact of jumper manufacturing. The study found that jumper manufacturing in New Zealand exhibited approximately 15% lower overall environmental impacts than that in Bangladesh. This difference can be attributed to the distinct energy mixes used by the two countries. New Zealand's reliance on hydro-based renewable energy sources enables a more sustainable energy production process, whereas Bangladesh's heavy dependence on natural gas significantly affects environmental performance (see section 5.3.2). In this study, integral-knitted jumpers manufactured in New Zealand showed substantially lower emissions with 0.27 kg CO_2 eq., compared to cut-and-sew jumpers produced in Bangladesh with 0.86 kg CO_2 eq. emissions (see section 5.2.1).

However, this study does not encompass the carbon emissions attributed to human labour, for example, the use of lighting, cooling etc. in garment manufacturing factories. This omission presents a limitation for comprehensively assessing the environmental impacts associated with garment production. Furthermore, this study acknowledges the importance of considering the social aspects, such as the social conditions of the workers working for jumper manufacturing. Thus, due to the abundance of skilled labour, factories in Bangladesh have been able to establish the technically more demanding but energy consumption wise more preferable cut-and-sew method. Conversely, in New Zealand, the scarcity of skilled labour means a more widespread use of the integral knitting method, which higher energy requirements are offset by New Zealand's preference for renewable energy.

Based on the analysis of technological energy consumption, environmental impact, and social considerations, the cut-and-sew method has emerged as the preferred choice for sustainable flatbed knitted jumper manufacturing for overseas manufacturing. Its lower energy consumption, ability to consistently produce high-quality jumpers, and potential for job creation contribute to overall sustainability. However, when considering a local manufacture in New Zealand, the integral knitting technology has emerged as the preferred option for fashion designers as it is a less labour intensive process compared to the cut-and-sew approach, which could not be managed in the current employment market and labour shortages force designers to look at processes that do not require many skilled staff. Future research should consider comprehensive assessments that encompass social factors, energy consumption, and environmental impacts to provide a holistic framework for decision-making in the garment manufacturing industry.

6.3 Local Acquisition and Transportation Modes

In the fashion industry, designers possess the capacity to adopt sustainable practices regarding material procurement and transportation methods. By favouring raw materials that are locally sourced and processed, designers can reduce transportation distances, which would diminish associated emissions, facilitate the development of an environmentally conscious supply chain, and supporting local economies (Farrer & Parr, 2008 and Farrer & Fraser, 2009)as cited in Gwilt and Rissanen (2012).

This study underscores the significance of locally sourced materials as a means of reducing carbon dioxide emissions in the fashion industry. Through the analysis of this study involving the Supply Chain Pathway 1, production of merino wool from sheep farms in Australia, wool processing in China, garment manufacture in Bangladesh, for subsequent use in New Zealand, showed highest carbon dioxide emissions due to longer transportation distances. This pathway yielded the highest overall life cycle impact owing to the additional transportation required for processing wool fibre in Asia. The analysis highlights the impacts associated with local material sourcing. To further mitigate transportation-related emissions, designers should consider local yarn processing, thereby shortening the supply chain. Additionally, the study demonstrates that Supply Chain Pathway 4, where polyester yarn was produced and processed in

China, while the garment was manufactured locally in Auckland, New Zealand, resulted in the lowest carbon dioxide emissions (see section 5.3.3). This underscores the importance of adopting transportation routes with minimal distance in conjunction with local manufacturing, which is important for facilitating substantial reductions in emissions.

The findings of this study underscore the pivotal role of transportation modes in curtailing carbon emissions within the fashion industry's supply chain. Sustainable transportation options such as sea transport have several advantages over roads. Container ships, with their larger cargo capacities than lorries, facilitate more efficient transportation, resulting in reduced emissions per unit of cargo transported. Notably, the study revealed that the emissions associated with shipping one kilogramme of material via cargo ship amounted to less global warming of 0.000009 kg CO_2 eq. carbon dioxide emissions, whereas the equivalent emissions in road transportation were much higher at 0.00016 kg CO_2 eq. (see section 5.3.3). Furthermore, established shipping routes and networks enable enhanced logistics and reduced travel distances, thereby curtailing emissions associated with transportation.

Consequently, designers play a pivotal role in propelling sustainability within the fashion industry by making conscious choices regarding material sourcing and transportation methods. The findings underscore the positive environmental impact achieved through the integration of sea transport with local manufacturing practices.

6.4 Packaging Impacts in Global versus Local Supply Chains

Packaging plays a pivotal role in the life cycle of sales commodities, exerting crucial environmental burdens throughout a product's journey from production to waste. Within this context, the present study investigated the specific impacts associated with packaging at various stages of the garment supply chain, with a particular focus on the transportation of yarn and finished jumpers. By examining the primary packaging impacts within different supply chain pathways, a comprehensive understanding of their environmental implications was obtained.

A comparative analysis of the impact of packaging (excluding transportation) on global warming emissions across different supply chain pathways yielded compelling insights.

Higher emissions of 0.22 kg CO_2 eq. were observed in Supply Chain Pathways 2 and 3 than pathways featuring domestic manufacturing as in Supply Chain Pathways 1 and 4, which demonstrated emissions of 0.11 kg CO_2 eq. (see section 5.3.3). This finding substantiates the notion that packaging impact tends to escalate when garments are manufactured abroad and require additional transportation.

The geographical location of production, along with the material employed in packaging jumpers has emerged as a critical factor influencing the impacts and subsequent emissions of packaging goods for transport. Notably, the requirement for additional packaging for overseas transportation via shipping has significantly contributed to the heightened emissions observed. It is evident that transportation distances and associated complexities in international shipping necessitate more extensive packaging measures, which consequently amplify the environmental burden. This insight underscores the need for careful consideration of packaging material and the manufacturing location when aiming for sustainability.

Thus, once again the exploration of local production options has emerged as a promising strategy to curtail packaging impacts, as it reduces transportation distances and the associated packaging requirements. By encouraging local production, the fashion industry can effectively reduce the environmental burden associated with packaging, thereby contributing to a more sustainable and responsible supply chain.

6.5 A Country-Specific Environmental Analysis for Laundry

Comprehending how people wash their clothing has a substantial impact on a garment's GWP through the use phase. The chosen cleaning methods have been shown to affect energy consumption, water usage and chemical inputs and the associated emissions (Laitala et al., 2017). Acknowledging the variability of washing practices across countries (Daystar et al., 2019; Laitala et al., 2017; Laitala et al., 2018; Sohn et al., 2021), it is crucial to seek country-specific data to understand the impacts for the use phase.

In New Zealand, unique washing methods were employed by individuals for woollen and synthetic blend jumpers as compared with other countries (Nautiyal et al., 2023b). In Germany and the United Kingdom, 27% of woollen sweaters were hand washed, 63% were machine washed, and 10% were dry cleaned (Wiedemann et al., 2020). In Norway, 19% of woollen garments are hand-washed, and 70% are machine-washed (Laitala et al., 2017). However, the answers provided by participants of a nationwide survey study in New Zealand indicated an equal split between hand washing (46%) and machine washing (54%) for woollen jumpers, deviating from the international trends (Nautiyal et al., 2023b). Hand washing uses less energy and water while emitting fewer greenhouse gases, thereby significantly contributing to reducing greenhouse gas emissions and preserving natural resources (BSR, 2009).

The method of drying the clothing was another factor that affected the environment during the use phase. Drying methods have been found to vary depending on the country's environment, economy, culture, and type of garment or fibre (Laitala et al., 2018). Nautiyal et al. (2023b) found that the drying habits in New Zealand differed from those in other countries, particularly when compared to the United States of America, where approximately 73% of wet laundry is tumble-dried (Daystar et al., 2019). However, in New Zealand, the majority of woollen jumpers (99%) and synthetic jumpers (88%) were air-dried without using a tumble dryer (Nautiyal et al., 2023b). Line or air drying is widely regarded as the most environmentally efficient method because it does not rely on electricity. Tumble drying consumes four times as much energy as washing clothes in a washing machine at 40 °C, making it the most energy-intensive process during laundering (Roos et al., 2016).

These findings underscore the significance of including country-specific washing practices and discourage generalisation in data collection for the use and end-of-life phases in an LCA study. Thus, understanding how people wash and maintain their clothing is not a mere curiosity but an essential endeavour with far-reaching implications for assessing the environmental impacts associated with garment use.

6.6 New Zealand’s Perspective on Garment Disposal

The way people dispose of their clothing at the end of its useful life also has an impact on the overall environmental profile of the garments (Daystar et al., 2019; Laitala et al., 2017; Laitala et al., 2018; Sohn et al., 2021). Notable disparities were noticed between New Zealand and other countries, particularly in their disposal methods. While European nations demonstrated a higher rate of disposing of woollen clothing in municipal bins (71%), New Zealanders displayed a different inclination, with a greater tendency to donate their woollen clothing than dispose of it (35.5%) (Nautiyal et al., 2023b; Wiedemann et al., 2020). In New Zealand, 62% of woollen and 54% of synthetic blend jumpers were reused. Additionally, a portion of both woollen and synthetic blend jumpers underwent downcycling (6.5% and 5%, respectively), providing environmental benefits by repurposing garments for other applications (Nautiyal et al., 2023b). The potential reduction in the greenhouse gas emissions, water consumption, and waste generation during production and manufacturing could be reassessed using reuse and downcycling percentages (Wiedemann et al., 2020).

In the LCA analysis of this study, after considering the avoided burden through reuse and downcycling, the carbon dioxide emissions of woollen jumpers made with cut-and-sew, in Supply Chain Scenario 1 was reduced from 14.03 kg CO_2 eq. emissions to 5.33 kg CO_2 eq. emissions (see section 5.2.3). Similar reductions were observed for all remaining life cycle scenarios investigated. Thus, reusing clothing is an impactful and sustainable approach that extends the lifespan of garments, saves resources, and reduces the need for new production. Understanding the proportion of garments undergoing downcycling makes the evaluation of potential waste reduction more accurate.

The disposal of garments in municipal bins or landfills represents the least desirable outcome due to its negative environmental consequences. The literature review highlighted the environmental burden caused by landfills, especially in relation to synthetic textiles, as microplastic fibres released during decomposition contribute to environmental pollution (DeVoy et al., 2021; Niinimäki et al., 2020).

In conclusion, country specific disposal behaviour are essential to consider to accurately assess the overall environmental impact of garments. The breakdown between reuse, downcycling, and disposal in municipal bins or landfills significantly influences waste generation, resource consumption, and the potential for impact mitigation. New Zealand should leverage this knowledge to develop targeted strategies, promote circular economic practices, and strive for a more sustainable and environmentally responsible approach to clothing disposal.

6.7 Empowering Designers by the Concept of "Avoided Burden"

Within the framework of LCA, a comprehensive understanding of the concept of "avoided burden" is crucial for fashion designers. Embracing circular economy practices, including reuse, recycling, and downcycling, enables designers to significantly reduce the environmental impact associated with their creation, thereby fostering a more sustainable and responsible fashion industry. By circumventing the extraction of virgin materials for new product development, designers can mitigate the environmental implications stemming from processing, packaging, transportation, etc. (Finnveden et al., 2009; Vogtländer, 2016).

Individual consumers also play a critical role in the adoption of the circular economy concept. However, convenience emerges as a crucial factor influencing consumers' decision-making processes (Laitala et al., 2017). Fashion designers can effectively support consumers in extending the active lifespan of their clothing by implementing strategies such as garment repair, alteration (Cooper et al., 2013), or the addition of creative embellishments such as embroidery, patchwork, or others on reused items (Connor-Crabb, 2017). By elevating the aesthetics of used garments, designers can reintegrate discarded garments into the mainstream consumer market, thereby reducing the reliance on new clothing production (Dissanayake & Sinha, 2015; Goldsworthy et al., 2018).

This study demonstrates the principle of avoided burden through reuse and downcycling. While reuse helps mitigate the impacts associated with producing a new jumper, downcycling accounts for the impacts involved in the production of raw materials, manufacturing, packaging, and transportation of another type of product, in this case cleaning cloths (Finnveden et al., 2009). Downcycling jumpers into cleaning cloths reduced the overall GWP of the jumper by 0.5 kg CO_2 eq. emissions across all eight scenarios, considering their transformation into cleaning cloths (see section 5.2.3).

Although recycling represents a more viable alternative to reuse and downcycling, it faces considerable challenges in countries with a small population spread across an extended geography like New Zealand as well as on a global scale. Textile fibre recycling, particularly fibre-to-fibre recycling, encounters complexities such as fibre separation, blending issues, and colour considerations (Sandvik & Stubbs, 2019). However, downcycling practices, exemplified by repurposing garments for lower-value applications, have gained popularity among consumers in New Zealand (Nautiyal et al., 2023b). Fashion designers can leverage these opportunities by designing products that are easily recycled or repurposed, thereby facilitating the transition toward more circular systems (Cooper et al., 2013; Dissanayake & Sinha, 2015; Goldsworthy et al., 2018). Consequently, collaboration among designers, manufacturers, policymakers, and other stakeholders is crucial for establishing effective fibre recycling practices in New Zealand (Casey & Brian, 2021; Cleveland, 2018). Through fibre-to-fibre recycling, the fashion industry can reduce its dependence on virgin textile materials, moving toward a more sustainable future.

In conclusion, comprehending the concept of avoided burden in LCA can empower fashion designers to exploit the environmental benefits of their creations. By understanding the environmental benefits of reuse and downcycling, designers can develop strategies to conserve valuable resources and curtail waste generation. Collaborative efforts among industry stakeholders are essential for overcoming the challenges of textile recycling and establishing effective practices.

6.8 Addressing Data Gaps for Garment Research in New Zealand

The LCA of garments plays a crucial role in understanding and mitigating their environmental impact, thereby promoting sustainability within the fashion industry. However, conducting comprehensive LCAs in New Zealand faces significant challenges due to data gaps and the limited availability of published research on the country-specific environmental impact of clothing and textile items. Unlike more profitable sectors, such as building construction or the dairy industry, the fashion industry has received less attention in terms of comprehensive environmental assessments within the country (Engelbrecht et al., 2018). This scarcity of published research creates a barrier to obtaining reliable inventory for the life cycle of garments.

This study highlights critical concerns regarding the authenticity of secondary data used in LCA, particularly in the domains of polyester fibre production and the wet processing of wool. Chapter 4 sheds light on the multiple limitations and challenges associated with relying on secondary data sources, underscoring the need to meticulously examine data to assess their applicability for the intended context.

New Zealand offers focused farm assurance programmes, represented by associations such as Oritain and NZFAI, which certify the origin-based quality of agricultural products. Oritain employs a methodology that focuses on precisely identifying the sources of organic materials. In parallel, the New Zealand Farm Assurance Programmes (NZFAP and NZFAP Plus) play a crucial role in ensuring the authenticity, safety, and excellence of wool sourced from sheep in the country. These programmes aim to instil consumer confidence both domestically and internationally by upholding rigorous standards of integrity and traceability for products originating from New Zealand (NZFAP website, 2023; Oritain website, 2023).

Although New Zealand prides itself on the quality of its wool production, there is a considerable data gap in the availability of life cycle inventory data concerning wool production in the country (Eady et al., 2012; Henry et al., 2015). Moreover, factors such as co-products such as meat and wool, variations in production methods, and farm management practices present challenges for accurately capturing the specific characteristics and practices of each farm (Biswas et al., 2010; Eady et al., 2012; Nemecek & Kägi, 2007). Consequently, relying solely on secondary data may fail to adequately represent the diversity of resource categories and production methods within the wool-production region in New Zealand.

This study identified limitations in the Ecoinvent dataset for wool production, including the lack of crucial information regarding wool quality and country-specific data, particularly for regions such as Australia and New Zealand. These limitations hinder the applicability and accuracy of datasets when assessing specific environmental contexts. Discrepancies between the Ecoinvent dataset and a dataset from Wiedemann et al. (2020) for New South Wales farms (see section 4.2.1) further accentuate the need for careful examination of data sources and methodologies. The presence of chemical fertilisers in the Ecoinvent dataset introduces potential gaps, underscoring the importance of accurately quantifying farm inputs for a comprehensive understanding of the environmental impacts associated with wool fibre production in New Zealand.

Furthermore, specific local data for critical processes in the garment life cycle, such as wool scouring in New Zealand, are unavailable for open domains (see Chapter 2, section 2.5.1). Data on wool scouring on Ecoinvent primarily originate from countries such as India and China, which may use different processes and chemicals and therefore may not directly apply to the local context of New Zealand (Wiedemann et al., 2019). This discrepancy poses considerable challenges for accurately assessing the environmental impact of wool production within a local context.

The value of New Zealand wool is adversely affected by a dearth of local data, leading to a limited understanding of its environmental impact. To improve the value of wool, experts propose substituting the use of synthetic materials with wool (Campaign for Wool General Manager, Tom O'Sullivan, as cited in Uys (2023, January 13). Despite the potential for recapturing market share among eco-conscious consumers, barriers persist in the acquisition of precise data on the environmental impact of wool production encompassing sheep methane production and carbon emissions during decomposition (Uys, 2023, January 13), which is crucial to addressing these challenges. By actively filling these data gaps, New Zealand can enhance its understanding of the environmental impact of woollen garments and pave the way for more sustainable practices within the fashion industry.

This study also raises concerns about the reliability of data regarding the production of polyester fibre (see section 4.2.2). The viability of the Ecoinvent dataset for polyester fibre production, particularly its inventory for ethylene production, a primary raw material, is flawed. Reliance on aggregated data limits the precision and ability to perform uncertainty analysis, hindering the assessment of the reliability of the dataset (Frischknecht et al., 2005). The lack of transparency, where crucial information is withheld for privacy reasons, raises doubts about the credibility of this dataset (Hischier et al., 2005). Furthermore, the absence of information on crude oil extraction hampers the identification of environmental hotspots in the life cycle of polyester fibres. Previous researchers have also noted discrepancies between the Ecoinvent dataset and other sources, further challenging its validity and reliability as a credible database for PET production (Gironi & Piemonte, 2011; Hischier et al., 2005).

Regarding dyeing inventories, the available Ecoinvent datasets lack inventories for wool and polyester fibre dyeing, limiting its accurate analysis (see section 4.3.2). To address this, a comprehensive literature search was conducted and suitable data inventories from Rosa et al. (2019) were identified. This literature provided detailed information on the chemicals and auxiliaries used in the dyeing process of both reactive and disperse dyes. Alternative inventories were applied when specific data were unavailable. By considering the specific dyeing requirements of wool and polyester fibres and employing an appropriate alternate inventory, this study aims to enhance the accuracy and reliability of the environmental impact assessments of material specific yarn dyeing processes.

In conclusion, this study highlights the concerns surrounding the authenticity of secondary data for LCA, particularly in the domains of wool and polyester fibre production and wet processing. The limitations and challenges associated with relying solely on secondary data sources underscore the necessity for meticulously examining the data available, considering context-specific factors, and using alternative data sources when required. This study's comprehensive literature search and acknowledgement of limitations contribute to enhancing the accuracy and reliability of the environmental impact assessment within the scope of the research investigation.

6.9 Implications for Reliability and Generalisability in Jumpers

It is crucial to acknowledge the assumptions made throughout the LCA of knitted jumpers as they may have implications for the reliability and generalisability of the findings. The limitations caused by the assumptions made in this study fall into three main categories: data accuracy and specificity, representativeness of production conditions, and applicability to the specific context of New Zealand.

First, the accuracy and specificity of the data used in this study raise concerns. The reliance on global datasets, as employed for wool fibre production, may introduce uncertainties regarding the representativeness of the data for merino wool grown in Australia. Furthermore, the application of secondary datasets by Wiedemann et al. (2019) and Rosa et al. (2019) on wool scouring and dyeing processes, respectively, may not accurately reflect the current practices and technological advancements in these stages of production. Similarly, the assumption that the dyeing information for polyester yarn is equivalent to that of polyester fibre might oversimplify the complexity of the dyeing processes and potentially lead to biased results.

Second, the representativeness of the production conditions considered in this study should be examined carefully. This study highlights the unavailability of data on mule spinning, which led to the use of ring spinning. This substitution assumes comparability between the environmental impacts of these spinning methods, which may not hold true. Additionally, the data gained from constructing the jumper in a laboratory environment may not accurately reflect the energy consumption and production practices in large-scale manufacturing facilities. Variations in equipment, production scale, and workflow could greatly affect the overall environmental impact, warranting caution when extrapolating the findings to real-world scenarios.

Finally, the applicability of this research to the specific context of New Zealand should be considered. This study points out the limitations of using generalised packaging statistics that might not accurately represent the specific supply chain pathway considered in this study. Similarly, the input data for detergent consumption may not accurately reflect the usage patterns in New Zealand, potentially affecting the assessment of overall environmental impacts. Furthermore, the waste scenarios assigned to the jumpers may not align with waste management practices specific to the country. This discrepancy could introduce uncertainties when evaluating the environmental consequences of the studied products in a local context.

These assumptions underscore the need for caution when interpreting the findings of this study. While the LCA modelling approach provides valuable insights into the environmental impacts of wool and polyester jumpers, the potential biases and uncertainties associated with the assumptions made should be acknowledged. Future researchers should strive to address these limitations by incorporating more accurate and specific data, considering the variability in production conditions, and accounting for the unique characteristics of the specific context under investigation.

Section 2

Discussion on Simplification of the LCA methodology

The second set of findings pertains to the development of a strategy for simplifying the LCA methodology to be included in fashion practice. The comprehensive LCA of woollen and polyester jumpers served as a basis for formulating a simplified LCA-based approach (Table 44, p.200) and a Simplified LCA Framework for Fashion Design (Figure 59) to assess the environmental impact of garments. Based on this system, this study propose a rapid assessment tool that can be extended to include additional material choices, garment manufacturing techniques, transportation modes, packaging information, and country-specific data on the garment lifespan, laundry habits, and end-of-life scenarios for various garment types and materials. The goal of developing this tool is to integrate environmental considerations into fashion practice.

6.10 Implementation of the Simplified LCA-based Approach

The adoption of the simplified LCA-based approach stands as a pragmatic measure in introducing reckoning as the fourth “r” of sustainability after reduce, reuse and recycle into the realm of fashion design. A potential tool that can inform sustainable design choices can be developed by simplifying the results of a comprehensive LCA using simple mathematical calculations. In this context, this research has unveiled an inventive avenue for calculating the environmental ramifications associated with knitted jumpers consumed in New Zealand. This approach is distinct from the traditional full-scale LCA methodology employed in similar assessments. Notable disparities between the comprehensive LCA technique typically used for the environmental assessment of fashion items and the simplified LCA-based approach are explained in Table 46.

Table 46

Differences between Comprehensive LCA and The Simplified LCA-based Approach

	Comprehensive LCA	The Simplified LCA-based Approach
Complexity:		
	It involves a comprehensive assessment of the garment's entire life cycle, including resource extraction, processing, manufacturing, transportation, use, and end-of-life, which can be overly complex, time consuming, and expensive.	This approach simplifies the LCA process by focussing on generalising certain data from a comprehensive LCA study, such as the impacts associated with producing and processing 1 kg of raw material, making it easier to apply in a tool format.
Data Intensity:		
	It requires access to specialised databases, detailed product-specific information, and environmental impact data, which can be challenging for fashion designers.	While access to data is still essential, this approach aims to use readily available data and general assumptions to estimate environmental impacts based on the weight of the garment.
Accessibility:		
	Typically conducted by environmental experts or consultants owing to its complexity. Most designers do not have the expertise to perform it and would require specialised training to do a comprehensive LCA independently.	It is designed to be more accessible to fashion designers and other stakeholders in the fashion industry. The approach provides a structured framework that designers can use to estimate and compare environmental impacts without requiring extensive expertise or extra training.
	Conducting a comprehensive LCA requires specialised software. Available solutions such as SimaPro and Gabi are expensive to acquire and are outside the scope of fashion designers who are working in small- and medium-sized sectors.	No specialised software is required, and the tool can be developed using easily accessible software such as Microsoft Excel or into a simple mobile application offering easy to pick and choose options.
Speed and Decision-Making:		
	It is often time-consuming owing to extensive data requirements and is typically conducted in the later stages of product development. This makes it nearly impossible to change any aspect of the garment design, production process, or garment life cycle to a more environmentally friendly option.	This approach is meant to be used early on in the design phase to enable designers to quickly assess the environmental impact of various design choices so that they can include environmental considerations where possible.

However, the pivotal question that arises when implementing LCA in fashion practice pertains to the challenges of data acquisition. This study posits that the successful implementation of a simplified LCA-based approach necessitates the provision of a tool pre-equipped with impact assessment data to be placed at the disposal of fashion designers. The following recommendations outline potential sources of data that can be instrumental in the development of such tools:

- *Database on Material and other pertinent life cycle stages:* This category encompasses comprehensive data concerning the environmental consequences associated with various facets of the garment life cycle, encompassing materials, processing, transportation, packaging and waste management that can be sourced from established data repositories such as Ecoinvent.
- *Data on Garment Manufacturing:* Data relevant to garment construction primarily include metrics for energy consumption and fabric waste. This information can be gleaned from sampling rooms engaged in the production of sample garments that mirror factory line practices.
- *Material Processing Data:* Data specific to specialised processes, such as scouring, bleaching, and dyeing, which exhibit material-specific variations, can be procured from scholarly articles and publications within the textile domain.
- *Consumption Statistics:* The garment use and end-of-life scenarios may be modelled by conducting online surveys utilising social media platforms tailored to the geographical region the tool is intended for. Additional avenues, such as surveys of laundromats and comprehensive wardrobe studies, could provide precise data regarding garment usage patterns and disposal practices among the populace.
- *Assumption-Based Data:* In situations where granular and specific data are unattainable, recourse to well-informed assumptions predicated on industry expertise or standard mean values can be judiciously applied.

A database of relevant environmental impact information can facilitate this process significantly. Such a database may include data on the environmental impacts of various materials, processes, and transportation methods that are commonly used in the fashion industry.

Thus, the advantages of the simplified LCA-based approach over a conventional full-scale LCA include the early stage decision-making capabilities, and a reduction in analytical complexity when juxtaposed with the conventional full-scale LCA methodology. Nonetheless, its effective deployment hinges upon designers' access to relevant data sources or databases, which are indispensable for facilitating efficient assessments of environmental impacts resulting from diverse design choices.

6.11 SWOT Analysis of the Simplified LCA-based Approach Developed

One noteworthy strength of the study is the ability to employ LCA data for future assessments of knitted garments in New Zealand. This study formulated the design for a simplified LCA-based tool that allows designers to effectively assess the environmental impacts of garments. The data collected for the comprehensive LCA (see Chapter 5, sections 5.1 and 5.2) were simplified in such a way that the information can be used for assessing other products in the same category. For example, the manufacturing data collected for wool production presented here could be applied to different wool-based knitted products such as gloves or scarves as it is not limited to jumpers. Similarly, the impacts associated with transporting one kilogramme of material by road remain the same regardless of the material being transported. This feature enhances the efficiency and versatility of the approach, enabling designers to make better-informed and sustainable decisions across a range of clothing items.

In addition to data reusability, the simplified LCA-based approach provides designers with an accessible and user-friendly system, making it easier to integrate sustainability considerations into their decision-making processes. This method offers a comprehensive evaluation of numerous factors influencing environmental impacts, including material selection, manufacturing techniques, supply chain pathways, transportation, packaging, product use, and end-of-life disposal. This comprehensive assessment enables designers to gain a holistic understanding of their product life cycle and identify opportunities for environmental improvement without spending excess time and resources in doing a rigorous LCA for each garment they design.

However, certain weaknesses need to be addressed. Currently, the accuracy and reliability of the potential tool depends heavily on the availability and quality of data. Insufficient or outdated data can introduce uncertainties and affect the accuracy of environmental impact evaluations, necessitating continuous efforts to improve data sources and transparency.

Furthermore, there are opportunities to enhance the effectiveness of the simplified LCA-based approach further. At present, the available simplified data is on the global warming impacts of knitted clothing. To enhance its effectiveness, this method should be expanded to incorporate a broader range of environmental indicators, such as water consumption or pollution, can provide a more comprehensive evaluation (Manfredi et al., 2012; Roos, 2016). Collaborative efforts among researchers, industry stakeholders, and data providers can also contribute to improving the quality and availability of data, thereby ensuring more reliable and accurate environmental impact evaluations (Kozlowski et al., 2019).

Finally, it is important to consider the potential threats to the effectiveness of this methodology. The applicability of the simplified approach may be limited to specific contexts or fashion industry segments, which could affect its widespread adoption. Additionally, the ever-changing dynamics of the fashion industry, including the development of new materials and technologies as well as changing consumer habits, require regular updates and adjustments to maintain the relevance and effectiveness of the potential tool, which may get expensive. Figure 60 sums up the SWOT analysis of the Simplified LCA- based approach.

Figure 60

SWOT Analysis of the Simplified LCA-based Approach

In conclusion, the simplified LCA-based approach showcases strengths, such as data reusability, accessibility, and comprehensive evaluation. Employing LCA data for future assessments, the approach enables designers to make informed decisions across a variety of garments. Although weaknesses such as a narrow focus on global warming impacts and data limitations exist, opportunities for improvement include integration with additional assessment tools and collaborative efforts for data enhancement. Being aware of potential threats, such as limited applicability and changing industry dynamics, allows proactive adjustments to ensure the potential tool's continued relevance and impact in promoting sustainable fashion design.

Section 3

Discussion on the Experiences Gained while Conducting LCA

The experience of performing LCA in the field of fashion design has brought its share of challenges. This section explores the experiences and challenges encountered by designers while conducting LCAs for garments in New Zealand. It discusses personal reflections on the challenges faced during LCA exploration and, data-related barriers encountered. These insights shed light on the practical application of LCA in everyday design operations and highlight the potential of implementing scientific strategies into fashion practice.

6.12 Navigating Complexities in LCA of Garments

Conducting a comprehensive LCA for clothing items is essential to accurately evaluate their environmental impact and align it with sustainability goals. Chapter 2 (section 2.4.4) discussed the complexities involved in the garment supply chain, the rapid pace of production, and the different processes involved in the construction of diverse garment varieties (Gwilt, 2012; Kozlowski et al., 2018; Ramani et al., 2010), pose significant challenges to LCA implementation. Overcoming these challenges is crucial to integrating sustainability into fashion practices.

Data collection and coordination with suppliers both upstream (processes before manufacturing) and downstream (processes after manufacturing) can be challenging (Curwen et al., 2013; Mentzer et al., 2001; Zbicinski, 2006). A major hurdle in employing LCA for garments lies in navigating the intricate network of suppliers, manufacturers, and retailers globally (Eder-Hansen et al., 2017; Strähle & Müller, 2017). Thus, gathering comprehensive data for each phase of the garment supply chain requires effective coordination among numerous stakeholders. Furthermore, the abundance and variety of products produced within a single fashion season further complicates data collection efforts. Understanding and managing the complexity of the fashion industry is crucial for effectively assessing the life cycle of clothing items (Abbate et al., 2023; Nayak et al., 2020).

Moreover, the speed-to-market production of fashion items is high, as is the variety of products available. The fashion industry's emphasis on fast-paced production to meet market demands presents a challenge for conducting LCA for every garment style. The volume and variety of products makes it impractical to assess each product individually. While conducting an LCA for a generic garment can provide valuable insights, subsequent redesigns and seasonal changes can introduce more design features, materials, trims, and treatments, necessitating additional LCA studies. Balancing sustainability considerations with quick turnaround times and constant innovation poses a challenge for designers (Aakko & Koskennurmi-Sivonen, 2013; Gwilt, 2012; Ramani et al., 2010).

The data constraints and assumptions made for clothing items influence the LCA findings. The intricate nature of the garment supply chain makes it challenging to gather comprehensive data on each process. Unreliable or insufficient data, such as the polyester fibre production dataset investigated in this study, can hinder accurate assessments (see section 4.2.2). Similarly, data gaps for locally produced merino wool and its wet processing further complicate the LCA process (see sections 4.2.1 and 4.3.1). Assumptions and substituted data are commonly employed to introduce uncertainties into the assessment. Standard usage figures may neglect variations influenced by material type and cultural practices, underscoring the need for more comprehensive and specific data (Daystar et al., 2019; Laitala et al., 2018; Sohn et al., 2021).

The challenges encountered in applying LCA to garments highlight the complexities involved in assessing their environmental impacts. To overcome these hurdles, it is crucial to enhance data collection and coordination efforts throughout both upstream and downstream supply chains. Furthermore, addressing speed-to-market pressure requires a balanced approach that encourages sustainable design practices without compromising innovation and market demand. Finally, reducing reliance on assumptions and filling data gaps by collecting specific information for various material types and garment categories would enhance the accuracy and reliability of LCA investigations.

6.13 Challenges in Finding Support for LCA in New Zealand

Conducting an LCA of garments in New Zealand presented considerable challenges owing to the limited support available within the country. The country faces a scarcity of organisations with expertise in assessing the environmental impact of clothing items. Unfortunately, the limited experience of LCA organisations in handling the complexities of the garment life cycle hampers their ability to provide adequate guidance and support. Establishing organisations well versed in the life cycle of garments, capable of conducting LCA on clothing items, could serve as valuable repositories for data on specific phases of the garment life cycle. These data repositories should be regularly updated by collaborating with data providers such as Ecoinvent to further enhance LCA assessments in the country.

The lack of certified practitioners with expertise in clothing poses challenges in the critical review process of LCA assessments. Certified practitioners play a crucial role in ensuring the accuracy and reliability of environmental assessments. However, finding experts well versed in the intricacies of the fashion industry is challenging in New Zealand. This scarcity of specialists hampers the provision of comprehensive feedback and guidance on LCA assessments, potentially resulting in inconsistencies and limitations in evaluating their environmental impact. Addressing this issue requires the training of certified practitioners with expertise in garments within the country.

The limited availability of educational courses tailored specifically for LCA in the fashion sector further compound the challenges in conducting LCA in New Zealand. Although some universities and colleges offer LCA courses, they are not targeted at the fashion industry, despite the importance of conducting LCAs for garments due to the substantial environmental impacts associated with their life cycle (Bick et al., 2018; Niinimäki et al., 2020). To effectively implement LCA for clothing items, offering targeted training and education that addresses these specific challenges is essential (Earley, 2017; Goldsworthy et al., 2018; Wren, 2022).

Overcoming this challenge necessitates understanding the unique characteristics of garments, promoting institutes that guide practicing LCA, certification for conducting critical reviews, and developing tailored LCA courses for the fashion sector. Strengthening support networks, promoting focused training opportunities, and fostering collaboration between LCA practitioners and the fashion industry are vital steps toward effectively integrating sustainable practices into the fashion sector in the country.

6.14 Chapter Summary

The previous chapter presented the results of a comprehensive comparative LCA of knitted jumpers, examining eight life cycle scenarios, and developing a simplified methodology. This chapter analysed the research findings and discussed them in the context of the aims and objectives of this study, which is to assist New Zealand-based fashion designers in examining the environmental impact of the clothing they create, simplifying the LCA methodology for its implementation in fashion practice, and sharing and contributing experiences for advancing research in sustainable fashion design.

Section 1 investigated the LCA of knitted jumpers, highlighting the importance of material choices in shaping the life cycle impact of garments. The study revealed significant differences in the environmental effects of woollen versus polyester fibre production. Wool exhibits higher impacts during production and processing, but lower impacts during the use and end-of-life phases. The analysis of knitting techniques revealed that the cut-and-sew method was preferred by overseas manufacturers because of its lower energy consumption and availability of workforce, whereas integral knitting technology was more suitable for local manufacturing in New Zealand. The role of the local energy mix in the environmental impact of jumper manufacturing is emphasised, with New Zealand showing approximately 15% lower overall impacts than Bangladesh owing to differing energy sources. Generally, the use of local manufacturing practices has been identified as environmentally beneficial as it reduces packaging impacts and shortens transport routes in the supply chains.

A country-specific analysis of laundry practices highlighted the significance of understanding washing habits for accurate environmental impact assessments. Moreover, examining garment disposal practices in New Zealand was deemed essential for developing targeted strategies and promoting circular economic practices. Additionally, the study shows significantly reduced emissions through reuse and downcycling, illustrating the importance of understanding the avoided burden in

LCA for fashion designers. Finally, While LCA modelling offers valuable insights, potential biases and uncertainties in the assumptions made should be acknowledged.

Section 2 focused on the simplification of the LCA methodology and its implementation as a pragmatic measure of introducing reckoning as the fourth “r” for establishing sustainability into the realm of fashion design. The simplified LCA-based approach showed strengths such as data reusability, accessibility, and comprehensive evaluation, while also addressing its limitations and potential threats. Future improvements were suggested, such as integrating additional assessment tools and proactively updating data to remain relevant in promoting sustainable fashion design.

Section 3 discussed communication with the design community and addressed the complexities of LCA in garment assessment. Enhancing data collection and coordination efforts throughout supply chains, developing industry-wide databases, and promoting tailored LCA courses were proposed as strategies to overcome the issues identified. Additionally, balancing speed-to-market pressures with sustainable design practices and reducing reliance on assumptions were highlighted as factors that need to be taken into consideration when developing sustainable practice strategies.

Chapter 7 Conclusion

This study underscores the advantages of conducting a life cycle assessment (LCA) investigation of garments. It emphasises the transformative impact of the simplified LCA-based approach for fashion designers and its capacity to seamlessly incorporate sustainability considerations into their routine design practices. This chapter provides a comprehensive overview of the research outcomes and their substantial scholarly contributions. At first, the findings of this research are intricately linked to the research question, highlighting the original knowledge that emerged from the pragmatic application of the chosen methodology and the ensuing results. Subsequently, the potential contributions of the research findings on sustainable fashion practices are examined. The chapter then addresses the inherent limitations of this research endeavour while concurrently proposing a compelling and ambitious agenda for future scholarly investigations in this domain. Finally, a concluding note on my personal growth and learning through this study is presented.

7.1 Addressing the Research Question

This exploratory research was grounded in the ecocentric theory for environmental sustainability, drawing inspiration from the Māori principle of “kaitiakitanga,” which embodies the guardianship of nature. Adopting a pragmatic philosophical stance of doing whatever works, this study integrates sustainable development principles into fashion practice. The main objective was to develop a simplified approach to the LCA methodology that is tailored specifically to fashion designers. The study proposes the notion of reckoning, meaning the assessment of the environmental impact of a product, as an important consideration for achieving sustainability in fashion design. The central research question addressed in this study was as follows:

RQ1. How can the life cycle assessment (LCA) methodology be simplified and effectively implemented in everyday operations to assist fashion designers in mitigating the environmental impact of the garments they design?

To address the complexity of the main research question, the study was structured into three primary areas of investigation, leading to the formulation of three research sub-questions (RSQ1 to RSQ3). The study subsequently answers the following three sub-questions below.

Answer to research sub-question 1

RSQ1. What are the environmental implications associated with various phases in the life cycle of a garment?

To address this question, a comprehensive evaluation of the environmental implications associated with the life cycle of a knitted jumper consumed in New Zealand was conducted. The LCA methodology, encompassing goal and scope definition, inventory analysis, impact assessment, and interpretation, was applied to evaluate knitted jumpers across eight different life cycle scenarios. The choice to focus on a jumper was based on its extensive usage in New Zealand as a winter clothing item and its considerable export volume from the country. The LCA assessment covered the entire cradle-to-grave life cycle of the jumper, from fibre production to end-of-life disposal. The study's functional unit was established as a single knitted jumper, weighing 385 g, in black colour, without any accessories or labels, intended for use and disposal in New Zealand. The system boundary encompassed all life cycle phases, including raw material extraction/fibre production, fibre processing and dyeing, garment manufacturing, transportation and packaging, use, and end-of-life phases. The eight scenarios analysed encompassed two material types (wool and polyester), three knitwear manufacturing technologies (cut-and-sew, fully fashioned, and integral knitting), and four varied supply chain pathways.

To ensure data accuracy and consistency, standard datasets such as Ecoinvent were employed to gather information on fibre production, while published literature provided insights into the fibre processing and dyeing. However, owing to the absence of published data on subsequent life cycle phases, primary data was gathered. Laboratory experiments provided information regarding garment manufacturing and a questionnaire survey was employed to gain insights into the use and end-of-life phases of jumpers in New Zealand (see Chapter 5, Section 1). Table 47 recapitulates the findings from the LCA of knitted jumpers in eight different life cycle scenarios.

Table 47

Summary of Findings from the Comprehensive LCA for Knitted Jumpers in Eight Life Cycle Scenarios (Global Warming Impacts presented in kgCO_2 eq.)

	WJCSNZ (Woollen Jumper, Cut-and-sew, New Zealand)	WJFFNZ (Woollen Jumper, Fully Fashioned, New Zealand)	WJIKNZ (Woollen Jumper, Integral Knitting, New Zealand)	PJCSAS (Polyester Jumper, Cut-and-sew, Bangladesh)	PJFFAS (Polyester Jumper, Fully Fashioned, Bangladesh)	PJIKAS (Polyester Jumper, Integral Knitting, Bangladesh)	WJIKAS (Woollen Jumper, Integral Knitting, Bangladesh)	PJIKNZ (Polyester Jumper, Integral Knitting, New Zealand)
Mean Impact of one jumper through its Cradle-to-Grave Life Cycle	14.03	11.17	10.94	5.11	5.04	5.28	12.64	3.64
Impact of Fibre Production	6.72	5.2	5.07	1.95	1.51	1.47	5.07	1.47
Impact of Fibre Processing and Dyeing	6.04	4.19	4.08	0.78	0.6	0.59	4.1	0.6
Impact of Garment Manufacture	0.11	0.22	0.27	0.86	1.45	1.75	1.75	0.27
Impact of Transport and Packaging	0.22	0.2	0.2	0.36	0.32	0.32	0.36	0.16
Impact of Lifetime Garment Use	0.9	0.9	0.9	1.02	1.02	1.02	0.9	1.02
Impact of End-of-Life	-0.02	-0.02	-0.02	0.13	0.13	0.13	-0.02	0.13
Adjusted Impact in Considering Reuse and Downcycling	5.33	4.26	4.18	2.39	2.36	2.47	4.81	1.72
Impacts Per Wear	0.0224	0.0179	0.0176	0.0139	0.0138	0.0144	0.0202	0.0100

A comparative assessment of the environmental impacts of wool and polyester jumpers has yielded significant findings, suggesting that wool jumpers exhibit greater global warming implications than their polyester counterparts. The primary contributors to these impacts were identified as the wool fibre production and subsequent wet processing stages involving scouring, bleaching, and dyeing. However, the veracity of these findings rests on the underlying data quality and assumptions for wool and polyester fibre production, some of which can be considered problematic, as discussed in Chapter 4, sections 4.2.1 and 4.2.2.

The comparative analysis that was conducted of wool and polyester fibre processing and dyeing delineates stark distinctions in their respective environmental impacts. The complex pre-processing regime required for wool fibres, attributable to the removal of inherent dirt and grease, were found to carry considerable environmental burdens vis-à-vis energy, water, and chemicals. Conversely, the available data suggested that the processing of polyester fibres was simple, contributing to its diminished environmental profile.

The exploration of flatbed knitwear manufacturing techniques illuminated the intricate dynamics between energy consumption and material loss. A synthesis of these findings is presented in Table 48, which succinctly presents the energy consumption and material loss percentages for each of the three flatbed knitwear manufacturing techniques.

Table 48

Summary of Energy Consumed and Material Loss in Three Flatbed Manufacturing Techniques

	Cut-and-sew	Fully Fashioned	Integral Knitting
Energy consumed in production of 1 Jumper	1,229 Wh.	2205 Wh.	2670 Wh.
Material Loss in production of 1 Jumper	26.2%	4.6%	2.1%

Note: Wh= Watts per hour

The findings advocate for making context-specific decisions as the cut-and-sew approach crystalised as the production approach with least environmental impact overseas, whereas integral knitting technology emerged as an attractive proposition for domestic manufacturing in New Zealand. This study underscores the need for holistic assessments to support informed decision making on production technologies within garment manufacturing.

The exploration of transportation and packaging dimensions within the fashion supply chain underscored the importance of using sustainable transportation alternatives, particularly sea transport, to reduce carbon emissions. A comparative analysis of GWP between sea and road transport accentuated the compelling advantages of maritime options. Additionally, this study shed light on the nuanced interplay between packaging materials, manufacturing locations, and their subsequent implications.

The comparative study of wool and polyester in the use and end-of-life phases of knitted jumpers in New Zealand highlighted the distinct usage patterns and practices that characterise each material. Table 49 captures the disparities in the use and end-of-life stages of wool and polyester jumpers within the context of New Zealand as elucidated by Nautiyal et al. (2023b). These distinctions fundamentally underlie the divergent environmental profiles of the two materials.

Table 49

Variances in Use and End-of-Life of Woollen and Polyester Jumpers Consumed in New Zealand

	Woollen Jumper	Synthetic-blend Jumper
Number of wears per lifetime	237 wears	171 wears
Number of wears before wash	11.5 wears	5.2 wears
Percentage Reuse	62 %	54 %
Percentage Downcycling	6.5 %	5 %
Percentage Disposal to Municipal Bin	35.5 %	41 %

Note: Sourced from (Nautiyal et al., 2023b)

The data in Table 49 demonstrates that wool, characterised by its prolonged usage duration, higher rates of reuse, and greater prevalence being used for downcycling, has the greater ability to mitigate global warming impacts and reduce waste generation compared to synthetic materials such as polyester. This study further underscored the nuanced interplay among material composition, usage patterns, and sustainable practices, highlighting the pivotal role they collectively play in sculpting the environmental footprint of garments.

In large firms, designers often face limitations in implementing sustainable practices. As noted by Hur and Cassidy (2019), the hierarchical structure of large firms can restrict designers' autonomy in incorporating sustainability into their manufacturing and lifecycle. However, in small- and medium-sized enterprises (SMEs), designers usually have more flexibility and control over their decisions. Knowledge of the GWP of garments throughout their lifecycle provides designers with critical insights necessary for making environmentally sustainable choices. The findings from the comprehensive LCA of knitted jumpers in New Zealand revealed several specific environmental impacts and potential actions that designers can take to mitigate them.

1. Material Selection: Choose materials with a lower GWP. For example, using polyester over wool could reduce the carbon footprint; however, the environmental impact of the use and end-of-life phases must also be considered while selecting material (Table 47).

2. Production Techniques: Implement more efficient production techniques, such as integral knitting, which has lower material loss and is more energy-efficient for manufacturing in New Zealand (Table 48).

3. Sustainable Dyeing and Processing: Use eco-friendly dyes and processes that minimize water and energy use, thereby reducing the environmental burden of fibre processing and dyeing (Table 47).

4. Sustainable Transportation: Prefer sea transport over road transport to significantly reduce carbon emissions during the transportation phase.

5. Sustainability in the use phase: Design garments that require less frequent washing and are easy to maintain (Table 49).

6. End-of-Life Management: Design garments for extended use, higher reuse, and easier recycling to minimize disposal to municipal bins and reduce overall waste (Table 49).

This section of the LCA analysis successfully addressed the first research sub-question by comprehensively assessing the environmental implications associated with the various life cycle phases of garments. The findings identified three critical phases (material selection, garment manufacturing, and supply chain pathway) that largely influence a garment's overall environmental impact. However, the data did not inform the research question, but helped to answer the subsequent research sub-question regarding the simplification of the LCA methodology.

Answer to research sub-question 2

RSQ2. How can the LCA methodology be simplified to make it practical for fashion designers to integrate sustainability considerations into their decision-making processes?

The second research sub-question aimed to facilitate the integration of sustainability considerations into everyday fashion practice. Building upon the comprehensive LCA investigation of knitted jumpers, this study focused on developing a simplified method for assessing the environmental impact of garments. A simplified LCA-based approach was devised to evaluate the environmental ramifications of garments and has the potential to be developed into a tool like a mobile application. The developed method was predicated on a thorough assessment that systematically dissected the intricate stages encompassing the entire life cycle of garments (see Chapter 5, Section 5.3).

Additionally, the development of a Simplified LCA Framework for Fashion Design provided a flowchart for assessing the environmental impact of garments utilising the simplified approach (see Chapter 5, Figure 59, p. 205). The flowchart breaks down the environmental assessment of garments into ten foundational processes. By integrating the impact of various materials, garment manufacturing techniques, and supply chain pathways, this framework can be applied to calculate the cradle-to-grave GWP for any garment weight. The ten processes involved in the development of the simplified methodology are explained in Section 5.3.6. Fashion designers, including those without a specialised background in LCA, can use the simplified framework to assess the impact of their creations, which can be further adapted to include many other processes and garment types according to their requirements. Consequently, environmental considerations can be incorporated as viable options in product development.

Answer to research sub-question 3

RSQ3. What are the barriers and challenges faced by designers in implementing LCA in the field of sustainable fashion design and how can they be addressed?

The third research sub-question aimed to enhance the understanding of implementing LCA in the field of sustainable fashion design. A designer by trade, the researcher encountered several challenges when exploring the field of LCA, which not only provided valuable learning experiences but also shaped the decision-making process and the overall design of the study (see Chapter 5, Section 3). By sharing these challenges with the design community, the researcher aimed to shed light on the broader obstacles faced by fashion designers, who despite their design expertise, often struggle to incorporate scientific principles such as LCA into their everyday practice.

Strategies such as developing industry-wide databases, collaboration platforms, and tailored LCA courses for the fashion sector to enhance data collection, coordination, and support networks were proposed to overcome these challenges. Additionally, it was suggested that prioritising the application of a pragmatic philosophy and employing diverse data collection strategies could enhance the validity and applicability of future research findings. Sharing these experiences and insights addressed the third research sub-question, providing valuable insights into the integration of LCA into fashion design.

Therefore, the main research question was answered through a systematic exploration of the three research sub-questions. The LCA methodology was comprehended and simplified to a prototype tool that can be used by fashion designers in their routine operations for reckoning, comparing, and mitigating the impacts of their creations.

7.2 Contribution of the Study

The findings and outcomes of this study will make a valuable contribution to the field of sustainable fashion design. These contributions can be categorised into theoretical, methodological, and practical, each adding valuable insights and advancing knowledge in their respective domains. Figure 61 presents a summary of the contributions of this study in the area of sustainable fashion design.

Figure 61

Contributions of the Study to Sustainable Fashion Design

Theoretical Contributions	Methodological Contributions	Practical Contributions
Exploring and measuring the environmental impact of garments.	Simplifying LCA for fashion designers.	Guidance on garment's LCA, including data collection and impact assessment.
Understanding the life cycle of knitted jumpers in New Zealand.	Development of "Simplified LCA framework for Fashion Design" to integrate sustainability into fashion.	Primary data collected for use and end of life phases of knitted jumpers in New Zealand.
To research environmental impact of materials, knitwear construction techniques, and supply chain pathways.	Simplified LCA methodology includes material selection, manufacturing scenario, and supply chain pathway selection.	Application of LCA to compare and mitigate the environmental impact of garments.
Integrating science and fashion expertise in sustainability.		Sharing practical insights of using LCA in fashion design.

7.2.1 Theoretical Contributions

This study makes an original contribution to the theoretical landscape of sustainability within the realm of fashion design by introducing the concept of reckoning as a key design principle that encourages fashion designers to assess and consider strategies to mitigate the environmental impact of clothing items. This study underscores the critical need to measure the environmental impact of fashion products, highlighting the integration of reckoning as a fourth “r” alongside the well-established principles of reduce, reuse, and recycle. This conceptual framework provides fresh insights and engenders reflective deliberations concerning production and consumption practices within the fashion industry. The theoretical contributions of this study are summarised as follows.

Advancement of knowledge in the application of LCA for sustainable fashion design

By exploring and quantifying the environmental impact of knitted jumpers using a comprehensive LCA methodology, based on ISO 14040-44 guidelines, this study contributes to an understanding of sustainability challenges in the fashion industry. This study sheds light on the specific environmental implications of the cradle-to-grave life cycle of jumpers in New Zealand. The research provides valuable insights into the environmental consequences of various stages of the garment life cycle, including raw material production, processing, manufacture, transport, usage, and end-of-life phases.

Understanding of the complete cradle-to-grave life cycle of knitted jumpers

This study expands our knowledge of the cradle-to-grave life cycle of garments with a specific focus on knitted jumpers. The methodology required to collect data for the distinct phases of the life cycle is demonstrated, highlighting the benefits of gathering primary data during garment construction as well as country specific data on garment use and end-of-life through survey methods. The research enhances our understanding of the impact of the complete life cycle of knitted jumpers by examining each stage of the life cycle in detail.

Filling the research gap in understanding the environmental implications of varied materials, manufacturing techniques, and supply chain pathways

This research provides comprehensive insights into the environmental implications of varied materials, knitwear manufacturing techniques, and supply chain scenarios. It emphasises the critical role of material selection in influencing the overall environmental footprint of garments. The study examines the impact of material selection on the production of fibres as well as the use and end-of-life phases, highlighting the importance of considering material choices. Along with the material, the research was able to quantify the variances in impacts associated with different flatbed knitwear manufacturing techniques and various supply chain pathways.

7.2.2 Methodological Contributions

A significant methodological contribution is made through the introduction of a simplified approach to LCA methodology tailored specifically to fashion designers. The methodological contributions of this study are summarised as follows:

Formulation of a simplified LCA-based approach

The need for a simplified LCA-based approach that is accessible and applicable to everyday design operations underpins this research. By simplifying the comprehensive LCA process, and using the simplified approach based on the weight of garments, a potential tool can be developed that can instantly assess the environmental impacts of garments. This simplified approach reduces the complexity and resource requirements traditionally associated with comprehensive LCA, thereby enabling fashion designers to integrate sustainability considerations into their design practices more effectively.

Development of the Simplified LCA Framework for Fashion Design

A structured and systematic flowchart, known as the Simplified LCA framework for Fashion Design is introduced. This framework facilitates the integration of sustainability into fashion practices. The framework considers then basic steps in conducting an LCA for measuring the environmental impact of garments. By providing a clear flow diagram of the steps involved, this study allows designers to scientifically assess and compare the environmental impacts of unique design options, thereby facilitating sustainable decision-making processes.

Components of the simplified LCA approach

This study identifies and emphasises three crucial components in the life cycle of a garment: the material, the garment construction technology, and the supply chain pathways considered. By considering these inputs along with the overall weight of the garment when ready, a simplified assessment of its environmental profile can be performed using the LCA method. This recognition is particularly valuable in the context of fashion design, where numerous garments and styles are produced daily, making it challenging to assess the environmental impact of each design using the comprehensive LCA methodology. This study demonstrates that, by focusing on these three components, a generalised assessment of a garment's environmental implications can be made, enabling designers to make more informed choices during the design process.

Integrating science and fashion expertise for sustainability

This contribution highlights the integration of scientific methodologies such as LCA with fashion industry practices and knowledge. By bridging these two domains, this study advances the theoretical understanding of sustainability in fashion design and provides a methodological framework for applying scientific principles to practical design operations. This interdisciplinary approach enhances overall knowledge and understanding of how sustainability can be integrated into the fashion industry, fostering a more environmentally conscious and responsible practice.

7.2.3 Practical Contributions

This research offers practical contributions that provide guidance and insights for the design community that aim to advance in the field of sustainable fashion design. The practical contributions of this study are summarised as follows.

Practical guidance on conducting LCA for garments

This study provides practical insights and guidance on conducting an LCA specifically for garments. The fashion design community and researchers can learn from the methodology and techniques employed in this study to estimate the environmental impacts of knitted garments in New Zealand. Data collection and impact assessment methods are outlined enabling practitioners to apply ISO 14040-44 LCA principles effectively in their work.

Application of primary data to estimate the environmental impact of use and end-of-life phases

The methodology for collecting primary data specifically for the use and end-of-life phases of clothing items is demonstrated. By conducting surveys and analysing key information such as garment lifespan, number of washings per lifespan, and disposal practices in New Zealand (Nautiyal et al., 2023b), this study generates the data it needs to calculate the environmental impacts of these crucial phases. The research shows how these data can be utilised to assess the environmental impact of knitted jumpers and inform sustainable practices aligned with circular economic principles.

Application of LCA to assess, compare and mitigate environmental impact

Through the application of LCA, the study shows how it can be used to compare and mitigate the environmental impact of garments. By considering material selection, manufacturing scenarios, and supply chain pathways, a holistic assessment of the environmental performance of garments was achieved. The research highlights the importance of making informed choices in these areas to reduce the overall environmental footprint of fashion design. This practical application of LCA can guide designers to create more sustainable and environmentally friendly garments.

Sharing practical insights with the design community through this thesis

The study goes beyond the theoretical aspects and provides valuable practical insights gained from applying LCA in the context of fashion design. By sharing the experiences, challenges, and barriers encountered during the research process, this study serves as a source of knowledge and lessons learned for future studies. This information is crucial for informing future designers to effectively navigate the complexities of integrating sustainability considerations into their work.

In conclusion, this study makes a significant contribution to the field of sustainable fashion design. Theoretical contributions include advancements in knowledge regarding the environmental impact of garments and an enhanced understanding of the complete cradle-to-grave life cycle of knitted jumpers. Methodological contributions involve the development of a simplified LCA approach and framework for integrating sustainability into fashion practices. Finally, practical contributions encompass practical guidance on conducting LCA for garments, the application of LCA to assess, compare and mitigate environmental impacts, and the sharing of practical insights and lessons learned. These contributions collectively contribute to fostering an environmentally conscious and sustainable fashion industry.

7.3 Limitations of the Study

While this study sought to address significant research problems and provide valuable insights into the environmental impact of clothing production and consumption, it is important to acknowledge certain limitations that affect the scope and generalisability of the findings. By recognising these limitations, we can gain a more comprehensive understanding of the study's boundaries and the implications of its outcomes.

Narrow focus on knitted jumpers and material

The focus of this study on the LCA of a knitted jumper using wool and polyester materials limits the findings to specific clothing items and materials. The impacts associated with the blends of materials commonly found in fashion items were not considered. Additionally, the LCA excluded accessories and trims typically present in fashion items such as buttons, laces, and labels, which may have additional environmental implications but were out of the scope of this study.

Assumptions and data quality

Several assumptions were made during the LCA process, which introduced limitations to the study. The quality and availability of data for wool and polyester fibre production, as well as the validity of assumptions about transportation modes, distances and packaging, may not have been entirely accurate, which may have affected the findings of this study.

The limited scope of the simplified LCA-based approach

While this study introduced a methodology for a potential tool or mobile application based on the simplified LCA approach for fashion design, its applicability is currently limited to knitted jumpers consumed in New Zealand. The database needs further development and expansion to include other textile fibre types (including blends), garment construction techniques, and more garment kinds such as shirts, T-shirts, bottoms and more. Additionally, the study focuses on road and sea transportation excluding consideration of other modes of transport such as rail, limiting the comprehensive evaluation of the environmental impact associated with different transportation options.

Limited practical insights for fashion designers

The practical insights provided to fashion designers in this study primarily focused on the experiences encountered during the current research process. Although this information can be valuable, it does not provide extensive practical guidance beyond a specific context. Further investigation is needed to offer more comprehensive practical insights that address a wider range of challenges that designers may face when integrating scientific assessment techniques and provide actionable recommendations for its integration into fashion practice.

Assessing the environmental implications of garments through LCA presents a multifaceted challenge that can vary substantially among individuals and organisations. However, it is imperative to emphasise the pressing need for a more extensive body of independent research dedicated to the comprehensive exploration of this field.

One notable concern in this regard is the predominant reliance on large industrial methodologies, such as the Higg Index, which has been a prominent tool for assessing the sustainability and environmental impact of garments. However, mounting allegations of a lack of data reliability and transparency have cast doubts on the credibility and objectivity of such methodologies. There is an urgent need for independent research endeavours that can offer a fair evaluation of the environmental consequences of garments.

In conclusion, while this study has certain limitations, it has made valuable contributions to the understanding of the environmental impact of knitted jumpers consumed in New Zealand and developed a simplified approach to conducting an LCA inquiry. Future research efforts can build on these limitations to expand the scope, improve data quality, and provide more comprehensive and practical guidance for sustainable fashion design.

7.4 Future Research Opportunities in the Field

The present study contributes to the quantification of the environmental impact of garments and establishes a methodology to evaluate these impacts across various life cycle scenarios. However, several avenues for further research can be built on the findings of this study. The following research opportunities are worth exploring:

Expansion of methodology: The methodology developed in this thesis can be extended to incorporate a broader range of material types, encompassing wet processes, garment manufacturing techniques, distribution channels, use, and end-of-life options. By including these additional factors, a more comprehensive assessment of the environmental impacts of clothing items can be achieved.

Interactive digital application: Future research could explore the key considerations and technical requirements for developing an interactive digital application that utilises the formulated methodology to assess the environmental impact of garments. Other areas of interest could include explorations into how user engagement and the adoption of such an application could be encouraged. Exploring these questions would contribute to the development of user-friendly applications to promote environmental awareness in the apparel industry.

Design and development considerations: Another area of interest could be identifying the design and development features that should be considered when creating an interactive digital application based on the formulated methodology. Understanding the best practices for designing and implementing such an application would enhance its usability and effectiveness as a decision-making tool by fashion designers.

Enhancing data accuracy: To improve the accuracy of life cycle analysis for garments, it is crucial to collect specific data on clothing production and consumption in the context of New Zealand. Investigating the most effective strategies for collecting such data would facilitate more precise assessments of the environmental impact of garments in the local context.

Reliable dataset on PET production: Future research opportunities in the domain of PET (Polyethylene Terephthalate) production datasets could revolve around enhancing the reliability, and relevance of them. This research avenue would contribute to a more precise assessment of the environmental impact associated with clothing items that rely on PET. To enable a more accurate analysis of PET production, researchers should focus on gathering comprehensive data for crude oil extraction and PET production, particularly at the unit process level.

Traceability and transparency in fashion supply chains: To ensure sustainable production practices in the fashion industry, it is vital to enhance the traceability and transparency of fashion supply chains. Investigating strategies that can be implemented to achieve this goal would enable better monitoring and accountability of the garment manufacturing process. Researchers can focus on ways to implement sustainable features in the supply chain.

Global warming impacts for end-of-life to landfills: The global warming impacts associated with end-of-life disposal to landfills for different textile materials have not yet been comprehensively established. Understanding the environmental consequences of different disposal practices would help guide sustainable waste management strategies and inform decision-making regarding the end-of-life phase of fashion items. More research identifying the waste-management for different textile material should be taken up.

Expanding beyond climate change: The present research has primarily focused on conducting an environmental impact assessment of garments with a specific emphasis on Global Warming Potential that causes climate change. However, future investigations could explore a broader spectrum of sustainability dimensions beyond climate change. This could include the incorporation of additional environmental aspects, such as microfiber pollution of water bodies during the use and end-of-life phases, and considerations of social dimensions within the life cycle analysis. Studies that explore the impact of different sustainability dimensions would help us develop a more comprehensive understanding of the overall sustainability of fashion products.

These suggestions for research provide a roadmap for future investigations in quantifying the environmental impact of garments. By addressing these issues, researchers can advance the knowledge necessary to drive sustainable practices in the apparel industry.

7.5 Concluding Note

Throughout this PhD journey, significant personal growth and learning have been experienced, which have deeply influenced both my research and academic identities. Undertaking the formidable task of conducting an LCA of a knitted jumper within the realm of design has proven to be a transformative experience, presenting numerous challenges that have contributed to personal development. This reflection provides an opportunity to acknowledge the encountered obstacles, valuable lessons learned, and diverse set of skills acquired along the way.

One of the most prominent challenges I have faced as a designer venturing into LCA is the need to comprehend the scientific terminology and quantitative methods inherent to environmental assessments. Bridging the gap between art and science requires dedicated efforts to understand the intricate scientific concepts related to energy conversion and the chemicals used in the garment supply chain. Extensive reading and thorough research were pursued to enhance the understanding and enable data collection for previously unreported life cycle phases. This experience highlights the importance of perseverance and a positive mindset when facing challenges.

The PhD journey marked a remarkable expansion of knowledge and skills for me. The recognition of the necessity to broaden my expertise and deepen my understanding of sustainability within the fashion industry has led to active participation in university-supported workshops, completion of a certificate course on LCA concepts, and rigorous critical review processes. This process resulted in the sharpening of critical thinking and analytical abilities as well as the refinement of academic writing and effective communication skills through surveys and publications in peer-reviewed journals.

Beyond the technical skills acquired, the university experience has provided a range of transferable skills that have proven invaluable throughout the PhD and will continue to be valuable in the future. My participation in the 3 Minute Thesis (3MT) competition required me to integrate of written and spoken communication abilities, thus enabling effective interaction with diverse audiences. Additionally, strong organisational and time management skills enabled me to navigate multiple research tasks and meet of deadlines.

Moreover, my personal growth during this PhD extends beyond academia. Engaging deeply in research and collaborating with scholars from diverse backgrounds broadened my perspectives and nurtured greater openness to different ideas and approaches. This has facilitated a more nuanced and well-rounded research perspective, fostering profound self-awareness and self-confidence. Self-reflection and guidance from supervisory mentors deepened my understanding of strengths and areas for improvement, empowering me to embrace any challenge with resilience and conviction.

In terms of contributions to the research field, personal growth is translated into tangible outcomes. Novel insights into quantifying the impacts associated with clothing items and innovative approaches have advanced knowledge at the intersection of fashion and sustainability. The recognition and acceptance of contributions by peers and experts in the field affirmed the impact of the research, opening doors for collaborations, and inspiring future research directions.

In conclusion, this PhD journey has been an enriching and transformative experience both academically and personally. Overcoming challenges has significantly contributed to my personal growth and shaped my identity as a researcher in the field of sustainability and fashion design. The recognition of contributions has laid a solid foundation for future collaborations and further research. With confidence, meaningful and lasting contributions to the field, along with ongoing personal and professional growth, will be forged.

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Appendices

Appendix A *Ethics Approval Letter (Stage 1)*

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

26 March 2021

Amabel Hunting
Faculty of Design and Creative Technologies

Dear Amabel

Re Ethics Application: **19/425 Design tool for assessing the environmental sustainability of knitted apparel products in New Zealand**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 4 December 2022.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: mitali.nautiyal@aut.ac.nz; Frances Joseph; Donna Cleveland

Appendix B *Survey Questionnaire- Impact of COVID 19 on the Knitwear Manufacturing Sector in New Zealand*

Start of Block: Default Question Block

Q1 What is your job profile?

- ▢ Managing Director
- ▢ Manager
- ▢ Employee
- ▢ Any other ____

Q2 Who do you manufacture for?

- ▢ Own brand
- ▢ Own and other brands
- ▢ Only for other brands
- ▢ Directly for customers
- ▢ Any other ____

Q3 Do you do other commercial activities in addition to knitwear manufacturing

- ▢ Farming
- ▢ Yarn manufacturing
- ▢ Fabric manufacturing
- ▢ Retailing
- ▢ Wholesale
- ▢ Exporting
- ▢ Any other ____

Page Break

Q4 Please identify the location of the relevant parts of the supply chain for the following processes in your company?

	Dependence		
	In-house processing	NZ based suppliers	International suppliers
Fibre processing (Scouring/ bleaching/ dyeing etc.)	☐	☐	☐
Yarn processing (Carding/ Spinning/ Twisting etc.)	☐	☐	☐
Yarn dyeing	☐	☐	☐
Fabric formation (Knitting)	☐	☐	☐
Fabric wet processing (Fabric dyeing/ Finishing etc.)	☐	☐	☐
Garment manufacture (Cutting/ Sewing/ Finishing etc.)	☐	☐	☐
Garment packaging	☐	☐	☐

Q5 What was the effect of border restrictions on your business? (Please type your answer)

____
____
____
____
____

Q6 How has COVID-19 affected your companies overseas supply chain?

- ☐ Business as usual
- ☐ Slow, but moving
- ☐ Supply chain is affected, will take time to resume work
- ☐ Unable to manufacture overseas after COVID-19
- ☐ Any other answer ____

Q7 How has COVID-19 changed your future business plans?

- ○ Planning to stay at the same scale
- ○ Planning to close international manufacturing and concentrate on New Zealand
- ○ Planning to close all manufacturing for the time
- ○ Planning to expand manufacturing in New Zealand
- ○ Planning to expand manufacturing both in New Zealand and internationally
- ○ Any other answer ____

Q8 Was there any change in revenue generation post COVID-19 lockdowns?

- ☐ Now we are solely dependent upon domestic market
- ☐ Now we are able to export to overseas markets
- ☐ Now we are selling online to both domestic and international customers
- ☐ Now we are selling to retailers/wholesalers at both domestic and international markets
- ☐ Any other answer ____

Q26 Are you also involved with sales of knitwear products?

- ○ Yes
- ○ No

Display This Question:
If Are you also involved with sales of knitwear products? = Yes

Q9 How were your sales affected by COVID-19?

	Increased	No change	Dropped
Domestic Sales	○	○	○
International Sales	○	○	○

Display This Question:
If Are you also involved with sales of knitwear products? = Yes

Q10 Do you anticipate your sales growing in the near future?

	Yes	No	Not Sure (Can't say)
Domestic Sales	○	○	○
International Sales	○	○	○

Q11 How satisfied you are with the New Zealand Government's COVID-19 support services?

	Extremely satisfied	Somewhat satisfied	Neither satisfied nor dissatisfied	Somewhat dissatisfied	Extremely dissatisfied
Monetary	○	○	○	○	○
Tariffs	○	○	○	○	○
Export Incentives	○	○	○	○	○
Tax Breaks	○	○	○	○	○

Q12 What additional help would you like to see from the New Zealand Government?

____

____

____

____

____

Q13 Did the COVID-19 affect your sustainability practices?

▢ I was always concerned about the environment

▢ Yes, it changed my way of doing business. Now I am more environmentally conscious

▢ No, it has nothing to do with my perception for the environment

▢ I am not sure/ cannot answer this question

▢ Any other answer ____

Q14 Do you think knitwear manufacturing in New Zealand is more sustainably done than in Asian countries?

- ☐ Definitely yes
- ☐ Probably yes
- ☐ Might or might not
- ☐ Probably not
- ☐ Definitely not
- ☐ Would you like to expand on this?

____

Q15 Do you use any tool to calculate the environmental impact of the garments that you make?

- ○ Yes
- ○ No

Display This Question:
If Do you use any tool to calculate the environmental impact of the garments that you make? = Yes

Q16 Can you please name the tool/tools?

____

Display This Question:
If Do you use any tool to calculate the environmental impact of the garments that you make? = Yes

Q17 Do you intend to use this tool to evaluate environmental sustainability in future?

- ○ Extremely likely
- ○ Somewhat likely
- ○ Neither likely nor unlikely
- ○ Somewhat unlikely
- ○ Extremely unlikely

Q19 Does your company manufacture from more than one location?

- ○ Yes
- ○ No

Display This Question:
If Does your company manufacture from more than one location? = Yes

Q20 Where are your other manufacturing units located?

- New Zealand
- Overseas
- Both New Zealand and overseas

Q21 What is the approximate number of employees across all of your locations?

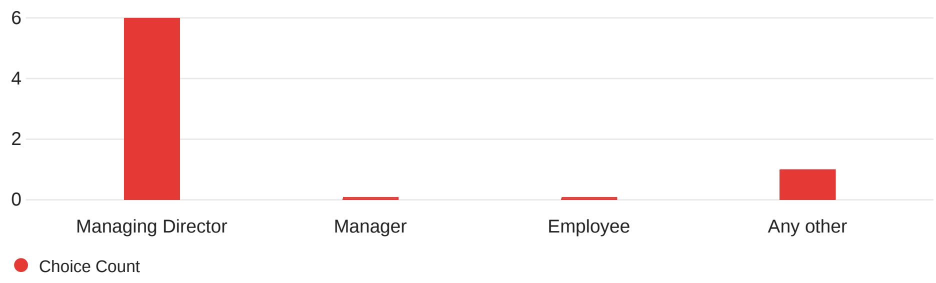
____

End of Block: Default Question Block

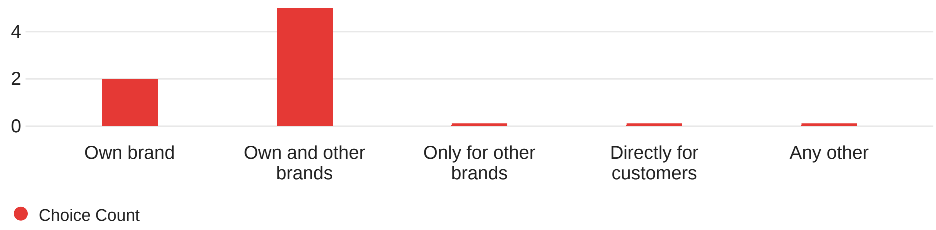
Appendix C *Survey results on the Impact of COVID-19 on Knitwear Manufacturers in New Zealand*

1

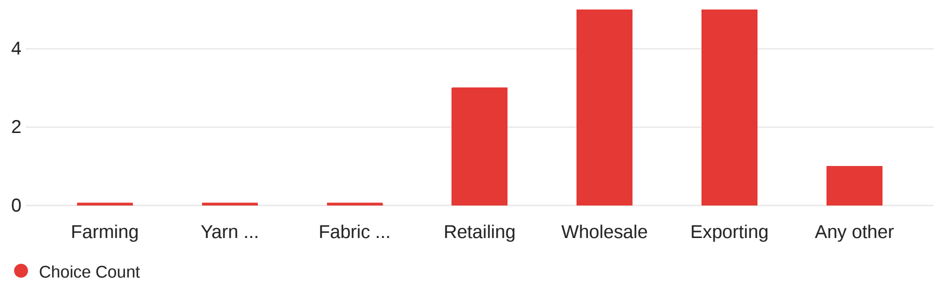
Participant's Job Profile

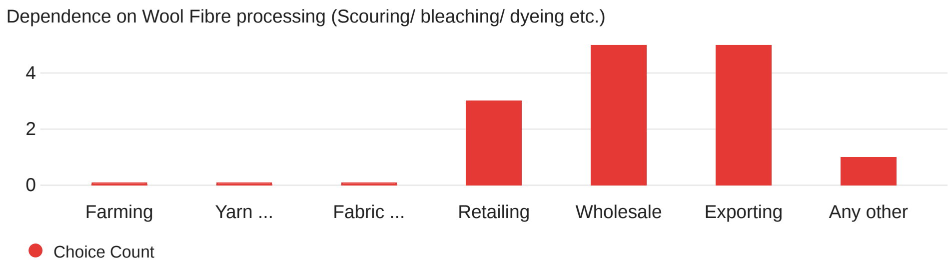


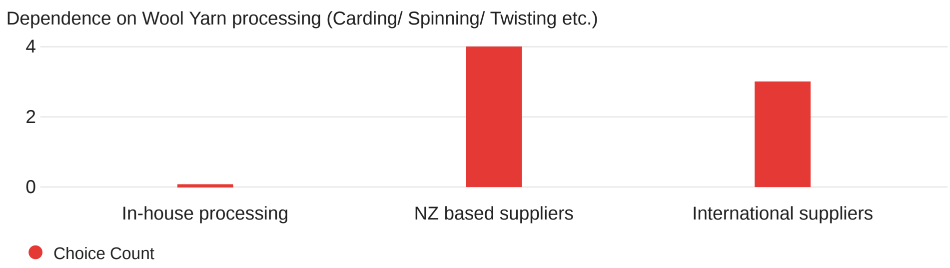
Participant's Business Model



Involvement in other commercial activities in addition to knitwear manufacturing



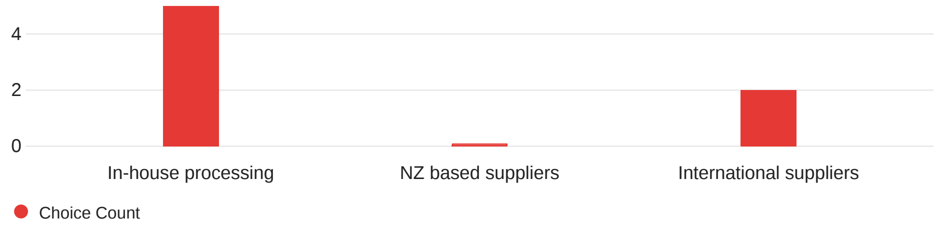

Dependence on Wool Fibre processing (Scouring/ bleaching/ dyeing etc.)
4
2
0
Farming
Yarn ...
Fabric ...
Retailing
Wholesale
Exporting
Any other
Choice Count


Dependence on Wool Yarn processing (Carding/ Spinning/ Twisting etc.)
4
2
0
In-house processing
NZ based suppliers
International suppliers
Choice Count

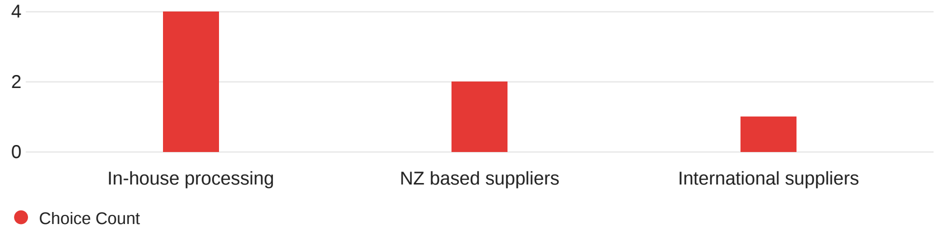

Dependence on Wool Yarn dyeing
4
2
0
In-house processing
NZ based suppliers
International suppliers
Choice Count

3

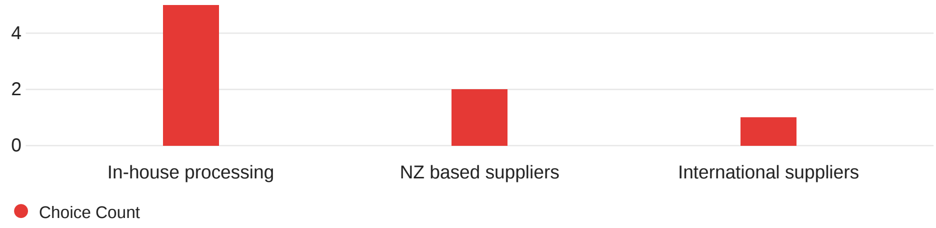
Dependence on Fabric formation (Knitting)



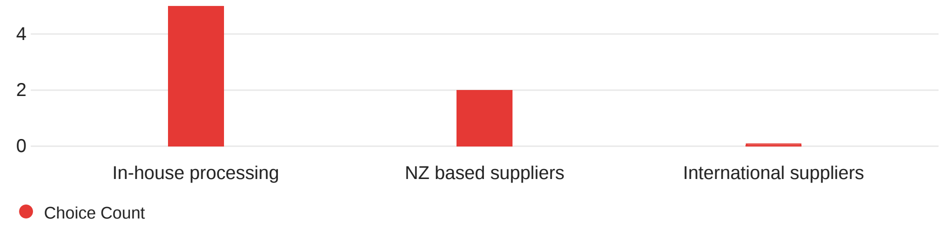
Dependence on Fabric wet processing (Fabric dyeing/ Finishing etc.)



Dependence on Garment manufacture (Cutting/ Sewing/ Finishing etc.)

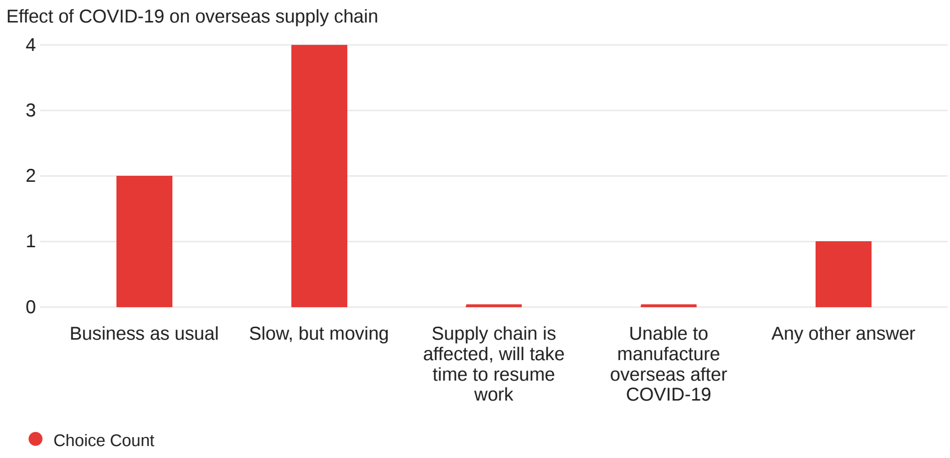


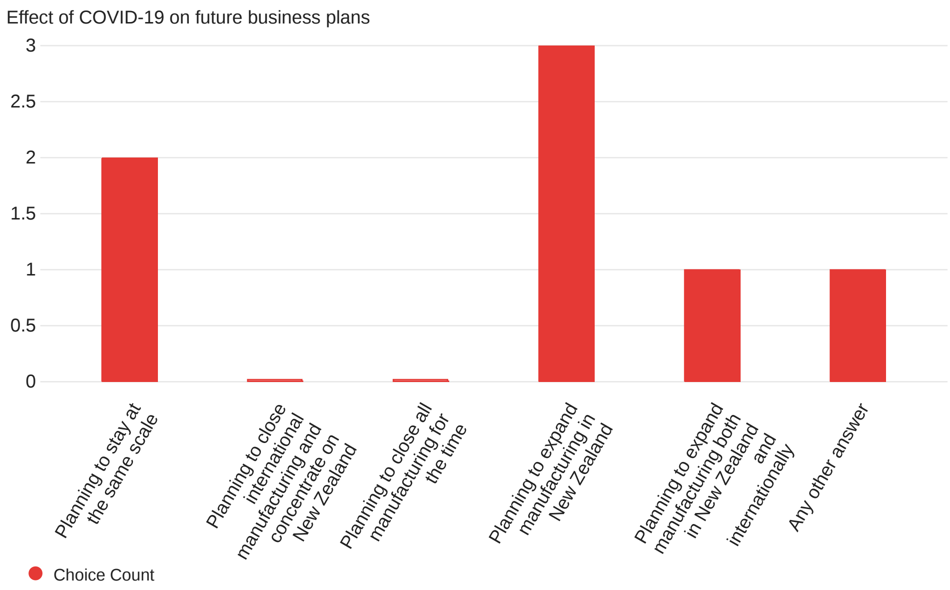
Dependence on Garment packaging



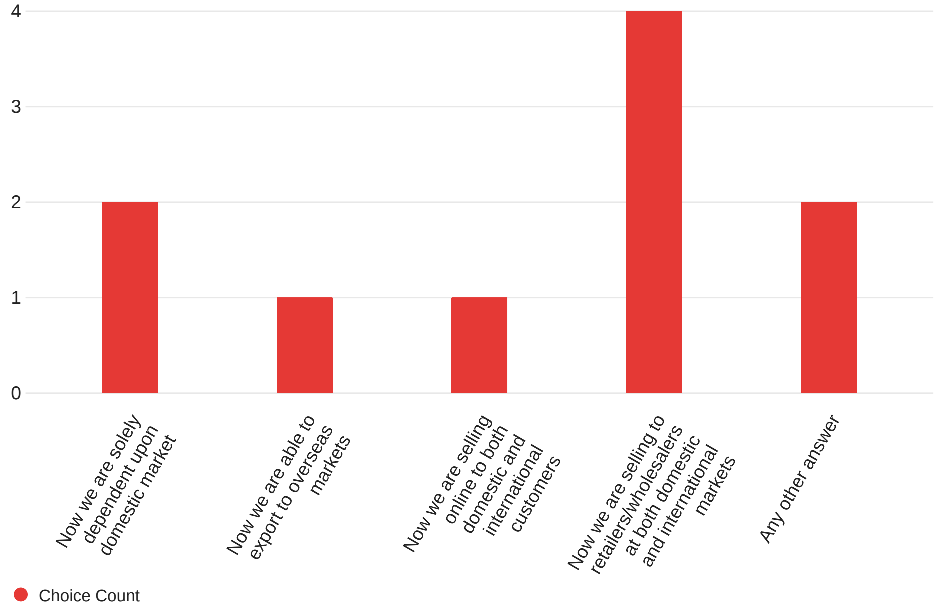
Q5 - What was the effect of border restrictions on your business? (Please type your answer)

What was the effect of border restrictions on your business? (Please type your answer)
Slower delivery of raw materials. Increased shipping costs
Lost our Tourist trade retailer business. 25% down for that year. We have now recovered to being 25% up on the previous financial year.
International Tourists were a significant part of our summer sales. In winter we sell to NZers and Australians who are cold.
Never made us so busy. Many companies bringing their production back from China to New Zealand
Catastrophic
We have two brands. On our wholesale only brand which had a lot of retailers selling to tourists in NZ and OZ the impact has been approx 80% down. Our other brand sold to a mix of domestic and tourist has been less affected overall knitwear production is 80% down (as we had/have high stock levels to work through) and the business overall 50% down

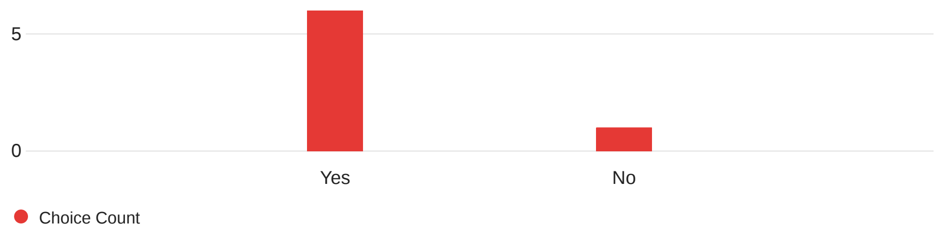

Effect of COVID-19 on overseas supply chain
4
3
2
1
0
Business as usual
Slow, but moving
Supply chain is affected, will take time to resume work
Unable to manufacture overseas after COVID-19
Any other answer
Choice Count


Effect of COVID-19 on future business plans
3
2.5
2
1.5
1
0.5
0
Planning to stay at the same scale
Planning to close international manufacturing and concentrate on New Zealand
Planning to close all manufacturing for the time
Planning to expand manufacturing in New Zealand
Planning to expand manufacturing both in New Zealand and internationally
Any other answer
Choice Count

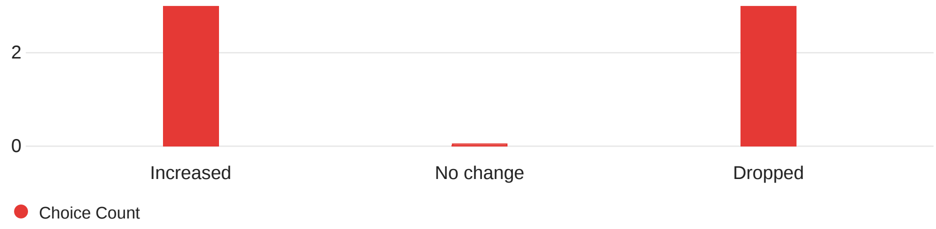
Changes in revenue generation post COVID-19 lockdowns



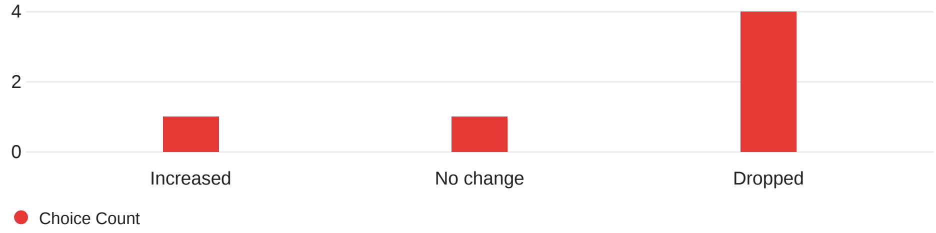
Participants involvement with sales of knitwear products



Effect of COVID-19 on Domestic Sales



Effect of COVID-19 on International Sales

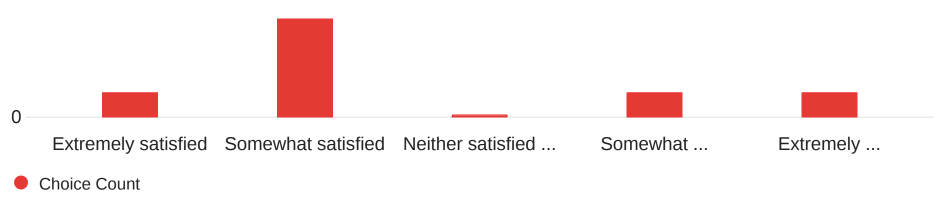


Anticipation to Increase Domestic Sales

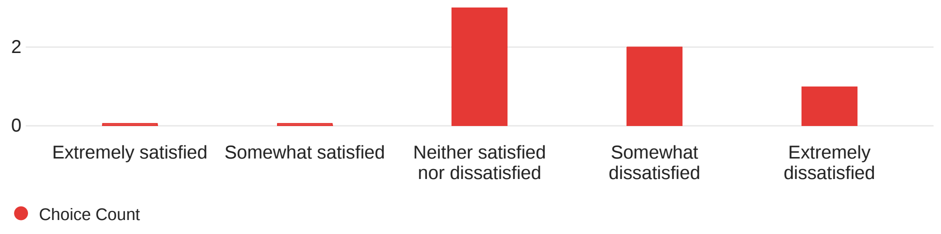
8


Anticipation to Increase International Sales
2
0
Yes
No
Not Sure (Can't say)
Choice Count

Satisfaction on NZ Governments Support: Monetary



Satisfaction on NZ Governments Support: Tariffs

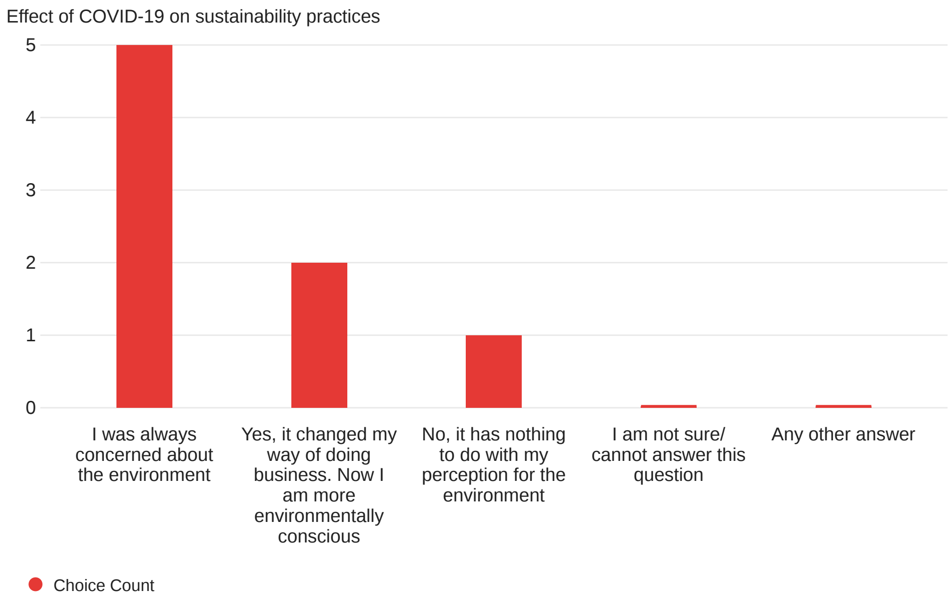


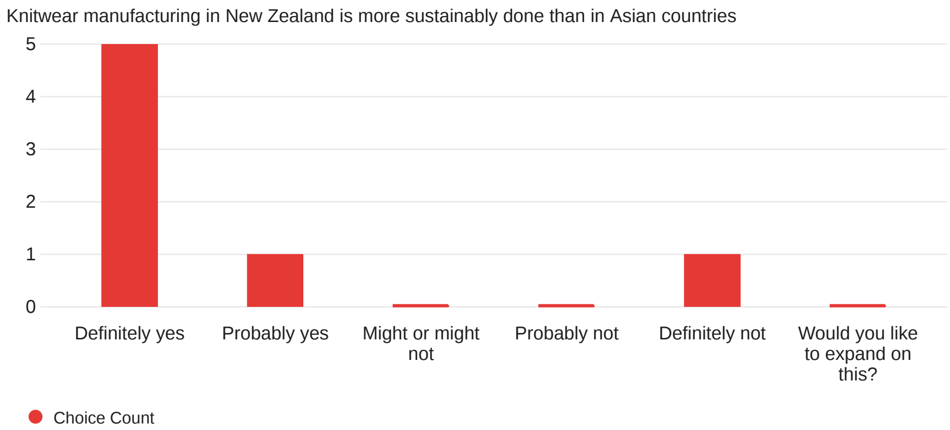
Satisfaction on NZ Governments Support: Export Incentives

Satisfaction on NZ Governments Support: Tax Breaks

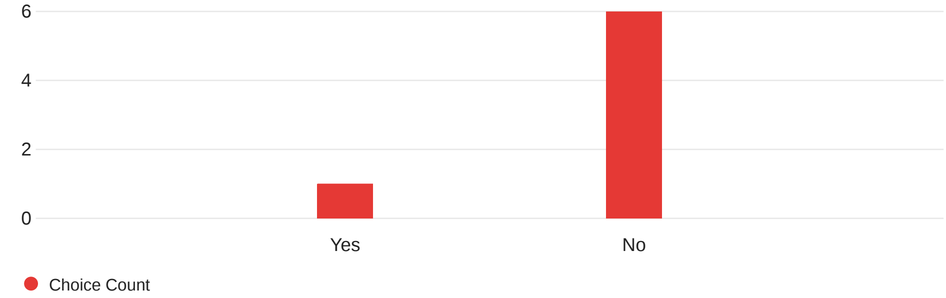
Q12 - What additional help would you like to see from the New Zealand Government?

What additional help would you like to see from the New Zealand Government?
Increase focus on easing restrictions to local manufacturing. Reduce depreciation time period for machinery etc, balance conditions for manufacturing - ie we increase minimum wage, work compliance costs etc but import from countries with terrible work place conditions and pay scales.
Stop increasing the cost of Labour by large amounts. It is stopping me from growing my business. Extra weeks sick leave. 5% minimum wage increase. Just not sustainable in clothing manufacturing.
Need to focus on buying locally for Govt contracts. They have a big cheque book that would make a big difference to the industry
Have Trade New Zealand more focused on helping all manufactures not just their favorites
more business grants, export support
Would like ongoing wage support to keep skilled people on board to buy us time as we pivot and focus on new markets, or different angels of the same market. In our industry a pivot takes around two years from design concept through to in the market. The recent Auckland shutdown wage subsidy wasnt available to us as it was for a drop in sales from the weeks prior, whereas we were already so far down from the closed borders, this was another hit as we work to recover the business.


Effect of COVID-19 on sustainability practices
5
4
3
2
1
0
I was always concerned about the environment
Yes, it changed my way of doing business. Now I am more environmentally conscious
No, it has nothing to do with my perception for the environment
I am not sure/ cannot answer this question
Any other answer
Choice Count


Knitwear manufacturing in New Zealand is more sustainably done than in Asian countries
5
4
3
2
1
0
Definitely yes
Probably yes
Might or might not
Probably not
Definitely not
Would you like to expand on this?
Choice Count

Do you use any tool to calculate the environmental impact of the garments that you make?

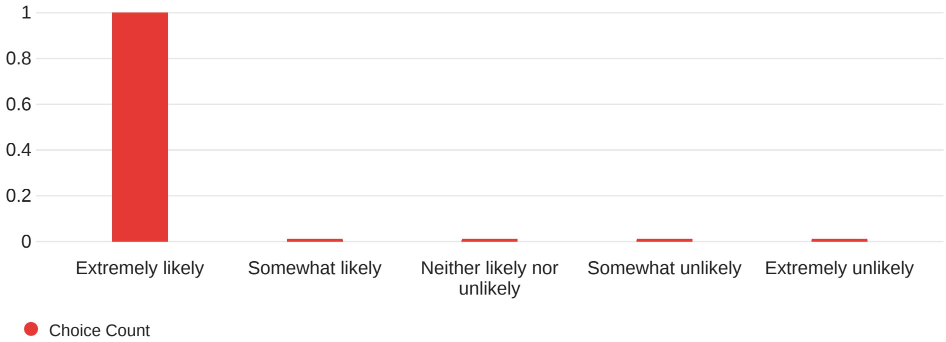


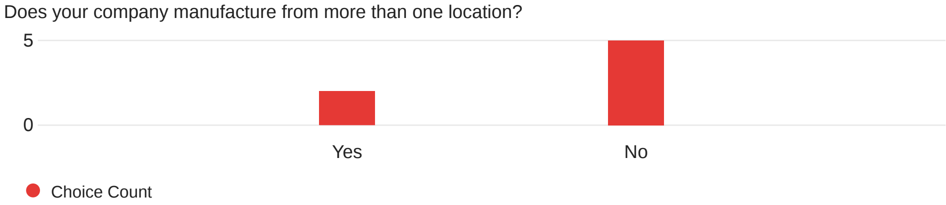
Q16 - Can you please name the tool/tools?

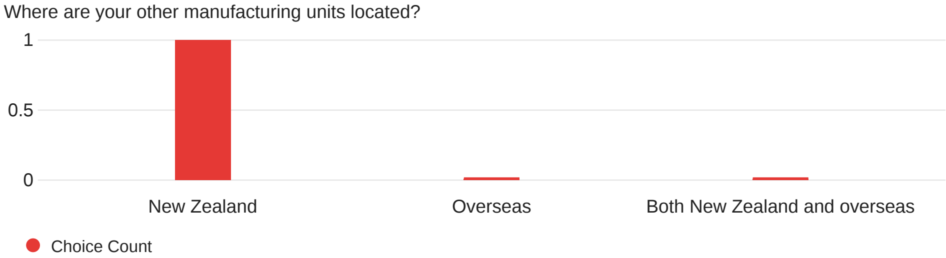
Can you please name the tool/tools?

we have a tool called 360

Do you intend to use this tool to evaluate environmental sustainability in future?







Q21 - What is the approximate number of employees across all of your locations?

What is the approximate number of employees across all of your locations?
12
12
34
20
12
150
87

Appendix D *Published Article on the Impact of COVID-19 on Knitwear Manufacturers in New Zealand for Journal Fashion Practice*

Routledge
Taylor & Francis Group

Fashion Practice, 2023, Volume 0, Issue 0, pp. 1–26
DOI: 10.1080/17569370.2023.2166707

An Investigation on the Impact of COVID-19 Pandemic on New Zealand's Knitwear Manufacturing Sector

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Frances Joseph is Professor of Material Futures in the School of

Abstract

Knitwear producers in New Zealand are looking for ways to deal with the uncertainties that have arisen due to the COVID-19 pandemic. This research considers the impact of the pandemic and its effects on the development and long-term survival of the knitwear sector. An anonymous online survey was undertaken among New Zealand's established knitwear manufacturers, with seven taking up the survey. The respondent companies accounted for around half of the total workforce employed in the country's knitwear sector. The data were analysed using both quantitative and qualitative methods. A SWOT analysis was

conducted to place the sector in a global context, identifying necessary measures for future strategic planning. The findings revealed that the supply chain has been disrupted, some businesses have stalled, and the cost of obtaining raw materials has skyrocketed. Due to the impact of the pandemic on the tourism industry, revenues have fallen. As COVID-19 is an ongoing challenge, knitwear manufacturers need to rearrange their supply chains to increase local suppliers and explore new and innovative ways to engage with domestic customers.

KEYWORDS: Knitwear manufacturing, COVID-19, New Zealand, supply chain, revenue generation, SWOT analysis

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Introduction

The COVID-19 pandemic has created uncertainties, forcing New Zealand's knitwear manufacturers to develop strategies to address the new economic context in order to survive. Manufacturing in general has been impacted, and there are indications that smaller manufacturers have been less able to withstand the consequences. Many are closing their operations. Between September and November, 2020, 16,234 enterprises in New Zealand permanently closed compared to 7154 during the same period in 2019, which is an increase of 127 percent (Edmunds 2021). Understanding the current state of the knitwear industry, how it is progressing, and sharing strategies for surviving this critical scenario are vital. This study is an initial attempt to gather current information and learnings from manufacturers' experiences to help develop solutions and identify future opportunities.

Coronavirus 2 or COVID-19, a novel type of severe acute respiratory syndrome, struck the world in late 2019, affecting every country around the globe. Governments throughout the world struggled to formulate strategies to stop the spread of the virus. Many countries went into months-long lockdowns, limiting cross-border travel and trade, with COVID-19 containment measures directly impacting the global economy. In 2020-21, the global gross domestic product (GDP) loss from the pandemic was estimated to be over USD 9 trillion, with countries that relied on tourism, travel, hospitality and entertainment for their growth being the most heavily impacted (Gopinath 2020).

The COVID-19 pandemic has had a significant impact on textile and fashion industries. Globally, there was a marked fall in demand for apparel products, with some 86 percent of garment manufacturing businesses seeing a drop in orders (Sedex 2021). A *Women's Wear Daily* article, published December 24, 2020, reported that as people stayed at home and economies shut down, several well-known brands were severely hit by COVID-19. Many international brands and retailers delayed payments or cancelled orders for goods that had already been manufactured or were in the process of being made (OECD 2020). As a result, many enterprises had to shut down most or all their operations (Roberts-Islam 2020).

Following confirmation of a few local cases of COVID-19 in March, 2020, New Zealand was one of a few countries to lock its borders, impose strong travel restrictions, and issue strict stay-at-home orders to prevent the spread of the disease. While mortality rates remained low, the country's economy was severely affected. Although the garment sector in New Zealand is well established, there has been little research or publication to date on the impact of the COVID-19 pandemic. This paper identifies the advancements that have been made in the country's knitwear manufacturing businesses and provides an outline of the industry's current situation in the aftermath of the pandemic.

Literature review

Many studies have recently reported the impact of the COVID-19 pandemic on global businesses, economies, and supply networks (Fairlie 2020; Maliszewska, Mattoo, and Van Der Mensbrugghe 2020; Xu et al. 2020). COVID-19-related publications have also begun to appear in the garment and textile industries. While some reports are there on its influence on the global textile and fashion supply chain (Chakraborty and Biswas 2020; Ahsan 2020), a few others have analysed its economic implications on countries with bigger apparel industries. Boudreau and Naeem (2021), for example, examined the economic impact of the pandemic on Bangladesh's ready-made garment factories, indicating significant revenue losses, order cancellations, and challenging times for smaller businesses. Other authors such as Wulandari and Darma (2020) have searched for positive outcomes, researching tactics and innovative ways to improve textile sales, and Zhao and Kim (2021) worked on a conceptual model that depicted the links between different value chain segments in the garment and textile sector. Studies that investigated the knitwear sector and the challenges faced by knit manufacturers were conducted in India (Mahajan and Bains 2020; Mehta and Kaur 2021), however, none has been conducted explicitly in New Zealand. The COVID-19 pandemic has had a significant impact on the industry globally; subsequently, it is important to understand both the positive and negative ways that local regions and economies have responded. As the pandemic's far-reaching impacts will not be resolved anytime soon (Kissler et al. 2020), businesses will need to enhance their preparedness to adapt, recover quickly and avoid unplanned interruptions in future.

Knitwear Manufacturing in New Zealand

Knitting is one of the earliest methods of clothing production (Au 2011), predating the industrial revolution as a method of mass production (Black 2012). It was introduced to New Zealand in the nineteenth century together with wool. Colonists from Britain who settled in the country realised that the topography was comparable to home, making it appropriate for raising sheep. Settlers brought spinning, weaving and knitting tools and used the wool grown in New Zealand to manufacture clothing (Smith and Finn 2015). This allowed them to meet their families' basic needs for woollen apparel, and to supplement their income by making and selling apparel products (De Pont 2018). Consequently, both wool and knitwear production found a home in the country.

During much of the twentieth century, wool and apparel enterprises were among the top industries and main contributors to the country's economy. From the early 1950s through to the 1960s, wool and its products were the main export earners (Briggs 2003). A considerable number of people worked in the knitting industry, from winding yarns through to cutting, linking, stitching and steaming garments (De Pont 2018). During the late 1980s and early 1990s, trade liberalisation and economic restructuring severely impacted the manufacturing industry. The domestic economy was opened to global trade, tariffs on goods entering were reduced, and clothing imports increased (Dalziel 2016). Domestic output in the garment manufacturing industry halved between 1992 and 2001, while imported clothing grew from 20 to 60 percent of the market (Burleigh Evatt and NZIER, in Lewis, Larner, and Heron 2008). The remaining garment production shifted to value products, with items characterised by higher quality, brand name, improved performance, product innovation, or the ability to fit a specialised function being exported (MBIE 2018a). Exports became critical to business survival. Despite a drop in domestic sales of locally manufactured goods, garment exports increased. Between 1992 and 2001, the percentage of output exported increased to more than 25 percent (Lewis, Larner, and Heron 2008).

There was a significant fall in local textile and garment manufacturing in the last few decades of the twentieth century. However, the industry survived, with knitwear manufacturing proving to be the most important remaining area of textile production. The knitwear production process has advanced significantly over the last few decades. Modern technologies and automated processes that require less labour and enhance production allowed knitwear manufacturing to endure (Smith and Finn 2015). The invention of 3D seamless knitting technology reduced the number of post-knitting activities such as cutting and sewing, by knitting a whole garment on the machine (Underwood 2009). Shima Seiki and Stoll are the pioneers and leaders in this field, having invented Wholegarment® and Knit&Wear®, respectively (Ramsay 2013). Since the early 2000s, the country's knitwear sector has been importing seamless knit technology, and its demand has continued to expand (Smith 2013).

Knitwear manufacturing represents a modest and medium-sized sector in New Zealand. Manufacturers produce high-end, knitted products for sale both domestically and internationally. In 2019, the gross export of knitted garments like jerseys, pullovers, cardigans, waistcoats and other related articles made of wool and fine animal hair was USD 6.4 million (WITS 2022). Auckland in the North Island and Canterbury in the South Island are major hubs for knit production. Other districts that support knitwear production include Palmerston North, Dunedin, the Bay of Plenty and Wanganui. There is currently a lack of accessible data on the exact size of the industry and the current number of garment manufacturers operating in the country, which this study aims to address.

Supply chain challenges

The knitwear supply chain starts with the production of fibres. Luxury fibres and blends are typically involved in New Zealand's knitwear exports and follow a similar pattern to the country's supply chain of strong wool. Conforte, Dunlop, and Garnevska (2011) demonstrated the flow of wool across the country's strong wool value chain, as shown

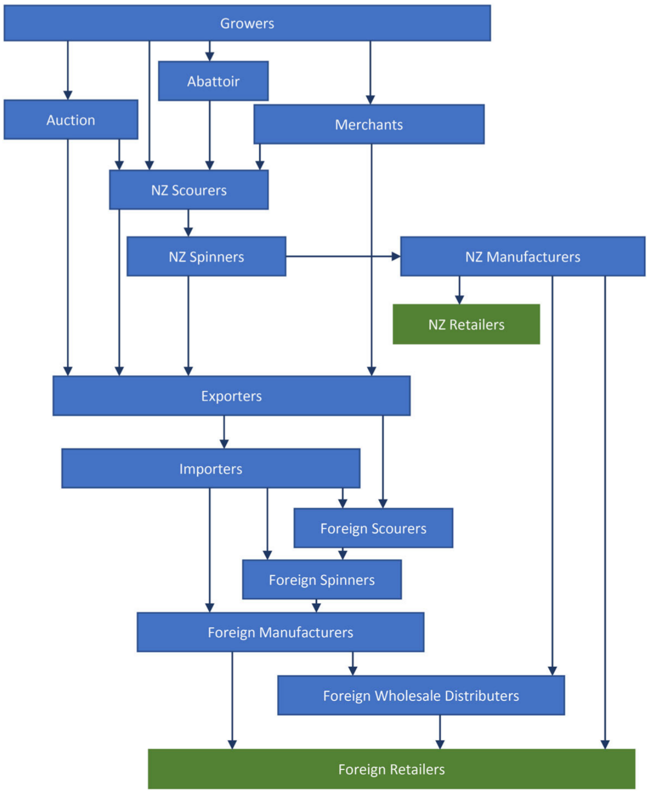

Figure 1
Flow of wool through New Zealand's strong wool value chain (Adapted from Conforte, Dunlop, and Garnevska 2011).

in Figure 1. Farmers sell the produce to brokers, who either export it to overseas processing facilities, or sell it to a limited number of locally based facilities. In a *NZ Herald* article, published August 13, 2020, Nigel Hales, chief executive of New Zealand Woolscouring, one of the country's largest scouring factories, reports that there were 28 wool scourers in the early 1980s, but that has now been reduced to two. One is in Napier in the North Island and another in Timaru in the South Island.

In the area of spinning, mule spinning is employed for finer fibres and blends like merino, possum and cashmere (Cottle and Wood 2012), which are specifically used in machine knitting. Woolyarns in Lower Hutt is the only mule spinning mill in the whole southern hemisphere (Khan 2020). Even though the country produces a substantial proportion of textile fibres, the supply chain engaged in yarn production is highly fragmented, which has a significant impact on the pricing of final goods. Today, New Zealand's broader apparel manufacturing businesses consist of a small handful of niche, ethical or high-end designer labels (Tearfund 2019), who are heavily reliant on international suppliers for most of their production needs.

Given the knitwear sector's reliance on local and foreign suppliers, as well as the unique circumstances of the COVID-19 pandemic, the authors believed it would be useful to understand how the industry has handled the crisis. There has been limited research into how New Zealand's knitwear sector has been disrupted and what tactics have been used to successfully maintain its viability (Bezuidenhout et al. 2021). By reviewing specific industry reactions and producing a SWOT analysis, this study provides insights into potential strategies and new possibilities. We have also made some concrete suggestions to help the knitwear sector emerge from the pandemic and carve out a distinctive, more sustainable niche in the global market, based on indications identified in the data.

Methodology

An anonymous online survey was conducted in April, 2021. An initial online search identified approximately 45 apparel knitting companies operating within New Zealand. Companies that manufactured offshore and did not have an online presence such as an e-mail address, were excluded, which decreased the number of manufacturers to 20. The Textile Design Lab (TDL), a research laboratory at Auckland University of Technology that is engaged with the country's textile industry, was consulted to collect e-mail addresses of companies that were legitimate and active in knitwear manufacturing.

The 20 manufacturers were approached through e-mail, to request their participation in the survey. Nine of the 20 business owners responded, with two stating that they were unable to participate due to unspecified reasons. Seven participants took up the survey, a valid return given the industry's modest size. Because the survey was anonymous, limited information about the respondents could be gathered. The participants owned small and medium-sized knitwear manufacturing facilities that together employ over 330 employees, which is half of the total number of employees involved in knitwear production. A 2018 report from the Ministry of Business, Innovation, and Employment identified 660 persons employed in knitting production within New Zealand (MBIE 2018a). The survey used Qualtrics software to present open-ended and closed-ended questions concerning COVID-19's impact on the supply chain, revenue and government support. Results were collected and the data analysed using both numerical and qualitative methods.

A SWOT (strengths, weaknesses, opportunities and threats) analysis was then carried out to synthesise the data about the current pandemic situation across the sector and to determine steps to be taken for future strategic planning. SWOT analysis is a method widely employed by businesses globally to examine an organisation's internal and external environments (Ghazinoory, Abdi, and Azadegan-Mehr 2011). It has been utilised either alone or in combination with other analysis methods to help find solutions to complex problems. SWOT analysis was utilised to formulate development strategies for the textile and garment sector in Pakistan (Kanat et al. 2018); Uzbekistan (Kim and Park 2019); South Korea (Jo and Lee 2018); Sri Lanka (Wickramasinghe and Abdullah 2011); Iran (Atilgan, Derafshi, and Kanat 2011); China (Han et al. 2017); and the United Kingdom (Li et al. 2016). The SWOT analysis has provided growth strategies to individual businesses in the apparel manufacturing sector (Colovic 2014; Tuan 2012; Görener, Kerem, and Korkmaz 2012), and can assist industries in responding to the challenges of the COVID-19 pandemic. Rahman (2020), for example, used SWOT analysis along with Porter's Five Force Model to recommend measures for preventing the Bangladesh Garment Manufacturing and Exporters Association from suffering COVID-related losses. There is potential for a SWOT analysis of New Zealand's knitwear industry to identify opportunities for its growth.

Scope and timing

This study did not look at the entire garment manufacturing business but focused specifically on knitted garment products. Other businesses supporting knitwear manufacturing such as fibre and yarn processing, dyeing and finishing, were omitted from this study. The research was conducted in April, 2021, following the first major lockdown in March-April, 2020, and prior to the second, extended lockdown in August-December, 2021. Although the COVID-19 outbreak was still affecting many regions globally at the time, New Zealand remained pandemic free, mostly due to its "COVID elimination" strategy and strict border restrictions (Baker, Kvalsvig, and Verrall 2020). At the time of writing, the COVID-19 vaccine was being rolled out to the public in a staged plan which commenced in April, 2021.

Table 1. Participant information.

Alphabetical names	Position in company	Employees working	Details on manufacturing	Commercial participation
Company A	Managing director	150	Own and other brands	Wholesale, exporting
Company B	Managing director	87	Own brand	Retail, wholesale, exporting
Company C	Managing director	34	Own and other brands	Wholesale, exporting
Company D	Managing director	20	Own and other brands	–
Company E	Director	12	Own brand	Wholesale
Company F	Managing director	12	Own and other brands	Retail, wholesale, exporting
Company G	Managing director	12	Own and other brands	Retail, exporting

Results

New Zealand supports small businesses, with small and medium-sized enterprises (SMEs) representing over 97 percent of all businesses, employing 29 percent of the workforce and contributing 28 percent of the country's GDP (MBIE 2018b). Small businesses in New Zealand have fewer than 20 employees, small-to-medium have between 20 to 49, medium have between 50 to 99, and large have more than 100 employees (MBIE 2014).

As the online survey was anonymous, the participants were given alphabetical identifiers 'A' through 'G'. Table 1 contains information about the participants and their businesses. The survey participants were New Zealand manufacturers who were owners of small and small-to-medium-sized enterprises; however, one participant owned a large business. All firms produced their own knitwear labels, and most of them produced for other apparel brands as well. Many of these manufacturers were also active in retailing, wholesaling and export activities. They were not involved in farming wool or yarn manufacturing.

Supply chain management

Participating companies depended heavily on external sources for fibre processing, yarn processing and yarn dyeing operations. The survey found that Companies B, D and G relied both on local and international suppliers for their yarn needs, whereas Company A depended solely on international suppliers. Companies C and E procured yarns from locally based suppliers, however, Company F made no mention of its yarn source. More developed in-house facilities were available for knitwear manufacturers across the latter stages of the supply chain. The survey reported that, other than Company F, all others had in-house fabric formation, wet processing and garment manufacturing capabilities. Packaging was done in-house by all except for Companies A and F, who relied on local vendors. Figure 2 shows the reliance of the participating firms throughout the knitted apparel supply chain.

The COVID-19 pandemic created global supply-chain bottlenecks, causing many enterprises to stall (The Treasury 2021). Nearly half of the manufacturers that participated in this survey were reliant on international suppliers for the initial stages of the supply chain.

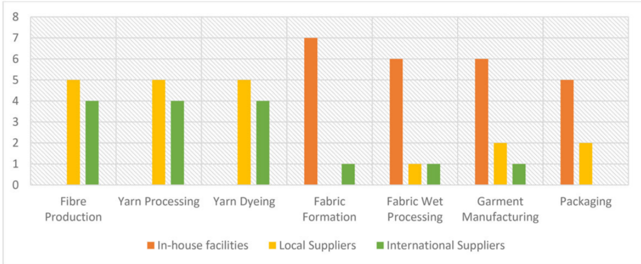

Figure 2
Manufacturers' reliance at various parts of the supply chain.

Manufacturers who relied on local suppliers were also affected due to the countrywide lockdown in the initial months of the pandemic. Knitwear makers had to deal with the consequences of slower deliveries and higher shipping costs from overseas suppliers. Figure 3 depicts the impact of COVID-19 on the supply chain. Company D reported an increase in business, Companies A and F indicated normal business operations, while Companies B, C, E and G stated that business had slowed down but was still moving. This could be because supply chains that were dependent on domestic suppliers had fewer blockages, whereas businesses that relied on foreign suppliers suffered a greater slowdown. Although border restrictions were a disaster for some manufacturers, they were a windfall for others. When asked to comment on the effects of border restrictions on their business, some contradictory responses were noted, presented here as quotes in Table 2.

Company D benefitted from border limitations and was able to increase production. As New Zealand was better able to control the spread of the virus than many other countries, a few of the country-based brands that were previously producing in China switched to domestic suppliers, keeping some manufacturers busier than normal. However, border restrictions hampered normal operations for Companies E and G.

Revenue generation

Revenues in the knitwear industry decreased, with the influence on commerce for domestic and foreign markets shown in Figures 4 and 5. Company A prefered not to answer questions related to revenue, but of the other six businesses, half reported a drop in domestic sales. They attributed this decrease to a drop in tourism as visitors were unable to enter the country due to the border restrictions. On the other hand, brands that catered to a wider range of consumers for domestic or online sales were less affected. Company B reported that: "*We have two brands. On our wholesale-only brand which had a lot of retailers selling to tourists in New Zealand and Australia, the impact has been approximately 80 percent down. Our other brand that sold to a mix of domestic and*

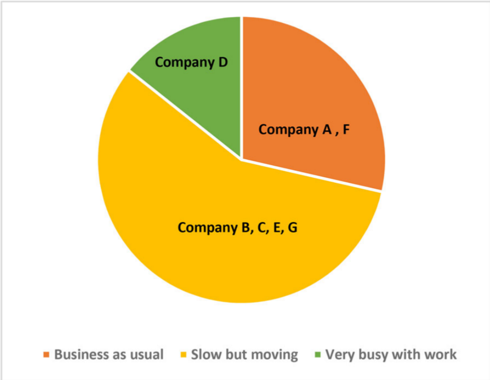

Figure 3
Impact on the supply chain.

Table 2. Selected quotes from survey participants on the impact of border restrictions.

Company name	Quote from participants
Company E	*"Catastrophic"*
Company D	*"Never made us so busy. Many companies bringing their production back from China to New Zealand"*
Company G	*"Slow delivery of raw materials. Increased shipping cost"*

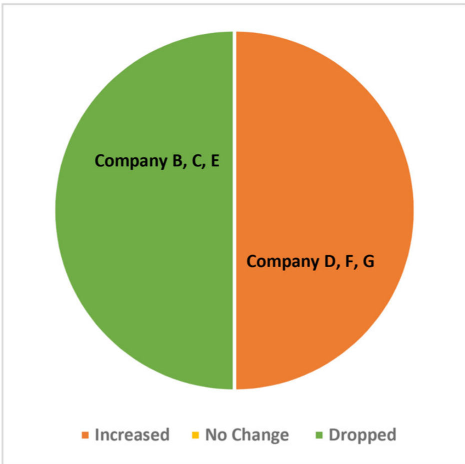

Figure 4
Impact on domestic sales.

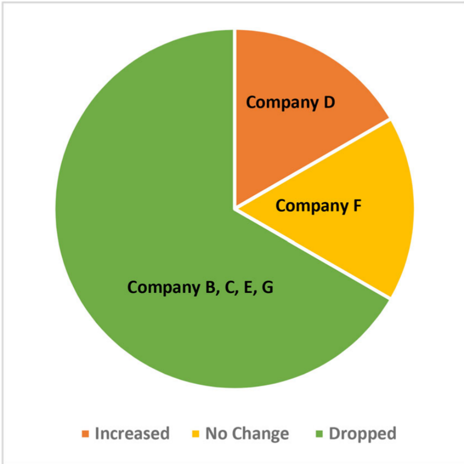

Figure 5
Impact on international sales.

tourists has been less affected." Half of the businesses, though, experienced an overall increase in domestic sales, reporting a jump in online sales as a result of an online shopping boom. International sales fell, with most businesses reporting a drop. There was no change in revenue for Company F and Company D reported an increase in sales. A few enterprises planned to restructure their operations to focus on the domestic market because they were more optimistic that things would return to normal in Australasia sooner than in other parts of the world. Company E suggested it could *"realign the business to a more domestic market"*.

On being asked about the impact of the pandemic on their future business plans, the feedback was extremely positive. Figure 6 shows the future aspirations of the companies surveyed. Companies D, F and G expected to boost manufacturing locally, Company A planned to expand both in New Zealand and globally, while Companies B and C planned to stay on the same scale. Company E, however, did not mention any growth plans but did express its desire to realign business strategies to a more local economy. Although most businesses reported lower sales, there was hope and positivity expressed for things to get back to normal.

Governmental intervention

The government offered a variety of tax relief to businesses, including a COVID-19 wage subsidy to assist firms in keeping people employed and ensuring their long-term viability (BDO NZ 2020). This study investigated knitwear manufacturers' satisfaction with the assistance and services provided by the government. Figure 7 depicts the participants'

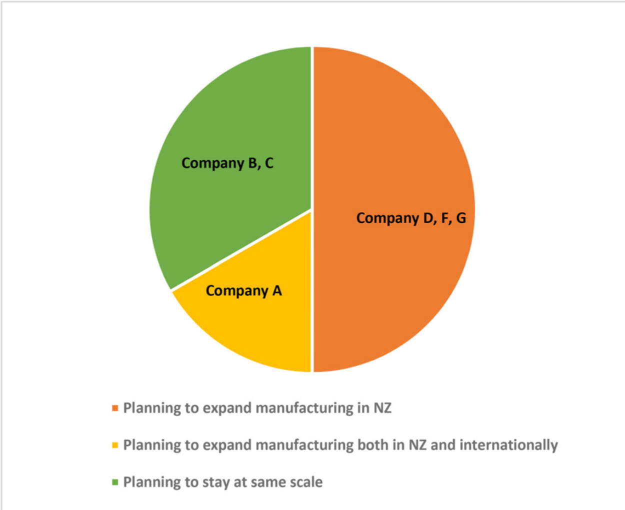

Figure 6
Future business plans.

satisfaction with the government's monetary assistance, tariffs, export incentives and tax exemptions during the COVID-19 outbreak.

Most manufacturers were very satisfied with the monetary support, but responses to the government's tariff policies and export incentives ranged from neutral to dissatisfied. The survey revealed a mixed response to the evaluation of tax breaks, with responses ranging from moderately satisfied up to extremely dissatisfied. There was no special consideration given to knitwear manufacturers, and the aid granted to all sectors was equal. Manufacturers had to contend with a shortage of skilled labour, rising wages and compliance expenses on top of the supply chain bottlenecks and ongoing restrictions on foreign tourism. Table 3 provides participant responses on additional help from the government. Manufacturers were looking for ways to save costs in order to retain their skilled workforce in times of falling revenue. Increasing labour and regulatory costs were sources of concern for small businesses such as companies F and G.

SWOT Analysis of New Zealand's Knitwear Manufacturing Sector

A comprehensive understanding of the business environment is required for strategic planning and is one of the key factors for facilitating this SWOT analysis (Hill and Westbrook 1997; Ying 2010). In a *Business News Daily* article updated October 19, 2022, the strengths and weaknesses of an industry are reported to include internal factors such as human resources, physical and financial resources, while opportunities and threats focus on external

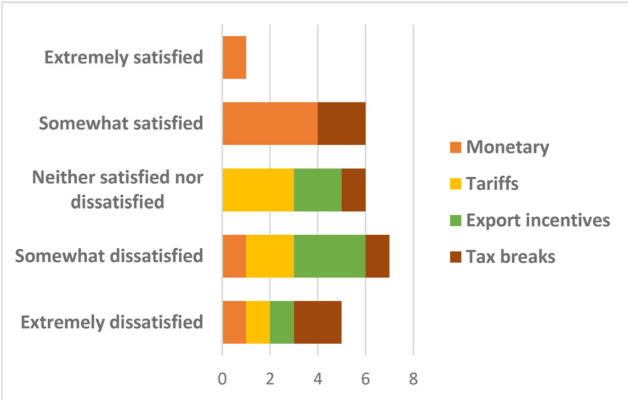

Figure 7
Review of government support.

Table 3. Some direct quotes from participants on additional help sought from the government.

Company name	Quotes from participants on additional help from the government
Company B	*"Would like ongoing wage support to keep skilled people on board to buy us time as we pivot and focus on new markets, or different angles of the same market"*
Company E	*"More business grants, export support needed"*
Company D	*"Have Trade New Zealand more focused on helping all manufacturers, not just some selected ones"*
Company C	*"Need to focus on buying locally for government contracts"*
Company F	*"Stop increasing the cost of labour by large amounts. Extra week sick leave, 5 percent minimum wage increase, stopping me from growing my business"*
Company G	*"Increase focus on easing restrictions to local manufacturing. Reduce depreciation time for machinery etc. Balance conditions for manufacturing such as we are increasing the minimum wage, work compliance costs etc., but are importing from countries with terrible workplace conditions and pay scales"*

factors such as market trends, economic forces and political regulations. The analysis reveals how strengths can be leveraged to create new opportunities, as well as ways to exploit growth avenues by addressing weaknesses. The authors carried out a SWOT analysis on New Zealand's knitwear manufacturing sector, based on the literature discussed in this paper and findings from the survey. The SWOT analysis is presented in Table 4.

Table 4. SWOT analysis of New Zealand's knitwear manufacturing sector.

Strengths	Weaknesses	Opportunities	Threats
• Historically rooted • Advanced technology • Automated machinery • High-quality raw material • Unique natural fibres and innovative blends • Design capabilities • Good production quality • Strong R&D activities • Organised vendor base • Socially and environmentally compliant	• Labour shortages • Reliance on foreign suppliers for yarn manufacture • Talent gaps in running machinery • Fall in sales post-pandemic • Dependence on tourist traffic for domestic sales • Few ancillary industries like dyeing, printing, embroidery, etc. • Higher cost of production • Underdeveloped recycling technology • Lack of direct government support	• Increasing global demand for knitted products • Huge scope in high-performance sportswear • Innovative yarn blends • Unexplored international markets • Increasing online sales growth • "Made in New Zealand" has a strong overseas reputation • Country's strong economy post-COVID-19 • Consumer awareness of sustainable products	• Impact of COVID-19 on global economy • New Zealand's ageing workforce • High cost of production • Market competition on price front • Limited size of the domestic market • Cheaper labour in other countries • Availability of cheaper knitted products overseas • High freight costs and increasing shipping delays

Proposed strategies for knitwear manufacturers

Looking at the influence of the COVID-19 pandemic and the SWOT analysis, the following strategies are put forward to assist in reshaping operations for knitwear manufacturing in New Zealand:

1. Maintaining a flexible supply chain and bringing in more local players will help lessen the dependency on foreign suppliers. Partnerships with local businesses including joint ventures, would help the industry and other ancillary sectors thrive (Wulandari and Darma 2020).
2. Due to rising consumer interest and a genuine need to address social and environmental concerns, prioritising sustainability when sourcing products and processes would be beneficial (Berg et al. 2019).
3. Using locally produced material would reduce the risk of supply shortage, promising good availability of resources at all times. It would also improve the niche and point of difference for New Zealand's knitwear manufacturing (Smith and Finn 2015).
4. Businesses should constantly strive to improve their supply chain and product innovation to increase their sales potential (Wangsa and Kristianti 2018).
5. Digitising operations need to be scaled to support innovation across the entire fashion value chain. This should include design

(3D design, AI planning), merchandising (virtual sampling, video sign-offs), sales (digital sell-in, virtual showrooms), consumer engagement (virtual shows, social selling), sourcing and the supply chain (nearshoring and vendor integration) (Berg et al. 2020).

6. Pursuing diversified markets through e-commerce to reach out to new customers (Wulandari and Darma 2020).
7. Training a locally available workforce to operate knitwear machinery, reducing the reliance on foreign talent.

Discussion

The seven enterprises surveyed for this study were small and medium-sized businesses that play a vital role in knitwear manufacturing. Although the response rate appears to be small, the size of the knitwear sector in New Zealand is relative to its population size and thus smaller than in more populous nations. The companies that participated represented a good portion of the sector, employing half of the employees working in knitwear production (MBIE 2018a).

Supply chain disruptions

The scope and magnitude of damage from COVID-19 is vastly different from prior catastrophes such as China's SARS outbreak in 2003, or Indonesia's tsunami in 2004 (Xu et al. 2020). COVID-19 not only disrupted local supply chains but had a significant impact on global supply chains at every stage, from raw materials to end consumers. It is likely the pandemic will fundamentally change the makeup of global textile, clothing, leather and footwear supply chains, accelerating the reshoring or nearshoring of manufacturing (ILO 2020).

New Zealand's manufacturers transfer their goods and raw materials across multiple countries due to the globalised nature of the garment industry. Depending on size and delivery time, these commodities are moved by a combination of land, sea and air freight. Multiple national and international lockdowns have disrupted manufacturing by slowing or halting the movement of goods. The costs to procure raw materials from overseas suppliers have increased significantly. Items and services needed for garment construction such as yarn, fabric, stitching threads, buttons, trims and other components, were often sourced from offshore companies. While raw material is produced in-country, it is often sent offshore for processing. For example, New Zealand-grown merino wool is sent to China or Vietnam for scouring, spinning and dyeing processes and later imported back to be knitted into apparel products.

Lockdowns around the world have drawn attention to the risks of high supply-chain interconnectedness and the problems associated with global trade. Interruptions, lockdowns and border closures on a national and worldwide scale impacted the movement of products. The cost of buying raw materials soared, and operations stalled. Cost increase, caused by a lack of availability of certain supplies as many countries imposed extreme lockdown measures, hampered routine production and deliveries. A global shortage of shipping containers and New Zealand's severe COVID-19 regulations for ships and sailors added to the shortages and costs (Walters 2020). Additional compliance and expense caused many shipping companies to abandon their journeys (Walters 2020). This resulted in yarn and supply shortages, which increased costs further. Knitwear makers that relied on overseas suppliers for goods also saw a slowdown in manufacturing. Businesses had little choice but to wait for their goods as fewer aeroplanes delivered freight and long delays were reported at the ports (Du Plessis and Drive 2020). Manufacturers who relied on home suppliers were found to be less affected. This study suggests that if manufacturers want to economise on raw material imports and avoid future disruptions they should seek to reduce their dependency on overseas suppliers and enhance their domestic supply chains.

Suppressed consumer demand

The garment industry has suffered a significant drop in demand globally. Consumer demand for clothes was suppressed by quarantine measures, retail store closures, loss of income, and a fear of spending money during a time of economic uncertainty (Xu et al. 2020). Major brands such as Adidas, Ralph Lauren, Gap and Inditex were forced to close stores in several countries in the first few months of COVID-19-related restrictions (ILO 2020). According to global statistics, 50 percent of factories and their supplier plants were not operating at full capacity in 2020, and 15 percent of all manufacturers produced less than half of their capacity (RBA 2020). The countries with the most trade integration and where tourism trade played a significant role in the economy suffered the greatest losses (Maliszewska, Mattoo, and Van Der Mensbrugghe 2020). As this study shows, New Zealand businesses that were reliant on the tourist market were heavily impacted. Globally, travel had come to a halt as of mid-March, 2020, and as of May, 2022, travel had yet to fully resume in New Zealand, with a gradual relaxing of border restrictions planned over the coming months.

Knitwear makers in New Zealand faced a significant economic impact because of the COVID-19 pandemic. Both local and international markets saw a drop in revenue. Brands that relied heavily on tourism for domestic sales were severely hurt but there was an increase in domestic sales. People had limited access to foreign marketplaces as travel was prohibited and shipping was delayed, shifting them towards local markets to meet their requirements. There was also a widespread drive to buy local and support domestic industries. During the early days of the pandemic, people were encouraged to buy locally made goods, not only to aid the economy and save employment, but also to ensure timely deliveries. The 'Buy New Zealand Made' campaign was launched as a long-term strategy to assist local manufacturers in competing with global suppliers (Jennings 2020).

International sales were also down during the pandemic, consistent with a reported drop in demand for garment products around the world. Social gatherings were rare, and people were primarily confined to their homes, preventing them from purchasing new clothing through normal retail channels. The pandemic also impacted transportation connectivity. A Mallory Alexander International Logistics news article, published May 7, 2020, reported that shipping services reduced the number of port calls due to declining demand and cargo imbalances, generating uncertainty for knitwear exporters. However, a few participants reported an increase in international sales, with a huge acceleration reported on online channels. A surge in online sales for both local and international markets was evident. New Zealand Post data indicates that there was a 105 percent increase in online buying when the country moved into lockdown (NZ Post 2020). A similar trend was observed around the world, which may have aided local exporters in gaining revenue from digital sales. This might be viewed as a silver lining and a growing opportunity for the sector moving forward.

Government responses and their effects

Government intervention was needed to contain the virus, with economic support measures necessary to offset the socio-economic effects. Monetary aid, bailouts, nationalisation and stimulus programmes were used by governments around the world to handle the tremendous economic consequences of halting business activity during the pandemic (OECD 2020). New Zealand unveiled an NZD 12.1 billion package, the world's largest per capita package, which included wage subsidies, healthcare reform, money for low-income families, and reforms to business taxation (Graham-McLay 2020).

Lockdown closures in garment manufacturing impacted both businesses and workers, therefore government assistance was vital. Companies benefitted from a short-term government scheme designed to subsidise wages and keep people employed during the lockdown. This survey found that while several respondents were content with the government's financial assistance, many were dissatisfied with its policies on tariffs, export incentives and tax breaks. During the pandemic's initial phase, manufacturers sought more help in the form of business subsidies and export incentives. Suggestions made by participants of this survey included involving more domestic companies in government procurement and considering compliance costs for local manufacturers. Knitwear producers would like to see more government support in developing a skilled workforce as there is currently a shortage of workers with specialised skills. Issues with the supply chain are also set to continue, with shipping delays contributing to the rising costs of trade. Subsequently, it is critical to be thinking long term, and consider how to support and protect local manufacturing. By assisting local producers, the government would not only address supply-chain difficulties but also contribute to the growth of the local economy.

Knitwear manufacturers in the country have experienced numerous obstacles since tariffs were removed in the late 1980s, and the industry today is much smaller due to increased international competition. Knitwear items make up a small but unique part of the country's manufacturing economy, and government support for the industry could be enhanced by initiatives tailored toward growing local manufacturing resilience and capability.

Reshaping business for the future

Despite the vulnerability of the supply chain and a significant drop in revenue, knitwear producers remained optimistic about future opportunities. They were unsure whether it was commercially feasible to produce clothing in the country prior to the pandemic. This scepticism was dispelled during the pandemic as it was discovered that procuring locally was more advantageous than relying on international suppliers and trade. While one participating company proposed to expand internationally, there was a clear indication that manufacturers anticipated growing locally, or staying at the same scale for a while. None of the businesses that replied to the survey planned to cut or close their operations. However, this may not be consistent across the industry, as companies planning to shut down may not have participated in the survey.

The overall impact of the COVID-19 pandemic on the country's knitwear manufacturing sector has been mixed. Sales are projected to stay low for the foreseeable future, since cross-border travel will take time to bounce back and foreign exchange earnings will be difficult to achieve. Continual disruptions in the supply of goods and services are likely to continue occurring around the world. For the manufacturing industry to recover and regenerate quickly, it is critical that all segments of the supply chain collaborate to develop sustainable and innovative business models. It is a moment to reassess and re-evaluate the industry's strengths and weaknesses, and to take advantage of the opportunities that the pandemic has brought. The SWOT analysis provided in this paper sees opportunities for increased global demand for quality knitted products, online sales, and consumer awareness of sustainable products, and suggests manufacturers work towards this. While staying ahead on digital platforms and supporting the sector, the government must assess the long-term consequences of the pandemic on manufacturing. The crisis provides a chance to increase the value of "New Zealand-made".

Conclusion

As a major wool producer, with some remaining domestic processing capacity and a growing interest in developing the value of the wool sector, the knitwear industry offers both technical and manufacturing capabilities that could be better utilised. Manufacturing was impacted by the global consequences of the COVID-19 pandemic in 2020. Lockdowns in New Zealand and other parts of the world have had immediate ramifications for local and international supply networks. Local providers, particularly in areas of fibre processing, yarn manufacturing and dyeing, require reinforcement. The supply chain has become more vulnerable and returning to normal will be difficult. Supporting local suppliers would help to remove the risk of over-reliance on international suppliers and mitigate the threat of rising freight rates and delivery delays. Prioritising sustainability when sourcing items and processes would be advantageous and employing locally produced material would lessen the danger of supply shortages, ensuring constant access to resources. It would also support the growth of knitwear products, a niche in the global market.

On the revenue side, the curtailment of the tourist trade has had a significant impact on domestic sales. With the country revising its approach to mass tourism (Withers 2021), it will be difficult for manufacturers to return to business-as-usual in tourism-related sales. Finding new methods for redirecting domestic markets needs to be a key focus. Internet sales should be prioritised in order to attract new international clients. Along with digitising all business operations, enterprises should seek to enhance their supply chains and product innovation to increase their sales potential. While the government's short-term wage subsidy was appreciated, further government assistance is critical. To take businesses forward, more skilled workers are needed, and manufacturers are seeking government assistance in educating new talent from within the community.

While the immediate priority of the knitwear apparel sector is to navigate through the crisis brought on by the COVID-19 pandemic, this is a suitable time to implement improvements that will have a long-term impact. There are potential strategies for change based on the industry's strengths, weaknesses, opportunities and threats that can benefit local knitwear enterprises and other small and medium-sized enterprises in other parts of the world in the design of longer-term, more sustainable industries.

Limitations and future studies

While doing an online survey amid a pandemic was convenient, it had several drawbacks. Given the uncertainty around the changing nature of the pandemic and its impact on the future, approaching individuals and asking them to share their experiences was difficult. The seven business owners who replied represent a small but useful sample size, but do not represent the entire industry. This issue could be addressed in future by conducting an online or telephone interview with a bigger set of companies. The SWOT analysis in the report is also a limited appraisal of the knitwear sector's performance and attributes identified by the authors, and there are opportunities for industry insiders to expand it further.

A follow-up study could corroborate the conditions described in this report over a longer period, and investigate further measures to rehabilitate and expand the knitwear industry. As several manufacturers declined to participate in this survey, it would be useful to find out how they have fared once the borders open and the supply chains are restored. Furthermore, it may be useful to compare the effects of the pandemic on the knitwear manufacturing industries of other countries to highlight global impacts and local responses.

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Appendix E *Ethics Approval Letter (Stage 2)*

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

8 December 2021

Amabel Hunting
Faculty of Design and Creative Technologies

Dear Amabel

Re Ethics Application: **19/425 Design tool for assessing the environmental sustainability of knitted apparel products in New Zealand**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

The 2nd stage of your ethics application has been approved for three years until 8 December 2024.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: mitali.nautiyal@aut.ac.nz; frances.joseph@aut.ac.nz; Donna Cleveland

Appendix F *Survey Questionnaire- A Consumer Survey on Woollen and Synthetic Knitted Jumpers*

Start of Block: Block 8

Q 41
Participant Information Sheet

A Consumer survey on woollen and synthetic knitted jumpers16

You are invited to participate in a research study by Mitali Nautiyal, Evaluating the environmental impact of knitted apparel products in New Zealand, in the School of Art & Design, Auckland University of Technology, New Zealand. The purpose of this research is to find the environmental impact of apparel products in the use and end-of-life phases. The intention is to calculate the energy and water used during its lifetime and the waste that is generated at the end of its life. The results would benefit my research as well as future studies in this area.

You are being asked to participate in this research because I believe you will provide important information to help me understand and research this topic. If you take part in this study, you will be asked to take an 8-10 minute survey where you will be asked 30 simple questions about how you wear, wash and dispose of your knitted jumpers. **By taking up this survey, you agree to participate in this study.**

Inclusion criterion:
To participate in this survey, you must be at least **18 years old, live in New Zealand and wash your own laundry.** You should also understand the distinction between wool and synthetic clothing.

Survey Risks:
The possible risk of participating in this survey include loss of confidentiality and investment of time. I guarantee you that the survey is **anonymous** and there would be no publication of your name. The survey link's IP address collector is disabled, and so you cannot be traced back. I assure you that the results will be used just for academic purposes and will not be sold to any other parties. The survey is being conducted using Qualtrics software and the collected data will be securely stored in a restricted-access folder and locked in a drawer in a restricted-access office. The survey will not take more than **10 minutes of your time** to complete and you can decline to participate at any point in the survey.

Survey Result Publications:
The findings of this survey would only be used for academic publications and would be presented at relevant conferences. It would be a part of my PhD in Art and Design at AUT.

If you are interested in learning more about the results of this survey, you can visit:

https://aut.au1.qualtrics.com/reports/public/YXV0LTYxYTk1YjQ1YTgzZDU1MDAwZjY5YTQxNi1VUl81QmJFS1JNamxEWkV1b3Q=
passcode-12345 anytime between 1 March 2022 to 1 March 2023.

Questions and concerns:
If you have any questions about this survey, or difficulty in accessing the site or completing the survey, please contact mitali.nautiyal@aut.ac.nz
If you require any further information about my research project, please contact my supervisor, Dr Amabel Hunting, at amabel.hunting@aut.ac.nz
Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, ethics@aut.ac.nz 921 9999 ext. 6038.

Thanking you in advance for your participation

***Approved by the Auckland University of Technology Ethics Committee on 03/12/2021, AUTEC Reference number* 19/425**

The survey is being conducted using "Qualtrics"

Q 42 Would you like to participate?

○ Yes

○ No

Skip To: End of Survey If Would you like to participate? = No
End of Block: Block 8

Start of Block: Default Question Block

Q1 In which region of New Zealand do you currently reside in?

- ○ Northland
- ○ Auckland
- ○ Waikato
- ○ Bay of Plenty
- ○ Gisborne/Hawke's Bay
- ○ Taranaki
- ○ Manawatu-Whanganui
- ○ Wellington
- ○ Tasman/Nelson/Marlborough
- ○ West Coast
- ○ Canterbury
- ○ Otago
- ○ Southland
- ○ If you are not residing in New Zealand, you are not part of the study's target group. Thank you for taking time to participate.

Skip To: End of Survey If In which region of New Zealand do you currently reside in? = If you are not residing in New Zealand, you are not part of the study's target group. Thank you for taking time to participate.

Q2 Please classify your age group?

- ○ Born between 1928-1945
- ○ Born between 1946-1964
- ○ Born between 1965-1980
- ○ Born between 1981-1996
- ○ Born between 1996-2002
- ○ Born after 2003 (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Skip To: End of Survey If Please classify your age group? = Born after 2003 (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Q4 Are you responsible for washing your clothes?

○ Yes, I am solely responsible

○ Yes, I share it with someone else at home

○ No, I am not responsible (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Skip To: End of Survey If Are you responsible for washing your clothes? = No, I am not responsible (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Q3 Please state your gender?

○ Male

○ Female

○ Non-binary

○ Prefer not to say

Q5 Have you owned a woollen or/and a wool blend synthetic jumper/ sweater/ cardigan before?

○ Yes

○ Probably yes, but not sure about the composition

○ No (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Skip To: End of Survey If Have you owned a woollen or/and a wool blend synthetic jumper/ sweater/ cardigan before? = No (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)

Q6 Do you follow the same or different washing method for both woollen and synthetic blend jumpers?

- ○ Yes, I wash both wool and synthetic jumpers the same way
- ○ No, I wash woollen jumpers different from how I wash synthetic blends
- ○ Can't say, I sometimes wash them the same way and sometimes separate
- ○ Don't know

End of Block: Default Question Block

Start of Block: Questions on woollen jumper

Q7 Recall a specific woollen jumper you currently own. Approximately when did you buy or acquire it?
Note: Please answer the next set of questions based upon the same woollen jumper.

- ○ In the last 6 months
- ○ 1 year ago
- ○ 2 years ago
- ○ 3-5 years ago
- ○ 6-10 years ago
- ○ 11-15 years ago
- ○ 16-20 years ago
- ○ 21-25 years ago
- ○ 26-30 years ago
- ○ More than 30 years ago
- ○ Don't know/ Cannot remember

Q8 How often do you typically wear this (woollen) jumper / sweater / cardigan?

- ○ Several times a week
- ○ Once a week
- ○ Once every 2 weeks
- ○ Once every 3-4 weeks
- ○ Once every 3 months
- ○ Once every 6 months
- ○ Less than once every 6 months
- ○ Don't know

Q9 Can you approximate the number of times to date you have worn this (woollen) jumper? An approximate indication will work.

- ○ 1-2 times
- ○ 3-4 times
- ○ 5-9 times
- ○ 10-19 times
- ○ 20-49 times
- ○ 50-99 times
- ○ 100-199 times
- ○ More than 200 times
- ○ Don't know

Q10 Can you please inform the approximate number of times do you expect to wear this (woollen) jumper in future?

- ○ 1-2 times
- ○ 3-4 times
- ○ 5-9 times
- ○ 10-19 times
- ○ 20-49 times
- ○ 50-99 times
- ○ 100-199 times
- ○ More than 200 times
- ○ Don't know

End of Block: Questions on woollen jumper

Start of Block: Questions on synthetic jumper

Q17 Recall a specific synthetic blend jumper you currently own. Approximately when did you buy or acquire it?

Note: Please answer the next set of questions based upon the same synthetic blend jumper.

- In the last 6 months
- 1 year ago
- 2 years ago
- 3-4 years ago
- 5-10 years ago
- 11-15 years ago
- 16-20 years ago
- 21-25 years ago
- 26-30 years ago
- More than 30 years ago
- Don't know/ Cannot remember

Q18 How often do you typically wear this (synthetic blend) jumper / sweater / cardigan?

- Several times a week
- Once a week
- Once every 2 weeks
- Once every 3-4 weeks
- Once every 3 months
- Once every 6 months
- Less than once every 6 months
- Don't know

Q19 Can you approximate the number of times to date you have worn this (synthetic blend) jumper? An approximate indication will work.

- ○ 1-2 times
- ○ 3-4 times
- ○ 5-9 times
- ○ 10-19 times
- ○ 20-49 times
- ○ 50-99 times
- ○ 100-199 times
- ○ More than 200 times
- ○ Don't know

Q20 Can you please inform the approximate number of times do you expect to wear this (synthetic blend) jumper in future?

- ○ 1-2 times
- ○ 3-4 times
- ○ 5-9 times
- ○ 10-19 times
- ○ 20-49 times
- ○ 50-99 times
- ○ 100-199 times
- ○ More than 200 times
- ○ Don't know

End of Block: Questions on synthetic jumper

Start of Block: Wash both the same way

Q31 How do you usually wash the (woollen or synthetic blend) jumper/ sweater/ cardigan?

- ○ Hand wash it
- ○ Wash it in washing machine
- ○ Send it for dry cleaning
- ○ Sometimes hand wash and sometimes machine wash
- ○ Sometimes hand wash and sometimes dry clean
- ○ Sometimes machine wash and sometimes dry clean
- ○ Don't know

Q32 Identify the washing machine settings you use for washing the (woollen or synthetic blend) jumper/ sweater/ cardigan?

- ○ Quick/ Fast Cycle
- ○ Delicate Cycle
- ○ Normal Cycle
- ○ Heavy-duty Cycle
- ○ Don't know

Q33 When in use, how often do you or someone else typically wash the (woollen or synthetic blend) jumper?

- ○ After every wear
- ○ After every 2 wears
- ○ After every 3-5 wears
- ○ After every6-10 wears
- ○ After every 11-19 wears
- ○ After every 20-29 wears
- ○ After every 30 wears or less often
- ○ Never
- ○ Don't know

Q34 Which detergent would you normally use for washing the (woollen or synthetic blend) jumper?

- ○ Synthetic detergent powder (E.g., Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)
- ○ Eco-friendly detergent powder (E.g., Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc.)
- ○ Special wool detergents (E.g., Woolskin wool wash/ Softly premium wash etc.)
- ○ Synthetic detergent liquid
- ○ Eco-friendly detergent liquid
- ○ Laundry pods or tablets
- ○ Other ____

Q35 How would you dry the (woollen or synthetic blend) jumper?

- ○ Dry it in wind or sun
- ○ Use a dryer

End of Block: Wash both the same way

Start of Block: Demographic information to ensure we are covering a cross-section of population.

Q27 How many people live in your household?

- ○ I live alone
- ○ 2 persons
- ○ 3-4 persons
- ○ 5-10 persons
- ○ More than 10
- ○ Prefer not to say

Q28 What is your employment status?

- ○ Part time
- ○ Full time
- ○ Casual
- ○ Seeking work
- ○ Not seeking work
- ○ Home duties
- ○ Student
- ○ Retired
- ○ Prefer not to say

Q29 Which of the following best describe your household's yearly income?

- ○ 30,000 NZD or less
- ○ 30,001 to 70,000 NZD
- ○ 70,001 to 100,000 NZD
- ○ 100,001 to 150,000 NZD
- ○ 150,001 NZD or more
- ○ Prefer not to say

End of Block: Demographic information to ensure we are covering a cross-section of population.

Start of Block: One last text question

Q30 Thank you for taking the time to respond to the questions above. This survey has come to an end but I have one more request.
Can you tell me the brand and model number of your washing machine (or, if that's not possible, it's capacity in kilograms)?

____

End of Block: One last text question

Start of Block: Questions on woollen jumper's washing habits

Q11 How do you usually wash this (woollen) jumper/ sweater/ cardigan?

- ○ Hand wash it
- ○ Wash it in washing machine
- ○ Send it for dry cleaning
- ○ Sometimes hand wash and sometimes machine wash
- ○ Sometimes hand wash and sometimes dry clean
- ○ Sometimes machine wash and sometimes dry clean
- ○ Don't know

Q12 Identify the washing machine settings you use for washing this (woollen) jumper/ sweater/ cardigan?

- ○ Quick/ Fast Cycle
- ○ Delicate Cycle
- ○ Normal Cycle
- ○ Heavy-duty Cycle
- ○ Don't know

Q13 When in use, how often do you or someone else typically wash this (woollen) jumper?

- ○ After every wear
- ○ After every 2 wears
- ○ After every 3-5 wears
- ○ After every 6-10 wears
- ○ After every 11-19 wears
- ○ After every 20-29 wears
- ○ After every 30 wears or less often
- ○ Never
- ○ Don't know

Q14 Which detergent would you normally use for washing this (woollen) jumper?

○ Synthetic detergent powder (E.g., Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)

○ Eco-friendly detergent powder (E.g., Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc.)

○ Special wool detergents (E.g., Woolskin wool wash/ Softly premium wash etc.)

○ Synthetic detergent liquid

○ Eco-friendly detergent liquid

○ Laundry pods or tablets

○ Other ____

Q15 How would you dry this (woollen) jumper?

○ Dry it in wind or sun

○ Use a dryer

Q16 How would you dispose of this (woollen) jumper /sweater/ cardigan when you no longer want it?

○ Donate to charity

○ Donate/ give to family/ friends

○ Put it in the rubbish bin at home

○ Recycle at home (E.g., use it as a cleaning cloth)

○ Sell (E.g., Garage sale, Trade me etc.)

○ Don't know

○ Other ____

End of Block: Questions on woollen jumper's washing habits

Start of Block: Questions on synthetic jumper's washing habits

Q21 How do you usually wash this (synthetic blend) jumper/ sweater/ cardigan?

- ○ Hand wash it
- ○ Wash it in washing machine
- ○ Send it for dry cleaning
- ○ Sometimes hand wash and sometimes machine wash
- ○ Sometimes hand wash and sometimes dry clean
- ○ Sometimes machine wash and sometimes dry clean
- ○ Don't know

Q22 Identify the washing machine settings you use for washing this (synthetic blend) jumper/ sweater/ cardigan?

- ○ Quick/ Fast Cycle
- ○ Delicate Cycle
- ○ Normal Cycle
- ○ Heavy-duty Cycle
- ○ Don't know

Q23 When in use, how often do you or someone else typically wash this (synthetic blend) jumper?

- ○ After every wear
- ○ After every 2 wears
- ○ After every 3-5 wears
- ○ After every 6-10 wears
- ○ After every 11-19 wears
- ○ After every 20-29 wears
- ○ After every 30 wears or less often
- ○ Never
- ○ Don't know

Q24 Which detergent would you normally use for washing this (synthetic blend) jumper?

○ Synthetic detergent powder (E.g., Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)

○ Eco-friendly detergent powder (E.g., Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc.)

○ Special wool detergents (E.g. Woolskin wool wash/ Softly premium wash etc.)

○ Synthetic detergent liquid

○ Eco-friendly detergent liquid

○ Laundry pods or tablets

○ Other ____

Q25 How would you dry this (synthetic blend) jumper?

○ Dry it in wind or sun

○ Use a dryer

Q26 How would you dispose of this (synthetic blend) jumper /sweater/ cardigan when you no longer want it?

○ Donate to charity

○ Donate/ give to family/ friends

○ Put it in the rubbish bin at home

○ Recycle at home (E.g., use it as a cleaning cloth)

○ Sell (E.g., Garage sale, Trade me etc.)

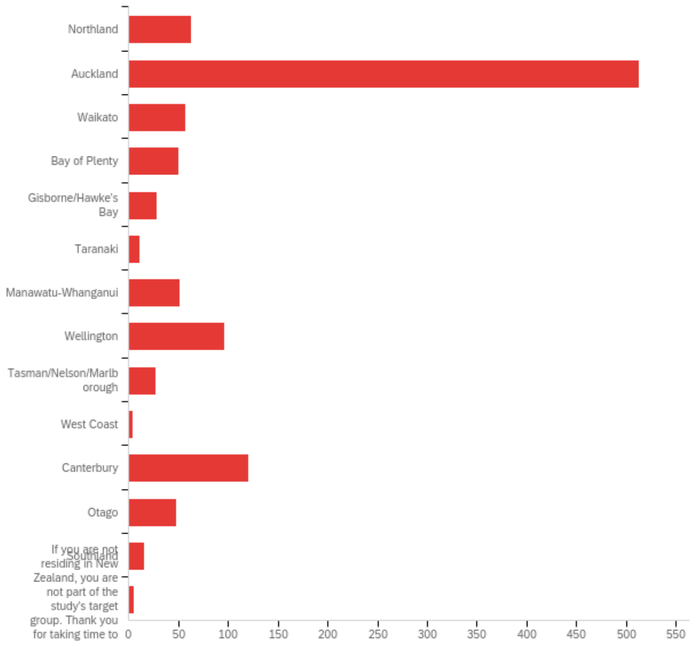
○ Don't know

○ Other ____

End of Block: Questions on synthetic jumper's washing habits

Appendix G *Survey results on Apparel Use and End-of-Life in New Zealand*

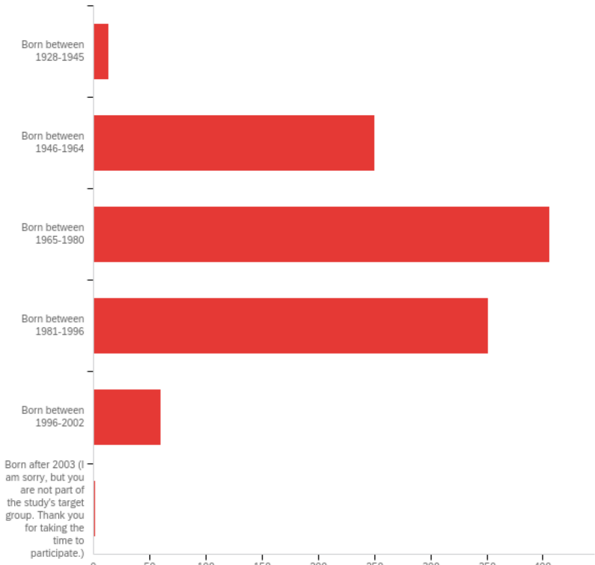
Q1 - In which region of New Zealand do you currently reside in?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	In which region of New Zealand do you currently reside in?	3.00	17.00	6.83	3.82	14.59	1088

#	Answer	%	Count
3	Northland	5.79%	63
4	Auckland	47.15%	513
5	Waikato	5.24%	57
6	Bay of Plenty	4.60%	50
7	Gisborne/Hawke's Bay	2.57%	28
8	Taranaki	1.01%	11
9	Manawatu-Whanganui	4.69%	51
10	Wellington	8.82%	96
11	Tasman/Nelson/Marlborough	2.48%	27
12	West Coast	0.37%	4
13	Canterbury	11.03%	120
14	Otago	4.41%	48
16	Southland	1.38%	15
17	If you are not residing in New Zealand, you are not part of the study's target group. Thank you for taking time to participate.	0.46%	5
	Total	100%	1088

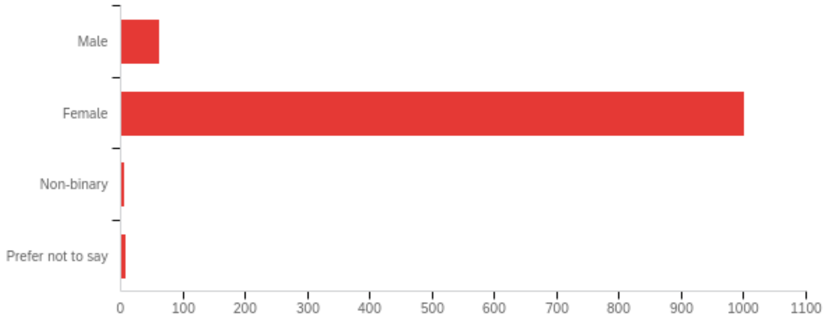
Q2 - Please classify your age group?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Please classify your age group?	1.00	6.00	3.18	0.89	0.80	1081

#	Answer	%	Count
1	Born between 1928-1945	1.20%	13
2	Born between 1946-1964	23.13%	250
3	Born between 1965-1980	37.56%	406
4	Born between 1981-1996	32.47%	351
5	Born between 1996-2002	5.55%	60
6	Born after 2003 (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)	0.09%	1
	Total	100%	1081

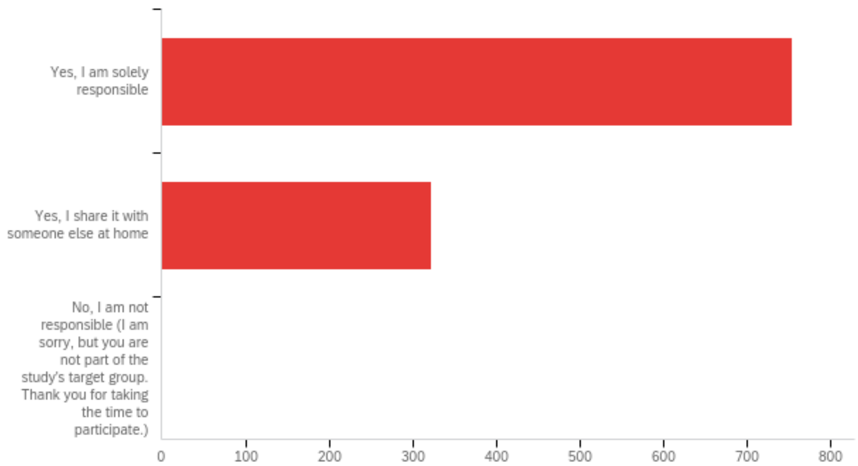
Q3 - Please state your gender?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Please state your gender?	1.00	4.00	1.96	0.30	0.09	1078

#	Answer	%	Count
1	Male	5.75%	62
2	Female	92.95%	1002
3	Non-binary	0.56%	6
4	Prefer not to say	0.74%	8
	Total	100%	1078

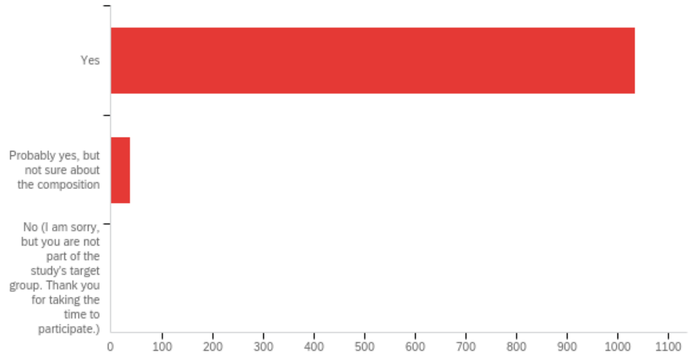
Q4 - Are you responsible for washing your clothes?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Are you responsible for washing your clothes?	1.00	3.00	1.30	0.46	0.21	1079

#	Answer	%	Count
1	Yes, I am solely responsible	69.97%	755
2	Yes, I share it with someone else at home	29.94%	323
3	No, I am not responsible (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)	0.09%	1
	Total	100%	1079

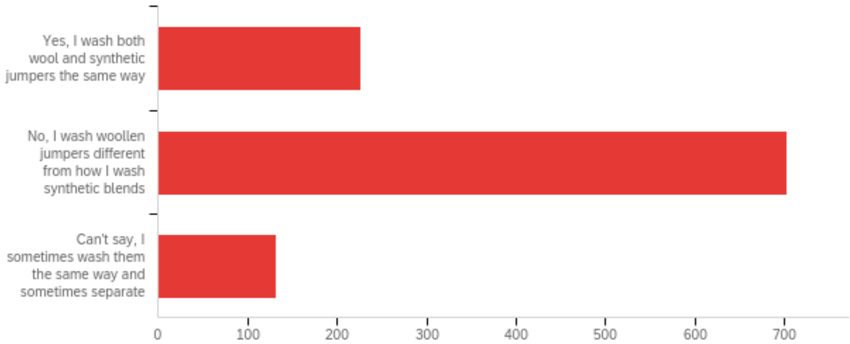
Q5 - Have you owned a woollen or/and a wool blend synthetic jumper/ sweater/ cardigan before?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Have you owned a woollen or/and a wool blend synthetic jumper/ sweater/ cardigan before?	1.00	4.00	1.08	0.39	0.15	1075

#	Answer	%	Count
1	Yes	96.28%	1035
3	Probably yes, but not sure about the composition	3.53%	38
4	No (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate.)	0.19%	2
	Total	100%	1075

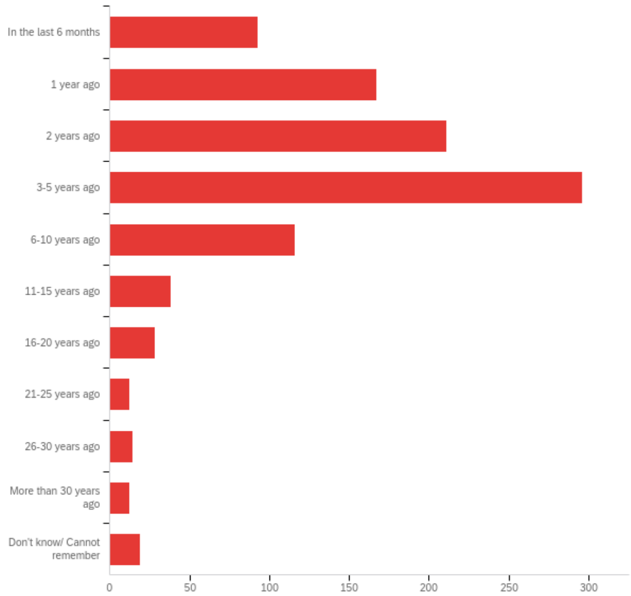
Q6 - Do you follow the same or different washing method for both woollen and synthetic blend jumpers?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Do you follow the same or different washing method for both woollen and synthetic blend jumpers?	1.00	3.00	1.91	0.57	0.33	1060

#	Answer	%	Count
1	Yes, I wash both wool and synthetic jumpers the same way	21.32%	226
2	No, I wash woollen jumpers different from how I wash synthetic blends	66.32%	703
3	Can't say, I sometimes wash them the same way and sometimes separate	12.36%	131
	Total	100%	1060

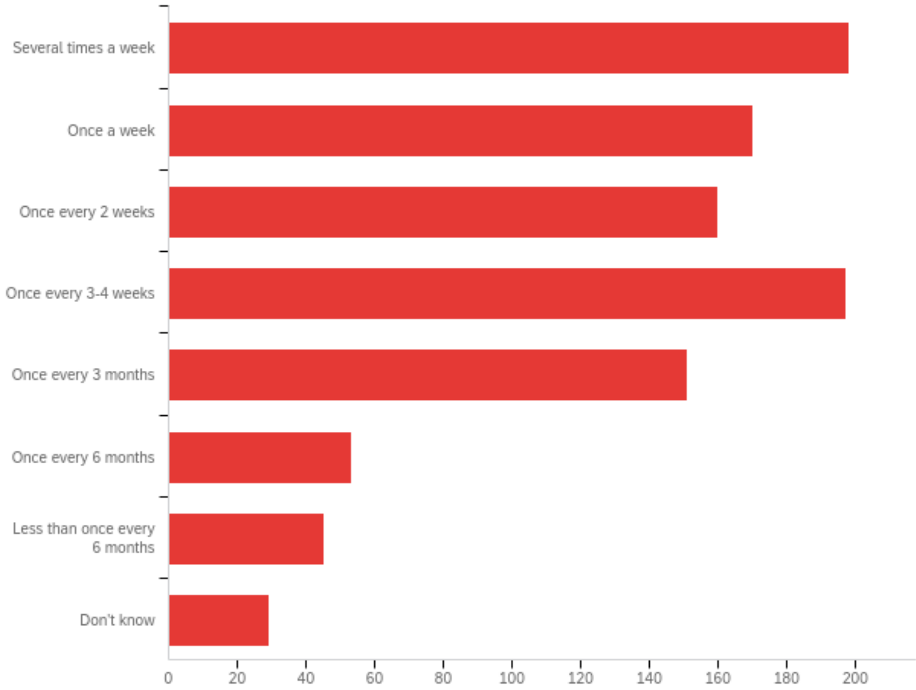
Q7 - Recall a specific woollen jumper you currently own. Approximately when did you buy or acquire it? Note: Please answer the next set of questions based upon the same woollen jumper.



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Recall a specific woollen jumper you currently own. Approximately when did you buy or acquire it? Note: Please answer the next set of questions based upon the same woollen jumper.	1.00	13.00	4.43	2.64	6.98	1006

#	Answer	%	Count
1	In the last 6 months	9.24%	93
2	1 year ago	16.60%	167
3	2 years ago	20.97%	211
5	3-5 years ago	29.42%	296
6	6-10 years ago	11.53%	116
8	11-15 years ago	3.78%	38
9	16-20 years ago	2.78%	28
10	21-25 years ago	1.19%	12
11	26-30 years ago	1.39%	14
12	More than 30 years ago	1.19%	12
13	Don't know/ Cannot remember	1.89%	19
	Total	100%	1006

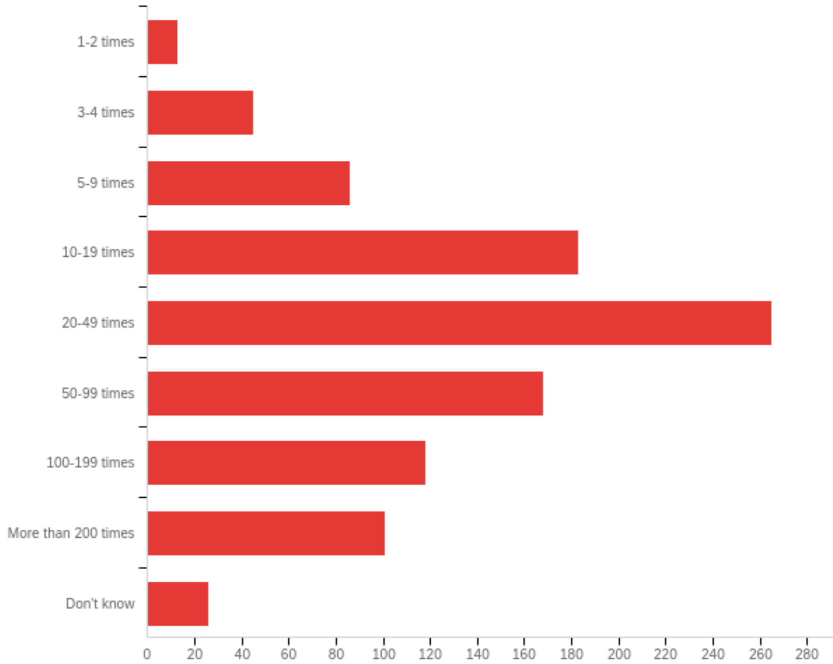
Q8 - How often do you typically wear this (woollen) jumper / sweater / cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How often do you typically wear this (woollen) jumper / sweater / cardigan?	1.00	8.00	3.42	1.87	3.50	1003

#	Answer	%	Count
1	Several times a week	19.74%	198
2	Once a week	16.95%	170
3	Once every 2 weeks	15.95%	160
4	Once every 3-4 weeks	19.64%	197
5	Once every 3 months	15.05%	151
6	Once every 6 months	5.28%	53
7	Less than once every 6 months	4.49%	45
8	Don't know	2.89%	29
	Total	100%	1003

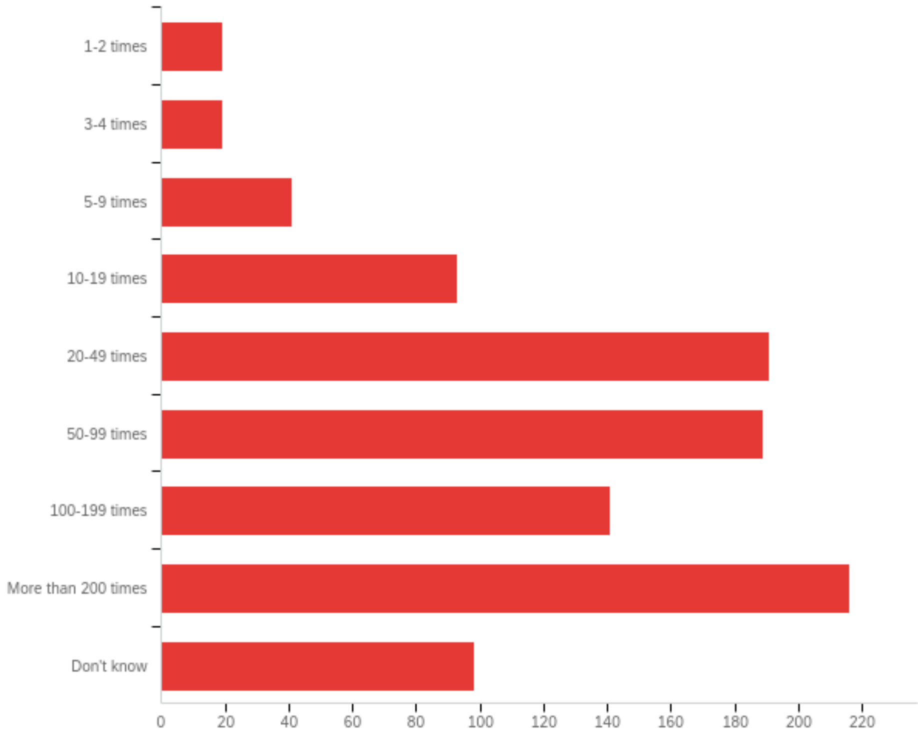
Q9 - Can you approximate the number of times to date you have worn this (woollen) jumper? An approximate indication will work.



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Can you approximate the number of times to date you have worn this (woollen) jumper? An approximate indication will work.	1.00	9.00	5.27	1.74	3.02	1005

#	Answer	%	Count
1	1-2 times	1.29%	13
2	3-4 times	4.48%	45
3	5-9 times	8.56%	86
4	10-19 times	18.21%	183
5	20-49 times	26.37%	265
6	50-99 times	16.72%	168
7	100-199 times	11.74%	118
8	More than 200 times	10.05%	101
9	Don't know	2.59%	26
	Total	100%	1005

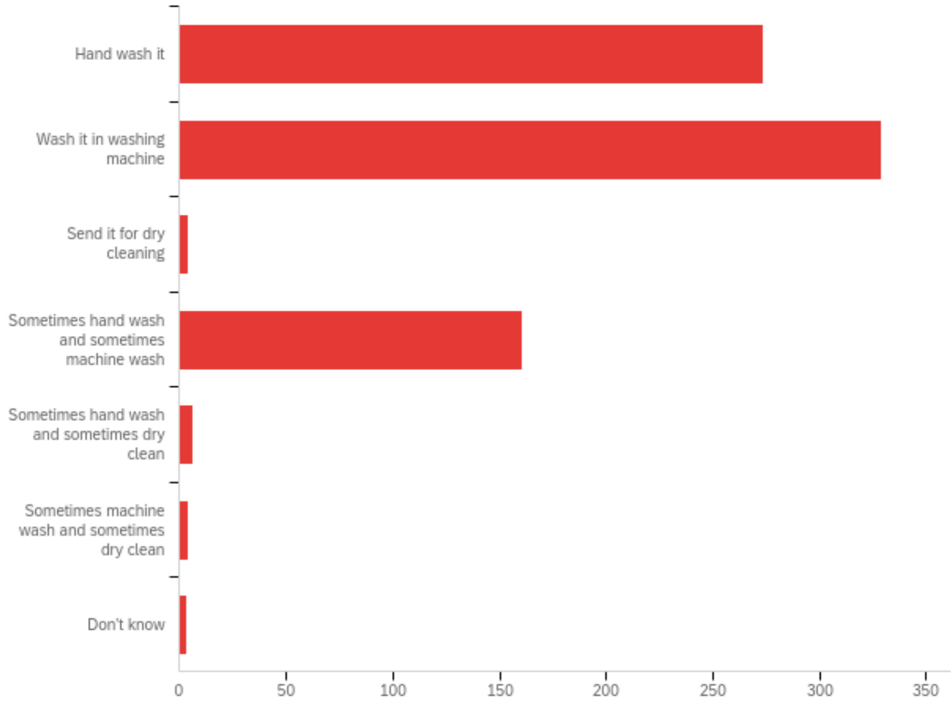
Q10 - Can you please inform the approximate number of times do you expect to wear this (woollen) jumper in future?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Can you please inform the approximate number of times do you expect to wear this (woollen) jumper in future?	1.00	10.00	6.51	2.25	5.07	1007

#	Answer	%	Count
1	1-2 times	1.89%	19
2	3-4 times	1.89%	19
3	5-9 times	4.07%	41
4	10-19 times	9.24%	93
5	20-49 times	18.97%	191
6	50-99 times	18.77%	189
7	100-199 times	14.00%	141
9	More than 200 times	21.45%	216
10	Don't know	9.73%	98
	Total	100%	1007

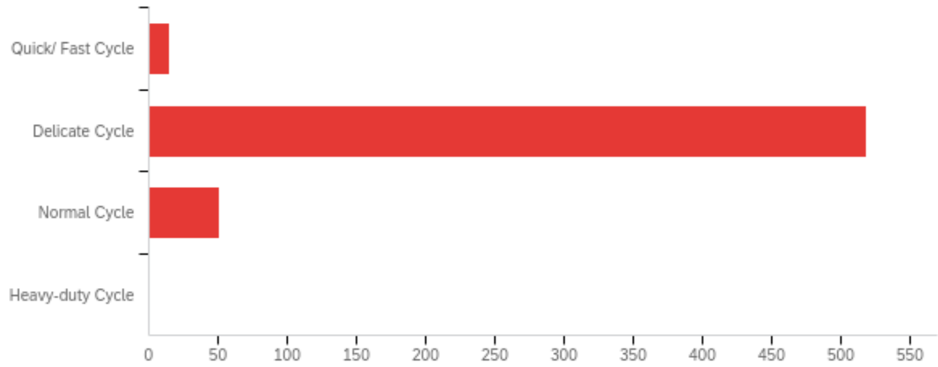
Q11 - How do you usually wash this (woollen) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How do you usually wash this (woollen) jumper/ sweater/ cardigan?	1.00	7.00	2.13	1.19	1.41	781

#	Answer	%	Count
1	Hand wash it	35.08%	274
2	Wash it in washing machine	42.13%	329
3	Send it for dry cleaning	0.51%	4
4	Sometimes hand wash and sometimes machine wash	20.61%	161
5	Sometimes hand wash and sometimes dry clean	0.77%	6
6	Sometimes machine wash and sometimes dry clean	0.51%	4
7	Don't know	0.38%	3
	Total	100%	781

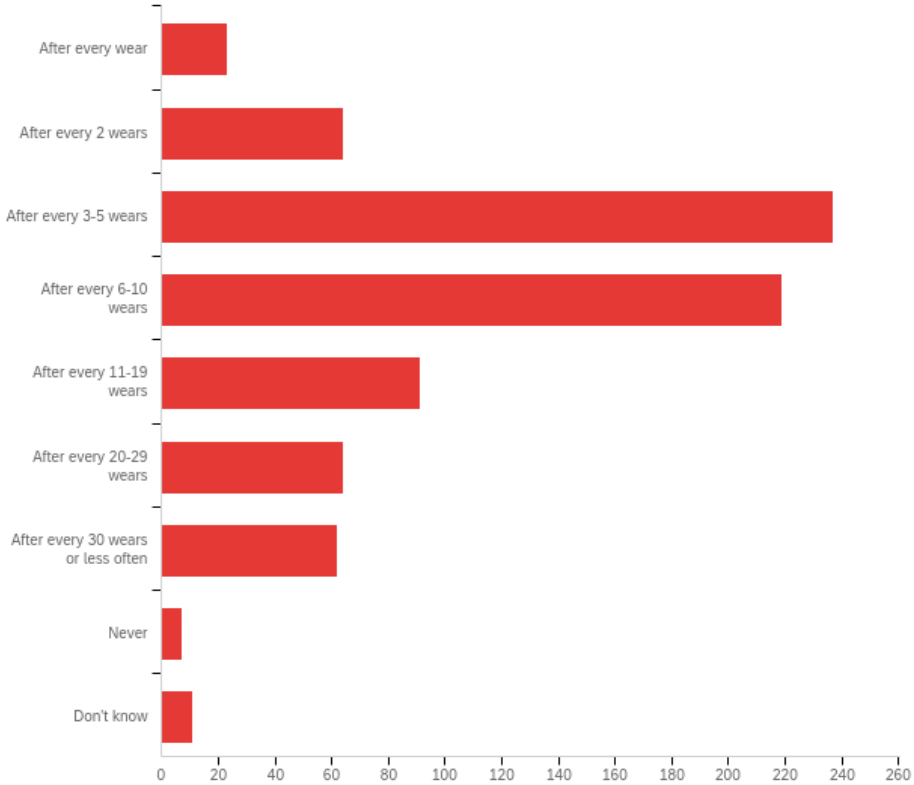
Q12 - Identify the washing machine settings you use for washing this (woollen) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Identify the washing machine settings you use for washing this (woollen) jumper/ sweater/ cardigan?	1.00	3.00	2.06	0.33	0.11	585

#	Answer	%	Count
1	Quick/ Fast Cycle	2.56%	15
2	Delicate Cycle	88.72%	519
3	Normal Cycle	8.72%	51
4	Heavy-duty Cycle	0.00%	0
	Total	100%	585

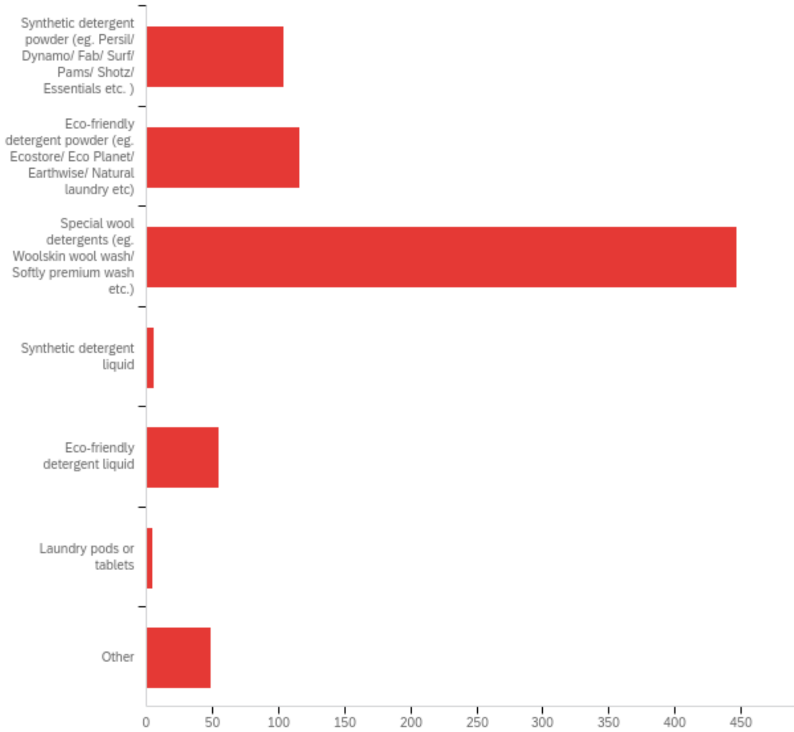
Q13 - When in use, how often do you or someone else typically wash this (woollen) jumper?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	When in use, how often do you or someone else typically wash this (woollen) jumper?	1.00	9.00	4.07	1.60	2.56	778

#	Answer	%	Count
1	After every wear	2.96%	23
2	After every 2 wears	8.23%	64
3	After every 3-5 wears	30.46%	237
4	After every 6-10 wears	28.15%	219
5	After every 11-19 wears	11.70%	91
6	After every 20-29 wears	8.23%	64
7	After every 30 wears or less often	7.97%	62
8	Never	0.90%	7
9	Don't know	1.41%	11
	Total	100%	778

Q14 - Which detergent would you normally use for washing this (woollen) jumper?



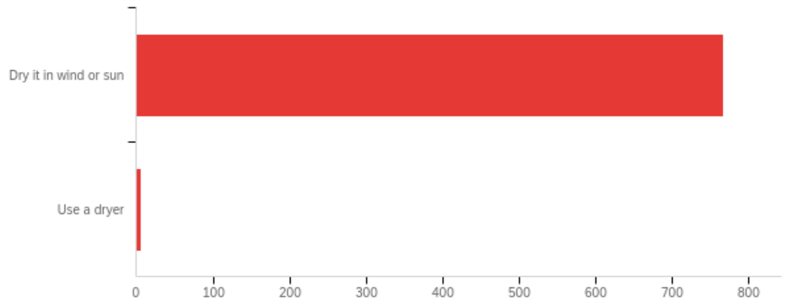
#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Which detergent would you normally use for washing this (woollen) jumper? - Selected Choice	1.00	7.00	3.00	1.42	2.03	782

#	Answer	%	Count
1	Synthetic detergent powder (eg. Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)	13.30%	104
2	Eco-friendly detergent powder (eg. Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc)	14.83%	116
3	Special wool detergents (eg. Woolskin wool wash/ Softly premium wash etc.)	57.16%	447
4	Synthetic detergent liquid	0.77%	6
5	Eco-friendly detergent liquid	7.03%	55
6	Laundry pods or tablets	0.64%	5
7	Other	6.27%	49
	Total	100%	782

Q14_7_TEXT - Other

Wool eucalyptus soap
None
Soap for a hand wash
I often use shampoo
soap nuts/machine wash or Ethique laundry bar for hand wash
Eco-friendly wool/delicate detergent (Ecostore)
Special eco friendly wool wash - both eco and wool wash
Hand soap
This is for next question - dry flat in the shade
Eco store wool liquid detergent
None just water or if my hand a dash like very little of dish washing liquid
Mixture of eco-friendly power and liquid
Eco friendly and wool specific
I use figgy and co laundry
Make my own laundry liquid
Lux flakes
Shampoo
Eco friendly wool wash
Special wool wash, but usually Soak, Unicorn, or Eucalan
Sunlight soap
Soap flakes
Combination of Eco Friendly / Wool Wash or just spray lightly with fabric freshener between wears as wool is self cleaning
I grate soap and add to the wash with small amount of washing soda
laundry egg or dish liquid
Home made solution of borax, washing soda and a little Dr Bronner liquid soap, with a few drops of lavender essential oil, the rinsed with white vinegar in the watera
I make my own laundry liquid with Sunlight soap
Sunlight cake soap
Luke warm water only
For question about machine washing cycles I never wash wool in a machine so answered don’t know
Modere washing powder
Wool eco friendly detergent
Hair shampoo
dishwasing liquid

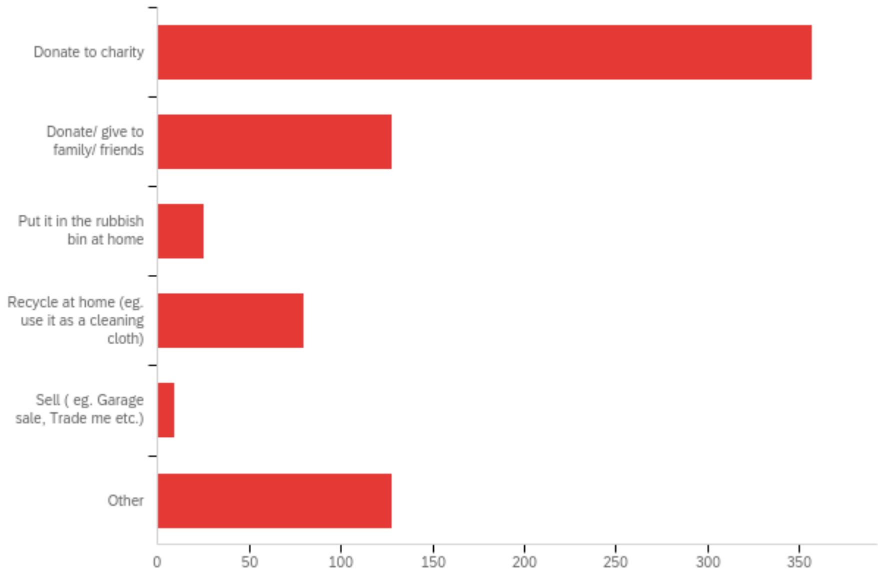
Q15 - How would you dry this (woollen) jumper?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How would you dry this (woollen) jumper?	1.00	2.00	1.01	0.09	0.01	774

#	Answer	%	Count
1	Dry it in wind or sun	99.22%	768
2	Use a dryer	0.78%	6
	Total	100%	774

Q16 - How would you dispose of this (woollen) jumper /sweater/ cardigan when you no longer want it?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How would you dispose of this (woollen) jumper /sweater/ cardigan when you no longer want it? - Selected Choice	1.00	7.00	2.68	2.24	5.02	727

#	Answer	%	Count
1	Donate to charity	49.11%	357
2	Donate/ give to family/ friends	17.61%	128
3	Put it in the rubbish bin at home	3.44%	25
4	Recycle at home (eg. use it as a cleaning cloth)	11.00%	80
5	Sell (eg. Garage sale, Trade me etc.)	1.24%	9
7	Other	17.61%	128
	Total	100%	727

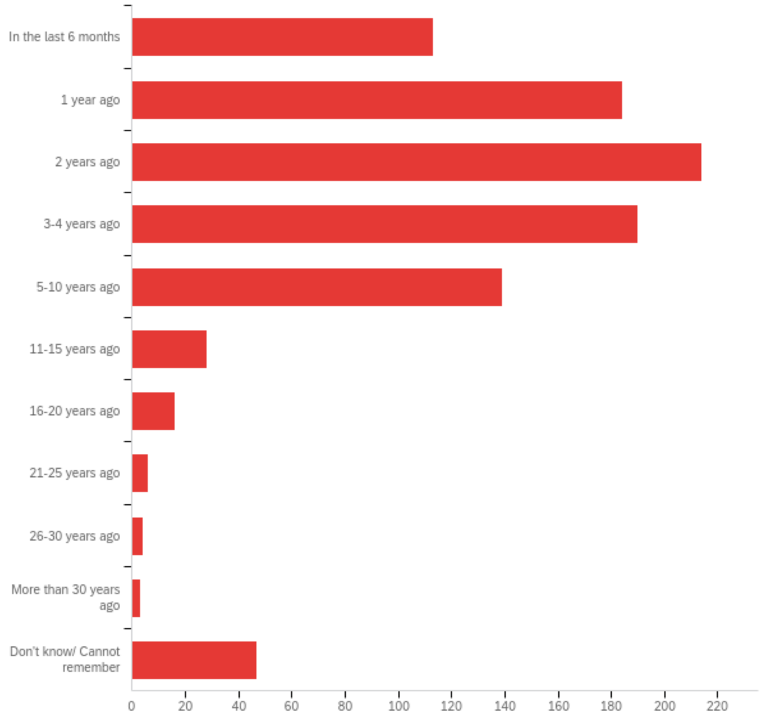
Q16_7_TEXT - Other

Unwind and reknit
See if family wants it or offer it on a community PIF page
Depends on condition
Compost
Depends on quality...if still has wear then charity shop, if not then probably rubbish bin
It was knitted by my Granny & I hope will long survive me
Depends what state it is at end, but definitely wont go to rubbish! Could be any of above
Compost. But I darn my jerseys so in fact I don't expect to stop wearing it.
Recycle at home, use as rag or compost at home
upcycle into hat, slippers etc.
natural fibre so mulch around a new planting
If it is worn out, I would darn it. If it is too worn out I would compost it. If it is too small I would donate it. All my wool jumpers come from charity shops.
Depends on whether it is still wearable.
Feec it to our worm farm
Compost it
When it is not suitable for daily wearing, I would use it either to cycle to work (don't mind if it has large holes) or for gardening). Then, given it is a woollen jumper, I would put it in the compost.
It will last for ever
It depends on the condition whether I would donate it or bin it.
Unravelling and reuse the yarn
Compost (un-dyed yarn)
At the point where my jumper is no longer repairable (no repairs yet needed) I will pop it in the compost. I will be surprised if I need to do so in the next decade.
Depends on condition
Compost or donate for animal bedding spca
Wear it until it's absolutely not wearable then upcycle into a nappy cover or mittens and leftovers become compost or weed mat
I imagine it will be worn out by then
Dog bedding

Create something else out of it or use for stuffing
compost
I will compost it if it is no longer wearable. Otherwose I would give to charity
Compost
Compost
Compost
Use in my garden as mulch
I will wear it until it is no longer wearable then I will use it as weed mat
Wear it until it can't be worn then home compost it
Unpick & reuse the wool in some way
If in enough condition, I donate otherwise I put it in the compost bin
Unravel and reuse wool in knitting
Depends on condition. possibly in the rubbish.
As it's one I hand spun, hand dyed and hand knitted myself I would make it into another garment or use it as weft yarn in my woollen weaving projects.
clothing bin to be used as cleaning rags
compost
Put it in a bag and think about making it into something else
Might try composting
Return to the store (Standard Issue) for their take back program
Depending on condition. If unwearable it goes into my compost if it's pure wool.
Wool is a natural fibre, so I'd compost it. It's been hand washed with wool shampoo, also natural.
I only throw out my merinos when they fall apart. Would love to be able to send them somewhere to be reused
Hand it down to one of my my children/ grandchildren
If not in a state to go to charity it will go on the compost.
If the yarn was still in good nick I would unravel the jumer so I could knit the yarn into something else. If not, then I would probably compost the jumper (although I currently still use and wear all of my woolens so this is hypothetical).
Compost at end of life
Plan to keep until it is worn out beyond saving. Then it will likely go in the compost or be used as weed matting
will never get rid of
Hopefully by the time this is worn out there will be textile recycling in NZ, but otherwise H&M textile recycling
I tend to keep things until they fall apart
Worm farm or compost
Re-knit it possible, down-cycle into pet beds, then H&M fabric recycling
This one has been accidentally shrunk! Will offer to charity first as otherwise in good condition and would be a shame to compost or use as beanbag stuffing which are my other options
i tend to wear the out/they are ruined and then put in rubbish or as garden matting/weed matting
Compost
Normally I wear my woollens until they are no longer suitable to give to charity - then I make them into dog rugs
Place in compost
I am thinking of unravelling this, as I like the colour, but don't love the sweater. Also for previous question - I lay flat out of sun to dry
Bury it
Possibly pull it down and use the yarn for another project
Re use the wool if not weak

I will never stop wearing it bc I am taking good care of it and it will last forever :)
pet bed
Unwind the wool and re-use to knit into something else
Either donate or upcycle (reuse the yarn) depending on the condition
Un ravel for yarn and knit or crochet into another item
clothing bin
Reuse the fabric for kids clothes
Compost bin
compost
Re knit it into something else
If it's too worn to be donated I'll compost it.
Reuse the yarn
100% wool garments will last and look great for years with careful laundering. Once they're absolutely worn out I deliberately felt them and use the deleted fabric to make bags/cushions/other soft furnishings or I shred and compost the fibre -it rots in a well kept compost heap.
Bury it to compost when it's full of holes and can no longer be worn by anyone
Around trees in the garden
Pull apart and reuse wool
Compost
Compost
Donate somewhere
Undo, and reuse the wool for another project
I would felt it and use it as a background to stitch on
Use it to make/pad a cat bed most likely or to line a cat carrier.
If possible unravel and reunite into another garment
Use it as an insulating layer in the worm bin
If it is worn out, use it as garden mulch, pet bedding.
Repurpose
Undo and reknit
Put in garden as weed mat
Put it in the Compost
Compost or burn
It will be with me for a quite a few years so I'm not sure
It is hand knitted so I would unpick it and use the wool again
I will wear it till it is beyond wear and then make cloths or compost it.
use it as a pet bed

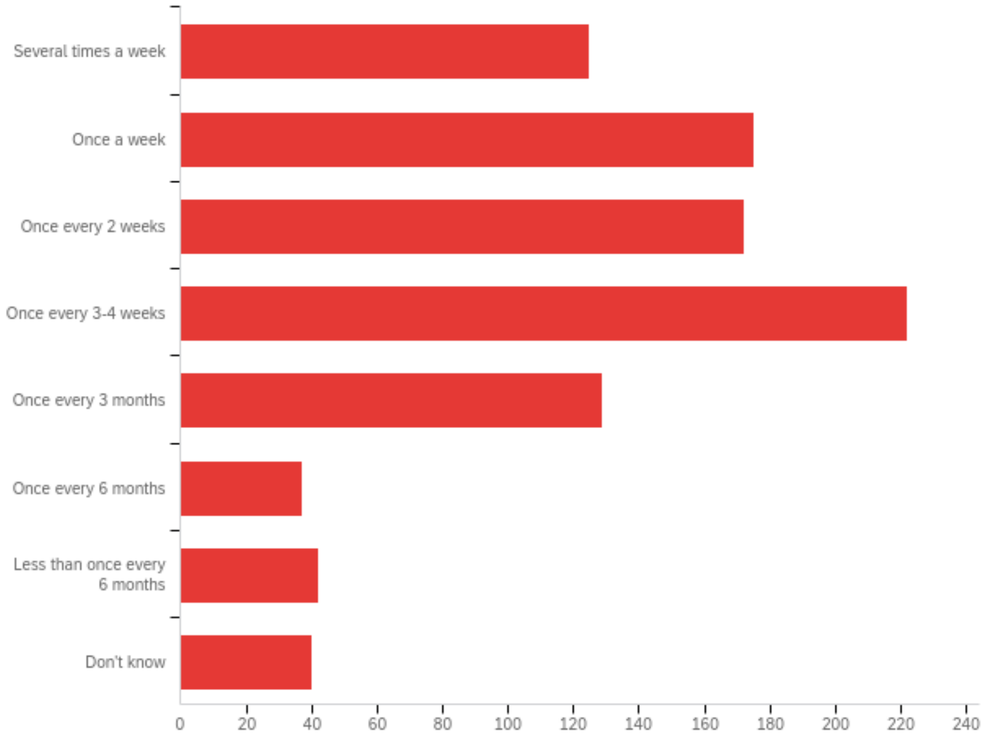
Q17 - Recall a specific synthetic blend jumper you currently own. Approximately when did you buy or acquire it? Note: Please answer the next set of questions based upon the same synthetic blend jumper.



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Recall a specific synthetic blend jumper you currently own. Approximately when did you buy or acquire it? Note: Please answer the next set of questions based upon the same synthetic blend jumper.	1.00	13.00	4.83	2.77	7.67	944

#	Answer	%	Count
1	In the last 6 months	11.97%	113
3	1 year ago	19.49%	184
4	2 years ago	22.67%	214
5	3-4 years ago	20.13%	190
7	5-10 years ago	14.72%	139
8	11-15 years ago	2.97%	28
9	16-20 years ago	1.69%	16
10	21-25 years ago	0.64%	6
11	26-30 years ago	0.42%	4
12	More than 30 years ago	0.32%	3
13	Don't know/ Cannot remember	4.98%	47
	Total	100%	944

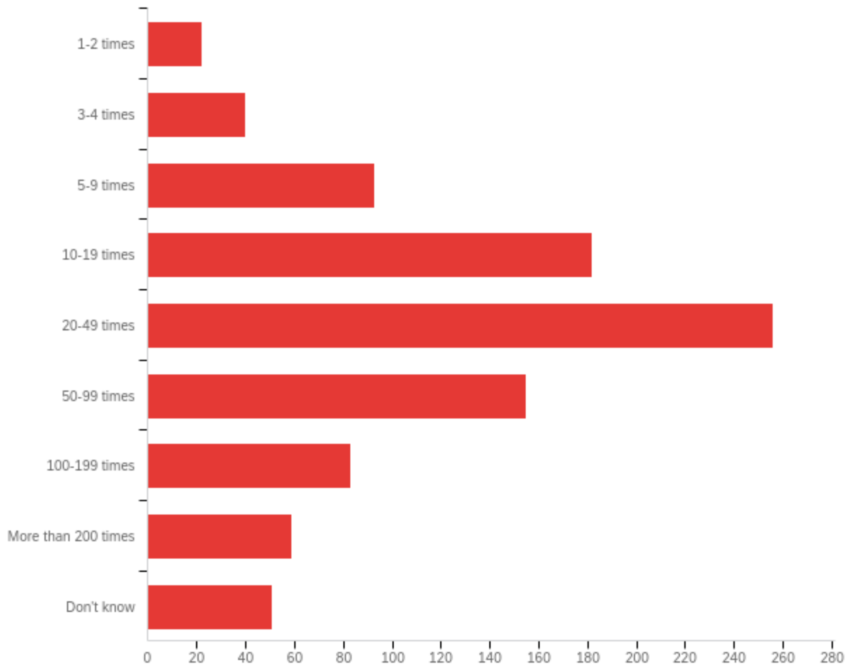
Q18 - How often do you typically wear this (synthetic blend) jumper / sweater / cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How often do you typically wear this (synthetic blend) jumper / sweater / cardigan?	1.00	8.00	3.57	1.82	3.31	942

#	Answer	%	Count
1	Several times a week	13.27%	125
2	Once a week	18.58%	175
3	Once every 2 weeks	18.26%	172
4	Once every 3-4 weeks	23.57%	222
5	Once every 3 months	13.69%	129
6	Once every 6 months	3.93%	37
7	Less than once every 6 months	4.46%	42
8	Don't know	4.25%	40
	Total	100%	942

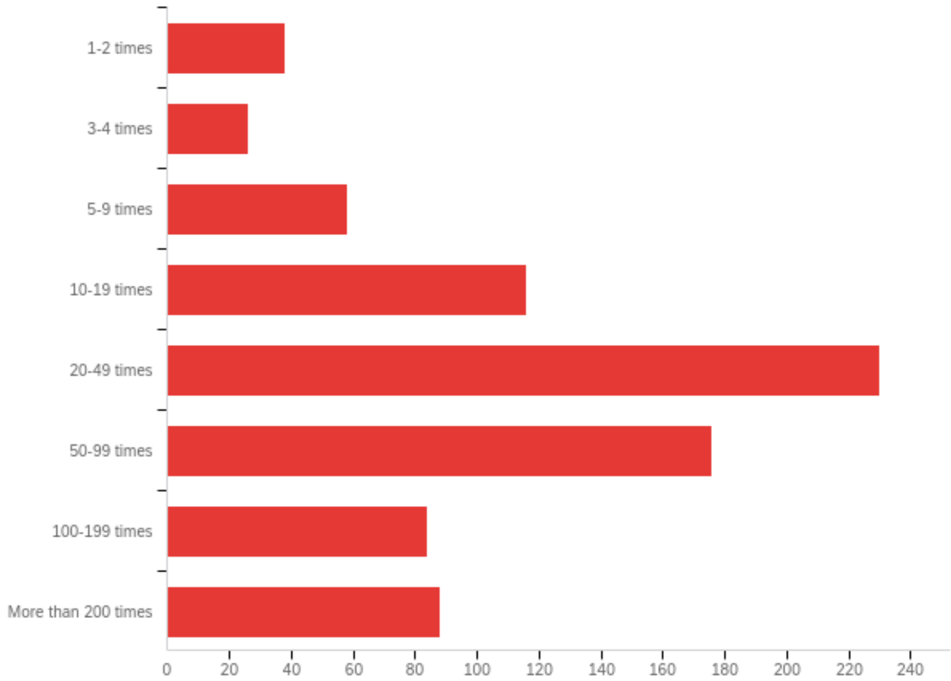
Q19 - Can you approximate the number of times to date you have worn this (synthetic blend) jumper? An approximate indication will work.



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Can you approximate the number of times to date you have worn this (synthetic blend) jumper? An approximate indication will work.	1.00	9.00	5.13	1.81	3.28	941

#	Answer	%	Count
1	1-2 times	2.34%	22
2	3-4 times	4.25%	40
3	5-9 times	9.88%	93
4	10-19 times	19.34%	182
5	20-49 times	27.21%	256
6	50-99 times	16.47%	155
7	100-199 times	8.82%	83
8	More than 200 times	6.27%	59
9	Don't know	5.42%	51
	Total	100%	941

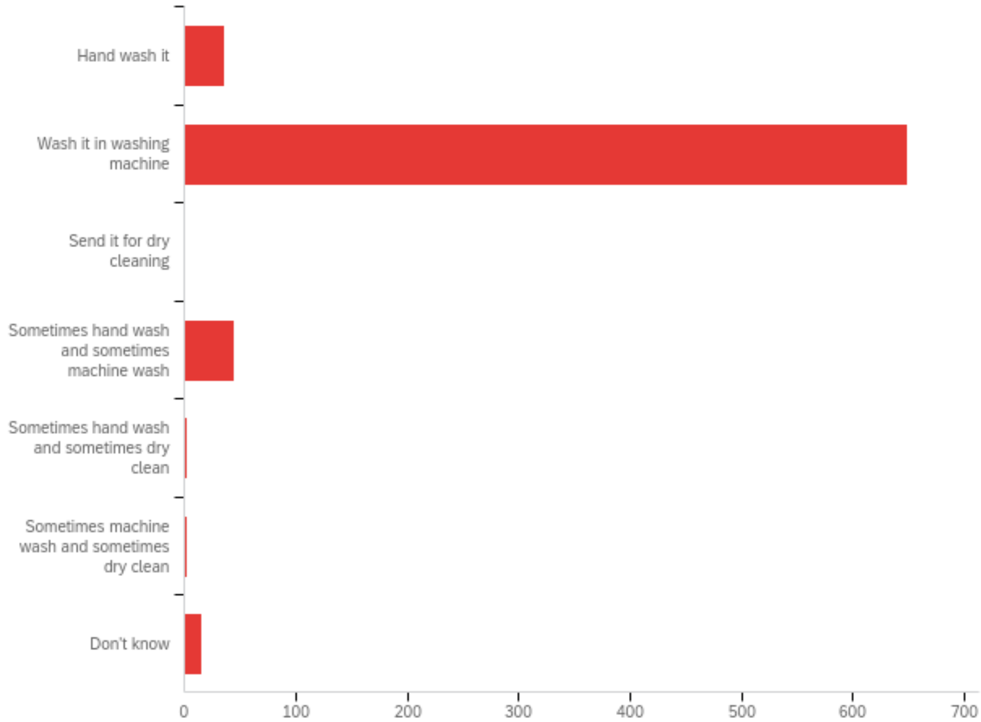
Q20 - Can you please inform the approximate number of times do you expect to wear this (synthetic blend) jumper in future?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Can you please inform the approximate number of times do you expect to wear this (synthetic blend) jumper in future?	1.00	9.00	5.29	1.93	3.73	816

#	Answer	%	Count
1	1-2 times	4.66%	38
2	3-4 times	3.19%	26
3	5-9 times	7.11%	58
4	10-19 times	14.22%	116
5	20-49 times	28.19%	230
6	50-99 times	21.57%	176
7	100-199 times	10.29%	84
9	More than 200 times	10.78%	88
	Total	100%	816

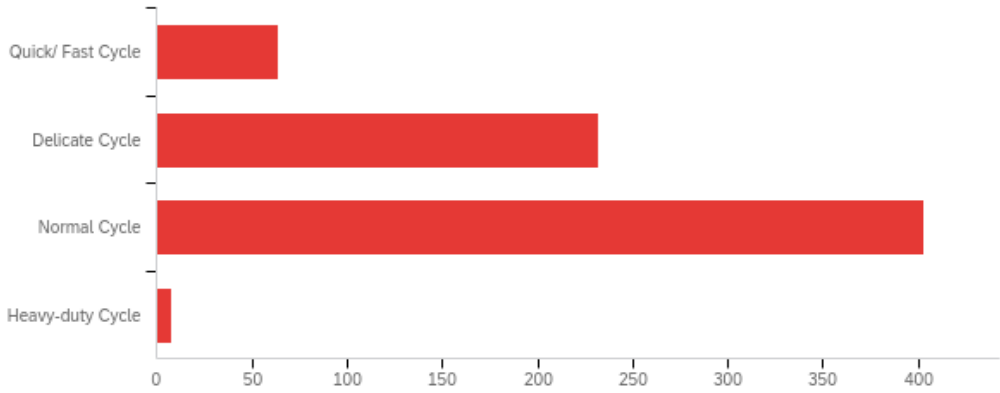
Q21 - How do you usually wash this (synthetic blend) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How do you usually wash this (synthetic blend) jumper/ sweater/ cardigan?	1.00	7.00	2.19	0.90	0.82	748

#	Answer	%	Count
1	Hand wash it	4.68%	35
2	Wash it in washing machine	86.76%	649
3	Send it for dry cleaning	0.13%	1
4	Sometimes hand wash and sometimes machine wash	5.88%	44
5	Sometimes hand wash and sometimes dry clean	0.27%	2
6	Sometimes machine wash and sometimes dry clean	0.27%	2
7	Don't know	2.01%	15
	Total	100%	748

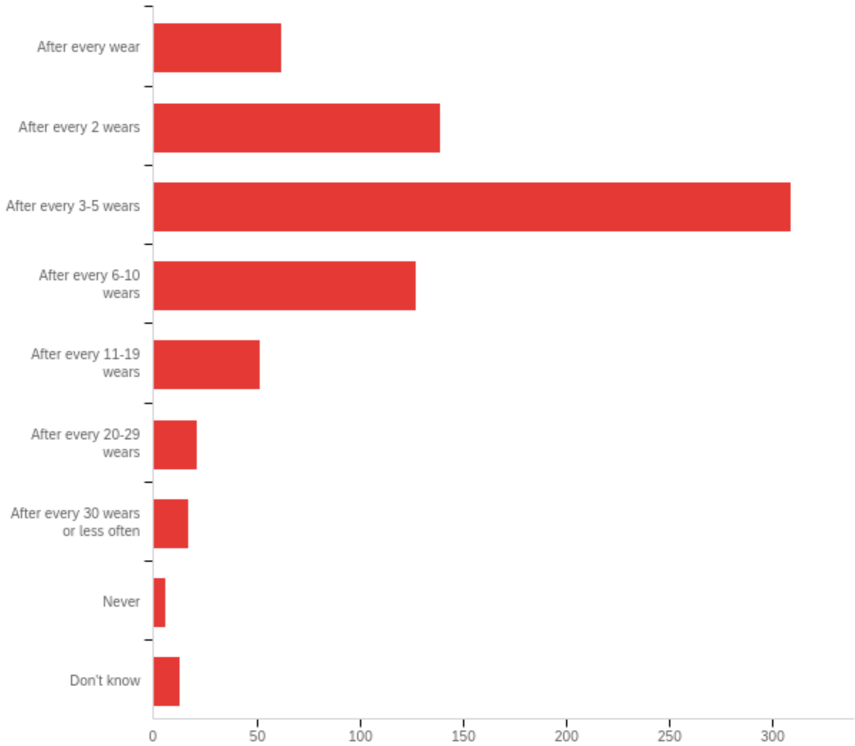
Q22 - Identify the washing machine settings you use for washing this (synthetic blend) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Identify the washing machine settings you use for washing this (synthetic blend) jumper/ sweater/ cardigan?	1.00	4.00	2.50	0.67	0.45	707

#	Answer	%	Count
1	Quick/ Fast Cycle	9.05%	64
2	Delicate Cycle	32.81%	232
3	Normal Cycle	57.00%	403
4	Heavy-duty Cycle	1.13%	8
	Total	100%	707

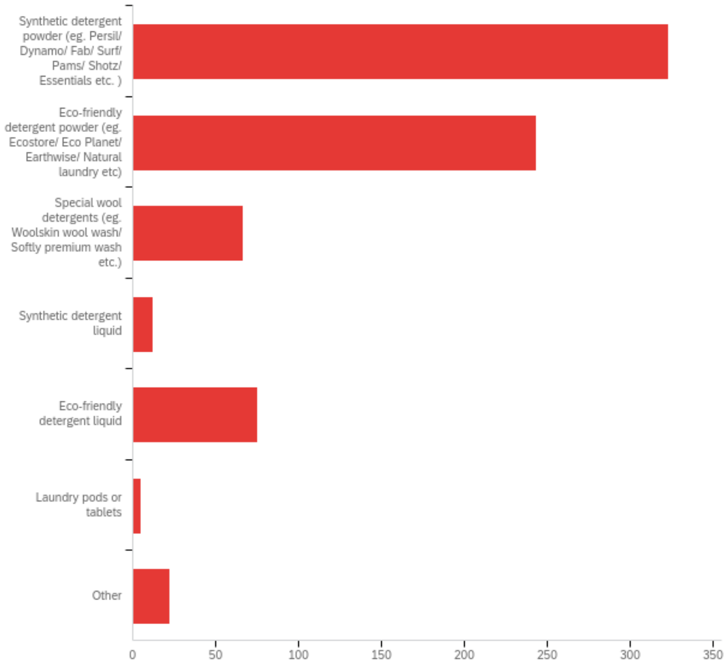
Q23 - When in use, how often do you or someone else typically wash this (synthetic blend) jumper?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	When in use, how often do you or someone else typically wash this (synthetic blend) jumper?	1.00	9.00	3.28	1.53	2.34	746

#	Answer	%	Count
1	After every wear	8.31%	62
2	After every 2 wears	18.63%	139
3	After every 3-5 wears	41.42%	309
4	After every 6-10 wears	17.02%	127
5	After every 11-19 wears	6.97%	52
6	After every 20-29 wears	2.82%	21
7	After every 30 wears or less often	2.28%	17
8	Never	0.80%	6
9	Don't know	1.74%	13
	Total	100%	746

Q24 - Which detergent would you normally use for washing this (synthetic blend) jumper?



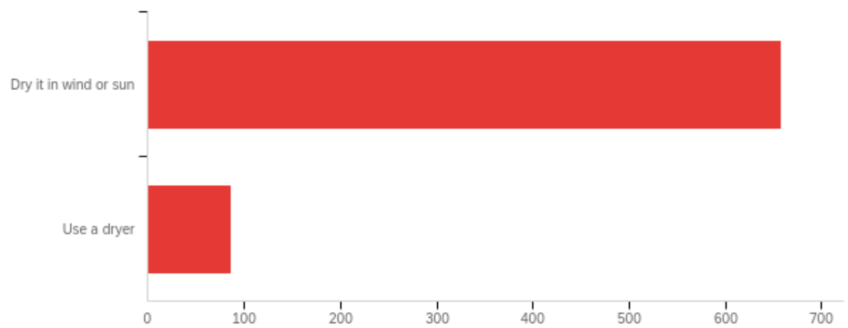
#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Which detergent would you normally use for washing this (synthetic blend) jumper? - Selected Choice	1.00	7.00	2.16	1.52	2.31	746

#	Answer	%	Count
1	Synthetic detergent powder (eg. Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)	43.30%	323
2	Eco-friendly detergent powder (eg. Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc)	32.57%	243
3	Special wool detergents (eg. Woolskin wool wash/ Softly premium wash etc.)	8.85%	66
4	Synthetic detergent liquid	1.61%	12
5	Eco-friendly detergent liquid	10.05%	75
6	Laundry pods or tablets	0.67%	5
7	Other	2.95%	22
	Total	100%	746

Q24_7_TEXT - Other

soap nuts
TruEarth laundry detergent eco-strips
dont wear synthetic
mixture of eco-friendly liquid and powder
Figgy and co
Own laundry liquid
Eco delicate / wool detergent
Hand grated soap and washing soda
The mix i described earlier
I make my own laundry liquid with Sunlight soap
Home made detergent
Modere washing powder

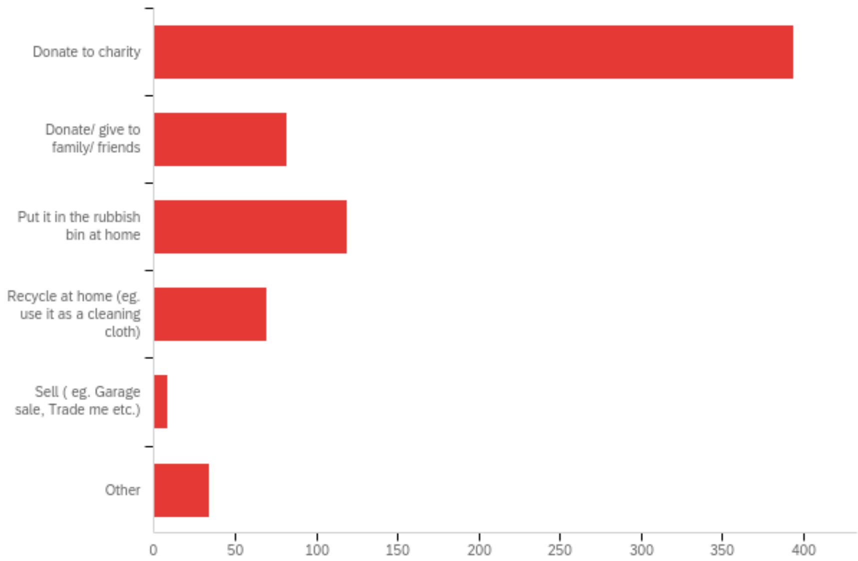
Q25 - How would you dry this (synthetic blend) jumper?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How would you dry this (synthetic blend) jumper?	1.00	2.00	1.12	0.32	0.10	744

#	Answer	%	Count
1	Dry it in wind or sun	88.44%	658
2	Use a dryer	11.56%	86
	Total	100%	744

Q26 - How would you dispose of this (synthetic blend) jumper /sweater/ cardigan when you no longer want it?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How would you dispose of this (synthetic blend) jumper /sweater/ cardigan when you no longer want it? - Selected Choice	1.00	7.00	2.08	1.55	2.42	706

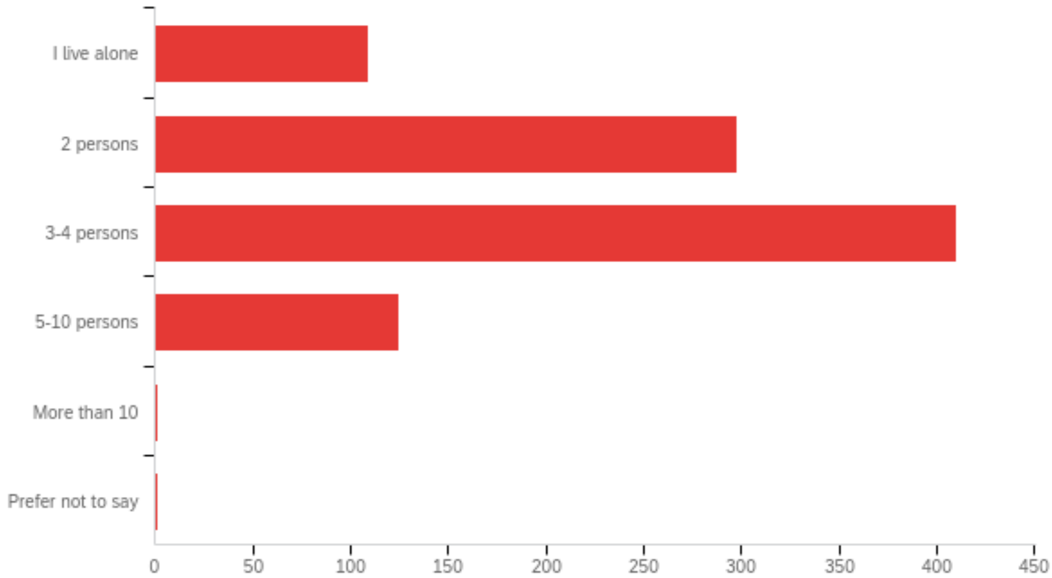
#	Answer	%	Count
1	Donate to charity	55.81%	394
2	Donate/ give to family/ friends	11.61%	82
3	Put it in the rubbish bin at home	16.86%	119
4	Recycle at home (eg. use it as a cleaning cloth)	9.77%	69
5	Sell (eg. Garage sale, Trade me etc.)	1.13%	8
7	Other	4.82%	34
	Total	100%	706

Q26_7_TEXT - Other

Compost
Offer to family or put it on a PIF community page
Use it as stuffing in sewn object (e.g. cushion or soft toy) Too scruffy to sell or donate
Upcycle it
I only dispose of clothing when they are not fit for wearing anymore
Again depends on its state of wear and if I still fit it. My last synthetic jumper got discoloured and burnt after being too close to a heat source.
Depends on condition.
If in good condition I would donate otherwise probably out in recycle rag bin

Dog Blanket
I don't own any synthetic jumpers
Use it till it's dead. Then trash
Recycle bin at home
Find some way of recycling. Have become very aware of the problem with synthetic garments & hope to avoid as much as possible in the future
Upcycle for sentimental reasons
clothing bin
Put it in a bag and think about creating a new item from it.
It depends on the state of it - if its still usable I would donate it and if not I would recycle at home
Depends on quality. If past it and not good enough to pass on the into the rubbish bin
Wool and wool blends, I put on a wool cycle if I have to put them in the washing machine.
Textile recycling (H&M) or best available at the time
Fabric recycling @ h&m or equivalent.
Don’t own one. But H&M fabric recycling
I usually wear my clothes until they can't be repaired any more so would look for a fabric recycle but haven't yet found a good option, so may put in rubbish
I do not own a synthetic jumper
This is my only piece of synthetic clothing, and it is a football hoody for the team I coach at school. I will probably keep it, and recycle it somehow into something else.
pet bed
This my gardening jumper so is well worn will probably use it in pet bed

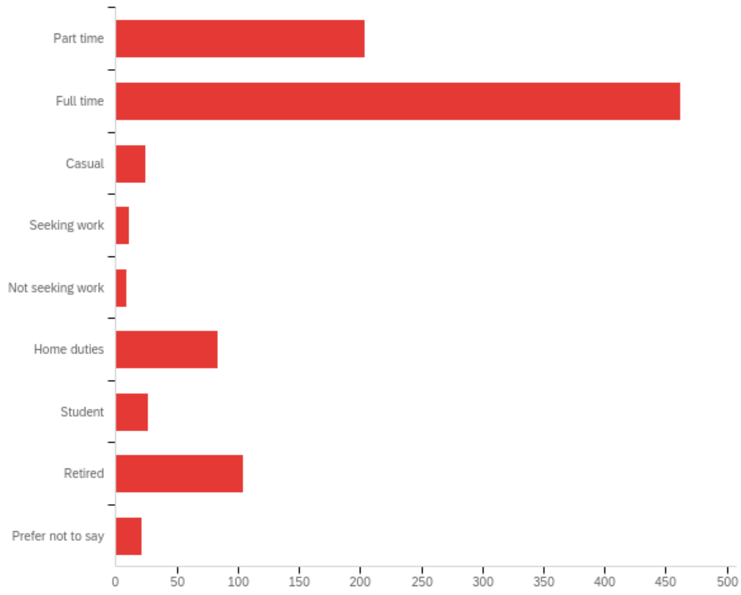
Q27 - How many people live in your household?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How many people live in your household?	1.00	9.00	2.60	0.90	0.81	944

#	Answer	%	Count
1	I live alone	11.55%	109
2	2 persons	31.57%	298
3	3-4 persons	43.43%	410
4	5-10 persons	13.24%	125
8	More than 10	0.11%	1
9	Prefer not to say	0.11%	1
	Total	100%	944

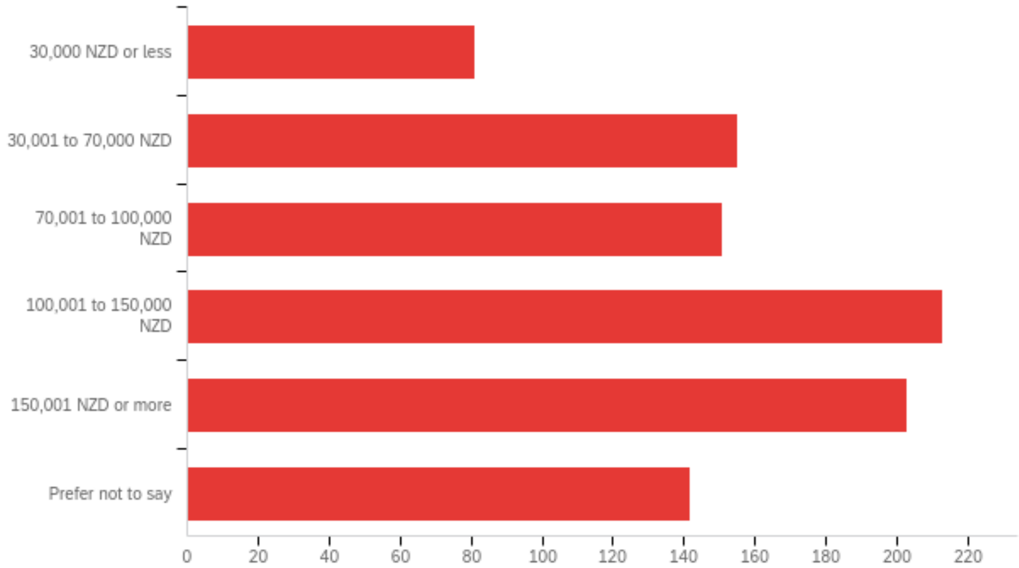
Q28 - What is your employment status?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	What is your employment status?	1.00	9.00	3.17	2.48	6.16	944

#	Answer	%	Count
1	Part time	21.61%	204
2	Full time	48.94%	462
3	Casual	2.54%	24
4	Seeking work	1.17%	11
5	Not seeking work	0.95%	9
6	Home duties	8.79%	83
7	Student	2.75%	26
8	Retired	11.02%	104
9	Prefer not to say	2.22%	21
	Total	100%	944

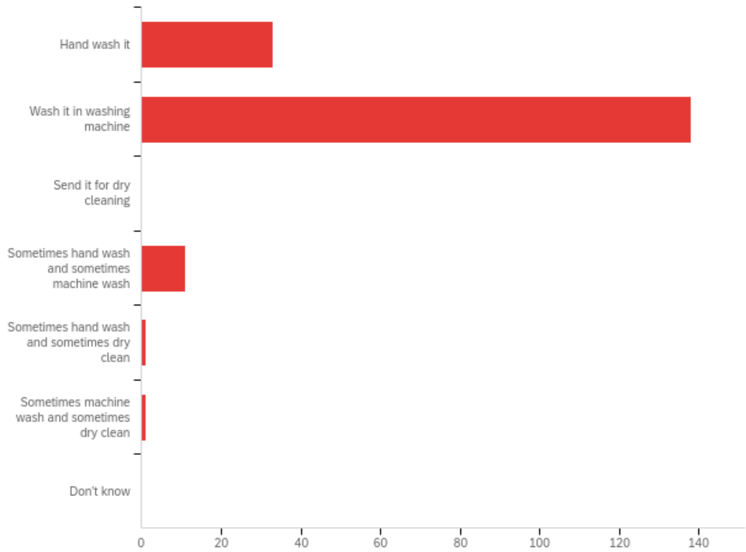
Q29 - Which of the following best describe your household's yearly income?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Which of the following best describe your household's yearly income?	1.00	6.00	3.77	1.53	2.35	945

#	Answer	%	Count
1	30,000 NZD or less	8.57%	81
2	30,001 to 70,000 NZD	16.40%	155
3	70,001 to 100,000 NZD	15.98%	151
4	100,001 to 150,000 NZD	22.54%	213
5	150,001 NZD or more	21.48%	203
6	Prefer not to say	15.03%	142
	Total	100%	945

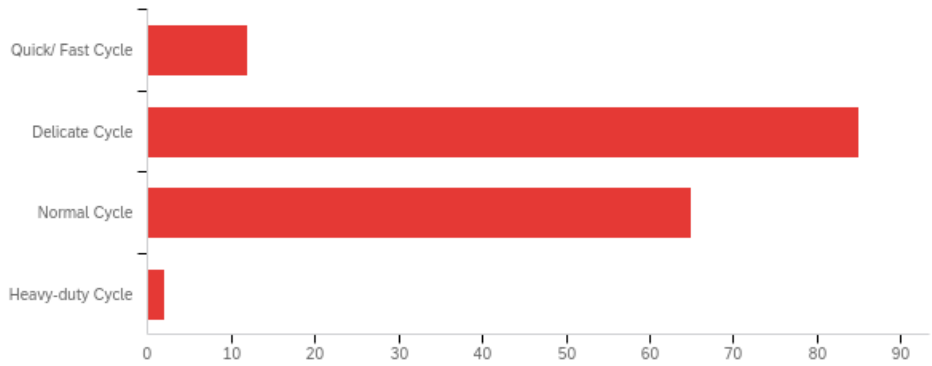
Q31 - How do you usually wash the (woollen or synthetic blend) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How do you usually wash the (woollen or synthetic blend) jumper/ sweater/ cardigan?	1.00	6.00	1.98	0.74	0.55	184

#	Answer	%	Count
1	Hand wash it	17.93%	33
2	Wash it in washing machine	75.00%	138
3	Send it for dry cleaning	0.00%	0
4	Sometimes hand wash and sometimes machine wash	5.98%	11
5	Sometimes hand wash and sometimes dry clean	0.54%	1
6	Sometimes machine wash and sometimes dry clean	0.54%	1
7	Don't know	0.00%	0
	Total	100%	184

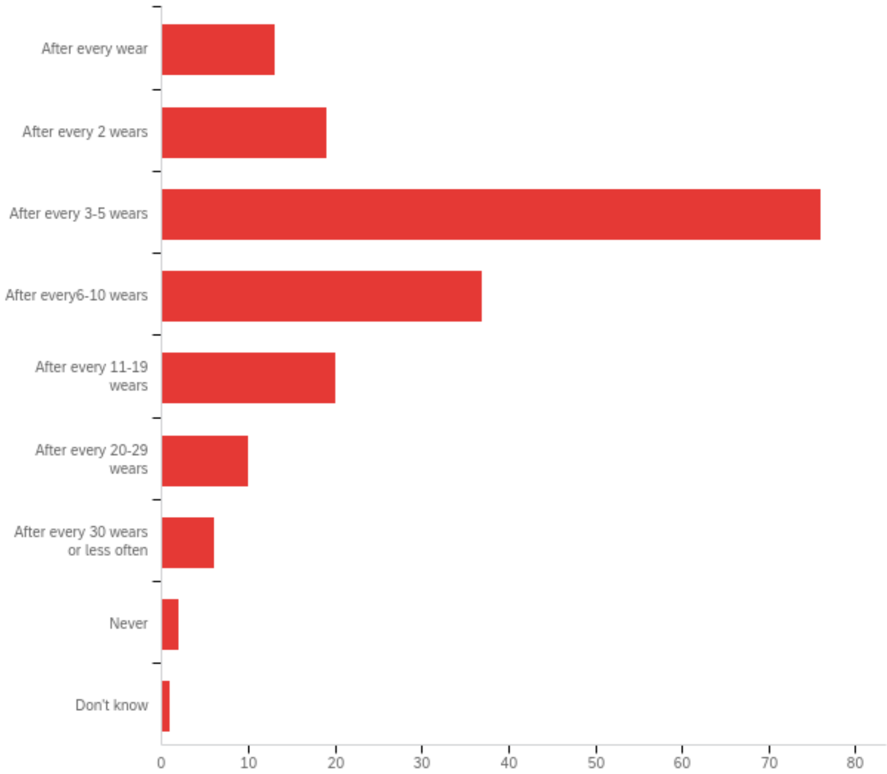
Q32 - Identify the washing machine settings you use for washing the (woollen or synthetic blend) jumper/ sweater/ cardigan?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Identify the washing machine settings you use for washing the (woollen or synthetic blend) jumper/ sweater/ cardigan?	1.00	4.00	2.35	0.63	0.40	164

#	Answer	%	Count
1	Quick/ Fast Cycle	7.32%	12
2	Delicate Cycle	51.83%	85
3	Normal Cycle	39.63%	65
4	Heavy-duty Cycle	1.22%	2
	Total	100%	164

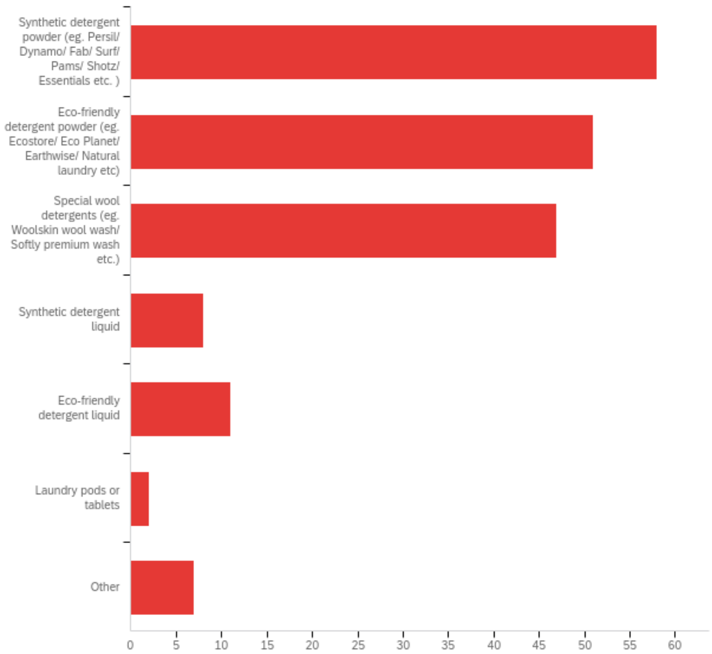
Q33 - When in use, how often do you or someone else typically wash the (woollen or synthetic blend) jumper?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	When in use, how often do you or someone else typically wash the (woollen or synthetic blend) jumper?	1.00	9.00	3.55	1.48	2.19	184

#	Answer	%	Count
1	After every wear	7.07%	13
2	After every 2 wears	10.33%	19
3	After every 3-5 wears	41.30%	76
4	After every6-10 wears	20.11%	37
5	After every 11-19 wears	10.87%	20
6	After every 20-29 wears	5.43%	10
7	After every 30 wears or less often	3.26%	6
8	Never	1.09%	2
9	Don't know	0.54%	1
	Total	100%	184

Q34 - Which detergent would you normally use for washing the (woollen or synthetic blend) jumper?



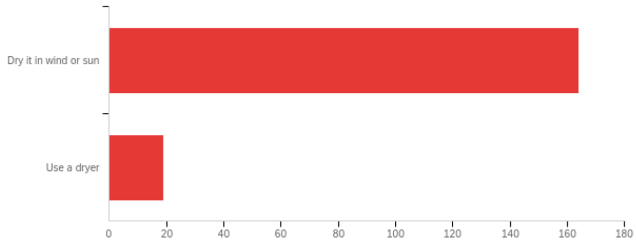
#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Which detergent would you normally use for washing the (woollen or synthetic blend) jumper? - Selected Choice	1.00	7.00	2.44	1.49	2.21	184

#	Answer	%	Count
1	Synthetic detergent powder (eg. Persil/ Dynamo/ Fab/ Surf/ Pams/ Shotz/ Essentials etc.)	31.52%	58
2	Eco-friendly detergent powder (eg. Ecostore/ Eco Planet/ Earthwise/ Natural laundry etc)	27.72%	51
3	Special wool detergents (eg. Woolskin wool wash/ Softly premium wash etc.)	25.54%	47
4	Synthetic detergent liquid	4.35%	8
5	Eco-friendly detergent liquid	5.98%	11
6	Laundry pods or tablets	1.09%	2
7	Other	3.80%	7
	Total	100%	184

Q34_7_TEXT - Other

Other - Text
Surf
Soap nuts- natural
Lux Flakes
Homemade (castille soap and washing soda)
Laundry balls, ionic cleaning

Q35 - How would you dry the (woollen or synthetic blend) jumper?



#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	How would you dry the (woollen or synthetic blend) jumper?	1.00	2.00	1.10	0.31	0.09	183

#	Answer	%	Count
1	Dry it in wind or sun	89.62%	164
2	Use a dryer	10.38%	19
	Total	100%	183

Q30 - Thank you for taking the time to respond to the questions above. This survey has come to an end but I have one more request. Can you tell me the brand and model number of your washing machine (or, if that's not possible, it's capacity in kilograms)?

The responses to this question have been intentionally omitted to avoid mentioning specific brand names.

Appendix H *Published Article on Apparel Use and End-of-Life in New Zealand for Journal Sustainability*

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Article

Examining Practices of Apparel Use and End of Life in New Zealand

Mitali Nautiyal, Amabel Hunting, Frances Joseph and Donna Cleveland

Topic Collection
Environmental Assessment, Life Cycle Analysis and Sustainability

Edited by
Dr. George Banias, Dr. Sotiris Patsios, Dr. Konstantinos N. Kontogiannopoulos and Dr. Kleoniki Pouikli

MDPI

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sustainability

MDPI

Article

Examining Practices of Apparel Use and End of Life in New Zealand

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Abstract: Throughout a garment's life cycle, the use and end-of-life phases are crucial in determining its environmental impact, due to the resources that would be utilised and waste produced during maintenance and disposal. Consumption patterns differ among countries and cultures; however, in New Zealand, there is limited published information to date. To address this gap, an anonymous online poll was conducted examining laundry practices, lifetime wear events and disposal practices for woollen and synthetic-blend knitted jumpers, which are predominantly used as winter clothing in New Zealand. The survey revealed considerable differences in the ways woollen and synthetic garments were worn, maintained and discarded. Over its lifetime, although woollen garments were worn a greater number of times, they were washed less. At the end of life, both types of jumpers showed significant reuse percentages. This information is useful for accurately modelling the inventory needed for assessing the environmental implication of apparel, using the life cycle assessment (LCA) methodology. By comparing New Zealand's washing and disposal practises to those of other countries, this study found significant differences, highlighting the need for country-specific data for future LCAs.

Keywords: apparel use; LCA modelling; laundry habits; New Zealand; wool; synthetic; sustainability; consumer behaviour

check for updates

Citation: Nautiyal, M.; Hunting, A.; Joseph, F.; Cleveland, D. Examining Practices of Apparel Use and End of Life in New Zealand. *Sustainability* **2023**, *15*, 5141. https://doi.org/10.3390/su15065141

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1. Introduction

The production and consumption of clothing and textiles have exponentially increased since the Industrial Revolution. Recently, the sector has been placed second to oil in regard to its detrimental impact on environmental sustainability [1]. The use and end-of-life phases of a garment's life cycle are critical, often with higher environmental impacts than those produced during the manufacturing processes [2]. Environmental systems are impacted by the excessive use of energy and water, as well as the release of toxic chemicals and harmful microfibres during laundering [3,4]. The use phase accounts for 50 to 80 per cent of the energy used in a garment's life cycle [5]. At the end of life, about 73 per cent of the textile fibres produced in 2015 (39 Gt) were landfilled [6]. When textile waste breaks down in open landfills and dumps, leachate and hazardous air pollutants such as methane and carbon dioxide gases are released into the environment [7,8]. Therefore, it is crucial to measure and formulate an inventory for the maintenance and disposal of clothing when considering sustainable development.

Internationally, researchers have examined the environmental profile of using and caring for clothing with varieties of fibre contents [9,10]. Electricity and water consumption during laundry [11], sustainable laundry technologies [12] and recommendations for improving resource efficiency in household laundry [13] have been studied to reduce impacts.

The garment lifespan is the other key factor that influences a garment's environmental footprint. Consumer surveys have identified factors such as gender, age and income as influencing clothing use [14]. Clothing use patterns in Germany, Poland, Sweden and the United States of America change depending on income [15]. Quantitative wardrobe surveys and qualitative laundry diaries conducted in China, Germany, Japan, the United Kingdom and the United States of America demonstrated that country-specific cultures dominate impacts associated with the use and end-of-life phases [16]. These factors influence the overall impact of materials and resources required and emissions to air, water and soil made across these stages of the garment's life cycle [17]. Thus, a variety of factors impact how a garment is consumed, with national and cultural behaviours having a high influence [18,19].

An in-depth analysis of the literature on the use and disposal practises of clothing revealed a paucity of studies in New Zealand [20]. The annual consumer spending on clothing and footwear in New Zealand was estimated to be about NZD 7 billion in 2021 [21], which is high given the country's small population of only 5 million [22]. Furthermore, it is acknowledged that New Zealand's textile waste recycling infrastructure is underdeveloped [23,24]. In this context, garment use and its consequences demand further consideration. Determining where the country is positioned in terms of apparel consumption is fundamental to supporting a sustainable future. The focus of this study is illustrated in Figure 1.

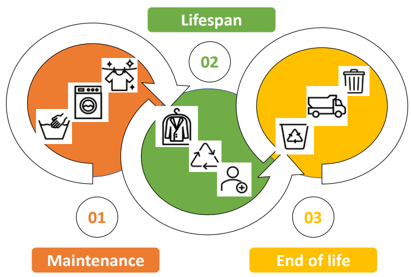

Figure 1. Focus of this study.

1.1. Selection of Material

New Zealand is the world's third-largest producer of wool [25]. Fine Merino wool fibre used in apparel production is produced in New Zealand and in the neighbouring Australian region [26]. A Consumer New Zealand research report, published 19 September 2019, identifies that cheap synthetic apparel predominates the country's retail market. New Zealand imports over 13,000 tonnes of synthetic textiles per annum [27], which is of concern, considering the negative environmental impact across its use and disposal [4,28]. In the use phase, synthetics show increased greenhouse gas emissions compared to natural materials [29] and also contribute to microfibre pollution in aquatic bodies [30]. About 87 per cent of the synthetic microfibre pollutants found on the beaches in Auckland, New Zealand's most populated city, come from clothing [31]. However, some higher environmental impacts are associated with the production of wool fibre [2,28]. Knitwear manufacturing is a modest industry in New Zealand. Knitted goods manufactured here are sold both at domestic and foreign markets. According to the World Integrated Trade Solution (2022), New Zealand's gross export of knitted items such as waistcoats, cardigans, pullovers and jerseys made of wool and fine animal hair was over USD 6.4 million in 2019. However, both wool and synthetic materials are used in winter clothing in New Zealand. Given New Zealand's reputation as an "outdoors playground" (N Z Govt, 2022) it is important for apparel companies and consumers to understand the environmental impacts associated with their use and disposal.

1.2. Life Cycle Assessment Method

Life cycle assessment (LCA) is widely recognised as a tool for estimating the environmental impact of products and services. Conducting an accurate LCA requires comprehensive, reliable data on the environmental performance of key inputs through extraction and processing of raw materials, manufacturing, distribution, use, reuse and/or maintenance and end of life [32]. There are four phases to any LCA: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. The LCI is the process of developing a thorough list of crucial inflows (resources) and outflows (emissions) from the product over its life cycle in relation to the functional unit studied [33]. When examining the effects of a product such as apparel that uses resources once during production but repeatedly during consumption, it is essential to model the inventory in accordance with its use. In a cradle-to-grave LCA of jeans and T-shirts, the consumption inventory was modelled based on country-specific consumer profiles in Germany, Poland, Sweden and the United States of America [19]. The study discovered major differences in clothing-related environmental consequences between nations. Thus, more extensive consumer behaviour data for each geographical region is needed for accurate LCA modelling [18].

The use of scientific techniques such as LCA to quantify the environmental implications of locally grown Merino wool garments compared with their global synthetic counterparts are critical in New Zealand in order to inform the choice of local designers and consumers. However, there is a substantial information gap due to the lack of inventory data on local use and end-of-life phases of clothing. This study investigates this issue through a consumer survey on apparel consumption patterns. The results provide New Zealand-specific data and insights. This paper reports on the survey findings and addresses the following questions:

1. Does the type of material a garment is composed of impact how it is washed and worn?
2. Do New Zealanders care for and discard garments differently from people in other countries?
3. How many times are woollen and synthetic jumpers laundered over their lifetimes, and what happens to them at the end of their useful life?

2. Methods

The study used a questionnaire for collecting data. An anonymous online consumer survey was carried out between December 2021 and January 2022. The survey was distributed among the currently popular social media platforms, such as Facebook, Linked In and Neighbourly and people were invited to participate. Social groups that seemed to be aware of the differences in textile material types were mainly approached. A confidence level of 95 per cent and a margin of error of ± 3 per cent were determined as variables. The formula employed to estimate the optimal sample size [34] was based on New Zealand's population of 5 million in the year 2020 [22].

$$\text{Necessary Sample Size} = \frac{(\text{Z score})^2 \times \text{Standard Deviation} \times (1 - \text{Standard Deviation})}{(\text{margin of error})^2}$$

where Z score for 95% = 1.96; Standard Deviation = 0.5; margin of error = 0.03.

$$\text{Necessary Sample Size} = \frac{(1.96)^2 \times 0.5 \times (1 - 0.5)}{(0.03)^2} = 1066.66 = 1067 \text{ respondents required}$$

The online poll received replies from 1094 New Zealanders, which was 27 more than the minimum requirement (with a margin of error of 0.03) for accurate results. All respondents were New Zealand residents, over the age of 18 and responsible for doing laundry. Participants were asked to respond if they had previously owned both woollen and synthetic knitted jumpers and thus were aware of their differences.

Thirty multiple-choice questions were included, however, some questions also contained text entry boxes for additional detail. The participants were asked to recall a woollen and a synthetic jumper, sweater or cardigan they had owned and provide information about how they were cleaned, how long they had been worn or would be worn in future and how they were to be disposed of. There were participants who laundered both wool and synthetic jumpers in the same manner. These respondents were put into a subgroup and were given access to a supplementary set of five questions on common laundry practices. Figure 2 depicts the survey flow in the form of a chart.

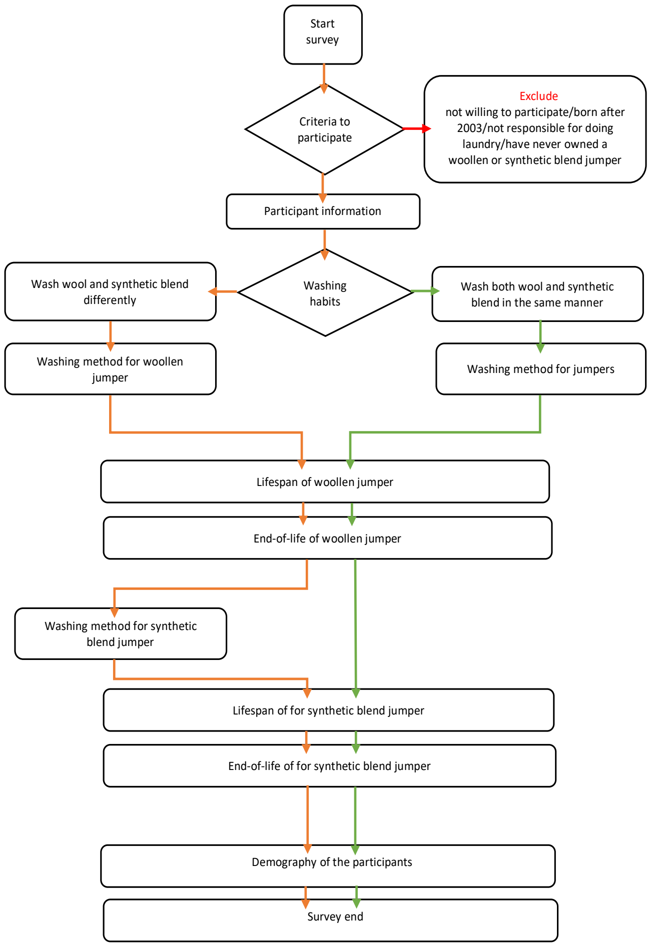

Figure 2. Survey flowchart.

The survey questions related to the woollen and synthetic-blend jumper and their relationship to the discussion of results in this paper are presented in Table 1. The survey data were mathematically analysed and divided into categories. The outcomes were then compared with available published material. Based on Wiedemann et al. (2020) [35], the study calculated the number of wears and washes per lifespan (including reuse) and end-of-life scenarios necessary to estimate the inventory requirement for an LCA.

Table 1. Survey questions on the two jumper types and their placement in this article.

No.	Questions on Woollen Jumpers	Questions on Synthetic Jumpers	Reference in Results Section
1	Have you owned a woollen or/and a wool blend synthetic jumper/sweater/cardigan before? ○ Yes ○ Probably yes, but not sure about the composition ○ No (I am sorry, but you are not part of the study's target group. Thank you for taking the time to participate)		
2	Do you follow the same or different washing method for both woollen and synthetic blend jumpers? ○ Yes, I wash both wool and synthetic jumpers the same way (this survey sub-group was given a separate questionnaire for questions 3 to 6 on washing habits) ○ No, I wash woollen jumpers different from how I wash synthetic blends ○ Can't say, I sometimes wash them the same way and sometimes separate ○ Don't know		
3	How do you usually wash this (woollen) jumper/sweater/cardigan? ○ Hand wash it ○ Wash it in washing machine ○ Send it for dry cleaning ○ Sometimes hand and sometimes machine wash ○ Sometimes hand wash and sometimes dry clean ○ Sometimes machine wash and sometimes dry clean ○ Don't know	How do you usually wash this (synthetic blend) jumper/sweater/cardigan? ○ Hand wash it ○ Wash it in washing machine ○ Send it for dry cleaning ○ Sometimes hand and sometimes machine wash ○ Sometimes hand wash and sometimes dry clean ○ Sometimes machine wash and sometimes dry clean ○ Don't know	Section 3.2.1 Washing methods.
4	Identify the washing machine settings you use for washing this (woollen) jumper/sweater/cardigan? ○ Quick/Fast Cycle ○ Delicate Cycle ○ Normal Cycle ○ Heavy-duty Cycle ○ Don't know	Identify the washing machine settings you use for washing this (synthetic blend) jumper/sweater/cardigan? ○ Quick/Fast Cycle ○ Delicate Cycle ○ Normal Cycle ○ Heavy-duty Cycle ○ Don't know	Section 3.2.3 Washing machine settings.
5	Which detergent would you normally use for washing this (woollen) jumper? ○ Synthetic detergent powder (e.g., Persil/Dynamo/Fab/Surf/Pams/Shotz/ Essentials etc.) ○ Eco-friendly detergent powder (e.g., Ecostore/Eco Planet/Earthwise/Natural laundry etc.) ○ Special wool detergents (e.g., Woolskin wool wash/Softly premium wash etc.) ○ Synthetic detergent liquid ○ Eco-friendly detergent liquid ○ Laundry pods or tablets ○ Other [Text entry option]	Which detergent would you normally use for washing this (synthetic blend) jumper? ○ Synthetic detergent powder (e.g., Persil/Dynamo/Fab/Surf/Pams/Shotz/ Essentials etc.) ○ Eco-friendly detergent powder (e.g., Ecostore/Eco Planet/Earthwise/ Natural laundry etc.) ○ Special wool detergents (e.g., Woolskin wool wash/Softly premium wash etc.) ○ Synthetic detergent liquid ○ Eco-friendly detergent liquid ○ Laundry pods or tablets ○ Other [Text entry option]	Section 3.2.4 Washing detergents.
6	How would you dry this (woollen) jumper? ○ Dry it in wind or sun ○ Use a dryer	How would you dry this (synthetic blend) jumper? ○ Dry it in wind or sun ○ Use a dryer	Section 3.2.5 Drying methods

Table 1. *Cont.*

No.	Questions on Woollen Jumpers	Questions on Synthetic Jumpers	Reference in Results Section
7	When in use, how often do you or someone else typically wash this (woollen) jumper? ○ After every wear ○ After every 2 wears ○ After every 3–5 wears ○ After every 6–10 wears ○ After every 11–19 wears ○ After every 20–29 wears ○ After every 30 wears or less often ○ Never ○ Don't know	When in use, how often do you or someone else typically wash this (synthetic blend) jumper? ○ After every wear ○ After every 2 wears ○ After every 3–5 wears ○ After every 6–10 wears ○ After every 11–19 wears ○ After every 20–29 wears ○ After every 30 wears or less often ○ Never ○ Don't know	Section 3.2.6 Laundry frequency/days per wear wash.
8	Can you approximate the number of times to date you have worn this (woollen) jumper? An approximate indication will work. ○ 1–2 times ○ 3–4 times ○ 5–9 times ○ 10–19 times ○ 20–49 times ○ 50–99 times ○ 100–199 times ○ More than 200 times ○ Don't know	Can you approximate the number of times to date you have worn this (synthetic blend) jumper? An approximate indication will work. ○ 1–2 times ○ 3–4 times ○ 5–9 times ○ 10–19 times ○ 20–49 times ○ 50–99 times ○ 100–199 times ○ More than 200 times ○ Don't know	Section 3.3.1 Lifetime wear events (based upon consumers' estimates).
9	Can you please inform the approximate number of times do you expect to wear this (woollen) jumper in future? ○ 1–2 times ○ 3–4 times ○ 5–9 times ○ 10–19 times ○ 20–49 times ○ 50–99 times ○ 100–199 times ○ More than 200 times ○ Don't know	Can you please inform the approximate number of times do you expect to wear this (synthetic blend) jumper in future? ○ 1–2 times ○ 3–4 times ○ 5–9 times ○ 10–19 times ○ 20–49 times ○ 50–99 times ○ 100–199 times ○ More than 200 times ○ Don't know	
10	How would you dispose of this (woollen) jumper/sweater/cardigan when you no longer want it? ○ Donate to charity ○ Donate/give to family/friends ○ Put it in the rubbish bin at home ○ Recycle at home (e.g., use it as a cleaning cloth) ○ Sell (e.g., Garage sale, Trade Me etc.) ○ Don't know ○ Other [Text entry option]	How would you dispose of this (woollen) jumper/sweater/cardigan when you no longer want it? ○ Donate to charity ○ Donate/give to family/friends ○ Put it in the rubbish bin at home ○ Recycle at home (e.g., use it as a cleaning cloth) ○ Sell (e.g., Garage sale, Trade Me etc.) ○ Don't know ○ Other [Text entry option]	Section 3.5 End-of-life practices.
11	Thank you for taking the time to respond to the questions above. This survey has come to an end but I have one more request. Can you tell me the brand and model number of your washing machine (or, if that is not possible, it's capacity in kilograms)? [Text entry option]		Section 3.2.2 Washing machine type

3. Results

Survey data on the use and end-of-life phases for woollen and synthetic knitted jumpers are presented in this section. The survey demographics are described in Section 3.1, followed by Section 3.2 on the differences in laundry practices for the two jumper types. These laundry practices are examined by focusing on washing methods, washing machine settings, washing detergents, drying methods and days per wear wash (Sections 3.2.1–3.2.5, respectively). In Section 3.3, the lifespans for the two jumper kinds are estimated, while their launderings per lifetime are evaluated in Section 3.4. The disposal practices of the two knitted jumpers are presented in Section 3.5.

3.1. Survey Demographics

The 1094 poll participants were all adults, responsible solely for laundry or sharing it with someone at home. Women made up a sizeable percentage of respondents (around 92 per cent). This is not representative of the country's population, which is 50 per cent male [22], but likely reflects gender norms that still involve more women than men doing laundry. According to a survey of New Zealanders' washing habits that was published in Waikato Times on 25 March 2013, women did more laundry than men.

3.1.1. Participant Information

Five age groups were identified. The largest group of responders was 41 to 56-year-olds, followed by the slightly younger 26- to 40-year-old age group. These demographics correspond with the median age of New Zealand, which was 37.4 years in 2018 [22]. Most participants were in the country's middle to upper-income brackets, but 16 per cent of those who took part in the study did not identify their annual income. The average household size of the poll was three to four persons. Figures 3 and 4 depict survey responses on the age and household size of participants.

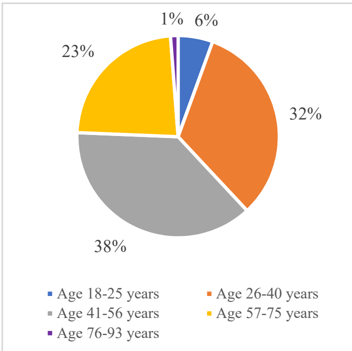

Figure 3. Age group of respondents.

3.1.2. Geographical Distribution

The survey had an acceptable geographic distribution that included both urban and rural homes (Figure 5). In New Zealand, 51.2 per cent of the population live in urban areas [36] and the poll exhibited a similar ratio, with 47 per cent of respondents living in the main centres of Auckland, 11 per cent in Canterbury and 9 per cent in Wellington, with the rest distributed across the country's provinces districts.

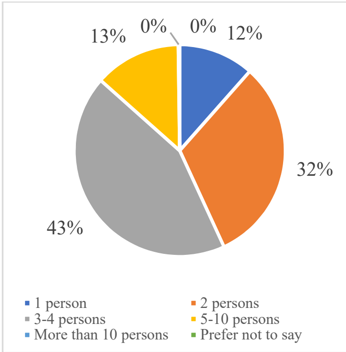

Figure 4. Household size of respondents.

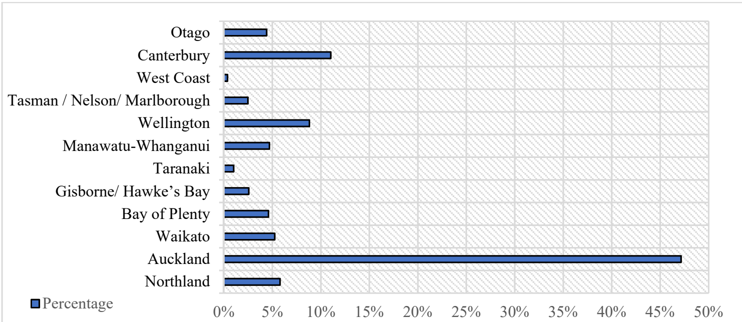

Figure 5. Geographical distribution of survey respondents.

3.2. Laundering Practices

In determining the environmental consequences of the use phase for apparel, it is essential to understand the methods employed for cleaning and the number of wears before each laundering. Both these characteristics fluctuate depending on a garment's material type and can also be influenced by the cultural or regional circumstances where it is used [20]. The following section considers the ways jumpers made of wool and synthetic material are laundered in New Zealand. Laundry comprises washing, drying and ironing. The survey included questions on washing methods, machine settings, machine types, washing detergents, drying practices and days per wear wash. Ironing data were not sought because typically it is not required for knitted jumpers.

3.2.1. Washing Methods

There are several ways to wash a garment and each method plays a role in determining the environmental impacts associated with the use phase. While machine washing is the most prevalent method used, hand washing is widely practised in the rural areas of many developing nations [37]. The usage of shared laundry facilities or laundromats is also common in many countries [18]. For woollen items, hand washing, airing, steaming or dry cleaning are considered appropriate to preserve their properties [20] but may have different environmental implications than cleaning by washing machine. Hand washing uses far less energy and emits fewer greenhouse gases than machine washing [38], positively affecting a garment's overall environmental profile. Participants were questioned about their typical washing routines for woollen and synthetic jumpers. Their responses are depicted in Figure 6.

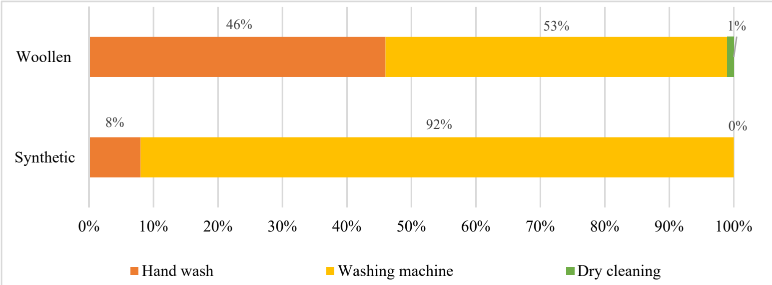

Figure 6. Washing methods in New Zealand.

Results showed washing behaviours for the two jumper types were distinctly different. About 46 per cent of New Zealanders washed woollens by hand, while 53 per cent used washing machines. In contrast, synthetics were machine washed by 92 per cent of respondents and the remaining 8 per cent were hand washed. Dry cleaning was not popular and only a few respondents dry-cleaned both jumper types. In the survey subgroup that laundered both types of jumpers in a similar fashion, 22 per cent hand washed and 78 per cent machine washed.

The findings on the washing methods for woollen jumpers in New Zealand do not align closely with international data. In Germany and the United Kingdom, 27 per cent of woollen sweaters are hand-washed, 63 per cent machine washed and 10 per cent dry-cleaned [35]. In Norway, 19 per cent of woollen garments are hand-washed and 70 per cent machine washed [20]. New Zealand's data for woollen jumpers was almost a 50/50 split between hand and machine washing, which is distinct from other international findings and would influence the LCI in modelling the use phase for apparel consumed in New Zealand. No global studies were identified to compare other countries' washing methods for synthetic jumpers to New Zealand's.

3.2.2. Washing Machine Type

Washing technologies are important factors in determining how a garment's life cycle is evaluated during the use phase. Distinct types of washing machines are utilised in different countries. Horizontal drum or front-loading machines, for example, are more frequent in Europe than vertical drum or top-loading machines, which are more common in the U.S.A., Australia and Asia [20]. Resource utilisation differs greatly between the front and top-loading washing machines, with horizontal drum front-load washing machines using far less water than vertical [20]. The energy intake of these devices varies as well, however, this is more dependent on the machine's age. Having better data on washing machine types in New Zealand would help estimate energy and water consumption. Survey respondents were asked to specify the type and load capacity of machines employed at home. Both top and front-load washing machines with capacities ranging from 5 to 10 kg were observed used in New Zealand, however, a front-loading machine with a load capacity of around 8.5 kg was the most popular.

3.2.3. Washing Machine Settings

In machine washing, the setting selected to launder is critical as it determines the energy and water consumed. Washing machines are available with various programmes such as heavy, normal, delicate or quick wash. A wool wash setting may not always be available on washing machines [20]; thus, a delicate wash programme was chosen for this study. Participants were asked to list the washing machine settings that they employ for cleaning woollen and synthetic jumpers. Figure 7 presents their responses.

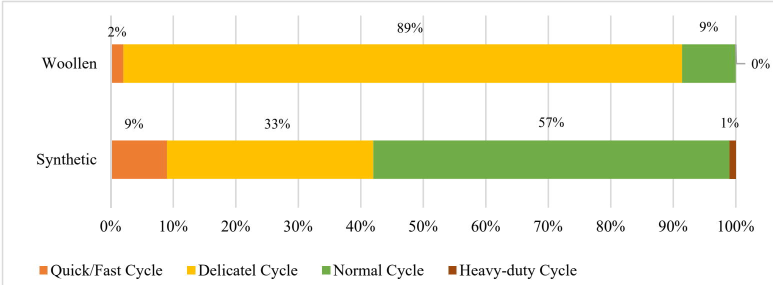

Figure 7. Frequency of washing machine settings in New Zealand.

A delicate wash programme was most preferred for woollens, chosen by 89 per cent of New Zealanders. For synthetics, 57 per cent chose a normal wash, while 33 per cent chose a delicate cycle. The subgroup who washed both materials, in the same manner, preferred a delicate setting (52 per cent), followed by a normal wash cycle (40 per cent), quick wash (7 per cent) and heavy-duty wash (1 per cent).

There is a scarcity of international data on the utilisation of various washing programmes based on material types. However, some studies have indicated that most people do not alter wash cycles to match laundry material [39]. Different washing settings impact the use phase inventory. A 4 kg load delicate wash cycle in a typical 8.5 kg capacity front-load washing machine uses 0.29 kWh of energy and 63 litres of water, compared to 0.93 kWh and 53 litres for a 4 kg load in a normal wash cycle [40].

3.2.4. Washing Detergents

The type of laundry detergent employed to clean clothes also has a sizeable environmental cost in the use phase. Detergents can require additional energy to dissolve in hot water and are made of chemical surfactants releasing toxins into the environment [41]. Detergents are made of different ingredients to suit different material types and can cause pollution in water bodies when drained out [20]. The survey sought to find out the detergents used in New Zealand and understand the differences in detergent use in washing woollen and synthetic clothing. Participants were asked to identify their preferred detergents for washing the two materials. Their responses to the detergents used are depicted in Figure 8.

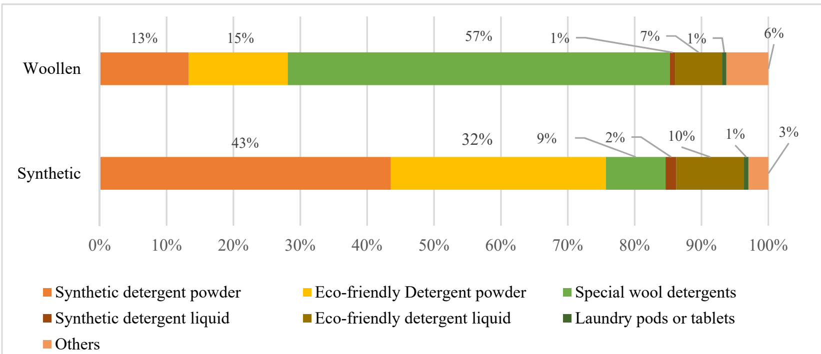

Figure 8. Detergents used in New Zealand.

In New Zealand, wool and synthetic sweaters were laundered with a variety of detergents. Most woollen sweaters were washed with wool-specific detergents (57 per cent) that mainly contain lanolin to preserve the properties of wool [20]. Synthetic jumpers in New Zealand were washed with either chemical-intensive synthetic powder detergents (43 per cent), or milder eco-friendly detergent powder (32 per cent). Other kinds of detergents were applied for both material types but the response percentages were small. The survey group that cleaned both wool and synthetic materials the same way employed synthetic detergent powders (32 per cent) followed by eco-friendly detergent powders (28 per cent), special wool detergent powders (25 per cent) and others in small quantities.

3.2.5. Drying Methods

The method of drying clothing is another factor that impacts the environment during the use phase. Line or air drying is widely regarded as the most environmentally efficient method of drying clothes, as it does not rely on artificial energy sources. Tumble drying is said to consume four times as much energy as washing clothes in a washing machine at 40 degrees Celsius, consuming the most energy during the laundering process [42]. Drying methods differ depending on a country's environment, economy and culture, as well as the type of garment or its fibre type [37]. Knowing the drying method and variances for woollen and synthetic clothing is vital for LCA. We asked the participants how they dried their woollen and synthetic sweaters.

Most participants preferred natural air drying for both woollen and synthetic jumpers, with 99 per cent of woollen and 88 per cent of synthetic jumpers dried in the air, while the rest employed a tumble dryer. The survey subgroup washing both in the same way similarly utilised air drying (90 per cent), while the rest used tumble drying.

These results are in line with most available data on the global use of tumble dryers. However, no studies were found on drying practices for specific fibre types. Sparse use of dryers was reported in Europe and Asia (12 per cent in the U.K. and Germany, 4 per cent in Italy and 3 per cent each in China and Japan), with a very high percentage in the United States of America employing tumble drying for 73 per cent of wet laundry [18]. Both wool and synthetic jumpers were primarily dried naturally in New Zealand without the use of energy-driven dryers, resulting in significant energy input savings for the use phase.

3.2.6. Laundry Frequency/Days per Wear Wash

Laundry frequency/days per wear wash is the number of days a person wears a garment before washing it. Many factors impact it. Base layers such as underwear and socks are washed more frequently than outerwear garments such as jackets and sweaters [20]. Clothing made of synthetic materials such as polyester accumulates odour faster than natural fibres such as cotton and thus requires more cleaning [43]. Even within the same garment type, days per wear wash varies by country or culture. Before each washing, a T-shirt was worn for 2.4 days in China, 1.6 days in the United States, 1.9 days in the United Kingdom, 1.8 days in Japan, 2.0 days in Italy and 1.9 days in Germany [18]. Thus, days per wear wash is an important parameter in calculating an item of clothing's cradle-to-grave environmental impact. It suggests the inventory that goes into cleaning over its lifetime. Participants were asked to recollect a woollen and a synthetic-blend sweater that they owned and answer how often they or someone else washed it. The results are depicted in Figure 9.

Woollen jumpers were found to be worn twice as long as synthetic ones before being washed. On average, a woollen jumper was worn 11.5 times and a synthetic jumper was worn 6.4 times before washing. This is crucial to take into account when creating the inventory for the two jumpers as it will influence the quantity of input materials and output emissions related to laundry.

The days per wear wash for woollen jumpers in New Zealand was slightly higher than the global average, with 6 to 10 wear events before washing [20]. In another survey in Germany and the United Kingdom, 5.2 wear events before wash were estimated for woollen sweaters [35]. Furthermore, 8.9 days of wear in Norway and 10.3 days of wear in the Netherlands were identified [37]. There is a lack of published studies comparing days per wear wash for woollen and synthetic garments.

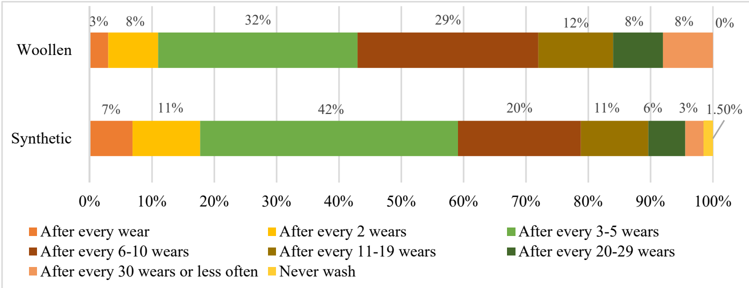

Figure 9. Laundry frequency in New Zealand.

3.3. Lifespan

The lifespan of a garment has a significant impact on its environmental footprint. The longer a garment is worn, the lower its environmental impact. The primary environmental benefits of extended product lifespans are realised through a decrease in the overall number of clothing items needed, i.e., the user does not need to purchase a new sweater. Moreover, the effects of garment manufacture are spread over a larger number of uses [44]. However, identifying a garment's lifespan is a difficult undertaking, as clothing does not have a date of production or expiration. A multitude of measures can be used to determine how long a garment might last, including counting the years of use, number of wears, number of users, or the number of wash cycles it has gone through [17]. Estimating the number of wear events has been cited as the most efficient way of calculating a garment's lifespan [35]. Our study calculated the lifespan of woollen and synthetic jumpers based on the number of wear days they received over their lifetime. Given that a substantial percentage of clothing was donated or sold for reuse, the number of wear events through reuse was also estimated.

3.3.1. Lifetime Wear Events (Based upon Consumers' Estimates)

A lifetime wear event is the number of times the first user, along with subsequent users, wears a garment from the time it is bought until it reaches its end of life [17]. Participants were asked to recall a specific woollen and synthetic-blend jumper they owned and respond with approximately how many times they had worn it in the past and the number of times they expected to wear it in future. The number of times each category was answered ranged from one or two times to over two hundred times. To calculate lifetime wear, mean values for each wear category were coded [35].

Past and future wear events for woollen jumpers were higher than that for synthetic jumpers. Woollen sweaters were worn on average 71 times while synthetics were worn 61 times. For future use, 110 wear times for wool and 74 times for synthetic were estimated. Integrating the past and future wear values, the lifetime number of wear events for a woollen jumper was 181, whereas, for a synthetic jumper, the number of wear events was 135. The wear events for a woollen jumper in New Zealand were almost double the 79 wear events indicated for Germany and the United Kingdom [35]. No comparative international data were found on wear events for synthetic jumpers.

3.3.2. Subsequent Use

According to the end-of-life findings (see Section 3.5), a good proportion of clothing in New Zealand is considered for reuse. A considerable percentage of the poll participants supported donating used jumpers either to charity, family and friends, or reselling them. Reuse was forecast for 83 per cent of woollen jumpers and 72 per cent of synthetic jumpers. However, not all clothing designated for reuse gets acquired by a subsequent user [17], with approximately 25 per cent left unused [45]. Hence, the survey's reuse rates were adjusted using these proportions. The lifetime wear events for the two jumpers were calculated with L1 being the first life of clothing and $L2_s$ [35]. The adjusted reuse rate for the woollen jumper (RW) was 62 per cent and for the synthetic (RS) was 54 per cent. The formula applied to identify the lifetime use (U) for both jumper types was

	$U =$	$L1 + (L2 \times R)$
Total use of woollen jumper	$U_W =$	$L1_W + (L2_W \times R_W)$ $181 + (90.5 \times 0.62) = 237$
Total use of synthetic-blend jumper	$U_S =$	$L1_S + (L2_S \times R_S)$ $135 + (67.5 \times 0.54) = 171$

During their lifetime, including reuse, the woollen jumpers were estimated to be worn 237 times and synthetic 171 times. The total lifetime wear for both jumpers along with past, future and reuse events is shown in Figure 10. This statistic was greater than the total number of wear events estimated for woollen jumpers in Germany and the United Kingdom (109 wear events with a reuse rate of 76 per cent) [35].

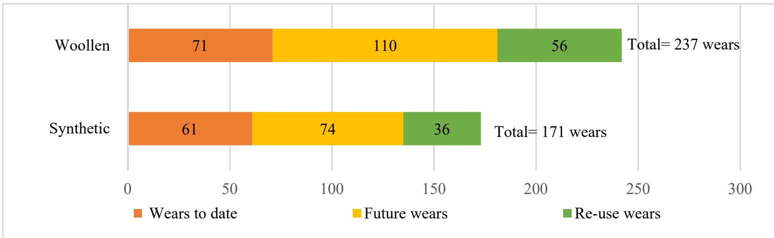

Figure 10. Lifetime wear events in New Zealand.

3.4. Laundering per Lifetime

The laundering per lifetime for both jumpers was estimated through their total lifetime wear events and days per wear wash. Woollen jumpers were estimated to be washed 21 times and synthetic 27 times during the entire course of their lives, including reuse. It was interesting to note that although woollen jumpers were worn more times during their lifetime, they were washed less. It is crucial to take this into account when creating the LCI inventory for the two jumpers as it will influence the quantity of input materials and output emissions related to the use phase.

3.5. End-of-Life Practices

Users discard clothing when it reaches the end of its useful life, resulting in a massive amount of wasted material [44]. Thus, the methods involved in the disposal of apparel play an important role in modelling the cradle-to-grave environmental impact. A global study from Germany, Sweden, Poland and the United States reported that 14 per cent of clothing sold is deposited in landfills every year [46]. The final destination of a garment is largely determined by the consumer and the facilities available to them [18]. The current survey attempted to identify what New Zealanders do with their jumpers when they no longer had use for them. Participants were asked how they preferred to dispose of their woollen and synthetic jumpers when they no longer desired them. Their response percentages are presented in Figure 11.

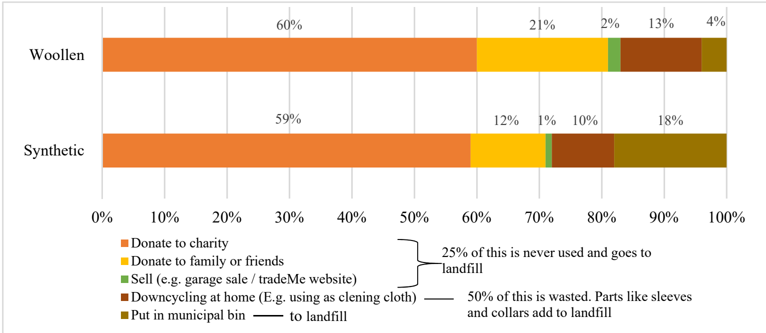

Figure 11. Disposal methods in New Zealand.

In New Zealand, charitable contributions were the most typical destination for both garments. A total of 83 per cent of wool and 72 per cent of synthetic jumpers were donated either to charity, family, friends or resold. This reuse rate for woollen clothing was a little above the rate stated for Germany and the United Kingdom, where 76 per cent of consumers donated or sold garments for reuse [35]. Removing 25 per cent from reuse, as garments that would never be worn [45], a new reuse rate was formulated, which was 62 per cent for woollen and 54 per cent for synthetic-blend jumpers (discussed previously in Section 3.3.2). According to the survey, 13 per cent of woollen and 10 per cent of synthetic jumpers were downcycled at home (mainly used as a cleaning cloth). However, not all of the jumper is downcycled; many of its parts, such as the neck and sleeves, would be cut off before use. So, for this study, 50 per cent of the downcycled jumper was anticipated to be thrown into municipal trash disposal. As a result, a new percentage breakdown for the end-of-life scenario was produced, differing from Figure 11 and presented in Table 2.

Table 2. End-of-life (EOL) scenarios for woollen and synthetic-blend jumpers.

Survey Response	Woollen Jumper (N = 727)		Synthetic-Blend Jumper (N = 706)	
		Adjusted Percentage		Adjusted Percentage
Donate to charity	83%	62% reused	72%	54% reused
Donate to family or friends				
Sell (e.g., Garage sale/Trade Me website)				
Dispose in municipal bin	4%	35.5% landfilled	18%	41% landfilled
Downcycling at home (e.g., using it as a cleaning cloth)	13%	6.5% downcycled	10%	5% downcycled

Responses have been adjusted to split between reuse, landfill and downcycling.

As the survey also provided a text entry option for respondents to explain their decisions on disposal, some participants communicated they would never want to part with their woollen jumpers because they last forever. A few participants specified passing on their woollen jumpers to their children or grandchildren or unravelling them to re-knit something new. A few respondents also talked about composting woollen jumpers. Regarding synthetic jumpers, some participants commented on re-knitting them or returning them to retailers from where they had been purchased, specifically mentioning H&M's stance on material recycling [47].

When looking at international data on disposal to municipal bins for woollen apparel, a 71 per cent disposal rate was observed in Germany and the U.K. [35], which was considerably higher than New Zealand's 35.5 per cent. European countries have well-developed fibre recycling facilities [48]. Present systems for recycling textiles from municipal waste or specific textile recycling systems are limited in New Zealand [23,24]; hence this option was not included in the poll.

The overall environmental performance of apparel in New Zealand is significantly impacted by the inventory modelled for the end-of-life phases for the two knitted jumpers. Compared to synthetic clothing, wool exhibits a lower disposal-to-landfill ratio. Wool is completely biodegradable [49]. However, microplastic fibres released from the degradation of synthetic textiles have been identified as creating noxious gases and leachate causing environmental pollution [50]. Thus, the environmental benefits of reusing and downcycling along with the differences in the landfilling scenario for woollen and synthetic jumpers will impact their overall life cycle performance. The LCA process heavily relies on the accuracy of this data and its modelling to assess the environmental impacts of the apparel over its lifespan. Table 3 summarises the key survey results comparing the consumption practices for woollen and synthetic-blend jumpers.

Table 3. Consumption practices for woollen and synthetic-blend jumpers.

Results	Woollen Jumper	Synthetic-Blend Jumper
Washing methods	Both hand and machine washing are practised equally	Washed primarily using a machine
Washing machine settings	A delicate wash cycle is used. However, there is uncertainty regarding the load size as it is possible that woollens are washed with only half of the machine's capacity [20]	A normal wash cycle is used
Washing detergents	Mainly by detergents made specifically for wool that contain lanolin	Almost equally by chemical-based and eco-friendly detergent powders
Drying methods	Both primarily dried naturally	
Days per wear wash	Worn more often before each wash. 11.5 times before washing.	Worn less often before each wash. 5.2 times before washing.
Estimated lifespan	237 wears in total, including reuse	171 wears in total, including reuse
Reuse rate	62 per cent	54 per cent
Downcycling rate	6.5 per cent	5 per cent
Landfilling rate	35.5 per cent	41 per cent

4. Discussion

Consumer use and end-of-life practices substantially impact the cradle-to-grave life cycle of clothing and thus should be appropriately accounted for while conducting an LCA [2,19]. These practices vary considerably between countries, garment types [18] and materials [37]. There is, however, a dearth of consumer data for estimating inventory for LCA of apparel products in New Zealand. This study addresses this gap by collecting the necessary data and, in the process, identifies several interesting facts and specific practices related to garment wear and care in New Zealand.

4.1. Critical to Account for the Use and End-of-Life Phases

The impact of clothing consumption on an LCA is not well understood among academics [19]. In order to assess the environmental impacts of knitted jumpers, this research gathered an inventory of their use and end-of-life phases. An extensive consumer survey provided detailed insights into how New Zealanders wear and care about their winter clothing. Jumpers constructed of two different materials, wool and synthetic, showed varying washing procedures, lifespans and disposal patterns, which alter the resource flow related to inputs (energy, water and chemicals) and outputs (emissions and waste, aside from the final product) in an LCA. Furthermore, compared to other countries, this study found substantial disparities in New Zealanders' consumption habits for clothing. The study affirms that using generalised worldwide data or making assumptions about consumer behaviour patterns regarding usage and disposal practices will not produce valid localised LCA results.

4.2. Various Wash and Wear Approaches for Different Materials

The environmental impacts of garments made using different fibre types vary as they are maintained differently [37]. Laundering requires various resources, including energy for washers and dryers, water for cleaning, chemical-based laundry detergents and waste disposal. Synthetic clothing is cleaned more frequently [43], utilising more resources, releasing microfibre waste into water bodies [50] and thus, having a greater negative environmental impact. Therefore, it is crucial to recognise the differences in days per wear wash of clothing made of various material types when evaluating the life cycle.

The material also impacts the garment's lifespan. The environmental implications diminish by increasing wear events since this utilises fewer resources than would be needed to produce new apparel [51]. Extending the life of a garment by three months would see an 8 per cent reduction in its carbon footprint (3 MtCO2 equivalents), 10 per cent lower water consumption (600 million cubic metres), a 9 per cent fall in waste (150,000 tonnes) and a 9 per cent reduction in its manufacturing cost (GBP 2 billion) [52].

4.3. Discrepancy in Use and End-of-Life Data across Nations

Compared to more popular machine-washing methods for woollens in Europe [20], a high percentage of New Zealanders hand wash. Although New Zealand's drying practices for jumpers are comparable to European and Asian nations (being mainly air-dried), they contrast with data from the United States of America (mainly tumble dried) [18]. Further, while many European nations have established fibre recycling facilities [48], New Zealand facilities are undeveloped [24]. However, this research shows that many New Zealanders intend to donate the clothing they no longer use. Donating used clothing to charity is largely practised in the country. Consumers make effort to travel to charity shops or clothing donation bins rather than simply placing their old clothes in the rubbish [53]. Comparatively, this is lower than what has been reported in other countries such as Germany and the U.K. [35].

This study was able to quantify the number of times a jumper was worn and washed in its lifetime and how it was disposed of in New Zealand. Establishing wash-and-wear events for woollen and synthetic-blend jumpers allows country-specific modelling of the resource flow for LCA.

5. Recommendations for Future Use

To assess the environmental impact of knitted jumpers in New Zealand, inputs from nature, such as the land and water utilised during their care and disposal, may now be accurately measured. Additionally, it is also possible to model the material and resource inputs from the technosphere, such as the chemicals (soap and other auxiliaries) and energy that are utilised for washing and drying the two jumper types. By applying these inventories to widely accessible databases such as Ecoinvent, CML and TRACI, the use and end-of-life phases can be modelled. These databases evaluate the environmental consequences throughout the life cycle of products and processes. It is now possible to make better comparisons between measurable values in many impact categories, such as kilogram carbon dioxide equivalent emissions for assessing the global warming potential and more. This study, however, focused on a specific product, the knit jumper. For the expansion of scope, further investigations on the use and disposal of a range of garment products in New Zealand would be helpful. There is also a need to explore other popular textile fibres and blends.

6. Limitations

The authors identified some anomalies in this study. While the survey met its target size, most participants were female, which may influence the findings. Furthermore, participants were asked to estimate past and future wear events, which may or may not be comparable to actual wear events. Instead of depending on surveys, practice-based methods such as maintaining laundry diaries and wardrobe studies [54] could be employed to address some of the survey's limitations. There were some assumptions made for reuse that were based on European statistics, such as halving the number of wear events of the first life for estimating the second [35], which might not be the case in New Zealand. Moreover, in drying, natural air drying methods sometimes may require energy, if it is conducted in a heated house where extra heat is required for evaporating water [39], which was not considered in this study. Finally, collecting more detailed information such as washing temperature and laundry load size would be valuable for improving the inventory modelling in the LCA.

7. Conclusions

The goal of this study was to acquire New Zealand-specific inventory data for the use and disposal phases of knitted jumpers that can be utilised for modelling the resource flow in an LCA. This study conducted a comprehensive consumer survey of 1094 New Zealanders to identify their clothing consumption habits. Three important findings were identified:

1. The washing practices, lifetime wear events and disposal methods of clothing made from various textile materials vary significantly. Woollen jumpers in New Zealand are worn and cared for differently from synthetic-blend jumpers.
2. Unique maintenance and disposal practices for garments evident in New Zealand are distinct from those reported in other countries. Different regions or cultures have different ways of handling clothing, and thus, these habits cannot be generalised.
3. Data on comparative lifetime wear events, wash counts and modes of disposal were quantified. For a meaningful LCA, the inventory used in washing and drying and their impact on the environment when disposed to a landfill can be worked out using these figures.

These findings are important for future LCAs in the garment industry, as they show the impact of modelling inventory for the use and end-of-life phases. The study identified the resource flow for the LCA and the method applied to obtain the data. These distinctions will enable a more comprehensive cradle-to-grave life cycle for woollen and synthetic jumpers, allowing an accurate comparison of their environmental impact.

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