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UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

A MULTI-CRITERION DECISION ANALYSIS (MCDA) APPROACH TO PALLET MATERIAL SELECTION FOR VARYING SUPPLY CHAIN NETWORKS.

Prepared by

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering

Supervisors:

Prof. Kevin Harding, Prof. Jean Mulopo, Mr. Paul Chego

Johannesburg, 2019

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

_____

(Signature of candidate)

9th day of **September 2019**, at **the University of the Witwatersrand.**

A MULTI-CRITERION DECISION ANALYSIS (MCDA) APPROACH TO PALLET MATERIAL SELECTION FOR VARYING SUPPLY CHAIN NETWORKS

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ABSTRACT

Pallets maintain a pivotal role in the storage and transportation of products within a supply chain. Although pallets have been traditionally constructed from wood, there has been a shift towards plastic and other composite materials for pallet construction. Subsequently, debate has inundated the industry with questions pertaining to the identification of “the best” pallet material type in relation to a supply chain, which could be highly subjective.

As such, the aim of this research is to provide insights into the impact that these materials of construction (MOC), of a pallet, have on a supply chain network and examine the limitations and drawbacks as well as strengths and benefits associated with pallets of a particular MOC. The goal is to assist the end consumer come to an informed decision when making the choice between pallets of different MOC. In order to achieve this, the main objective of the research was to develop a decision support tool that can be used by industry professionals when deciding between alternative pallets for their supply chain.

Four main facets were used in order to conduct the study namely: (I) a theoretical framework and market analysis, which laid the foundation of the study; (II) a material analysis phase which looked at the material properties of the selected pallets with the incorporation of modelling; (III) a macro study phase which looked at the “big” picture in the form of a case study; and (IV) a final phase which culminated the findings of the study and presented the backdrop for the formation of a decision support tool. A mixture of qualitative and quantitative research methods, feature in this study in order to fully examine the research objectives.

In addition to the literature review, surveys were circulated to prominent pallet manufacturers and consumers within the local South African (SA) market. This was the method of choice for data collection in phase I. Within phase II, the materials used for pallet construction were characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM)

for surface morphology and topology characteristics respectively. Fourier transform infrared spectroscopy (FTIR) analysis was used to confirm the chemical structure of the MOC and assess if major additives were present that could affect pallet performance. Lastly tensile testing was carried out as a means by which to assess mechanical properties of the pallet MOC and provide useful data for the simulation models. A case study was the main feature of phase III.

Pallets of wood and plastic were introduced into 3 different supply chain types namely: i) a cold chain loop in the frozen vegetable sector, ii) an ambient goods chain primarily featuring household cleaning agents and iii) a perishable foods chain. This then presented the opportunity to substantiate test results (from phase II) with real world data. In the final phase, a multi-criteria decision analysis (MCDA) tool is formulated using analytic hierarchy process techniques.

From the first phase of the study, a survey was used to evaluate the local landscape and market perception of pallets from a consumer and manufacturer perspective. The survey results confirmed the dominance of wood as a MOC in the SA marketplace with 86 % of the total pallet market being wood, as per respondents from pallet manufacturers and poolers alike. With 85.71 % of respondents asserting that they supplied fast moving consumer goods (FMCG) industries, the decision to conduct the case study in this field also proved justified.

The characterization of the MOCs provided critical material data for use in the pallet modelling and provided insight into the chemical and mechanical properties that the materials possess. In terms of pallet tests, all the pallets performed well in the stacking and racking tests. Average deflections of 5.7 mm, 3.7 mm and 5.0 mm in the racking tests were recorded for the wood (Pallet B – SA Pine), plastic (Pallet A – HDPE + PP) and plastic (Pallet C – PP) pallets respectively. In terms of the stacking tests, deflection rates were 4.0 mm, 3.5 mm and 4.8 mm for these pallets as well.

The case study results indicated that each pallet had areas of strength and weakness with respect to a particular supply chain network or operating environment. The scorecards for each pallet were specified and derived from site observations (based on performance within supply chains). The plastic (Pallet C – PP) pallet was however the best performer overall (as an aggregate across all 3 supply chains was considered) with an average rating of 4.81/5 and closely followed by wood (Pallet B) at 4.70/5 and lastly 4.54/5 for the Pallet A plastic pallet. These results stem from a comparison of the pallets across a number of criteria with a focus on the various stages along the supply chain.

As a consequence, the study also proved that deciding on a pallet type for a particular supply chain is an arduous task due to the complexity of assessing pallets in different scenarios and the varied performance attributes presented and requires consideration of multiple criteria.

Therefore, the proposed solution may have practical implications for all users of pallets in that the formulated tool can support in optimising the consumer's supply chains by choosing the best pallet solution to meet their needs. The resulting MCDA tool along with pertinent media from the case study is hosted on the following web address and can be accessed at: https://pallet-mcda.firebaseapp.com. Here the tool will perform the relevant calculations on the basis of customer requirements and output a suggested pallet solution.

Keywords: Analytic Hierarchy Process (AHP); Fast moving consumer goods (FMCG); Multi-criteria decision analysis (MCDA); Pallet; Supply chain network (SCN)

DEDICATION

Dedicated to my family

for all their support and patience.

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NOMENCLATURE

AFM	Atomic Force Microscope
AHP	Analytic Hierarchy Process
APZ	Automated Palletising Zone
ASTM	American Society for Testing and Materials
Au	Gold
C	Carbon
CBA	Cost Benefit Analysis
CDC	Central Distribution Centre
CHEP	Commonwealth Handling Equipment Pool
CI	Consistency Index
CR	Consistency Ratio
CSR	Corporate social responsibility
CSS	Cascading Style Sheets
DC	Distribution Centre
DD	Dispatch Dock
EMC	Equilibrium Moisture Content
FMCG	Fast Moving Consumer Goods
FTIR	Fourier Transform Infrared Spectroscopy
GDP	Gross Domestic Product
HDPE	High Density Polyethylene
HTML	Hypertext Markup Language
iGPS	Intelligent Global Pooling Systems
ISO	International Organisation for Standardization
JPW	Jozi Park Warehouse
JS	JavaScript
LCA	Life Cycle Assessment
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
MOC	Material of Construction
MOO	Multi-objective optimization

MPZ	Manual Palletising Zone
OFG	Outbound finished goods
Pd	Palladium
PECO	Pallet Exchange Company
PHE	Pallet Handling Equipment
PMS	Pallet Management Strategy
PP	Polypropylene
PS	Pallet Storage
RCI	Random Consistency index
RD	Receiving Dock
RFID	Radio-frequency identification
RH	Relative Humidity
RWA	Real World Application
SA	South Africa
SCM	Supply Chain Management
SCN	Supply Chain Network
SEM	Scanning Electron Microscope
TM	Tabular Method
U.S.A	United States of America
UTS	Ultimate Tensile Strength
WPC	Wood-plastic Composite
WWII	World War Two

CHAPTER 1:
INTRODUCTION

This chapter lays out the foundation for the research by detailing the necessity of the study and gives an insight into how the structure of the dissertation aims to meet the objectives of the research project.

1.1 Background and Motivation

A pallet is a "portable, rigid platform used as a base for assembling, storing, stacking, handling and transporting goods" (Elia & Gnoni, 2015). The application of pallets covers a wide spectrum of industries such as the food and beverage industry, automotive, mining, manufacturing as well as the chemical and pharmaceuticals sectors to name a few.

The competitive and dynamic nature of today's marketplace necessitates the need for constant improvement and innovation in many of these industries. A common fixture in most industries is the pallet. Considering the prominence of pallets, improving upon their performance should improve the operations in most of these industries. As such, this research aims to gain an understanding of the pallet, local supply chains and how the material of construction (MOC) may impact on these industries and supply chains.

The importance of pallets within the supply chain is often one that is not valued as much as it should. White and Hamner (2005) gave a more fitting description to the pallet as they termed this piece of equipment as being responsible for "Moving the world". Pallets are the backbone of the transportation industry when it comes to the logistics of product or goods movement. In the United States of America (U.S.A) alone, 1.9 billion pallets are in use (Elia & Gnoni, 2015; Tornese et al., 2016). Most of these pallets are made of wood, which constitutes up to 86% of all pallets sold worldwide, however, there is a growing trend towards plastic and other composite pallet types and away from the traditionally favoured wood (Soury et al., 2009).

Given this, a critical facet for many in industry is determining which pallet type to use. As a result, the effect of pallet material of construction has brought about a major point contention in industry. The end consumer faces multiple pallet types and a plethora of criteria that these pallets need to meet in order to optimize their application in a specific industry or supply chain.

Supply chains form the foundation of the management of the forward flow of products from manufacturers to the end consumer (Mentzer et al., 2001). They play a critical role in today's modern global economy as palletised products traverse down these chains (Reefke & Sundaram, 2017), hence understanding how they work and the role of pallets within them is crucial for the study. Supply chain management (SCM) was a core theme of this work. It deals with the management of relationships between the supplier and customer in order to deliver great value to the customer at a lower cost to the supply chain (Christopher, 2016). Improving on the performance of a pallet in the supply chain ensures a better SCM strategy.

The purpose of this research is to assess the relative performance of pallets of different materials of construction within different supply chains and establish which pallet type would be better suited for a particular supply chain. The widespread application of pallets substantiates a need to determine scenarios under which the use of a certain type of pallet is applicable. The use of a decision support tool or technique is a favourable technique to use in order to assess the relative performance of pallets.

More often than not, decision support algorithms and tools in the pallet industry are more focussed on the management of these returnable transport items within the supply chain (Glock, 2017) as opposed to pallet selection. As such, this work aims to break this trend by offering such a support tool. To date, no literature presents the solution proposed within this work and hence provides a unique opportunity for an effective tangible contribution to the industry.

This work also fills an important research gap by giving a quantifiable approach to the decision-making process when it comes to deciding

between wood and plastic pallets by producing a multi-criteria decision analysis (MCDA) tool. The end goal of the software-based MCDA tool is to assist industry managers and stakeholders in making more informed decisions when it comes to pallet selection.

1.2 Research Problem

The design, production, and delivery of products in a safe and reliable manner has become a strong issue for most manufacturing companies. For a number of years, this issue has been exacerbated by the global nature of products flows. In this regard, it has become imperative that beyond optimizations of product formulations, processes and packaging, careful consideration of multichannel distribution as well as product logistics be assessed as sources for continuous improvement and potential savings. A controlled and agile supply chain is therefore required to achieve the above and often rely on packaging as an important and essential factor for products protection and transportation. In this context, pallet is a fundamental element of any product development and organization of a sound logistics chain. The use of a particular pallet type may prove to be source of aforementioned improvement.

There is therefore a need to probe the benefits and consequences of using a particular pallet MOC in a given supply chain over multiple criteria. Within this study, wood and plastic are investigated and emphasised due to their market dominance.

1.3 Research Aims and Objectives

The aim of this research is to provide an understanding of the factors that impact on the performance of various pallets, in differing supply chains and culminating this data into a customer oriented multi-criteria decision analysis (MCDA) software tool. The research looks to contribute to the fields of engineering and supply chain logistics by focussing on identifying how the pallet MOC can affect the performance of a pallet.

The main objectives of this study are to:

1. Investigate the local pallet market.
2. Compare the properties of wood & plastic pallets.
3. Conduct a qualitative analysis of pallet types in supply chain networks (SCNs).
4. Create a decision matrix as a basis of a software-oriented MCDA tool.

1.4 Research Design

In order to meet the objectives of the study, the work into 4 phases as outlined in the following sections.

1.4.1 Phase I: Market Analysis

This phase offers an exploratory role into the validity of the research topic and aim of the dissertation at large. Various claims are made in industry regarding the subject matter (pallet material of construction) and how a specific type is expected to perform. There is little to no conclusive research done on the matter and as such this phase looked to do that through a thorough data and market analysis. The following methods were used in the work to conduct this:

- Comprehensive literature review (Chapter 2)
- Electronic surveys (Chapter 4)

1.4.2 Phase II: Material Analysis and Modelling

The second phase of the research looked to explore the pallets material properties and design from a micro and macro perspective. Tests were done in order to ensure the specified pallets conformed with industry standards from safety and operational points of view. In addition to this, a further objective was to model the pallets in a 3-D imaging software in order to correlate model results with experimental data and conduct predictive modelling on the pallets.

1.4.3 Phase III: Case Study

The third phase looked to gauge the performance of pallets of differing MOC within separate supply chain networks (SCNs) in order to obtain a first-hand experience into how different operating conditions affect a pallet. The target for the study was to expose the pallets to the traditional fast-moving consumer goods industry. Supply chains in the dry goods, perishables and frozen produce markets were used. The specifics regarding the scope of involvement is briefly summarised in the following bullets:

- 27 Trial pallets (9 of each specification of pallet)
- 3 Supply chain networks (Household detergents, perishable beverages and frozen chips & vegetables)
- 7 Partner Companies

Chapter 3 elaborates on the specific designs and methods used in the execution of the case study.

1.4.4 Phase IV: Multi-Criteria Decision Analysis

This final phase is a culmination of the aforementioned phases. Results and analysis of the 3 phases were used in order to create a decision analysis tool to aid the pallet industry and decision makers in the market when it comes to pallet selection for their respective supply chain. The tool is based on Analytic Hierarchy Process (AHP) techniques and runs on a JavaScript framework.

1.5 Structure of the Dissertation

This document has a total of 8 chapters with an appendix section that holds supplementary information. Chapter 1 introduces the subject matter and the scope of the work. The research aim and objections are formulated and presented. Chapter 2 probes all the relevant published academic work pertinent to the study in order to meet the first objective and provide a foundation for the empirical research by looking into: pallet definition and characteristics; supply chain networks; consumer markets and; the theory behind multi-criteria decision optimisation and related techniques.

The research design and methodology adopted are presented in Chapter 3. Herein, the methods applied for data gathering and arguments in support for the method choices are described. Four phases are outlined to that look at methods relating to market analysis, material characterization and modelling, case study setup and MCDA tool formulation.

Chapter 4 (Phase I – Market Analysis) presents the results of manufacturer and consumer market responses to an online questionnaire on pallet usage within the local context. Chapter 5 (Phase II – Material Analysis & Modelling) outlines the material characterization and mechanical testing results that were carried out on the pallet MOC. Testing of the pallets and 3D modelling is also reported. Within Chapter 6 (Phase III – Case Study), the field study is defined and process mapping is presented. Results from each of the 3 supply chains are presented and pallets are ranked on the basis of their relative performance at each stage.

In Chapter 7 (Phase IV – Multi-Criteria Decision Analysis), the chapter looks to illustrate how the MCDA tool is developed and highlights the manner in which the results of the research study contribute to it. Lastly, Chapter 8 (Conclusions and Recommendations) wraps up the findings of the study and gives some insight into future work that can build upon the current research.

1.6 Summary

The introduction to this research gives a brief insight into the background and motivation of the project. The pallet conundrum relating to the need in industry, for the selection of a pallet material of construction is presented. In order to find a solution, a set of aims and objectives are set and listed herein along with a research design. Finally, an outline of this dissertation is presented in order to help the readers navigate quickly and efficiently through the research work.

CHAPTER 2:
LITERATURE REVIEW

2.1 Introduction

This chapter presents a theoretical frame of reference by means of a review of literature relating to pallets, supply chain networks and the theories on multi-criteria optimisation as is applied in this work.

To start with, a pallet is defined in terms of its structure, purpose and prevalence. This is followed by a review of supply chain networks in order to understand the role that pallets play in the industry as well as the various supply chain types and markets that dictate its applicability. Lastly, multi-criteria decision analysis is presented with the aim of giving a theoretical description of the techniques and tools that will be used in order to present a solution to the pallet selection problem as defined in Chapter 1.

2.2 Pallet Literature

This section gives a brief introduction to pallets, outlines the different types or designs of pallets available and describes the various materials used in their construction. Literature pertaining to the testing of pallets and the equipment normally associated with them is presented as well.

2.2.1 Pallet Introduction

A pallet is a portable and rigid flat platform used for the transport, storage and handling of products such as boxes, bags, cartons etc. in groups (Elia & Gnoni, 2015; Masood & Rizvi, 2006; Raballand, 2005). This unique feature allows them to minimize handling costs, which in turn alleviates the economic transaction costs (Buehlmann et al., 2009).

Pallets play a critical industrial role through the transportation and handling of various products and cargo (Soury et al., 2009). With regards to the economy, they help with the efficient and reliable transportation of various goods across several different economic sectors (Buehlmann et al., 2009).

Prior to their invention in the 1920s - 1930s wooden barrels were the primary form of product storage and transportation (Baker, 2016; National Pallets, 2016). There is however, mention of the use of skids as far back as ancient Egypt. Pallets came into prominence after WWII (Leblanc, 2011), as they brought about a more efficient method of transporting goods and equipment for military personnel. During this time, various designs were patented by the likes of George Raymond and William House (Baker, 2016).

Pallets are engineered load-bearing structures designed in order to meet specific materials handling requirements as set by customers. They are important functional products and must be damage tolerant in order to meet performance requirements (Emiliani & Stec, 2005). Various patents over the years attest to the detailed engineering required for their design and construction (US3861326, 1975; US6199488, 2001; US7000549, 2006; US2178646, 1937; US5367960, 1994; US3059887, 1962).

In terms of their prevalence, literature sources have stated the approximate numbers of pallets in circulation at about 2 billion, 280 million and 1.2 billion pallets in the United States, European Union and China respectively (Ren et al., 2018).

Pallets are also perceived as the interface between the products and the various pallet handing equipment (PHE) within a distribution environment. As such, pallets should also be suited to handle all the dynamic and static forces that arise. The interactions can come in the form of the following (White & Hamner, 2005):

- Vibrations (from shipping and conveying);
- Transfer shocks (during unit load transfer in the distribution environment);
- Impact forces (from forklifts and other PHE);
- Compressive forces (from warehouse rack and bulk stack storage); and
- Load shifting (from surface friction due to unit load movement on the pallet surface).

Given all these interactions and required performance expected of them, pallets have over the years been engineered to meet these specific demands. Various designs and types exist within the market and the following section will elaborate on these further.

2.2.2 Designs and Types of Pallets

Although earlier designs and patents by the likes of Raymond and House (US2178646, 1937) illustrated a two-way entry “stringer” pallet design (Figure 2.2) that gained market dominance, these designs came with access limitations as a major drawback. As such, “block” pallet designs (Figure 2.1) have come to fruition as they are favoured for the ease of four-way entry (Baker, 2016). In essence all pallets fit into these two broad categories, either stringer or block.

Stringer pallets make use of a frame of three parallel pieces of wood called stringers. Deckboards are then placed perpendicular to the stringers in order to form the product loading surface (A. M. Bilbao, 2011).

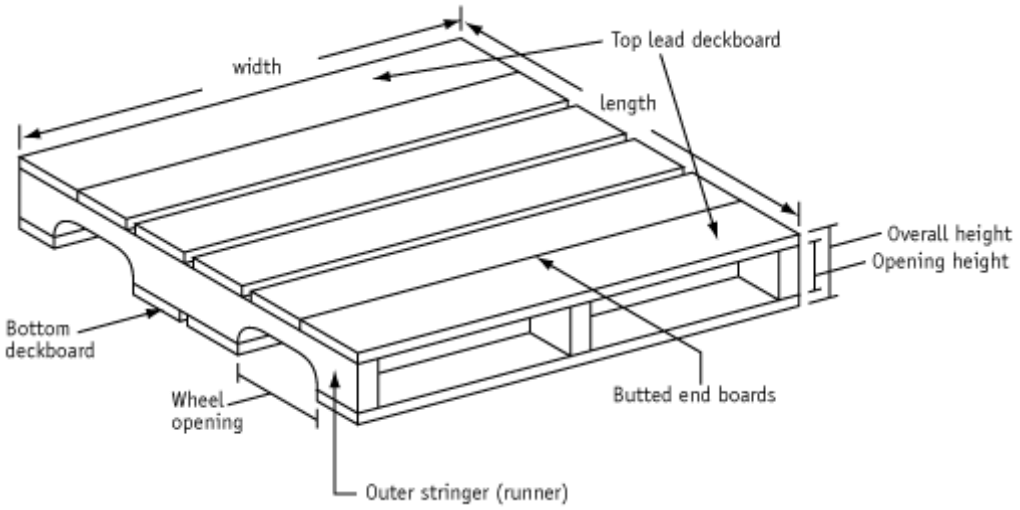


Figure 2.1: Typical Stringer pallet design (Freightquote, 2018)

Block pallets make use of wooden blocks which are attached to stringers that run across them. The deckboards are then attached to the stringers that are fastened to the surface of the blocks. This use of stringers and blocks facilitates for more efficient handling (A. M. Bilbao, 2011). The terminology used in these schematics will be used moving forward in this work.

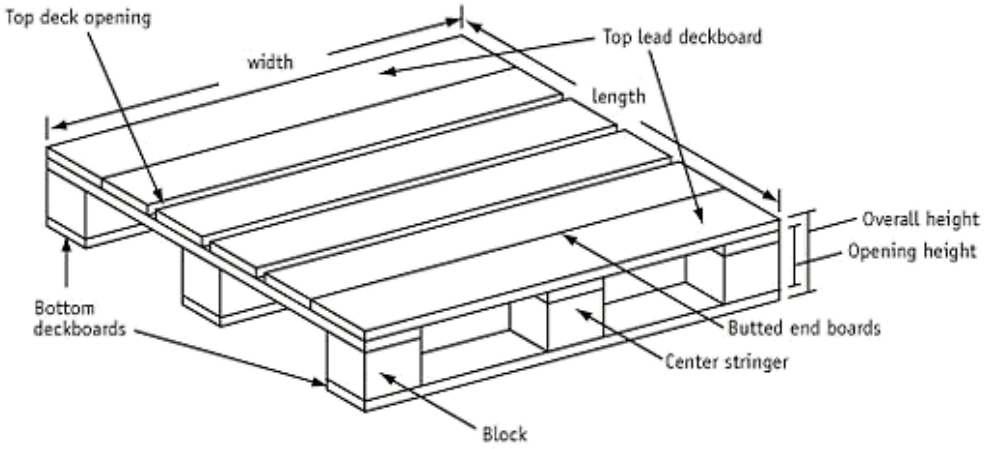


Figure 2.2: Typical Block pallet design (Freightquote, 2018)

Plastic pallets on the other hand, tend to follow a “block design” type as indicated by some of the examples in Figure 2.3. The main distinction is that most plastic pallets are formed from an injection moulding process (Leblanc, 2012), unlike wood which is fastened together by nails.

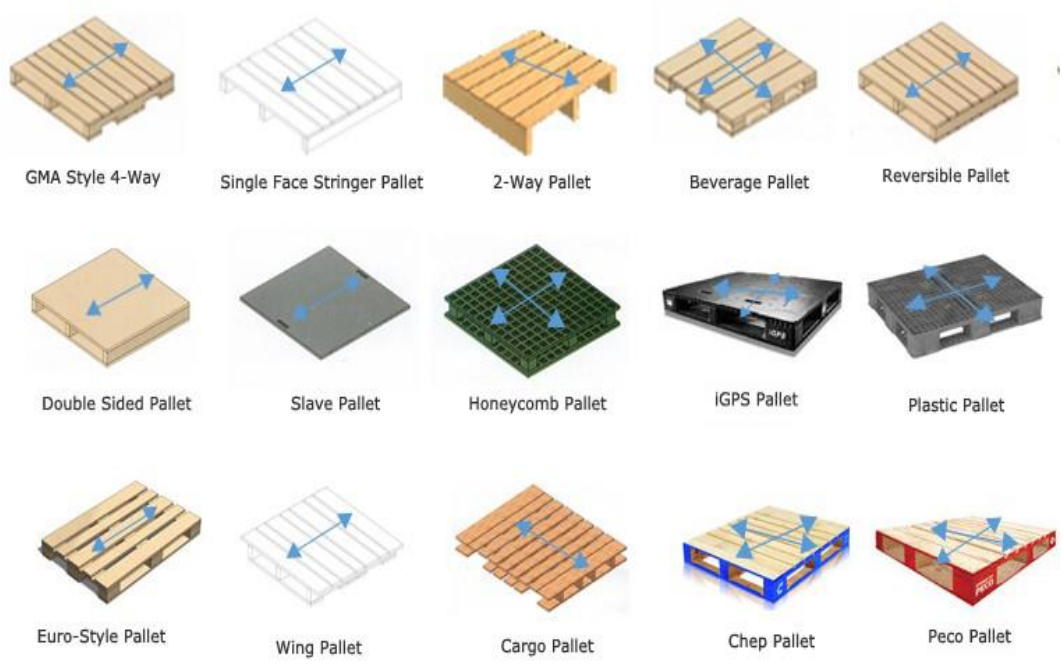


Figure 2.3: Common pallet types found in industry (Mallard Manufacturing, 2015)

Commercially available pallets come in various designs and types primarily to serve the purpose of being easy to retrieve and transport using various pallet handling equipment (PHE), such as; pallet jacks, reach trucks and forklifts (Soury et al., 2009).

In addition, pallets can be designed to meet an array of different applications and hence could have a large degree of freedom when it comes to size specifications. As such, the International Organisation for Standardisation (ISO), has come up with specific standard pallet dimensions, coinciding with regions in which it is used.

Table 2.1: Typical pallet dimensions as recognized by ISO 6780 (International Organization for Standardization, 2003)

CONTINENT	SI (mm.)	US CUSTOMARY (in.)
Europe, Asia, India, Central and South America	1200 x 1000	42.24 x 39.37
Europe, Asia, India	1200 x 800	47.24 x 31.50
North America	1219 x 1016	48.00 x 40.00
Australia	1140 x 1140	44.88 x 44.88
Asia	1100 x 1100	43.30 x 43.30
North America, Europe, Asia	1067 x 1067	42.00 x 42.00

For any given market or supply chain, pallet sizes are often well established and standardised unless customer requirements change (Leblanc, 2017). However, for the context of this study, the 1200 x 1000 mm pallet spec will be used and referred to as it is primarily used in African market although the continent does not feature on the ISO standards table. This will henceforth be the primary dimension used within the context of this study, unless otherwise stated.

2.2.3 Materials of construction

Pallets can be made from any structural building material, however, most pallets are made from wood, plastic and metal, with wood accounting for a predominant share of about 86% of the market (Soury et al., 2009). Although this market share dominance is well over 80%, wood as a MOC of pallets is increasingly being edged out of the material handling industry by plastic (Soury et al., 2009).

The uptake of plastic has brought about opposing views (Hassiotis, 2016), relating to which of the two (wood or plastic) provides a better value proposition to the customer from an economic, environmental and operational point of view in a given industry. The factors this study will look to cover span across the entire spectrum from industrial application, customers, supply chain, environment, economy (costs), hygiene (cleanliness), sustainability and scale of application.

The economic and performance requirements of the end user usually determine the material of construction of the pallet. This tends to come about from either a technical or a regulatory standpoint (Buehlmann et al., 2009). As pallets form the foundation of the materials handling industry, they are often made of new or used metal, plastic, corrugated, wood, or wood composite materials, PVC and rubber (M. A. Bilbao et al., 2011; Buehlmann et al., 2009; Kay, 2012; Masood & Rizvi, 2006; Rogers, 2011). Although they may appear as a basic commodity to the outside world, those in the materials handling industry do realise how essential a pallet is to the operation's success and ultimately its bottom line (Rogers, 2011).

Considering the fact that most of the products transported throughout the supply chain make use of pallets, the resounding question is what type of pallet to use and why? There are various materials used in the construction of pallets and as described by Buehlmann et al. (2009), however, wood and plastic pallets remain the focus in this study and are elaborated upon further in the following section.

Wooden Pallets

Wood pallets are constructed from the renewable resource lumber (Lacefield, 2008). Besides fuel usage, pallet production for consumer and industrial use is the largest consumer of wood fibre (White & Hamner, 2005). As such, it is no surprise that solid wood pallets have a 80-95 % market dominance (Trebilcock, 2013) in most industries. This is primarily due to the low material and production costs of lumber along with its relative abundance. However, certain applications have necessitated a move away from wood pallets. One such application is in the grocery industry in which plastic pallets are utilised in preference to wooden pallets in order to conform to sanitary regulations (Buehlmann et al., 2009).

A few advantages and disadvantages of wood as a material of construction for pallets are listed here and give an indication of the relative strengths and weaknesses of this material.

Advantages:

Wood and by extension a pallet of this MOC, is cheap due to the low material and production costs (Soury et al., 2009; Tepic et al., 2012). The relative abundance of solid wood is a major advantage and thus ensures for the ease of manufacture (Buehlmann et al., 2009). It is the most common pallet type mainly due to its low initial and repair cost. The cost is estimated between $5 and $25 per pallet (Kay, 2012). Disposal and/or reuse of wood pallets is less challenging than plastic as wood pallets can be recycled / down cycled (Hassiotis, 2016; Prostack, 2016) or can meet a variety of other end-of-life scenarios like incineration for energy recovery and even landfilling due to biodegradability of the wood (Carrano et al., 2015).

The strength of wood as a material is responsible for giving these pallets a good load bearing capacity of between 1500 lbs and 3000 lbs (680 kg – 1360 kg) (Freightera, 2018; Hassiotis, 2016) making them well suited for heavy loads. In terms of hygiene, some studies have found wood pallets to be just as hygienic as plastic pallets within the distribution environment as all materials are equally exposed to the risk of biological, physical and

chemical contamination (Gudbjörnsdottir et al., 2002). Further work has also highlighted that some wood species like pine show excellent antibacterial properties which can be a significant advantage in the food industry (Fink et al., 2013; Milling et al., 2005; Vainio-Kaila, 2017).

Disadvantages:

In spite of their popularity, wooden pallets have a number of disadvantages. One such major con of wooden pallets is that mechanical failure can often result in damage to goods, delays in material movement, injuries, product returns, legal repercussions, additional transaction processes and in general an overall increase in costs from both the consumer and pallet supplier (Emiliani & Stec, 2005; Freightera, 2018; Materials Handling, 2011). The porous surface associated with wood pallets (Hassiotis, 2016) may present the potential for harbouring of pests (Prostack, 2016) and hence heat treatment is a requirement for export (Hassiotis, 2016) as per ISPM15 standards (Sela et al., 2017). Wood is normally dense and coupled with its porosity and affinity for moisture retention, may result in pallets of this material being much a much heavier than alternative MOC (Freightera, 2018).

Pallets made from wood are also known to take up a lot of landfill capacity in many countries (Tsang et al., 2007) which has adverse environmental effect even though wood is biodegradable. Wooden pallets have a further disadvantage in terms of useful lifespan. These pallets may have an estimated life of just 5 trips (Kay, 2012)) however, in a pooling environment with pallet refurbishment / remanufacture, this lifespan is a function of both pallet structural design and service environment condition (Tornese et al., 2016) and may thus be extended considerably . A further disadvantage comes in terms of material consistency, wooden pallets are known to have unreliable performance over time and may degrade due to environmental factors (Soury et al., 2009).

Plastic Pallets

Plastic pallets are typically made from polypropylene (PP) and polyethylene (PE), normally high density polyethylene (HDPE), which are materials normally derived from petroleum products and natural gas (Lacefield, 2008; Tepic et al., 2012). In plastic pallet manufacturing, a thermoplastic is formed into a desired design through processes such as injection moulding, structural foam moulding, thermoforming, compression moulding, rotational moulding and profile (Leblanc, 2012), which are energy intensive processes. These pallets are normally used in industries that require high hygienic or sterile environments like the pharmaceutical and fresh foods manufacturing plants (Freightera, 2018). Normally plastic pallets are used in closed loop environments (Freightera, 2018) as pooling of plastic pallets is still in its infancy.

Plastic pallets are favoured over wood due to their strength, durability and lightweight properties. The main hindrance is that plastic pallets tend to be three to five times more expensive than their wooden counterparts. However, the extra cost is usually offset by the increased number of trips and shipments that can be achieved with plastic pallets (Soury et al., 2009).

Further elaboration on the advantages and disadvantages of plastic pallets are listed here and give an indication of the relative strengths and weaknesses of this material as MOC.

Advantages:

Plastic pallets are lauded for their long lifespan (Freightera, 2018; Materials Handling, 2011), high durability (Freightera, 2018; Hassiotis, 2016; Lacefield, 2008) and relative low pallet weight as opposed to wood pallets (Hassiotis, 2016; Soury et al., 2009). This associated durability ensures that plastic pallets require little to no maintenance or repair over the lifespan of the product. Further advantages are from a regulatory standpoint. Due to their nature, plastic pallets are not subject to regulatory frameworks in terms of phytosanitary requirements such as heat treatment for export pallets as they are exempt from the ISPM 15 standards (Sela et al., 2017).

Due to the non-porous (Freightera, 2018) nature of plastic pallets, they tend to be more easily cleaned of debris (Freightera, 2018; Hassiotis, 2016; Materials Handling, 2011) and do not retain cleaning agents like water in the process. They can thus also be hot washed, steam cleaned, or chemically sanitized to remove any bacteria or mould (Pallet Management, 2017). The relative attractive design (Pallet Management, 2017) of plastic pallets is also advantageous as it makes them ideal candidates for use at retail level for display purposes within stores. Plastic pallets also have a uniform “tare weight” and are consistent in terms of material uniformity and also carry an estimated lifespan of 2-3 years (Kay, 2012).

Disadvantages:

Some of the shortfalls of plastic pallets are based on the associated costs and environmental effects. In comparison with wood pallets, plastic pallets tend to be approximately 3 – 5 times more expensive than wood (Freightera, 2018; Soury et al., 2009). The estimated cost is a major disadvantage at between $45 and $90 per plastic pallet (Kay, 2012). Although, it should be noted that, quality and type of wood may produce costly wood pallets as more durable pallets (Bengtsson & Logie, 2015), like those used in the pooling market, may use better quality elements.

The difficulty and general lack of repair procedures for plastic pallets in also a major disadvantage (Freightera, 2018; Hassiotis, 2016) as damaged pallets may have to be scrapped, recycled or landfilled. Smooth slippery surfaces (Freightera, 2018; Hassiotis, 2016) associated with polymer surfaces (when unmodified) may be a significant disadvantage as product damage or injury may be a subsequent consequence if loads shift from the pallet surface during transport or storage.

Disposing of waste to landfill, especially plastic, is becoming increasingly undesirable due to legislative pressures (Achilias et al., 2007) and given that plastic pallets are non-biodegradable (Soury et al., 2009), landfilling is not a suitable end-of–life option for this market. Safety in terms of flammability is another potential source of concern for use of plastic pallets (Mokhlesi &

Saman Lohrasebi, 2009) as plastics can burn for considerably longer at higher temperatures than wood.

Plastic pallets are often quoted with low load bearing capacities as some are quoted at less than 1500lbs (680kg) (Eightohtwo, 2017; Prostack, 2016) for most plastic pallets, although there are some in the market with higher load bearing capacities that compete with wood especially when reinforced with steel (Freightera, 2018; Hassiotis, 2016). This disadvantage makes them unsuitable for environments that make use of heavy loads.

Plastic materials like polypropylene, which are commonly used for pallet construction, are also known to have a low impact strength especially at low temperatures unless copolymerization of propylene with other α-olefins like ethylene is employed (Tepic et al., 2012).

Wood-plastic Composite Pallets

An interesting development in the field is that of wood-plastic composite (WPC) materials and their application as a pallet MOC. A WPC material is made of wood (sawdust) as well as polymeric materials such as polyethylene and polypropylene (Soury et al., 2009). This pallet design might give the impression that combining the benefits of both materials can solve the pallet conundrum between wood and plastic. However, their study revealed that the existing wood-plastic pallets in the market are mainly heavy weighted and hence not favoured in industry.

Comparison between wood and plastic pallets

As this study focusses mainly on the wood and plastic materials of construction of pallets, their characteristics have been compared and tabulated in order to give an insight into how they are known to perform. Table 2.2 below indicates the differences between wood and plastic pallets as can be found from various sources (Hassiotis, 2016; Nortpalet, 2017; Olympic, 2013; Ruriani, 2008).

Table 2.2: Reported differences between wood and plastic pallets (Hassiotis, 2016)

CHARACTERISTIC	WOODEN PALLETS	PLASTIC PALLETS
Prevalence	90 – 95% of all pallets	Less than 5% of pallets
Cost	3 times lower per unit	High cost, trade off savings may outweigh initial cost
Recyclable	Recycled as pallets / other wood products	Resin may be melted and reused
Repairable	Easy to repair	Difficult to repair unless made from component parts
International Shipment	ISPM 15 certification required	ISPM 15 certification not required
Nails / Fasteners	Nails and fasteners can damage products	No fasteners, little pallet induced damage
Moisture	Highly susceptible	No Moisture
Aesthetics	May contain debris, splinters and sawdust	Cosmetically pleasing
Microbes / Fungus	Requires some preventative treatments against	None
Load Bearing	Standard 48”x40” (1200mm x 1000mm) can handle up to 3000 lbs. (1360 kg).	Standard 48”x40” (1200mm x 1000mm) can handle up to 1500 lbs. (680 kg).
Durability	Durable with repairs	Highly Durable
Weather Resistance	Storage consideration for weather/moisture	More weather resistant than wood
Environmental Impact	Sustainable resource, easily recycled, biodegradable	Long shelf life, energy intensive recycling, non-biodegradable

2.2.4 Pallet Testing

The mechanical failure of pallets can cause significant damage to goods, bring about delays in product movement, result in additional transactions especially due to customer returns and potentially cause injuries to personnel. In essence any failure can result in higher costs to both buyers and sellers (Emiliani & Stec, 2005). As such it is pivotal to ensure that pallets operate in a safe and reliable manner. To ensure this, pallet testing standards have been set up by various bodies.

Standards for the requirements of pallet performance, ISO 8611 and ASTM 1185 are widely accepted in industry (Baker, 2016) and are applied with modification in this work. The test parameters cover a range of storage conditions and applications, hence the tests involve drops, incline impact, compression, bending, forklifting and various other setup tests (American Society for Testing and Materials, 2003; International Organization for Standardization, 2011).

Storage and handling conditions normally determine which of the pallets components are most exposed to stresses and hence likely to fail (Baker, 2016). These conditions are catered for in the standards extensively. An illustration of the types of conditions covered in the standards can be seen in Figure 2.4. In this figure an indication of the force distribution on the pallet is presented for stacking, forklifting and racking configurations along with the resulting deflection profiles. These features are an important source of investigation as they may impact on the pallet performance and interaction with pallet handling equipment (PHE) and the load itself.

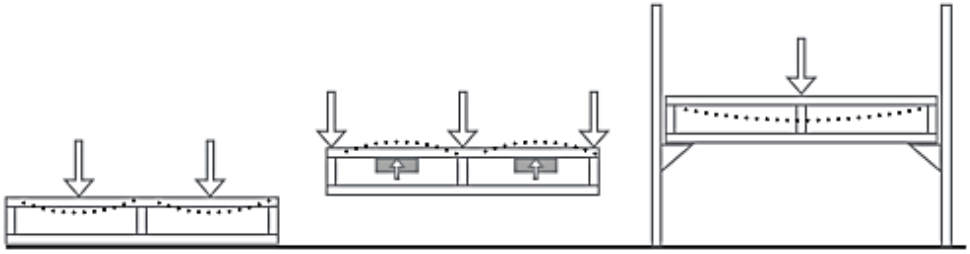


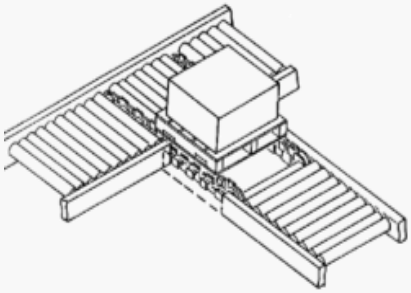
Figure 2.4: Floor stacking, fork tine support and a warehouse rack system depiction of force distribution on deckboards (Baker, 2016)

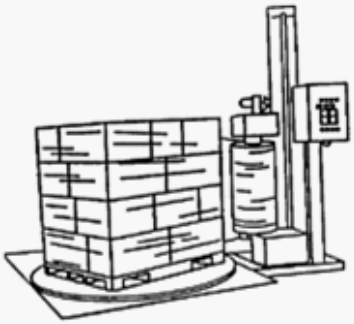
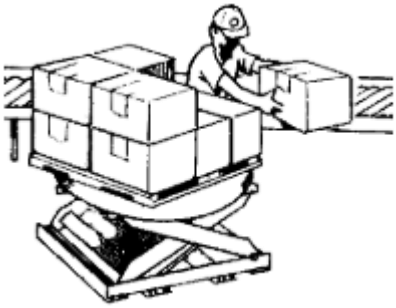
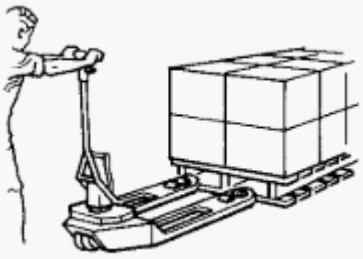
2.2.5 Pallet Handling Equipment (PHE)

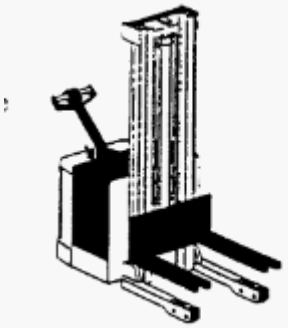
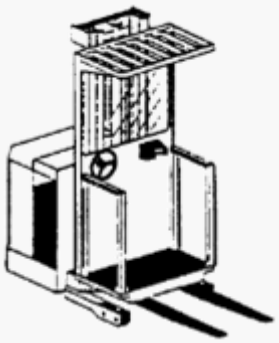
The material handling equipment associated with pallets varies in scale and size. An understanding of the various types of PHE that exist is important in order to note the performance of pallets in relation to them and the unit loads they interact with. A “unit load”, as is referred to in this work, is a single or number of items that are arranged and restrained as a bulk material that can be moved as a single mass.

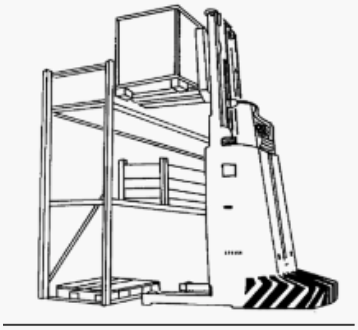
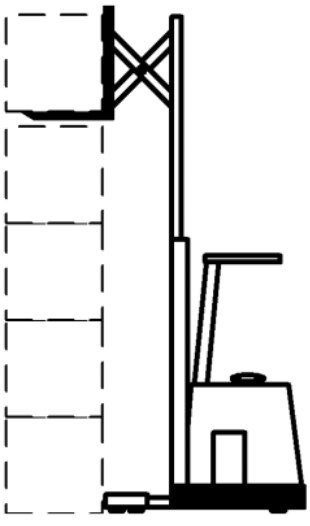
Supply chains are comprised of three main components, namely: pallets, packaging and unit load handling equipment. These system logistics components physically interact with each other during product shipping and storage (White & Hamner, 2005). As such it is important to understand the role of these unit load handling, or in essence, pallet handling equipment (PHE) for the study. Table 2.3 shows the various types of PHE commonly found in industry, and gives a brief description of their usage and main properties.

Table 2.3: Typical PHE found in industry (Kay, 2012).

TYPE	DESCRIPTION / PROPERTIES	DEPICTION
Conveyors	• One or more rows of rollers / wheels / chains used to move and direct material. • Move material on fixed path. • Hydraulic, pneumatic or motor driven.	

TYPE	DESCRIPTION / PROPERTIES	DEPICTION
Stretch wrap machines	• Used to stabilize loads. • A film is used to wrap around the pallet load while it is stretched. • Has lower material, labour and energy costs than shrink-wrapping.	
Palletizers	• Used for load formation by building unit loads / palletizing. • Methods can be manual or robotic.	
Pallet jacks (Powered or manual)	• Used to move material over horizontal surface. • Cannot be used for stacking purposes.	

TYPE	DESCRIPTION / PROPERTIES	DEPICTION
Walkie stackers	• Used to move material horizontally and may be used for stacking vertically. • Operators cannot ride the equipment.	
Forklift trucks	• Used to move material horizontally and may be used for stacking vertically. • Operators ride the equipment. • Often counterbalanced	
Order pickers	• Used to move material horizontally and may be used for stacking vertically. • Operator lifted with load and allows for less than unit load picking.	

TYPE	DESCRIPTION / PROPERTIES	DEPICTION
Automatic guided vehicles	• Used to move material horizontally and may be used for stacking and racking vertically. • Do not require an operator. • Fully automated and may be guided by a fixed path or free-ranging.	
Narrow-aisle (NA) reach truck	• Used to move material horizontally and may be used for stacking and racking vertically. • Load rests on the outrigger arms during transport, but a pantograph (scissors) mechanism is used for reaching. • Operators ride the equipment. • Counterbalanced	

2.2.6 Pallet Management Operations

Pallets are expected to meet their design specifications and performance expectations throughout their lifespan (Emiliani & Stec, 2005). Through effective use of pallets and their management, this performance can be ensured. Pallet management is consequently key in the pallet industry and is often a factor of the type and design of the pallet in question.

There are three prominent pallet management strategies (PMS). These are single use expendable, reusable buy/sell and reusable-leased pooling (Carrano et al., 2015). The approach to pallet management can be further classified as either being a closed or an open loop system. The application of single-use pallets, wherein the ownership of the pallet is granted to the end-user is often an example of an open loop system. Closed loop systems on the other hand, incorporate a pallet pooling system wherein which pallets are contracted from a pooling company or a company's own pallets are managed in a pool by a third party company (M. A. Bilbao et al., 2011).

Open-Loop System (with or without salvage value)

Within this system, the flow of pallets is one-directional. A forward flow of the pallet ensues as it goes from either manufacturer or reseller to end user and ultimately end of life (Ren et al., 2018). The distinction between open loop systems with and without salvage value is inherently in the fact that with salvage value, the pallets are sold and can be reused further. In the latter scenario (without salvage value), single use pallets are disposed of or are sent for other end of life processes.

Closed-Loop System (rental or pooling system)

The closed-loop system involves "pooling" of pallets. In essence, these systems also consider the return flow of used pallets in addition to downstream flow of palletised products (Glock, 2017). This system is by far the most common in industry (Ren et al., 2018). Many large companies have found a foothold and are major players in this market such as the Pallet Exchange Company (PECO), the Commonwealth Handling Equipment Pool (CHEP) and Intelligent Global Pooling Systems (iGPS) (Ren et al., 2018).

With the complex nature of the supply chains and industries within which pallets are employed, careful management of pallets is necessary as they are prone to damage, theft, destruction, misplacement and so forth (Ren et al., 2018). Employing these systems of operation typically ensure a more sustainable supply chain. As such, the role of a pallet should be understood within the context of a supply chain. Supply chains are in essence systems designed to manage and handle unit loads (White & Hamner, 2005) of which a pallet is the main functional constituent.

2.3 Supply Chain Networks

Supply chains and the networks that they construct are key elements in the flow of products and material between suppliers, manufacturers, distributers and the end consumer. This section looks to define supply chains and outline the different management strategies used.

2.3.1 Supply Chain Defined

A supply chain is defined as an integrated system of people, organizations, activities, information and resources that are used to synchronize a series of inter-related business processes and primarily functions in order to:

1. Acquire parts and raw materials;
2. Convert raw materials and parts into finished products;
3. Add value to the finished products;
4. Distribute and promote products to end consumers or retailers; and
5. Facilitate for the exchange of data across various business entities such as:
    - Suppliers
    - Manufacturers
    - Distributers
    - Logistics providers
    - Retailers (Kain & Verma, 2018; Min & Zhou, 2002).

Essentially, a supply chain is a complex logistics system that illustrates the steps or stages required in order to convert a raw material into finished

products or services and have them distributed to a customer or end user (Govindan et al., 2017).

The operations procedure of supply chains, from the context of pallets, contains at the very least the following processes, namely; distribution, purchase or rent, maintenance, reposition and recycling (Ren et al., 2018).

A typical supply chain process is illustrated in Figure 2.5, herein, a supply chain network is characterized by a “forward flow of goods and a backward flow of information” (Min & Zhou, 2002).

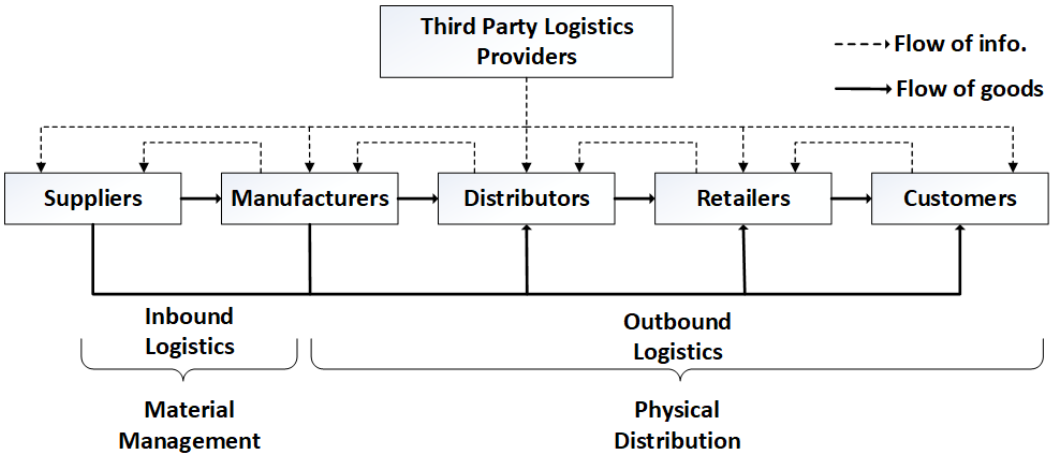


Figure 2.5: A typical supply chain network as redrawn from (Min & Zhou, 2002)

2.3.2 Supply Chain Management

Supply chain management (SCM) is inherently the management of multiple relationships across a supply chain (Govindan et al., 2017; Kain & Verma, 2018; Lambert et al., 1998). As finished goods emerge from different factory locations, they traverse various chains of distribution networks involving warehouses, cross border exports, local markets, distributors, retailers and eventually the end consumer (Chinna, 2016). This complex network requires management, along with the pallets that handle these finished goods.

Pallets are important throughout this distribution network and the correct pallet should be utilised in all these various settings. In many instances, the choice of pallet and its accompanying PMS is highly dependent on the type

of product transported and the configuration of the supply chain (M. A. Bilbao et al., 2011). An understanding of these supply chains is necessary in order to address the comparison of wood and plastic pallets sufficiently. Supply chains contain material handling systems that constantly interact with one another on a physical and mechanical level. These interactions bring about direct knock-on effects onto either one or both of the other components when one of the components is redesigned, which in turn affects the overall performance of the entire system (White & Hamner, 2005).

Such considerations are the basis of SCM, which is a complicated task. It involves all tiers of suppliers and customers, from point of origin to point of consumption (Lambert et al., 1998) as well as an understanding of the implications of change within the system such as that illustrated previously by White and Hammer (2005). Figure 2.6 indicates graphically what a basic overview of a supply chain would look like for consumer and industrial products. The impact of the various pallet types at each level in the chain should be investigated.

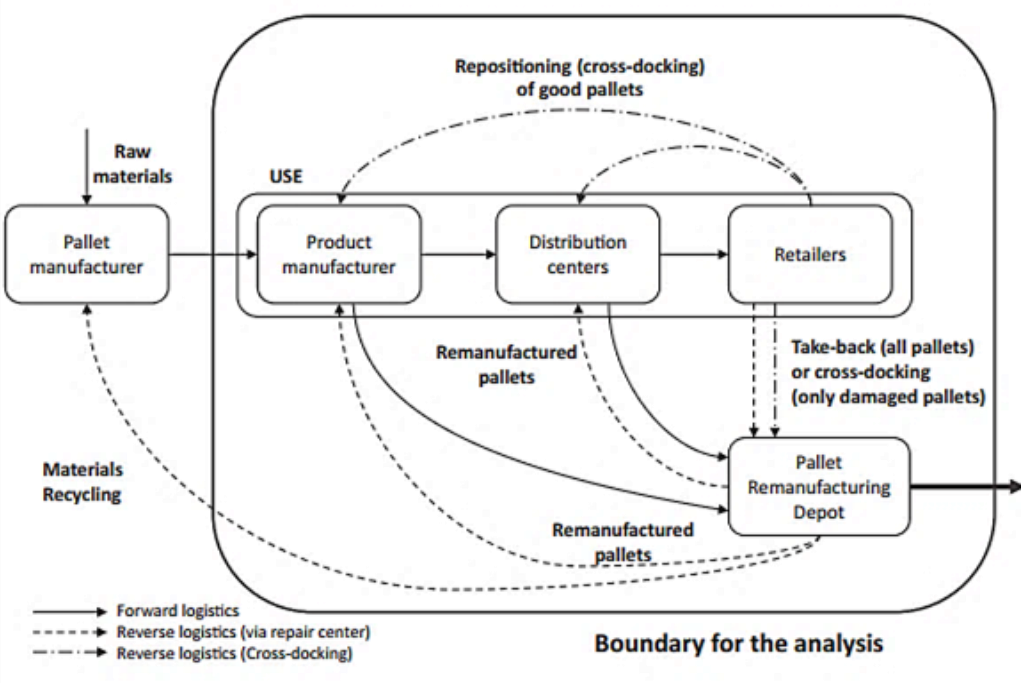


Figure 2.6: System boundary for project. Simplified supply chain network as adopted from (Tornese et al., 2016)

2.3.3 Temperature Controlled Supply Chain

Supply chains can be defined by the nature of their temperature control. Most supply chains are operated at ambient conditions i.e. product movement is independent of the surrounding temperatures, however, some products such perishable goods require an environment with moderated temperatures.

When it comes to temperature-sensitive products, thermal and refrigerated packaging methods are required in order to maintain the integrity of the products throughout transport and distribution (Göransson et al., 2018; Mercier et al., 2017). A supply chain that incorporates this is referred to as a “cold chain” (Bharti, 2017).

Perishable foods can be grouped into different temperature categories on the basis of maximizing product shelf-life (Göransson et al., 2018). In industry, these temperature ranges are: ambient = 15°C to 20°C; cool = 2°C to 15°C; cold = −9°C to 2°C; and frozen ≤ −10°C (Mercier et al., 2017). Table 2.4 gives an indication of how the temperatures in a cold chain vary for common perishable goods.

Table 2.4: Optimal storage temperature of common perishable food products (Mercier et al., 2017)

FOOD PRODUCT	OPTIMAL STORAGE TEMPERATURE
Deep-frozen	
Meat	-25°C or colder
Poultry	-24°C or colder
Fish	-29°C or colder
Fruits and Vegetables	-18°C or colder
Chilled	
Fresh meat	-1.5°C
Meat products	-2°C
Poultry	-1.5°C
Fish	-0.5°C to 0°C
Dairy products	0°C to 2°C
Fruits and Vegetables	
Low temperature (apple, blueberry, carrot, lettuce)	0°C to 2°C
Moderate temperature (carambola, melon, pumpkin)	6°C to 9°C
High temperature (banana, cucumber, grapefruit)	12°C to 16°C

2.4 Consumer Market & Local Context

The pallet supply base is large and fragmented, making pallets obtainable from a variety of sources (Emiliani & Stec, 2005). An understanding of this supply base and the customers in the market is necessary in order to understand solution paths for the pallet MOC selection conundrum. In the following sections, a brief looked at the overall market from a local standpoint is followed up by a focussed market analysis of the target industry (FMCG).

2.4.1 General Market

It is estimated that the South African (SA) market produces 30 – 45 million pallets per year to cope with market demands (Writer, 2012). These numbers are a function of the underlying economy and by extension, the gross domestic product (GDP) of the country. This is implied by the definition of GDP being: “the total market value of all final goods and services produced within the country in a given period of time” (Kira, 2013). Pallets are of course critical in the handling and distribution of such goods as noted earlier in this chapter.

From a local standpoint, there are three main provinces that contribute substantially to the GDP, namely; Gauteng, Kwazulu-Natal and the Western Cape. According to 2012 data, the Western Cape contributed 14% to the country’s GDP (Havenga et al., 2015) and due to readily available data, this province was used to make assumptions on the overall market.

The primary customers of pallets are manufacturers of consumer and durable goods (Emiliani & Stec, 2005) as confirmed by the market data from the Western Cape. Amongst these customers, the largest packaging sectors of consumer goods are inherently the food and beverage industries (White & Hamner, 2005). Figure 2.7 confirms this assertion and gives a representation of the freight flows in the Western Cape. The majority of the freight flows relates to fast-moving consumer goods (FMCG), construction, energy and agricultural activities (Havenga et al., 2015). With all these freight flows, there comes an associated logistics cost.

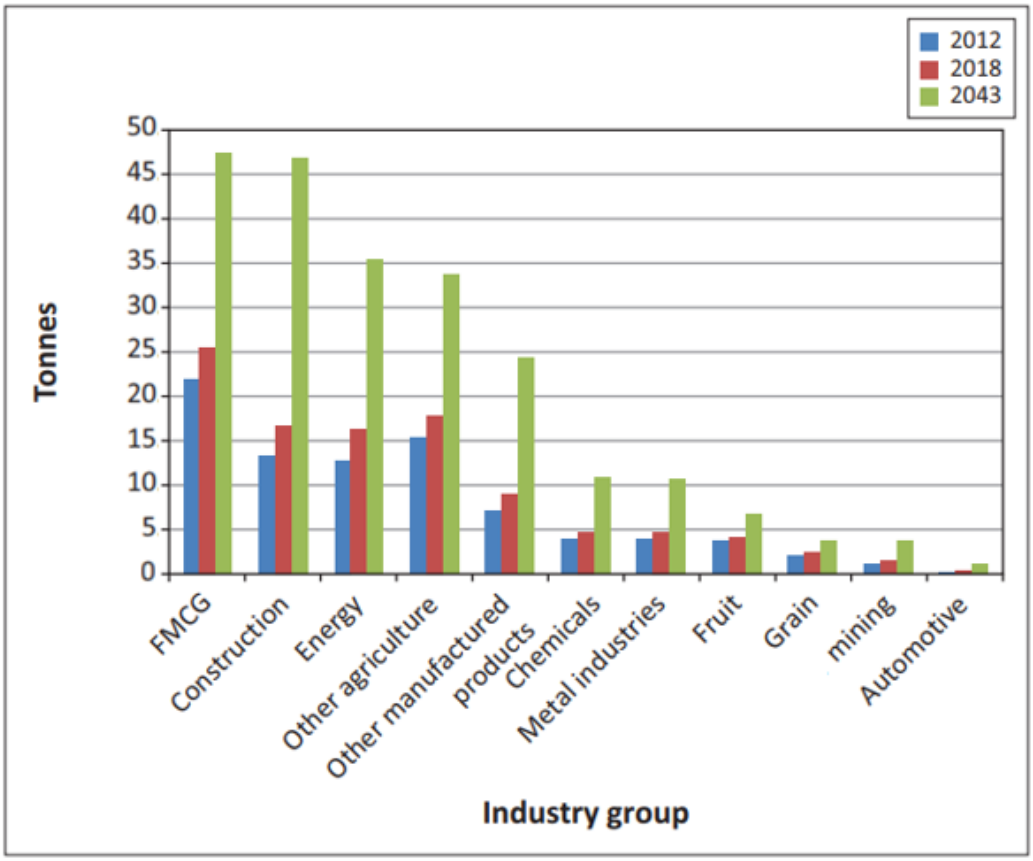


Figure 2.7: Western Cape freight volumes for each industry group (Havenga et al., 2015)

The elements that make up the logistics cost are transport, storage and port handling costs, management and administration costs and lastly, inventory carrying costs (Havenga et al., 2013). Pallets fall firmly in the storage costs and may have a bearing on the transport costs. From Figure 2.8, it can be noted that these costs are largest for the fast moving consumer goods (FMCG) industry which indirectly hints at a larger pallet market as consequence. Thus, this FMCG sector was the focus of the study.

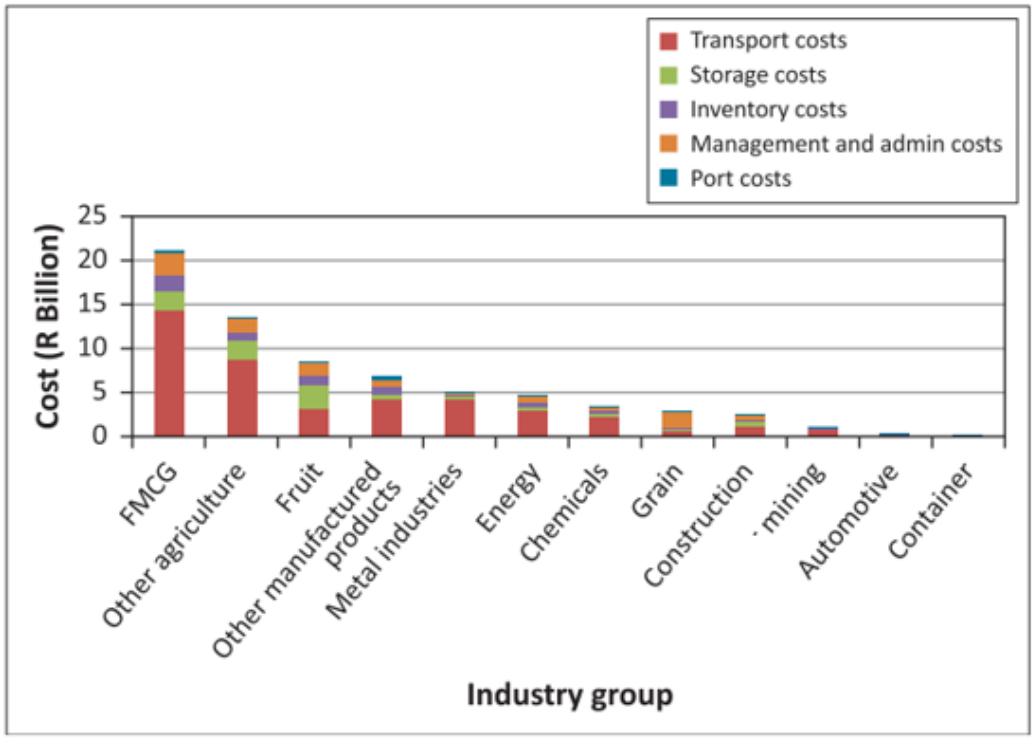


Figure 2.8: Western Cape logistics costs elements per industry group in 2012.

2.4.2 Fast Moving Consumer Goods

The FMCG industry encompasses an array of consumer-based products such as soaps, dairy products, confectionery items, batteries, fruits and vegetables. These products occur in large volumes but tend to have low unit costs (Chinna, 2016). According to Wadi and Gebhart (2017), the World Bank has anticipated an average growth of 4.8% in Africa's GDP. The driver of this growth is partly by private consumption of these consumer-based products and cements the future of the African FMCG sector.

The gross domestic product (GDP) of South Africa totalled R4 014 billion in 2015, which helped it reclaim the top spot as Africa's biggest economy. South Africa's logistics costs amounted to R429 billion in 2014 which equates to approximately 11% of the GDP (Havenga et al., 2016). This value gives an indication of the magnitude of the logistics sector and more often than not, this sector is "carried" by the pallet. Figure 2.9 shows a detailed breakdown of this logistics cost.

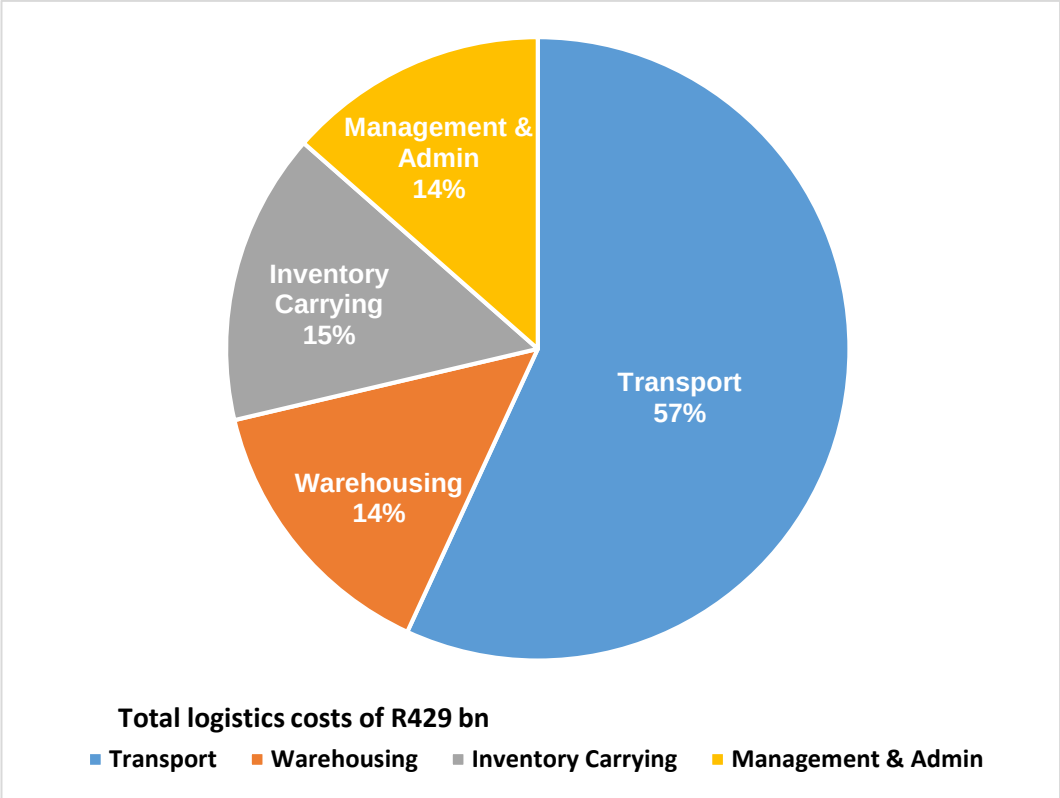


Figure 2.9: Logistics cost elements (R billions) 2014 (Havenga et al., 2016)

The competitive nature of this FMCG industry, which is characterized by complex distribution networks, encourages constant innovation in the supply chain in order to meet the demands of this logistics sector (Chinna, 2016). Cost reduction and system optimization are critical for any form of improvement of a SCN within which pallets are found (Emiliani & Stec, 2005). In order to then optimize these supply chains, tools and methods that enable this should be explored. This brings about the concept of multi-criteria decision analysis (MCDA).

2.5 Multi-Criteria Decision Analysis

Decision support tools in industry normally revolve around the management of supply chains as they help in assessing the potential impact that changes can have on a system prior to their implementation (Glock, 2017). These support tool strategies can also help in finding optimum solutions for pallets as they interact with various PHE in a specific supply chain of a particular market as indicated in previous sections.

The economic drive towards cost saving measures have driven many industries to review their packaging costs and the pallet is no exception (Gangadhar et al., 2017). At present, wooden pallets have the perceived advantage over pallets of other materials of construction due to their low cost, versatility and ease of disposal (Gangadhar et al., 2017). However, plastic pallets have taken some market share primarily because they are stiff, durable and recyclable.

The basis of the multi-criteria decision analysis approach taken here is to model the pallet selection conundrum as a multi-objective optimization (MOO) problem. The decision to select a particular pallet for a SCN is one based on the evaluation of multiple objectives with regards to a set number of criteria. As such, a clear definition of what constitutes a MOO problem is required as well as the theories that are best suited for solving them.

2.5.1 Multi-Objective Optimization

The generic representation of a MOO problem can be formulated as follows (Abakarov et al., 2013):

$$\Phi(x) = [f_1(x), f_2(x), f_3(x), \dots, f_m(x)] \longrightarrow \frac{min}{x \in X} \quad (1)$$

Where:

- $X \in R^n$ is a non-empty set of viable decision options;
- $x = [x_1, x_2, x_3, \dots, x_n] \in X$ is a real n-vector set; and
- $f_i = R^n \longrightarrow R$ are the particular objective functions for the problem.

Assumptions:

- All constraints are embedded within each particular objective function.
- Constrains utilised by means of penalty functions which are of the form $a_j \leq f_j(x) \leq b_j$.

As can be noted from Equation (1), the objective when solving a MOO problem is to find the optimal solution by finding the extreme value (be it min, max or equal) of each of the functions that make up the problem.

However, this is a difficult task and often unattainable. As a result, the decision problem solver often seeks a compromise solution to the problem which is the best of the possible solutions (Zhang & Zuo, 2013). This notion is what leads to concepts of Pareto Optimality.

2.5.2 Pareto Optimality

Pareto Optimality or a Pareto Optimal Solution (especially in the context of MOO) can be defined as "finding a solution that maximises the degree of satisfaction and minimises the degree of dissatisfaction of an intuitionistic fuzzy decision" (Razmi et al., 2016). These forms of solutions are the only acceptable types within the realm of MOO as all other solution types may be improved upon.

The Pareto optimal solution can be mathematically defined as the subset:

$$WP(X) = \{x^p \in X: \ such\ that\ there\ does\ not\ exist\ x \in X\ with\ f_i(x) \leq f_i(x^p), \forall i \in 1{:}\, l\ \} \quad (2)$$

This Pareto optimal solution may be further illustrated graphically as seen in Figure 2.10 for a two dimensional MOO problem harbouring two objective functions (Abakarov et al., 2013). As illustrated by Abakarov et al. (2013), the utopia vector Φ^* is the vector that contains the individual global minimums for each of the objective functions.

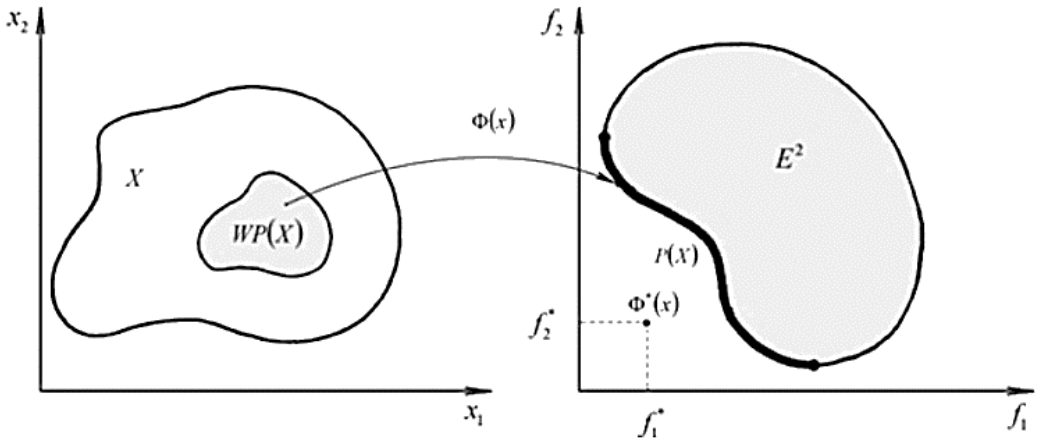


Figure 2.10: Two Dimensional representation of MOO problem and Pareto optimal solution (Abakarov et al., 2013)

In order to find Pareto optimal solutions, to MOO problems, there exists a number of methods that can be used in order to solve these multi-criteria problems. Common to all of them is the notion that most decision making can be improved by reducing the complexity of the decision through the evaluation of alternatives by means of a set number of relevant criteria. Methods such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Multi-Attribute Utility Theory (MAUT), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) and ELimination Et Choix Traduisant la REalité (ELECTRE) and more are applied (Tramarico et al., 2015). However, in the context of this work, focus will lie mainly with the Tabular method and AHP, which employs a decision matrix and Cost Benefit Analysis (CBA) as the final stage once cost data is presented.

2.5.3 Tabular Method

The tabular method (TM) as established by Sushkov in 1984 is used as a flexible approach for effectively and quickly selecting the best alternatives from a wide range of initial alternatives (Abakarov et al., 2013).

The steps that underpin the TM are as follows (Abakarov, 2011):

1. Create table / matrix with rows representing the alternatives and columns relating to the criteria of these alternatives as indicated by Equation (3).
2. For each given criteria (column), put the set of alternatives in order of the most to the least favourable.
3. Delete all non-Pareto-optimal solutions from the table.
4. Impose constraints on the remaining criteria mainly worst-case values.
5. Check if there exists non-empty set of solutions (alternatives) that satisfy the constraints.
6. Repeat steps 4 and 5 until a feasible set of solutions is obtained.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_1 & \dots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_2 \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{array} \quad (3)$$

Tabular method table / matrix where:

A_y = Alternative

C_y = Constraint

x_{yy} = Value of given criteria

2.5.4 Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is an effective decision-making approach when dealing with MOO problems. It is a type of multi-criteria decision making technique that was initially introduced by Saaty in about 1977 and again in 1994 (Triantaphyllou & Mann, 1995). The method simplifies complex decisions by making the process more systematic (Yusof & Salleh, 2013).

This decision support tool makes use of a multi-level hierarchical structure that is comprised of objectives, criteria, sub-criteria and alternatives (Triantaphyllou & Mann, 1995). This hierarchy approach is illustrated in Figure 2.11. In order to obtain pertinent data to be used in its mathematical approach, the approach makes use of the measurement of pairwise comparisons and judgements of experts in order to derive the priority scales used in its analysis (Russo & Camanho, 2015).

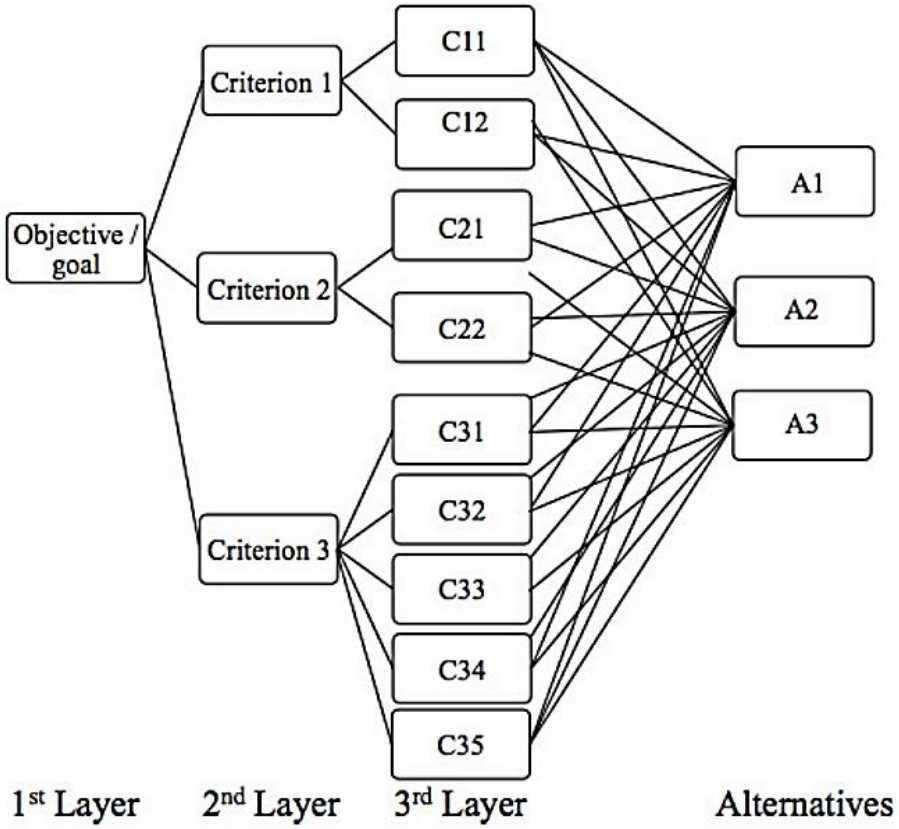


Figure 2.11: Standard Hierarchy architecture of AHP (Russo & Camanho, 2015)

AHP is a common method used to solve multi-criteria decision making challenges in various industrial sectors such as supply chain, logistics and training as it is great for assessing strategy and performance and as such it would be well suited for the application to pallet selection (Tramarico et al., 2015).

2.5.5 Cost Benefit Analysis

When looking to find an optimum solution to any problem, the aforementioned methods are excellent at determining best alternatives based on property data. However, in real world scenarios costs are often the predominant deciding factor. In order to cater for this in decision making, the concept of cost benefit analysis (CBA) has to be introduced as it allows for a more thorough decision-making process from a financial perspective.

A CBA is a tool used to rank alternative solutions on the basis off expected economic costs and benefits. In essence, a project or given alternative of a

product should be selected if the lifetime benefits exceed all the costs of the given alternative (DEAT, 2004).

It is possible to combine the standard CBA with other multi-criteria analysis methodologies in what is known as an adjusted cost-benefit analysis, however, an argument against this technique is that it may distort results of a CBA by promoting less economically favourable solutions as opposed to efficient ones (Transport and Main Roads, 2011).

2.6 Current State of Research

According to Elia and Gnoni (2015), the main research fields on pallets are currently focusing on three main issues, namely: the product design, the pallet loading and the pallet logistic problems.

The classification of the research topics is as follows (Elia & Gnoni, 2015):

1. The product design problem:
    - Usually affects pallet producer companies
    - Focus on improving performance by analysing different materials and process technologies
2. The pallet-loading problem:
    - Affects logistic and producer companies
    - Looks to define optimal loading level of pallet in order to minimize warehousing and transportation costs
3. The pallet logistic system design problem:
    - Mainly logistic and consumer companies affected
    - Aims to design and optimise complex logistics networks that may include both direct and reverse flows.

The proposed study is a fusion between the product design problem and the pallet logistic system design problem. Literature surveys yield few publications of this nature on a comparative basis.

A study by Clarke et al. as indicated by Tornese, et al. showed the comparison between used and new pallet parts in terms of modulus of

elasticity, flexural modulus of rupture and density (Tornese et al., 2016). This study concluded that the Equilibrium moisture content (EMC) greatly influenced the average flexural strength and stiffness of a pallet (Clarke et al., 2001).

Another recent study by Dias and Alvarez (2017) compared the mechanical properties of wood. They compared 57 coniferae and 183 dicotledon wood species from the northern and southern hemispheres to data on 25 commercialised plastic lumber and 146 experimental thermoplastic products (Dias & Alvarez, 2017). These two approaches to the analysis of used wood pallet parts as well as the static mechanical test procedures was adopted in this work.

Although some studies have investigated the impact of returnable pallet models versus one-way pallet alternatives (Bengtsson & Logie, 2015; M. A. Bilbao et al., 2011; Carrano et al., 2015), few efforts seem to address the impact of the selected material of construction, be it wood, metal or plastic. This study aims to address this gap and contribute to literature on this subject whilst concurrently assisting in decision making processes for various stakeholders within the pallet supply chain, including pallet pooling providers, recyclers and end users.

There are plenty of “in-house” studies from pallet manufacturers and service providers, which do carry some merit, however, some assumptions used in these studies may be biased and not completely transparent (Carrano et al., 2015). Table 2.5 indicates some of these publications. The trend as seen here illustrates that wood pallet manufacturers and suppliers see their product as the better option and likewise for plastic pallet companies, whereas neutral parties identify the benefits of either under certain conditions. The lack of independent academic research in this regard opens up an opportunity to probe issues relating to pallet-type selection criteria as well as provide reproducible comparisons from the study.

Table 2.5: Wood vs. plastic publications on perceptions

#	PREFERRED PALLET MOC				
	WOOD	**PLASTIC**	**DEPENDS**	**KEY DECIDING FACTOR(S)**	**REFERENCE**
1	√			Wood sustainability, low energy requirement	(Pallet Management, 2017)
2			√	Multi-criteria decision	(Hassiotis, 2016)
3		√		Quality, durability and dependability of plastic	(Custom Built Plastic Pallets, 2018)
4			√	Multi-criteria decision	(Prostack, 2016)
5			√	Load weight (if >1500 lbs. or 680 kg), International shipment	(Lund, 2015)
6	√			Cost, Environmental impact	(Kronus, 2016)
7			√	Multi-criteria decision	(Eightohtwo, 2017)
8		√		Carbon footprint, lifespan	(MECS, 2017)
9			√	Multi-criteria decision	(Olympic, 2013)
10		√		Load savings, sustainability	(IGPS, 2017)

2.7 Summary

In this chapter the foundation was laid for understanding the pallet, which happens to be the foundation of the product value chain in the distribution environment when it comes to materials handling. The different types, designs and materials of construction are presented herein. Following this, the author looked to enlighten the readers on the different equipment that the pallet interacts with and further demonstrated the manner in which all these components are managed by means of pallet management strategies.

As pallets are a main component of a product supply chain, the topic of supply chains is investigated in order to gain a better insight as to the role pallets play in the overall product life cycle. A brief segment on consumer markets with a look at local context ensures that the reader is made aware from the onset about some decision factors that were considered in preparing the methodology of the study.

The theory relating to different decision support tools is displayed in order to allow the reader some insight into the underlying theory for the MCDA tool development. Lastly a brief summary of the current state of research on this topic is presented in order to highlight the reason as to why this work is critical in filling an observed gap in this field of research.

CHAPTER 3:

RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

The objective of this chapter is to illustrate the research design and methodology used within the body of this work. A unique approach is taken in the study that probes the pallet from a micro analysis and simulation model basis. This is then followed by a macro analysis approach wherein a case study is conducted in order to actively compare the pallets by means of a field-study or trial. Lastly, a theoretical approach culminates the work by analysing data (including survey responses) in order to produce a multi-criterion optimization and decision-making tool.

3.2 Research Design Strategy

A research design strategy was used as the basis for structuring the approach for this project. The research onion from Saunders et. al. (2009), has been adopted and is depicted in Figure 3.1 outlining this works strategy.

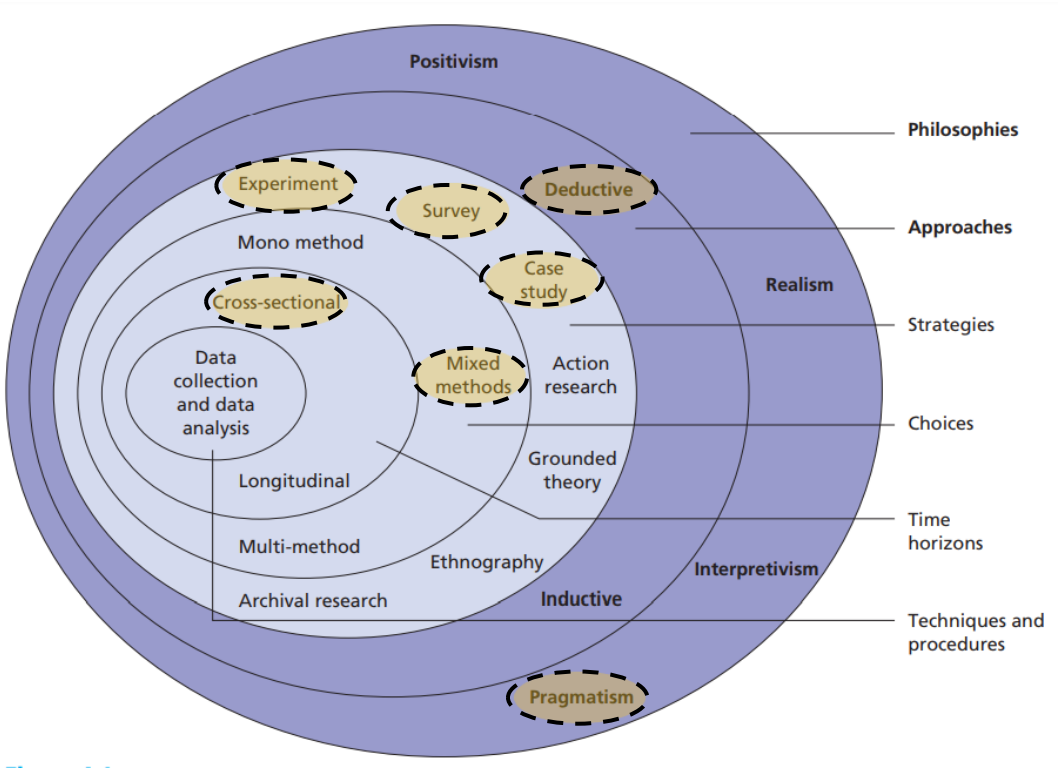


Figure 3.1: Selected strategy on the modified research onion (Saunders et al., 2009)

It is a technique of depicting the choices of data collection methods for any given research (Saunders et al., 2009). Within this figure, the process selected has been highlighted to give an indication of the philosophy, approach and strategies that underpin the methodology chosen for this research.

3.2.1 Research Philosophy

The research philosophy undertaken in this study is that of pragmatism. Although positivism and interpretivism are the two main paradigms within which a lot of academic research falls into (Dudovskiy, 2018). The nature of this work requires a more pragmatic approach in that it allows the research to combine elements from these extremely mutually exclusive paradigms within the same study. Table 3.1 indicates the relative differences between these philosophies and gives an indication for the rationale behind selecting pragmatism.

Table 3.1: Differences between philosophies (Dudovskiy, 2018)

	Research Approach	**Ontology**	**Axiology**	**Research Strategy**
Positivism	Deductive	Objective	Value-free	Quantitative
Interpretivism	Inductive	Subjective	Biased	Qualitative
Pragmatism	Deductive or Inductive	Objective or Subjective	Value-free or Biased	Qualitative and / or Quantitative

3.2.2 Research Approach and Strategy

Of the two commonly applied approaches, i.e. inductive and deductive, this study follows a deductive approach as it is formulated on the basis of a sound theoretical position with the aim of affirming or disproving certain preconceptions. In order to accomplish this, the strategies employed include experiments, surveys as well as a case study. These will all be elaborated upon further in the following sections.

3.2.3 Research Methods

As the work in this dissertation is aimed at understanding the impacts that the selection of a pallet on the basis of its MOC has on the respective supply chain network, it was decided that a mixed methods approach was the best way to achieve this. As outlined in chapter 1, the work was streamlined into four phases. Herein, a mix of both qualitative and quantitative research instruments were used.

Qualitative methods, as is presented in the following sections, offer an effective avenue for examining the market and pallet users of experiences and perceptions. Coupling these methods with quantitative instruments ensures that performance expectations are aligned with real world handling experiences of pallets.

This unique mixed methods strategy ensures that both the quantitative and qualitative approaches, in combination, provide a much better understanding of the research problem than either would in isolation. As such, the decision proved to be in line with the aims and objectives of this project.

3.3 Phase I Methods

Phase I aims to form an understanding of the motivations and perceptions behind the selection of a pallet for a particular supply chain network, a qualitative research method proved more ideal for this phase.

3.3.1 Research Instrument

As previously stated, this phase of the study aimed to obtain insights of the market sentiments with regards to the impact of pallets in their respective industries. As such, the study made use of online surveys as primary research instruments for this phase. The surveys were aimed at both pallet manufacturers as well as the clients that make use of pallets within their business activities.

The surveys contained questions (in summary) on company type and industry, pallet type usage, pallet management model, end of life treatments

and a Likert scale style segment relating to decision factors affecting choices around pallets. A copy of the digital surveys may be found in Appendix B and contains the individual surveys circulated for both pallet manufacturers and pallet consumers / users. In addition, an ethics certificate has been attached as well.

Surveys are a popular method of data collection for research studies. The main justification to use this technique in this work was that it allowed for extensive data collection at a low cost and easy distribution (Dudovskiy, 2018).

3.3.2 Data Collection and Sampling

Relevant questions pertaining to pallet use case, environment of use, industry and deciding factors in pallet selection were all incorporated into two separate online surveys. Email as well as other online methods (contact forms), were used as the mode of distribution of the surveys.

The nonprobability sampling technique, convenience sampling, was used in this phase as the sampling method (Shukla, 2008). This was motivated by the variability in the population and the nature of this research. Company selection was primarily done by focussing on those registered on the Johannesburg Stock Exchange (JSE, 2018), with the remaining sources being a general search for companies within a specified industry. The objective was to maximise the number of respondents from the consumer study.

3.3.3 Analysis procedures

The data from the responses from the surveys was collated and compiled into Microsoft Excel spreadsheets. This data was then used to determine the market state pertaining to pallet type adaptation and use case scenarios. Market size for each of the MOC could subsequently be estimated on the basis of responses as well.

3.4 Phase II Methods

A key objective of the study was to determine the material properties of wood and plastic pallets and in essence correlate mechanical properties to overall performance of the pallet. In order to carry out this objective, a combination of experimental work and simulations were coupled together. This allowed for the ability to conduct a form of “micro analysis” by looking at the material properties and then a “macro analysis” by conducting standard pallet tests and then modelling / simulating the pallet behaviour.

3.4.1 Research Instruments

The first segment of this phase employed experiments, as outlined in the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) documentation, relating to material properties and to carry out pallet tests. The second segment of this phase involved modelling the test pallets in order to simulate loads and conditions. For this purpose, Autodesk® Inventor® was used in order to conduct the simulations. Inventor® is a popular professional grade solution for creating 3D mechanical design, simulation and visualization solutions for engineers and designers and as such proved to be the best tool to use in this phase.

3.4.2 Sample Selection and Preparation

The goal of the study was to thoroughly assess the impact that the selection of a pallet of a specific MOC has on the supply chain. As such sample pallets had to be identified, selected and prepared for use and study within the scope of this work.

Selection

As part of the study, the Chemical and Metallurgical Engineering Faculty at the University of Witwatersrand partnered a client within the local pallet industry, as part of a CSR initiative. Henceforth referred to as “the client”. This partnership allowed for access to pallets supplied by the client and were chosen as the basis of some sections of the study. The client made 3 different specs of pallets available to Wits University, namely; wooden pooling pallets, plastic polypropylene (PP) pallets and composite plastic

pallets made of high-density polyethylene and polypropylene (HDPE + PP) with steel reinforcement. The specifications of the pallets are outlined in section 3.5.1.

In terms of pallet selection and justification, the wooden pallet (Pallet B) made by the client was the best wood option for the wood specimen of the study as this pallet has been used extensively in local pooling markets with a proven track record. However, in terms of plastic pallets, a number of options were eliminated in preference to pallets from the client mainly due to cost of procurement and the unsuitability of the competing plastic pallets for the SA pooling environment.

It should however be noted that for phase II (characterization and modelling), particular emphasis is placed only on the wood pallet and the PP pallet as both these pallets are made predominantly of one material allowing for distinct comparison of “wood” vs “plastic”.

Preparation

In order to carry out the material analysis experiments, the pallet samples had to be resized in order to obtain adequate test specimens. Figure A.1 and Figure A.2 illustrate the reduction and sample extraction technique followed in this work for both the wooden and plastic pallets.

For the wooden sample, the deckboard slats were dislodged from the support stringers as shown in Figure A.1, these slats were further planed down to the prerequisite thickness for the testing as per the given standard. Once the samples were resized correctly, a Trotec Speedy 400 Laser engraver was used to cut the specimen samples to the required specification (Figure A.15) as per the ASTM standards.

The plastic (PP) sample on the other hand was cut into sizable samples by way of a Mössner Rekord band saw. However, unlike the wooden specimen, the decision was made to have the specimens water-jet cut in order to reduce them to the required dimension as ASTM standard D638 (Figure A.15).

3.4.3 Material Characterization & Analysis

In order to confirm materials of construction of the supplied pallets, Fourier transform infrared spectroscopy (FTIR) was used as the validation technique. FTIR is a widely used analysis tool used for the identification of functional groups and ultimately the chemical structure of a substance (Esteves et al., 2013).

A PerkinElmer Spectrum Two FTIR spectrometer was used to gather spectra between the 4000 cm^{-1} to the 450 cm^{-1} boundaries. The PerkinElmer software uses a peak height algorithm to identify absorption bands (Jung et al., 2018). These bands were compared with those reported in literature in order to confirm the identity of the material under analysis.

Material Morphology and Topology

In order to compare the wood and plastic specimens for the morphology and topological characteristics, speciality imaging analytical instruments were employed in order to facilitate for this imaging. A quantitative dimensional measurement of the surface features of both materials provides an understanding of how these materials interact with their environment at the surface level from a microscopic point of view.

Understanding the plastic and wood structure aids in better formulating an analysis on how the different materials can be affected due to a change in environment and how this can ultimately affect the performance of the overall pallet unit.

A scanning electron microscope (SEM), as depicted in Figure A.8, is particularly useful most types of surface morphology examination (Výchopňová et al., 2007). This is done by 2D imaging of the sample surface. In order to prepare the plastic specimens for SEM analysis, it was coated with 30nm of carbon (C) followed by a gold (Au) coat (Figure A.9). The wood specimens were however mounted as usual on a stub, and coated with 10nm C and 5nm Au/palladium (Figure A.10). Both samples were bridged.

On the other hand, in order to gain a quantitative analysis of the surface for parameters such as surface roughness, a different analytical technique needs to be employed. Within this work, atomic force microscopy (AFM), as can be seen in the unit in Figure A.7, was the technique used to investigate this area of interest. It gave a three-dimensional representation of these sample surface properties. No special sample preparation was required apart from size reduction to meet unite operating size.

Mechanical Characterization Experiments

When it comes to modern product design and development, design decisions are often market related and driven by functional and market value. As such, the objective of any good design is to meet user requirements whilst respecting the properties, mechanical or otherwise, of the materials used for construction (Tepic et al., 2012).

An understanding of the materials used in the design of pallets hence plays an important role particularly from a mechanical standpoint. The mechanical properties of a MOC can often be extended to its structure, in this case the pallet it is used to construct.

Mechanical properties such as tensile strength and elasticity modulus were determined by standard procedures with the goal of comparing these properties for each respective material. In addition, the tests were coupled with weathering tests and exposure of specimens to low temperatures of approximately -12°C (over a 1-month duration) in order to study how the influence of operating conditions and weather on the mechanical properties. Figure A.13 and Figure A.14 illustrate these setups.

A Shimadzu Universal testing machine as pictured in Figure A.11 and Figure A.12 was used in order to carry out the tests. A schematic of the tensile testing apparatus is presented in Figure 3.2. Selection and preparation of standardized test specimens was outlined in section 3.4.2.

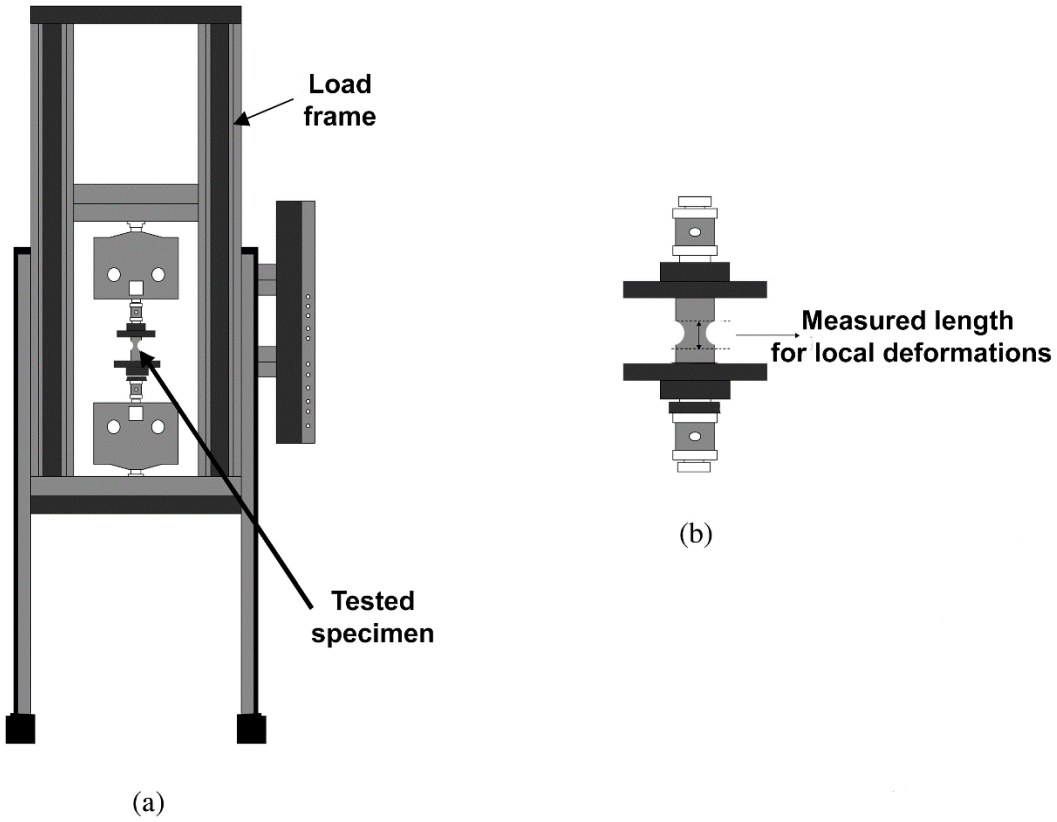


Figure 3.2: a) Mechanical test setup. b) Sample schematic in grips

Specimen size, geometry and finish etc. was all done as per the relevant standard in order to obtain accurate and reproducible results. The tests were carried out on dumbbell-shaped samples and approximately 4 mm thick (Figure A.15) at 22 ± 3°C at 40% RH, with a crosshead speed of 5 mm/min.

3.4.4 Pallet Analysis

The International Organisation for Standardization (ISO) has documented a number of standards relating to pallets and how their performance maybe be tested in order to meet industry expectations. The standards include rules and regulations that manufacturers should adhere to regarding pallet dimensions, designs, types of MOC, testing methods and performance expected of pallets. In this work, ISO 8611 is the main standard used in studying the pallets with a particular emphasis on tests regarding racking and bulk storage as these are the main use case environments that the test

pallets would be exposed to. The modifications made to the standard for the testing have been outlined in appendix C.

In addition to the standard, the StackBuilder open source tool, was used to determine optimum case palletization configurations. The objective was to conduct the tests with a typical load whilst adhering to the specifications set out by the standard. This is further elaborated on in section 5.3.

3.5 Phase III Methods

This phase of the work looked to incorporate an interactive assessment of pallets within the supply chain in order to gain a better understanding of the impact of each pallet type within the industry. As such, this phase featured qualitative research methods such as brief on-site interviews and a case study.

3.5.1 Research Instrument

Observations by means of a case study was the chosen research instrument. The objective of using this method was to ensure that the study incorporated a first-hand experience of the performance of the pallets of varying MOC in unique supply chains. As defined by Robert K. Yin., a case study is “an empirical inquiry that investigates a contemporary phenomenon (the ‘case’) in depth and within its real-world context” (Hollweck, 2016). This notion is precisely what is imposed within this phase of the project in order to study and analyse pallet performance.

As indicated in previous sections, the study makes use of 3 different specs of pallets as supplied by the client. Within the scope of the case study, 27 of the pallets were earmarked to form the basis of the study, comprising of 9 pallets of each spec, i.e. wood, plastic (PP) and steel reinforced plastic.

The following table indicates the pallets that were procured for the purposes of running trials and testing within the study.

Table 3.2: Pallet properties of pallets in study

PALLET TYPE			
Pallet Property	**Plastic: Pallet A**	**Wood: Pallet B**	**Plastic: Pallet C**
Dimensions (mm)	1000x1200x150	1000x1200x166	1000x1200x160
Approx. Mass (kg)	26-27	33	22
Material of Construction	HDPE (top) + PP (bottom) + steel reinforcement	Timber: SA Pine	PP
Load Capacity (kg)	1250	1000	1000
Max Pallet Stack	3x	3x	4x

The case studies conducted were on the basis of trialling the sample test pallets within well-defined supply chain networks which are prevalent in the South African consumer goods industry. A focus of the study was to work within the fast-moving consumer goods (FMCG) industry as it provides an assortment of working environments within which to test the pallets.

Three such environments were of focus in this study, namely; dry goods, perishables and cold chain consumer goods. The case study process involved introducing the pallets at manufacturer sites at the start of one of these chains and allowing the pallet to traverse the supply chain until it exits either at retailer level or along the chain.

3.5.2 Data Collection

A goal of this phase is to understand and analyse how the test pallets perform in the field in relation to one another and expectations on the basis of a few critical metrics. The following key metrics indicate the sort of interaction to be observed within the study from a PHE point of view and serves as the basis for data collection in this phase:

- Pallet interaction with human operated electrical or engine powered machinery, e.g. a forklift truck (Figure 3.3).
- Pallet interaction with human operated manual machinery, e.g. a pallet jack (Figure 3.4).
- Pallet interaction within a fully automated system e.g. a conveyor system (Figure 3.5).
- Pallet interaction with other unit loads or products and storage settings, e.g. stacking configurations with other unit loads (Figure 3.6).

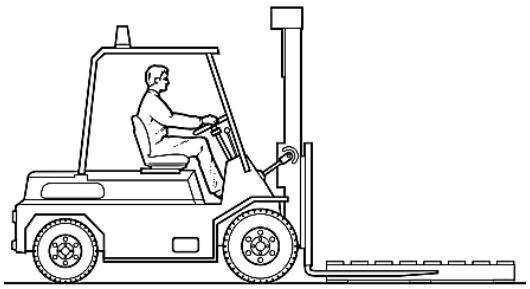


Figure 3.3: Pallet use with Forklift truck (Health and Safety Executive, 2014)

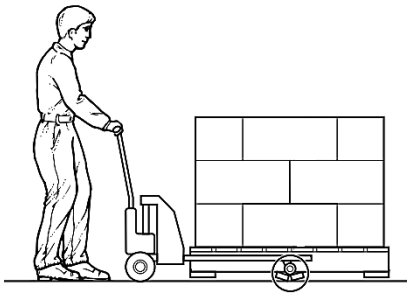


Figure 3.4: Pallet use with pallet jack (Health and Safety Executive, 2014)

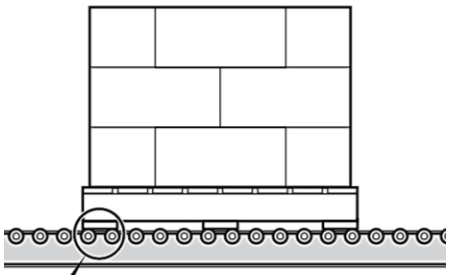


Figure 3.5: Pallet use on roller conveyor system (Health and Safety Executive, 2014)

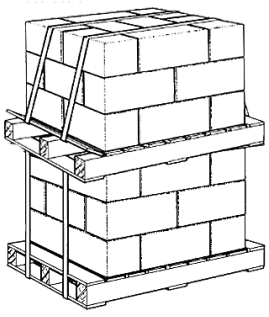


Figure 3.6: Stacked pallet configuration

3.5.3 Analysis Procedures

Pallets are exposed to various conditions in the distribution environment. This comes in the form of operating parameters i.e. temperature, moisture etc. and operating environment i.e. warehouses, pallet handling equipment, logistics transportation etc. Thus, the data collected is analysed by inferring pallet performance with how well it interacts with the given key metrics mentioned above as well as ascertaining how the conditions in a particular distribution environment may have affected this performance.

This analysis was done purely by inference and the theoretical propositions from this phase are combined with the results of phase II in order to confirm the perceived behaviour as a function of the given environmental exposure.

3.6 Phase IV Methods

One of the main objectives of this research work was to develop a form of multi-criteria decision analysis (MCDA) tool for pallet selection. This phase is dedicated to formulating this tool and ensuring its viable use in the relevant industries.

3.6.1 Research Instrument

Computer modelling was undertaken in this phase. A web application was the chosen method of implementation of the model execution as it allows for easy access to potential users of the tool. As such the tool was developed in HTML, CSS with a JS backbone being the main language used to carry out the mathematical calculations.

This tool is based on the simultaneous application of the AHP and TM processes as are incorporated in the underlying code.

3.6.2 Data Collection

Data from all three previous methods, i.e. phase I, II and III were collated and streamlined in order to meet the requirements of the MCDA tool. The analysed data from the surveys in phase I coupled with the extensive literature review, formed the foundation of the tool development. The characterization and simulations carried out in phase two allowed for better

approximations of expected pallet behaviour and performance in varied supply chains and this data was incorporated as part of the data for this phase. Lastly, phase 3 gave an in-depth view into the specifics of real-world application of pallets of varying MOC, and this analysis forms part of the tools “validation” step as it allows the research to correlate theoretical results and assumptions with real world experiences.

3.6.3 Analysis Procedures

As this phase is essentially a culmination of the prior 3 phases, the analysis of the data is undertaken prior to this phase and no subsequent analysis is required. The tool will operate as a source of data in itself as it aims to guide consumers on decisions pertaining to pallet selection.

3.7 Summary

In this chapter, the steps and methods carried out in each phase of the study are outlined. Phase I looked at market analysis by exploring literature and conducting surveys in order to gain an understanding of market perceptions and current state of the pallet industry.

In the second phase of the study, the methods utilised were focussed on material characterization, mechanical testing and modelling. The objective was to gain an understanding of wood and plastic materials of construction from a microscopic level and further testing and modelling the pallets with the aim of predicating behaviour and performance.

The methods for the third phase, the case study, looked to give practical performance statistics to the study by allowing for a macroscopic analysis of the pallets within the distribution environment. Key metrics of observation were highlighted for this phase of the study,

Lastly, a brief insight into the methods and tools used for the MCDA tool formulation are presented which, in essence, is a culmination of all the methods and phases outlined in the preceding sections.

CHAPTER 4:

PHASE I – MARKET ANALYSIS

4.1 Introduction

In addition to the comprehensive literature review conducted in Chapter 2, a survey was carried out in order to assess the current landscape of the South African pallet industry and how various MOCs impact on known businesses.

4.2 Survey Analysis

As part of the initial phase of the project, surveys were distributed in order to fulfil the requirements for research validation. Two main surveys were distributed, one to prominent pallet manufacturers and leasers, the other to pallet consumers or end users. The survey was entirely focussed on businesses or service providers within the South African marketplace as the study looked to explore the impact within this region.

4.2.1 Pallet Manufacturers

From the pallet manufactures, a total response of 7 was received from a total of 40 targeted (surveyed) pallet manufacturers and suppliers in the South African market. The respondents were well distributed in terms of company size, as indicated in Figure 4.1, with most respondents being small businesses with 10 to 49 employees. The manufacturers were mainly located in major cities of Johannesburg, Pretoria and Cape Town, with one respondent having operations in Germiston, Sasolburg and Secunda.

The manufacturers represented entire business operations and were not limited to just one branch. In addition to this, the results showed that most of the manufacturers were involved in a diversified product offering in terms of the pallets they produced. This was evident in that 28.5% of respondents noted that they produced both block and stringer pallet designs and a further 71.4% had a product mix consisting of both 4-way and 2-way entry pallet types.

Furthermore, in terms of pallet dimensions, the respondents provided a variety of product offering with the 1000 mm x 1200 mm pallet dimension being the most common among them all. The following list outlines the popularity of the different pallet dimensions as per the respondents (dimensions given in - W × L millimetres (inches)):

1. 1000 × 1200 (39.37 × 47.24) – 100% of survey respondents
2. 800 × 1200 (31.50 × 47.24) – 85.7% of survey respondents
3. 1100 × 1100 (43.30 × 43.30) – 57.1% of survey respondents
4. 1016 × 1219 (40.00 × 48.00) – 42.9% of survey respondents
5. 1067 × 1067 (42.00 × 42.00) – 28.6% of survey respondents
6. 1165 × 1165 (45.9 × 45.9) – 28.6% of survey respondents

These results cemented the popularity and common use of the 1000 mm x 1200 mm pallet dimension in the local market.

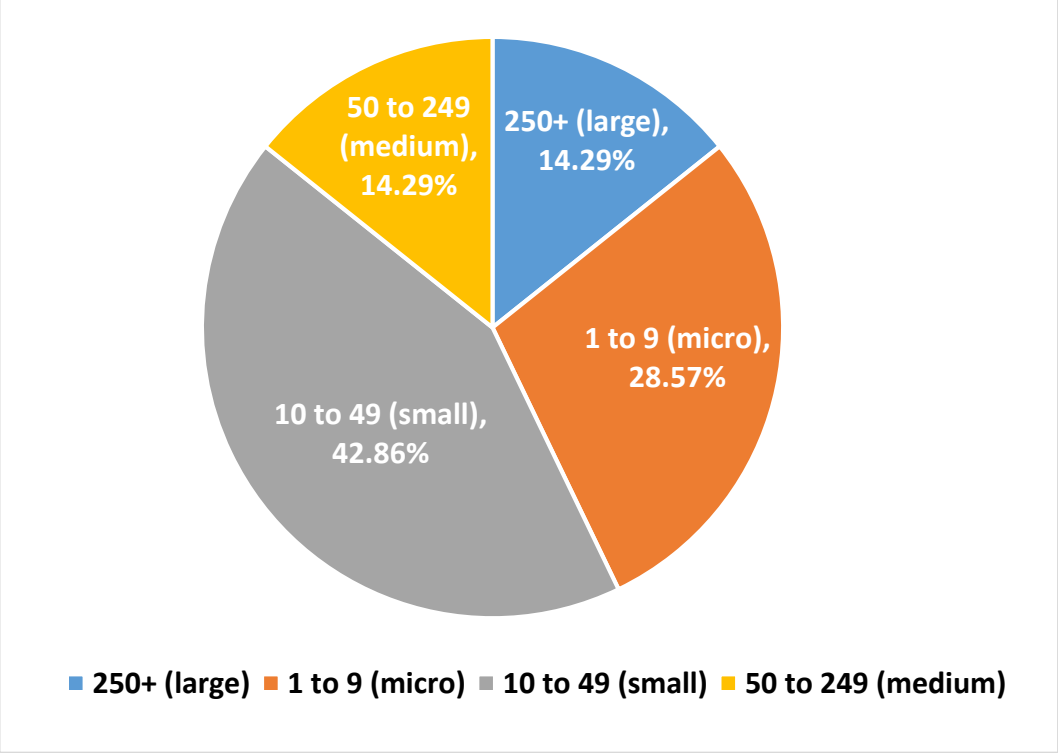


Figure 4.1: Company size of respondents - Manufacturers

These pallet manufacturers also outlined the various industries they provide pallets to (Figure 4.2). All respondents noted that they supplied more than one type of industry, however, the majority of them (6) indicated having clients within the FMCG industry. This does suggest that this industry is the main consumer of pallet products and this is consistent with theory outlined in Chapter 2.

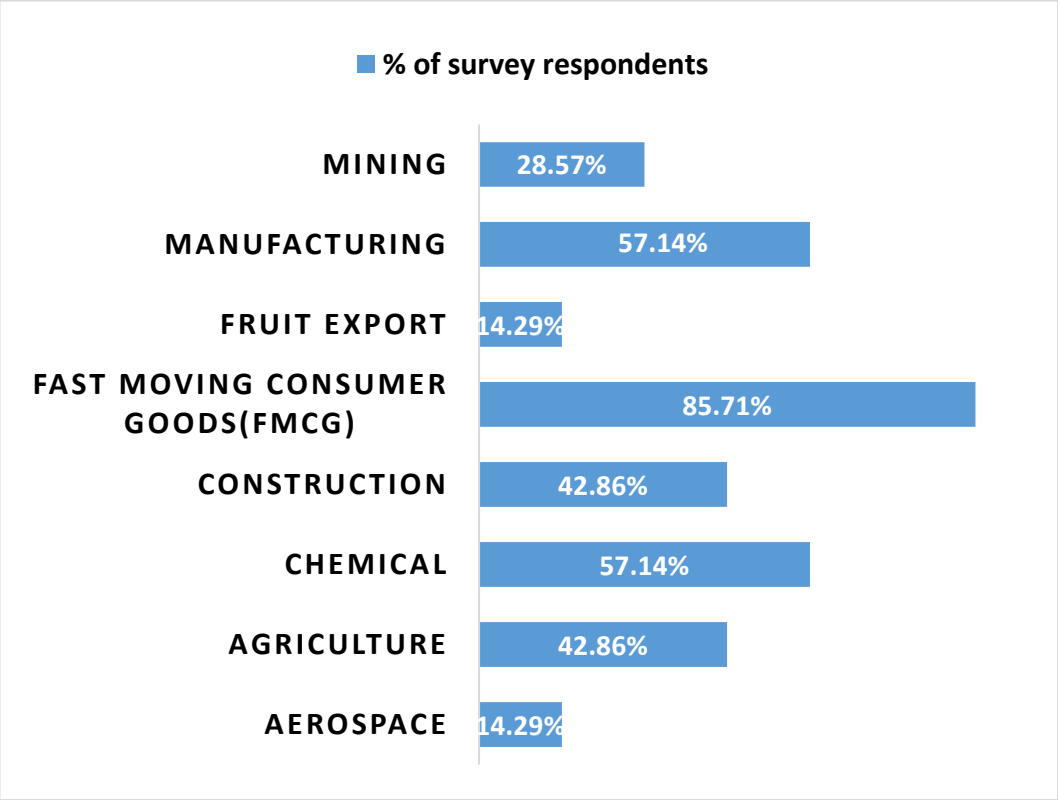


Figure 4.2: Industry types supplied by local pallet manufacturers

A key objective of the survey was to present an understanding of the pallet market in terms of availability and prevalence of the different pallet MOC. Of the survey respondents, 71.43% manufactured pallets from plastic (either virgin or recycled) and only 14.29% of respondents represented the wood market. This could be attributed to the large and fragmented nature of the wood pallet retail industry that may contain a lot of intermittent manufactures ("fly by night") (Wiggill, 2016), given that wood pallets are easy to manufacture and procure.

A further reasoning could be attributed to the strong market presence of a leading pallet pooling company in SA, in terms of wood pallet pooling, as they are believed to have well over 16 million pallets in circulation in the SA market. This data also confirms the growing appetite for plastic pallets in the local market as demand rises.

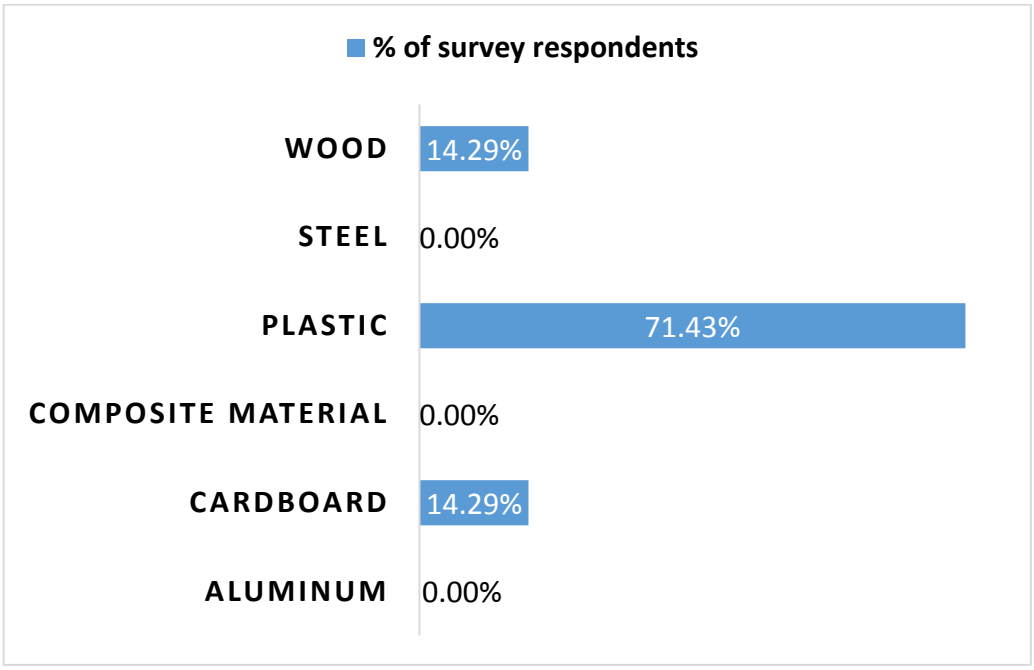


Figure 4.3: Materials used for pallet manufacture

Although the wood pallet manufacturers only represented 14.29% of respondents, they represented 86% of the total number of pallets produced by the respondents at 1 800 000 pallets of the 2 056 400-total quantity from all survey participants. These figures continue to assert the dominance of wood in the local market as a pallet MOC.

In terms of retail strategy, the respondents were overwhelmingly only in the business of manufacture and sell or resell business. Only 14.29% of respondents incorporated a leasing method to their retail strategy as can be seen from Figure 4.4. This data, coupled with that of the types of MOC manufactured, suggests that the majority of consumers of plastic pallets predominantly use them in closed loop supply chain settings or within business facilities which is also consistent with literature.

When considering the financial distinctions for pallets produced, the data was in favour of wooden pallets. The reported costs of between R230 – R2000 for new virgin plastic pallets may also validate the reasoning for closed loop application as opposed to the wood and cardboard pallets that were quoted at marginally lower prices of R150 and R250 respectively. This is due to the likelihood of pallets going missing within the supply chain as the possibility of return is low.

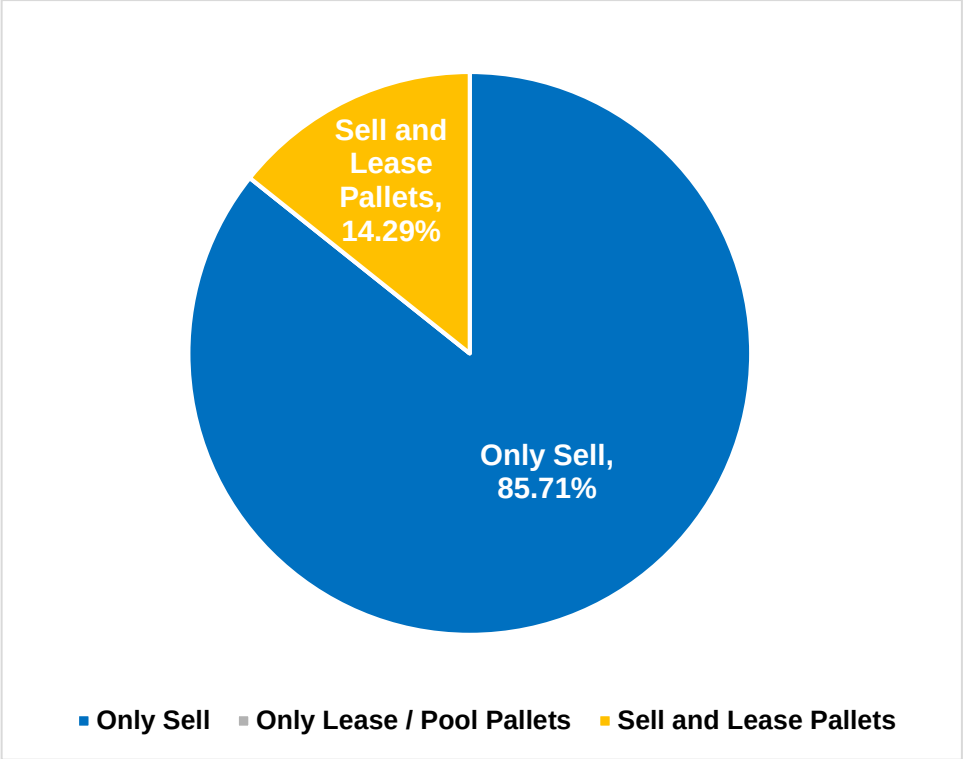


Figure 4.4: Retail strategy of pallet manufacturer

4.2.2 Pallet Users

With regard to pallet consumer data, a total of approximately 102 local businesses were targeted for the survey within various sectors of the economy. However, the response rates were not sufficient and diversified enough to present compelling results upon which assertions could be made.

The data obtained was all from the FMCG sector, in particular, the retail segment of the supply chain. Wood and plastic pallets were both present as materials utilised however, these pallets were said to be managed by third

party businesses. The use of the pallets was said to be both within and between company facilities, as well as one-way between trading partners. In addition to this, the main challenge noted for their use of pallets was the damage of pallets due to the size of the operation. As such pallet repair is a daily occurrence and unwanted problem.

4.3 Summary

The surveys provided an important insight into the pallet market within South Africa. The manufacturers survey featured sections on business type, size and location; types of industries supplied; pallet specifications and configurations produced as well as retail strategies and associated costs.

The results were largely in agreement with literature in terms of the dominance of wood as a pallet MOC at 86%. Signs of a growing plastic market are also evident with the majority of respondents being in this industry. Retail strategies are mainly focussed on reusable once off sales of pallets, which suggests that there is a small market for plastic pallet leasing and may also confirm literature considerations that suggest that many plastic pallet consumers use these pallet types within closed loop settings.

Unsurprisingly, costs for plastic pallets were up to R1850 more expensive than wood pallets which may be a reason for the reluctance of adaptation of plastic pallets within various supply chains.

Limitations

In the data centric phase 1, the quality of the research was limited by the lack of response of survey participants. As the survey aimed to gain an understanding of market perceptions, a large representative response pool is required to give greater substance to the survey results.

CHAPTER 5:
PHASE II – MATERIAL ANALYSIS AND MODELLING

5.1 Introduction

In this chapter, the primary objective is to gain an understanding of the mechanical properties of the materials used to construct pallets. Once these are well understood, tests on pallet specimens are carried out according to the ISO standards. This gives an indication of the compliance to industry guidelines and indicates the relative performance of the given pallets. Once the foundation is set with the testing, pallet modelling is carried out for further analysis.

5.2 Material Characterization

5.2.1 Material Validation

In order to best identify the specific structural chemistry of each of the materials from which the pallets were constructed, Fourier transform infrared spectroscopy (FTIR) was adopted. Specimens were extracted from the pallets used within this study as is detailed in Table 3.2 of Chapter 3. FTIR spectrum of each of the specimens were analysed for each major element of the pallet. Given that the materials are already known to some extent, particular emphasis is made on the diagnostic region (left of the 1500 cm^{-1} wavenumber) in order to identify the functional groups and confirm the materials. Thus, the fingerprint region (right of the 1500 cm^{-1} wavenumber) is mostly ignored. Furthermore, once the analysis was complete, the spectra were compared to reference spectra for further validation.

The FTIR spectrum of the MOC of the (Pallet C) pallet is given in Figure 5.1. The different bands on the FTIR spectrum, along with each of the following spectra, represents the different functional groups found within the material of analysis.

Plastic Pallet (Pallet C) - Homogenous Material (Polypropylene)

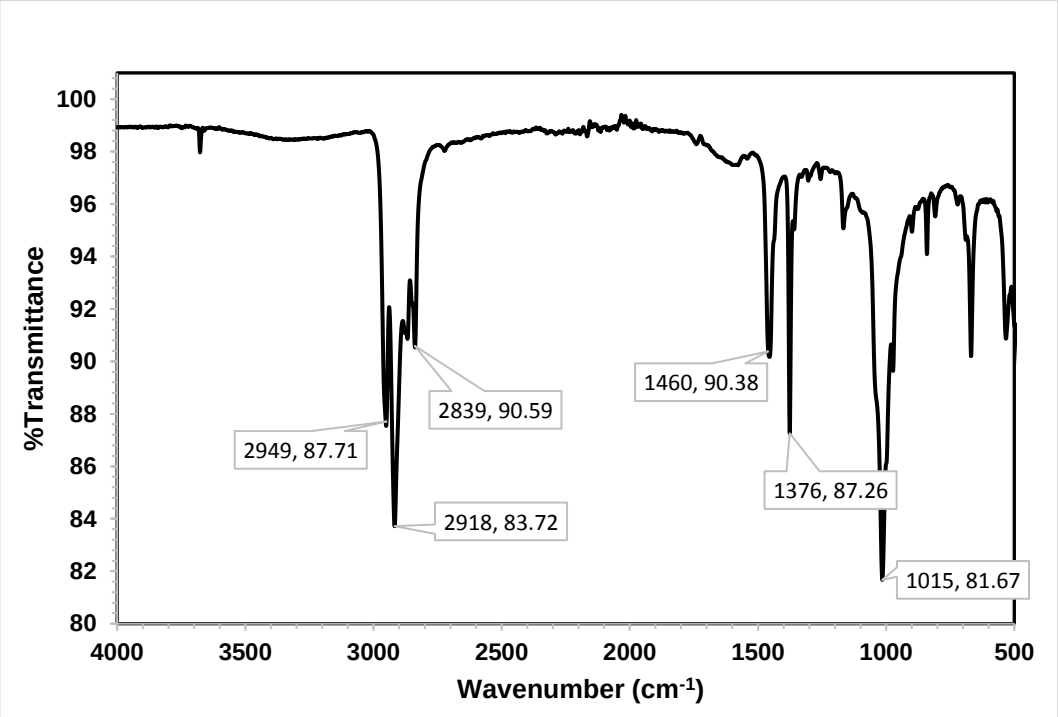


Figure 5.1: Specimen sample FTIR spectrum of Pallet C pallet body

This spectrum exhibits the profile of polypropylene as expected and is underpinned by notable peaks at 2949 cm^{-1}, 2918 cm^{-1} and 2839 cm^{-1} which represent a C-H stretch assignment. The peaks at 1460 cm^{-1} as well as 1376 cm^{-1} are indicative of CH_2 and CH_3 bends respectively (Jung et al., 2018).

Plastic Pallet (Pallet A) - Mixed Material (HDPE + Polypropylene)

The Pallet A plastic pallet is predominantly made of two components. A HDPE top layer is attached to a PP base layer. This was validated by the spectra in Figure 5.2 and Figure 5.3. The HDPE peaks are distinguished by their prevalence at 2914 cm^{-1} and 2847 cm^{-1} wavenumbers in Figure 5.2. These indicate the C-H stretch assignment, whereas the peak at 1472 cm^{-1} within the fingerprint region demonstrates evidence of a CH_2 bend assignment (Jung et al., 2018).

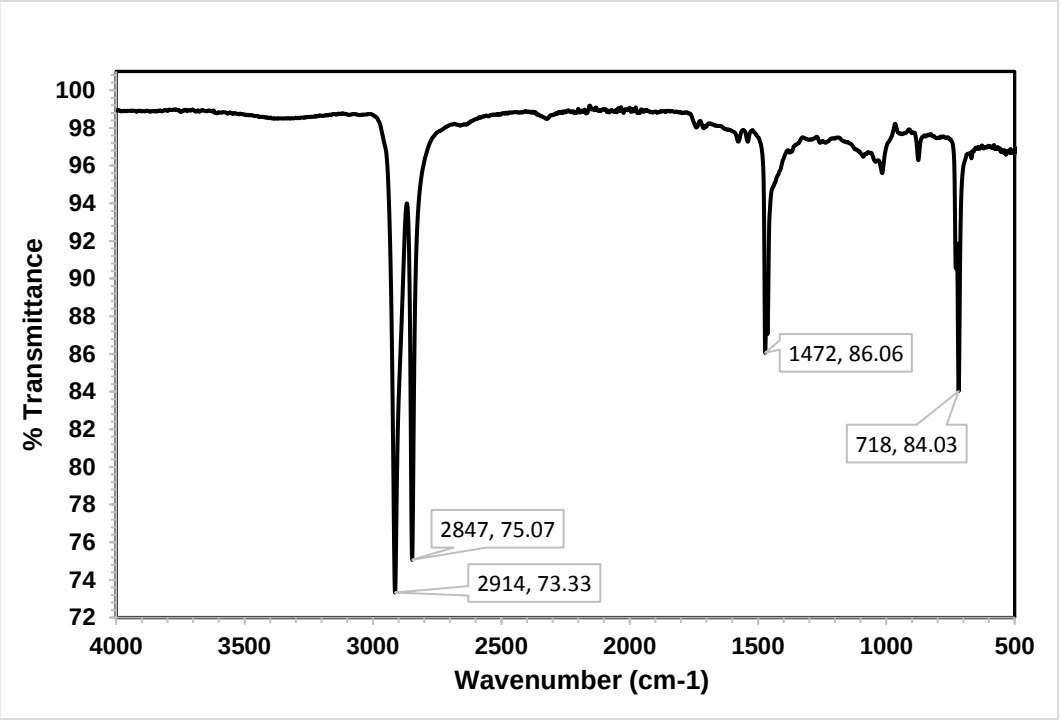


Figure 5.2: Specimen sample FTIR spectrum of Pallet A plastic pallet top layer

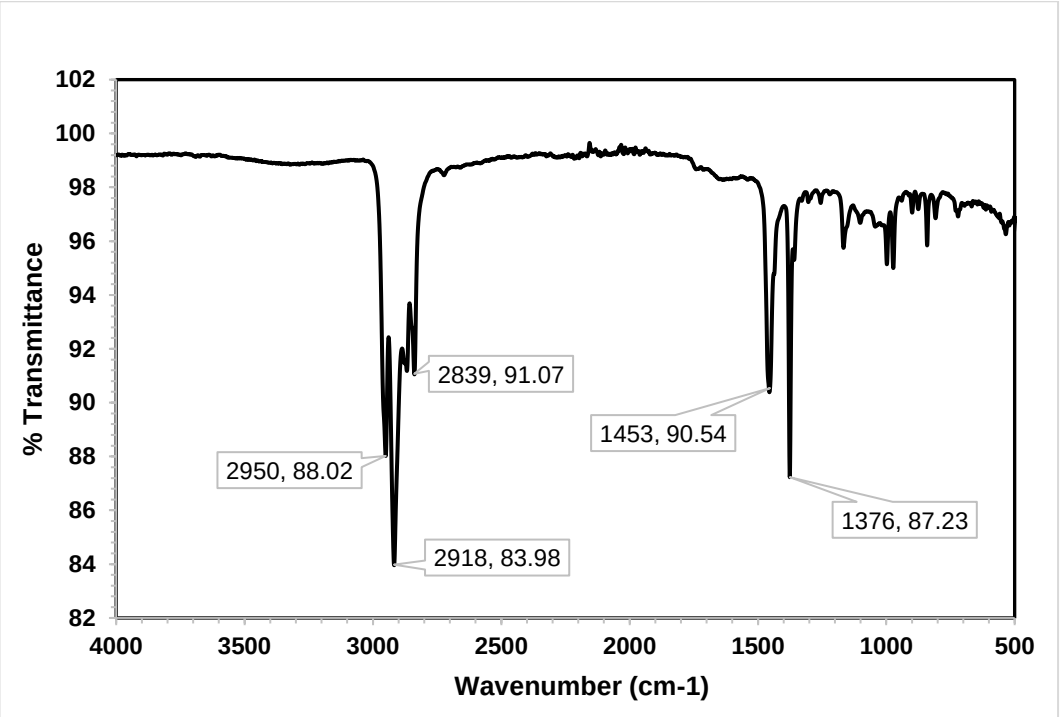


Figure 5.3: Specimen sample FTIR spectrum of Pallet A plastic pallet base layer

As with the Pallet C pallet, the base layer in the Pallet A pallet does confirm that the MOC is polypropylene as indicated by the spectrum in Figure 5.3. All the peaks in the diagnostic region (given at 2950 cm^{-1}, 2918 cm^{-1} and

2839 cm^{-1}) seem to relay the same functional groups. The only major difference between the two was that of an intense peak on the Pallet C pallet spectrum at about 1015 cm^{-1} wavenumber within the fingerprint region. This could be attributed to CH_3 rock, CH_3 and CH bend assignments respectively.

These spectra are similar to those published by other researchers in various publications (Jordi, 2014; Jung et al., 2018; Lin et al., 2015).

In Figure 5.4 and Figure 5.5, images representing the chemical formula for both HDPE and PP is given which show the respective functional groups of the given MOC.

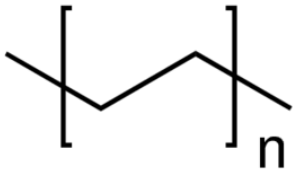


Figure 5.4: Chemical Structure HDPE

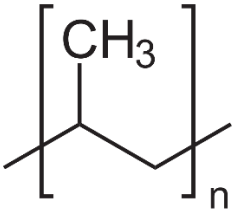


Figure 5.5: Chemical Structure PP

<u>Wood Pallet (Pallet B) - Homogenous Material (SA Pine)</u>

Pine is made up of epidermal and sclerenchyma cells which contain cellulose, hemicellulose, lignin, rosin and tannins in their cell walls. Given this, pine contains polar functional groups such as alcohols, aldehydes, carboxylic, ketones, phenolic and other groups (Sen et al., 2010).

The FTIR spectrum of the pine from the Pallet B wooden pallet is shown in Figure 5.6. Analysing this spectrum for functional groups confirms its identity. The peak at 3331 cm^{-1} indicates O-H stretching vibrations common with alcohols, phenols and acids (Esteves et al., 2013). The peak at 2869 cm^{-1}, although low in transmittance intensity, may be an indication of CH_n due to C-CH and C-CH_2 bonds. The peaks between 2000 cm^{-1} and 1500 cm^{-1} are indicative of aromatic C=C and C=O stretching bands within lignin (Emmanuel et al., 2015).

Similar spectra for pine has been reported by researchers (Chupin et al., 2013; Emmanuel et al., 2015; Esteves et al., 2013; Sen et al., 2010), however, it should be noted that pine may come in different species with varying physical properties. This can explain some of the differences in presented spectra.

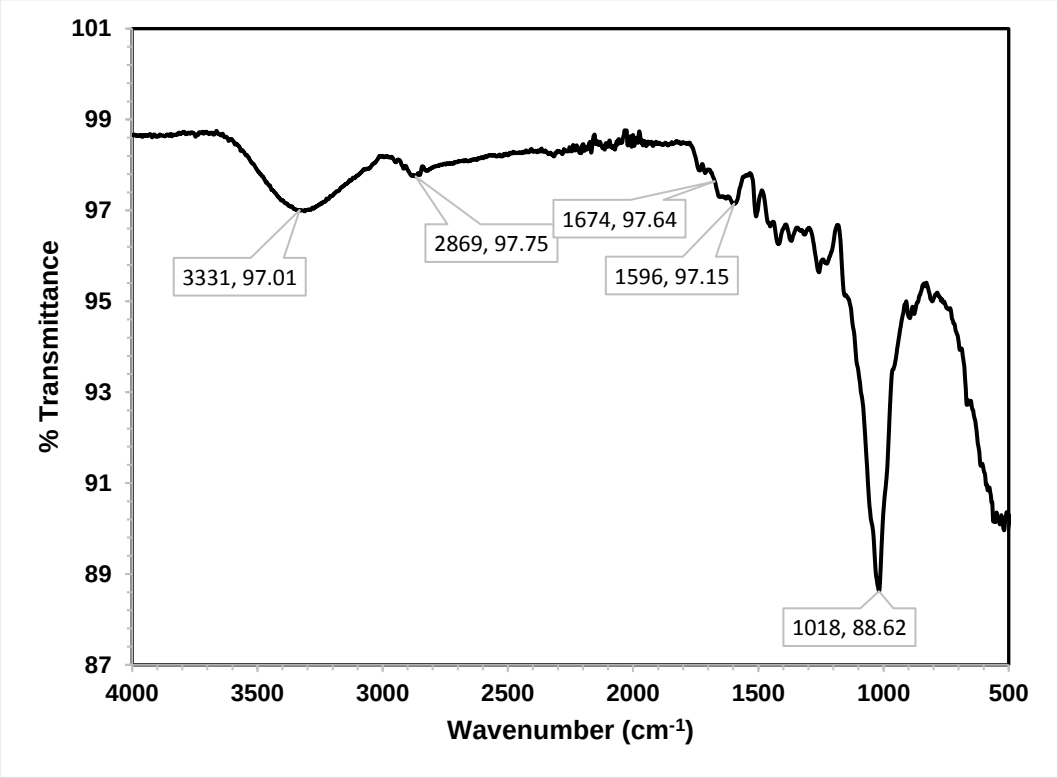


Figure 5.6: Specimen sample FTIR spectrum of Pallet A wood pallet

5.2.2 Morphology and Topology

In order to understand the surface properties of the pallet MOC and how they impact on the material handling properties of the pallets, atomic force microscopy and scanning electron microscopy was used to analyse the samples. SEM analysis gave a great indication of the morphology of both the wood and plastic specimens. Both specimens were extracted from new pallets that were yet to be exposed to the harsh conditions of the distribution environments. In terms of topology, AFM measurements presented the average roughness for both of the pallet MOC types.

Scanning Electron Microscopy (SEM)

In this work, the morphology of plastic and pine, from the Pallet C plastic and Pallet A wood pallets respectively, was observed. Figure 5.7 - Figure 5.10 show the SEM micrographs of the polypropylene samples from the Pallet C plastic pallet at magnifications between 100x and 1000x. From these, a smooth polymer surface is observable with no pores or major surface defects or cracks.

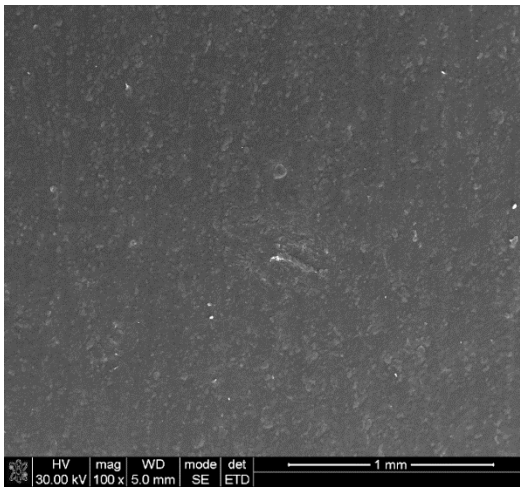


Figure 5.7: PP plastic SEM @ 100x magnification

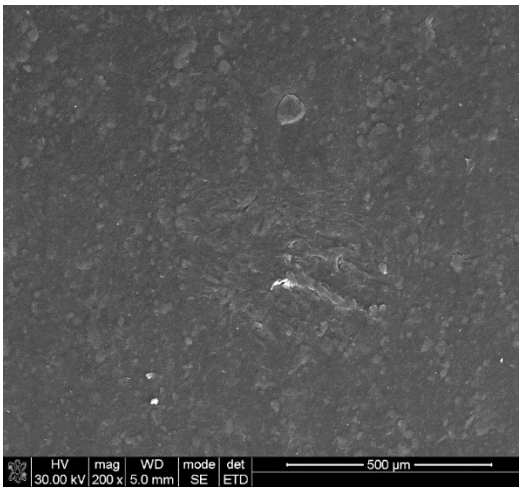


Figure 5.8: PP plastic SEM @ 200x magnification

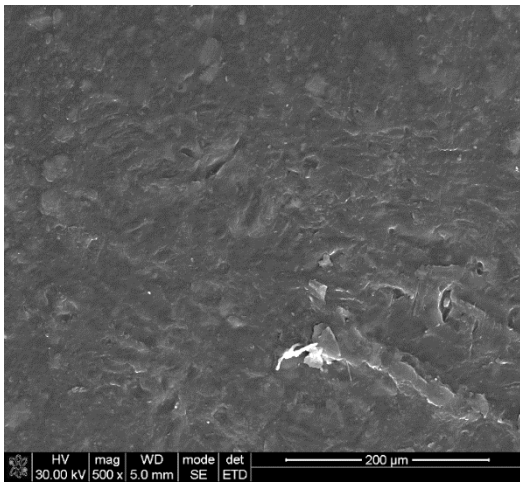


Figure 5.9: PP plastic SEM @ 500x magnification

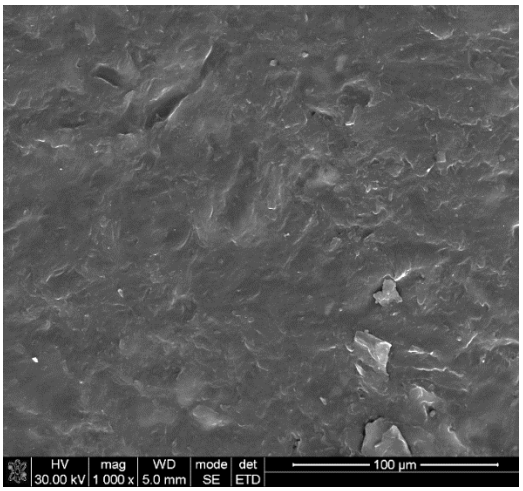


Figure 5.10: PP plastic SEM @ 1000x magnification

These characteristics of the morphology of the specimens validates findings in literature that attribute the surface properties for the ease at which plastic pallets may be cleaned and used in sterile environments as the surface leaves no room for adhesion of foreign substances. The surface is uniform and as such lends itself to predictable behaviour throughout the pallet structure from which it was obtained.

Unlike the plastic specimen, the SEM micrographs of the pine sample from the Pallet B wooden pallet (Figure 5.11 – Figure 5.14) , as shown here, indicate the porous structure of the wood.

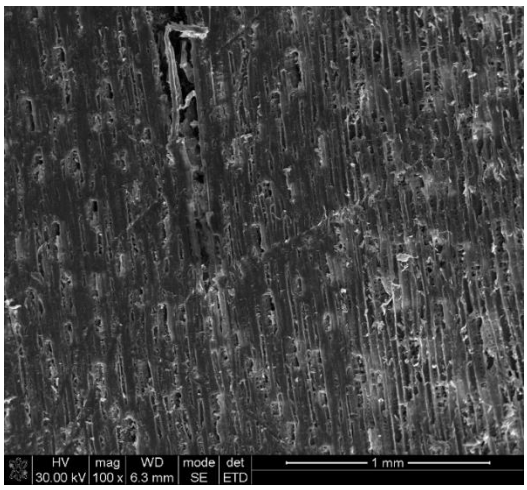


Figure 5.11: Pine wood SEM @ 100x magnification

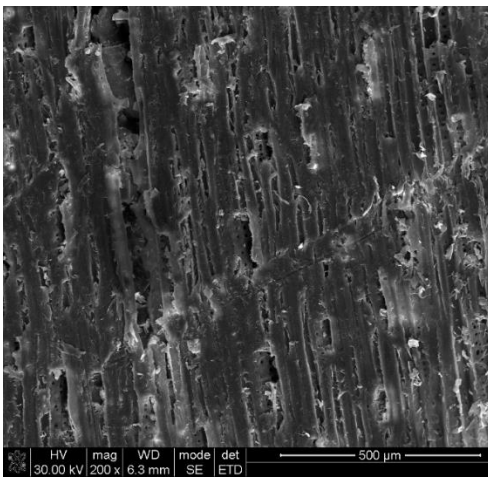


Figure 5.12: Pine wood SEM @ 200x magnification

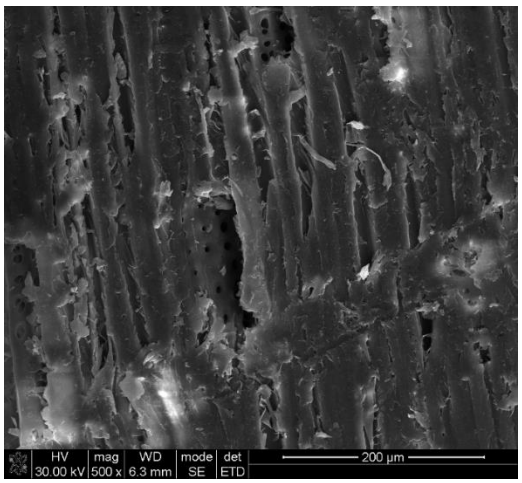


Figure 5.13: Pine wood SEM @ 500x magnification

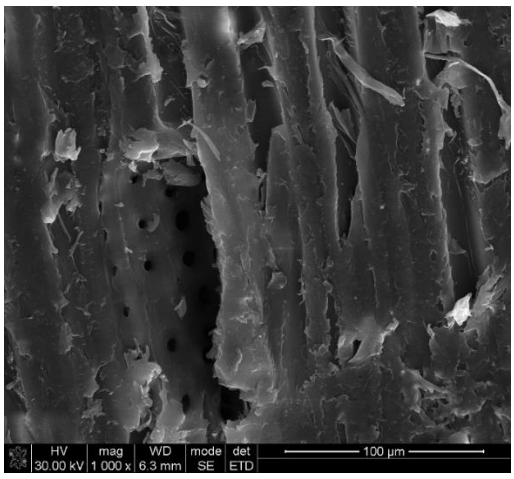


Figure 5.14: Pine wood SEM @ 1000x magnification

Similarly, the micrographs are displayed at magnifications between 100x and 1000x and allow for a better assessment of the fibrous nature of the given MOC.

This fibrous morphology may be what is responsible for the materials strength and stiffness in comparison to the plastic PP and confirms why pallets of this MOC tend to have better characteristics in terms of load bearing capabilities. The porous nature of the material though, allows for infestation by microbes or pests and may prove difficult to eradicate due to all the cracks and crevices visible in the micrographs.

The morphology of both these materials differs considerably, both in magnitude and appearance. These morphological properties presented here confirm literature findings for the different characteristics found in each pallet type and hence proved to be of significance in this work.

Atomic Force Microscopy (AFM)

Using atomic force spectroscopy aided in the quick analysis of the topology of both materials. The purpose was to gain an understanding of the roughness of the surfaces at a microscopic level. Both samples were obtained from new pallets which were smooth in comparison to those found in the distribution environment.

From the results obtained, it is unsurprising that the polymer surface is much smoother and uniform as indicated by the Ra value of 482.27 nm and has a more even height distribution as can be seen in Figure 5.15 and Figure 5.16 as opposed to that of the wood (pine) with an Ra value of 575.85 nm and a more pronounced height variation in Figure 5.17 and Figure 5.18. This data supports the findings from the SEM analysis conclusively and is in line with that presented in literature.

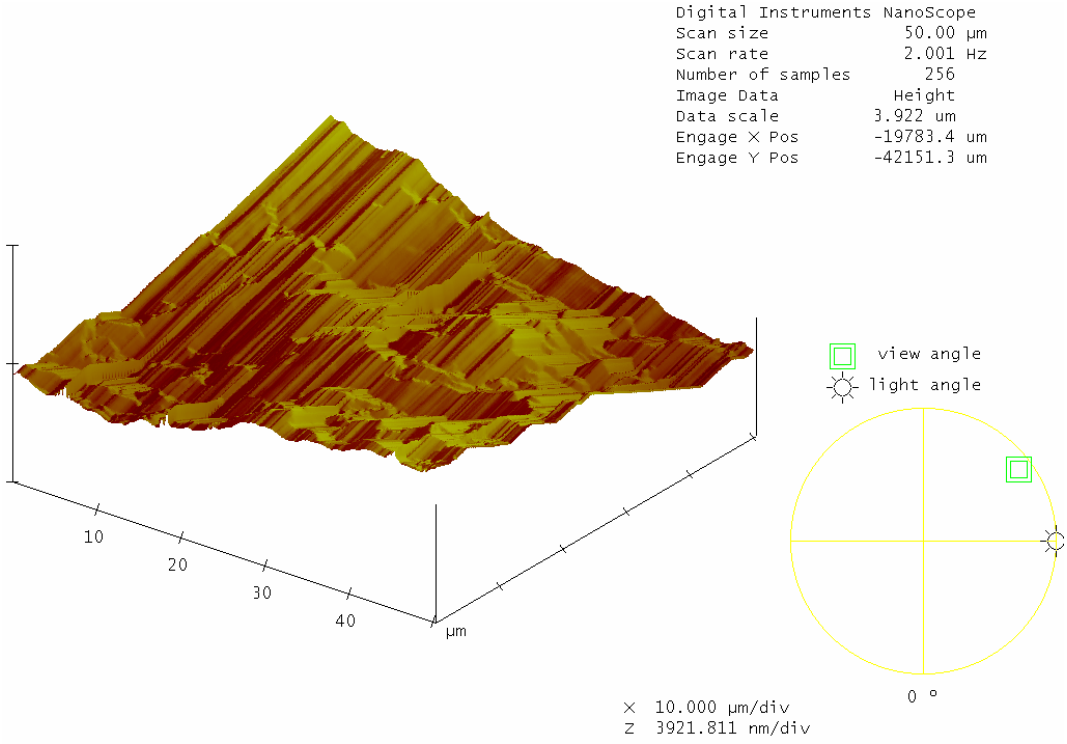


Figure 5.15: Height measurement of PP plastic at 50 µm

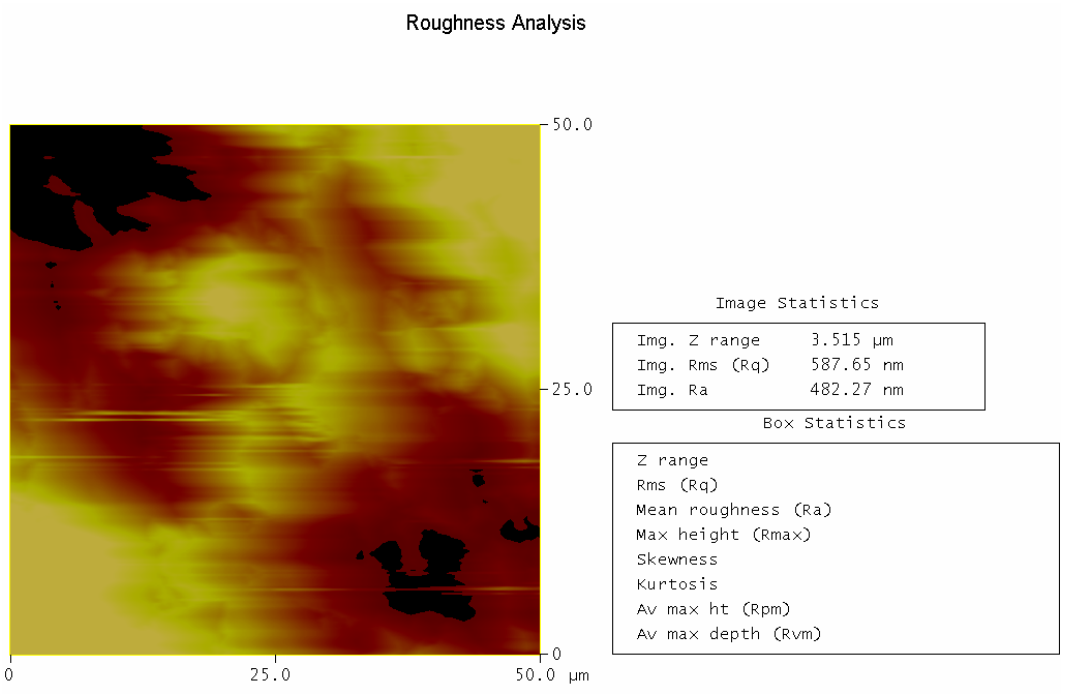


Figure 5.16: Roughness measurement of PP plastic at 50 µm

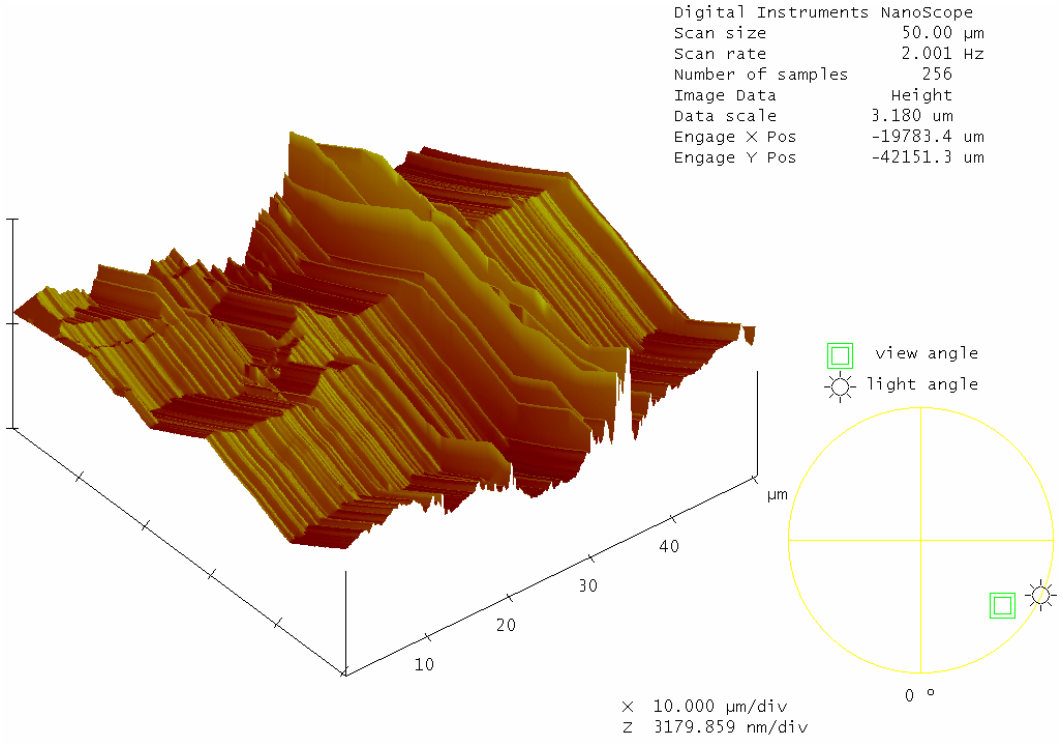


Figure 5.17: Height measurement of pine wood at 50 µm

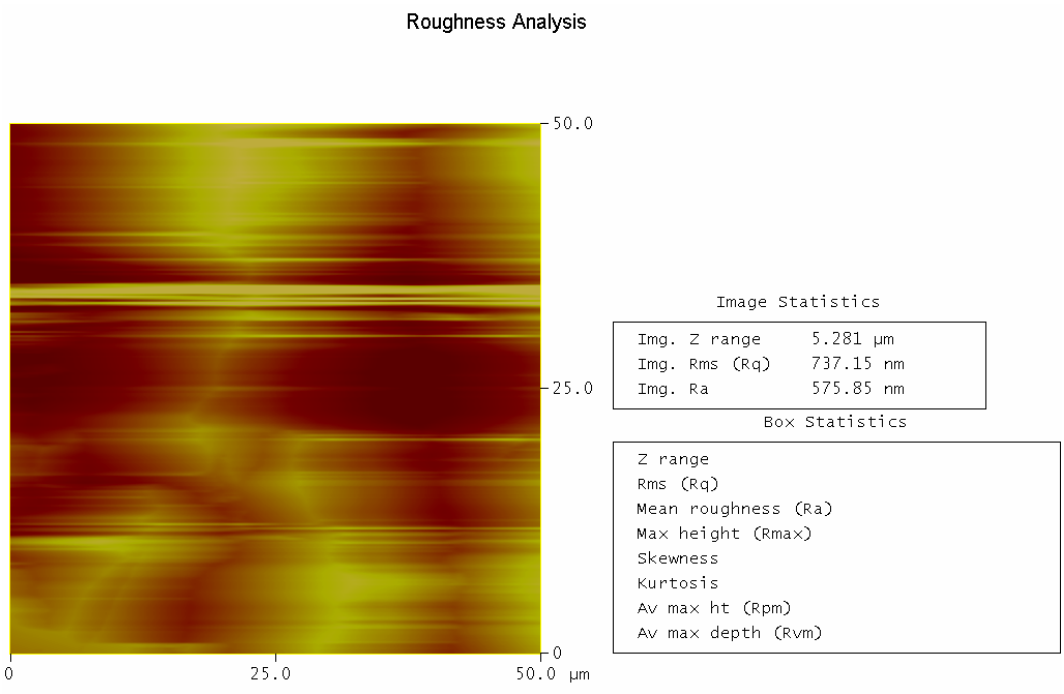


Figure 5.18: Roughness measurement of pine wood at 50 µm

5.2.3 Material Tensile testing

Material tensile testing was conducted following the procedure outlined in section 3.4.3. A set of test samples as per specification (Figure A.15) were machined from the pallets (pine from the Pallet B and plastic from the Pallet C plastic pallet) and subsequently exposed to conditions similar to the distribution environment in order to gauge the change in material properties over time. Natural weathering of the samples (Figure A.14) as well as storage in sub-zero temperatures (at -12°C : Figure A.13) were used.

These sample specimens then underwent tensile testing in order to probe the effects of these operating conditions on stress-strain behaviour. Tensile strength is an important parameter of analysis as it gives an indication of mechanical strength of a material (Sahu & Sudhakar, 2017). Figure 5.22 shows some wood test specimens after the tensile tests were concluded. Each specimen was identified by a letter that denoted the type of exposure condition and a number to distinguish the specimens. For example, N denoted normal (ambient conditions), F denoted frozen storage and W denoted weathering exposure. Fracture points are visibly identified on each specimen and results of the tests are given in Figure 5.19 - Figure 5.21.

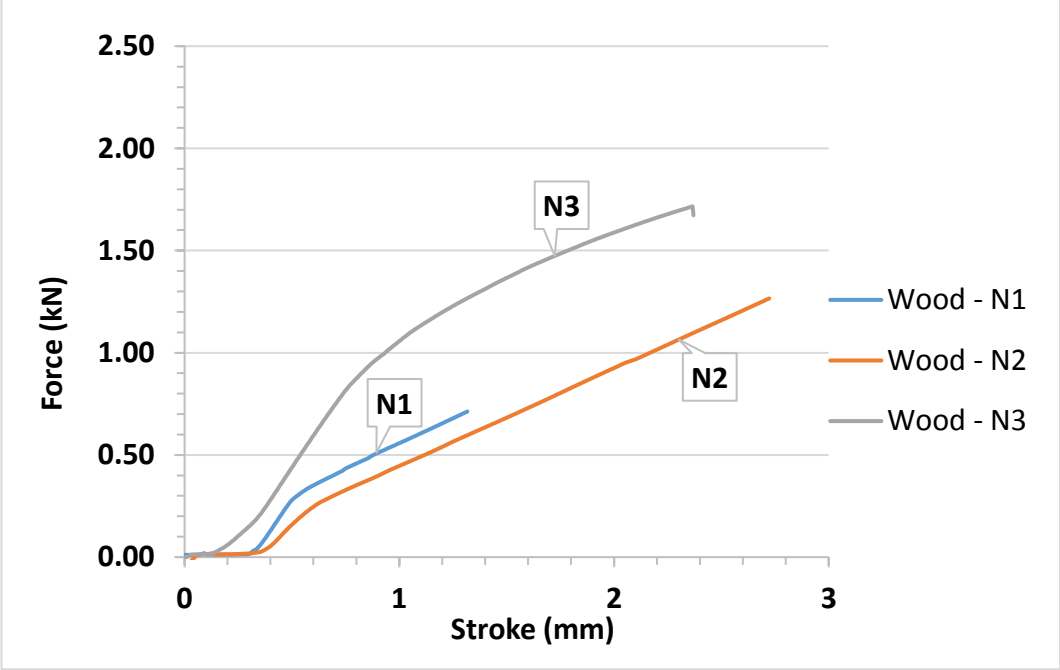


Figure 5.19: Tensile Test - wood normal

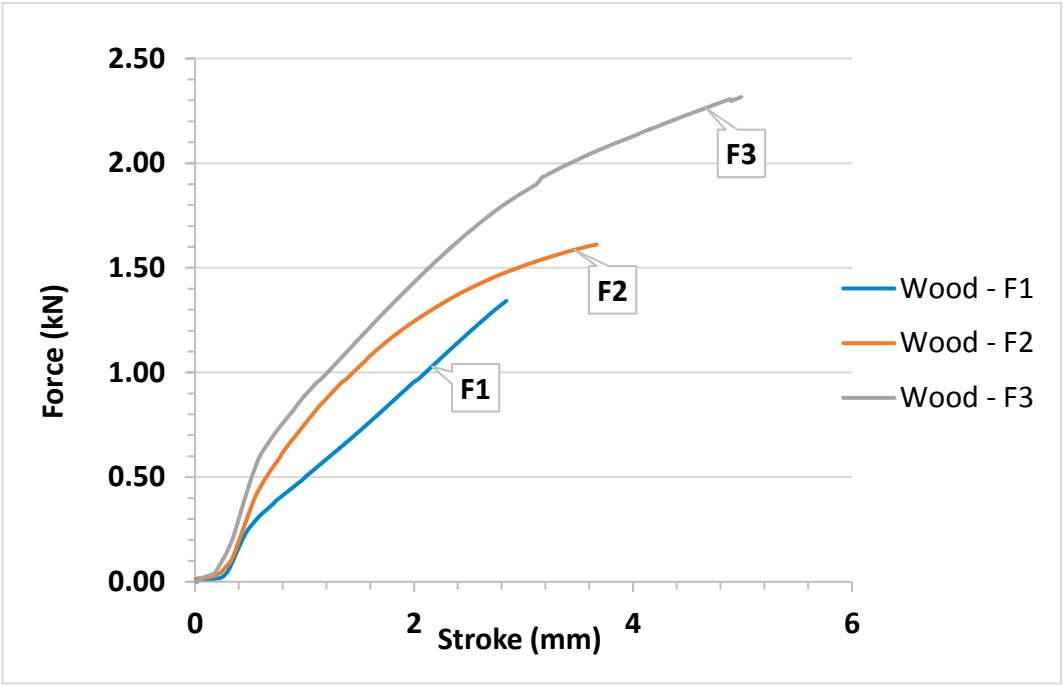


Figure 5.20: Tensile Test - wood frozen

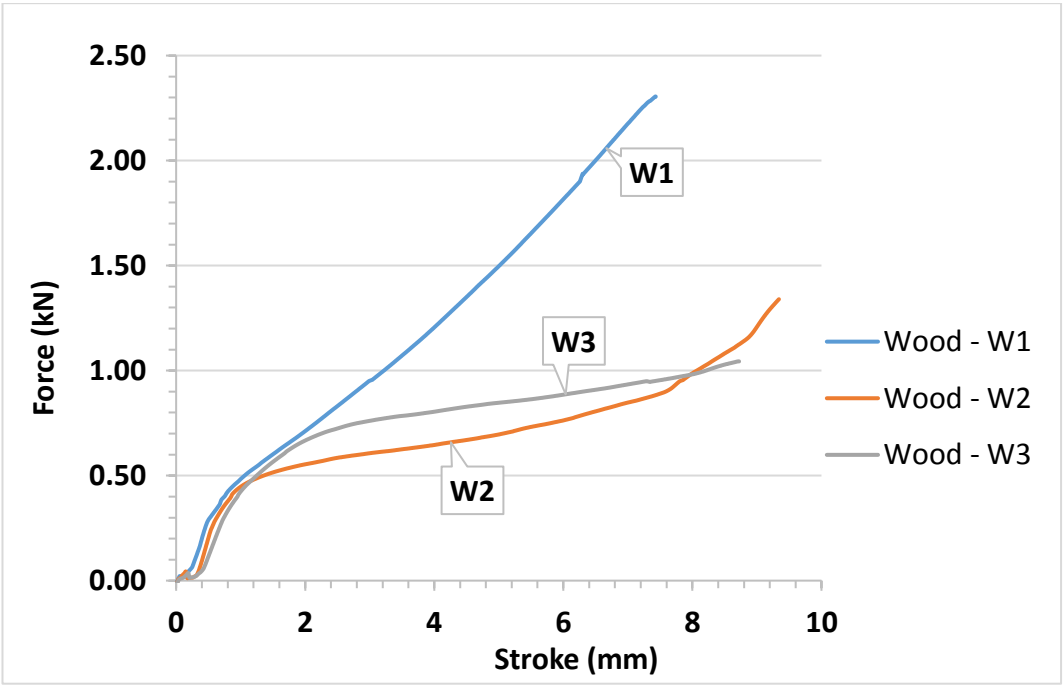


Figure 5.21: Tensile Test - wood weathered



Figure 5.22: Tensile test wood specimens

The tensile testing served two purposes. The first was to produce results that illustrated the effect of operating conditions on material properties. The second was to provide useful material data that may be introduced into pallet model simulation in section 5.4 of this study. In order to do this, the results from the testing had to be converted into readily usable data such as stress, strain and the modulus of elasticity.

The following equations define how these parameters are obtained:

Stress (σ)

The tensile stress is expressed as the force per unit area and is given by Equation (4),

$$\sigma = \frac{F}{A} \tag{4}$$

where:

σ = stress (N/m^2, Pa);

F = applied force (N); and

A = stress area of object (m^2) – In this case, the cross-section area of the specimens i.e. $6.5x10^{-5}$ m^2.

Strain (ε)

Strain is defined as "deformation of a solid due to stress" and is expressed as given in Equation (5),

$$\varepsilon = \frac{dL}{L} \tag{5}$$

where:

ε = strain (m/m);

dL = elongation or compression (offset) of object (m); and

L = length of object (m).

Elongation at break (fracture strain) is derived from this strain and is what was reported from the test analysis. It is one of the most essential tensile properties that are used when studying polymer degradation, as it can give an early indication of mechanical failure (Ling et al., 2018).

Young's Modulus (E)

Young's modulus, also known as the modulus of elasticity, can be expressed as given in Equation (6),

$$E = \frac{\sigma}{\varepsilon} \tag{6}$$

where:

E = Young's modulus (N/m^2, Pa).

By applying these equations to aforementioned results and making use of average or best specimen results, the wood property data from the tensile testing was obtained and is presented in Table 5.1. From this data it is noted that the "normal" exposure specimens recorded an ultimate tensile strength (UTS) of 33 MPa which was similar to those published in literature. It is also evident that the UTS was much greater for frozen specimens as they measured a value of 44.54 MPa and is consistent with theory that states that UTS decreases with increasing temp. (Gerhards, 1982; Sulzberger,

1953). The low UTS for weathered samples may be attributed to the higher moisture content and weather damage.

Table 5.1: Mechanical properties of tested wood (pine) samples

	WOOD (NORMAL)	WOOD (FROZEN)	WOOD (WEATHERED)
Ultimate Tensile Strength (MPa)	33.00	44.55	25.76
Elongation at break (%)	1.44	3.02	5.66
Elastic modulus (MPa)	2297.38	1473.11	455.19

Similarly, the tensile testing results for the polypropylene (plastic) specimens obtained from the Pallet C plastic pallet are displayed in Figure 5.23 to Figure 5.25 with an image of the tested samples in Figure 5.26. As can be noted from the test specimens, not all samples were tested to fracture point as some samples were only tested to a stroke of 70 mm due to time and equipment limitations. This however did not impact on calculations for the UTS as it is independent of fracture.

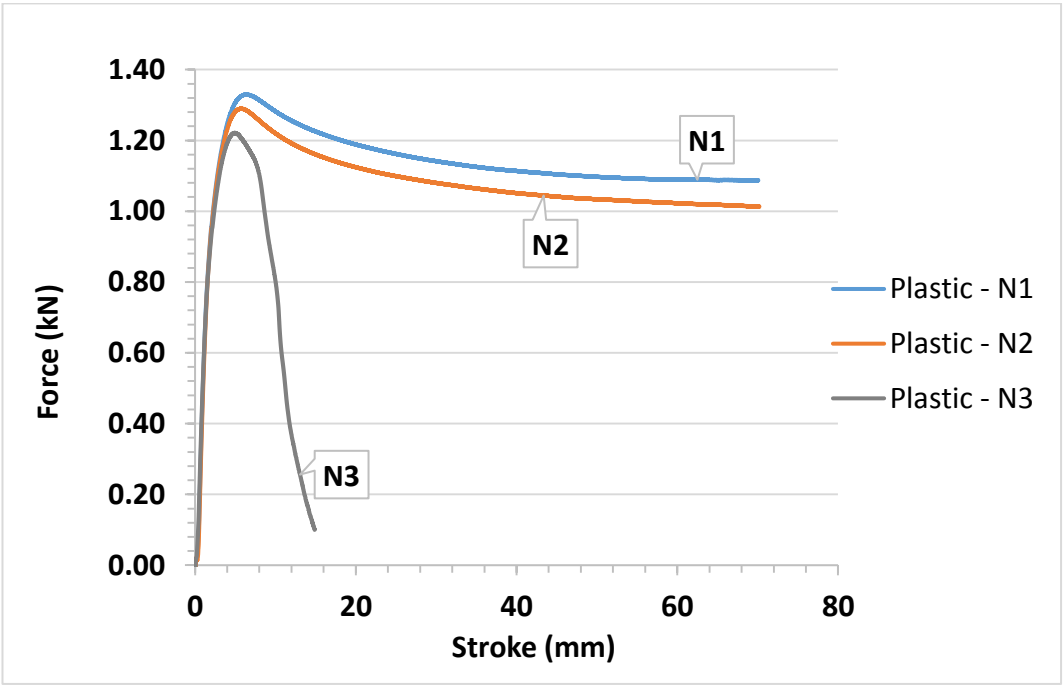


Figure 5.23: Tensile testing - Plastic normal

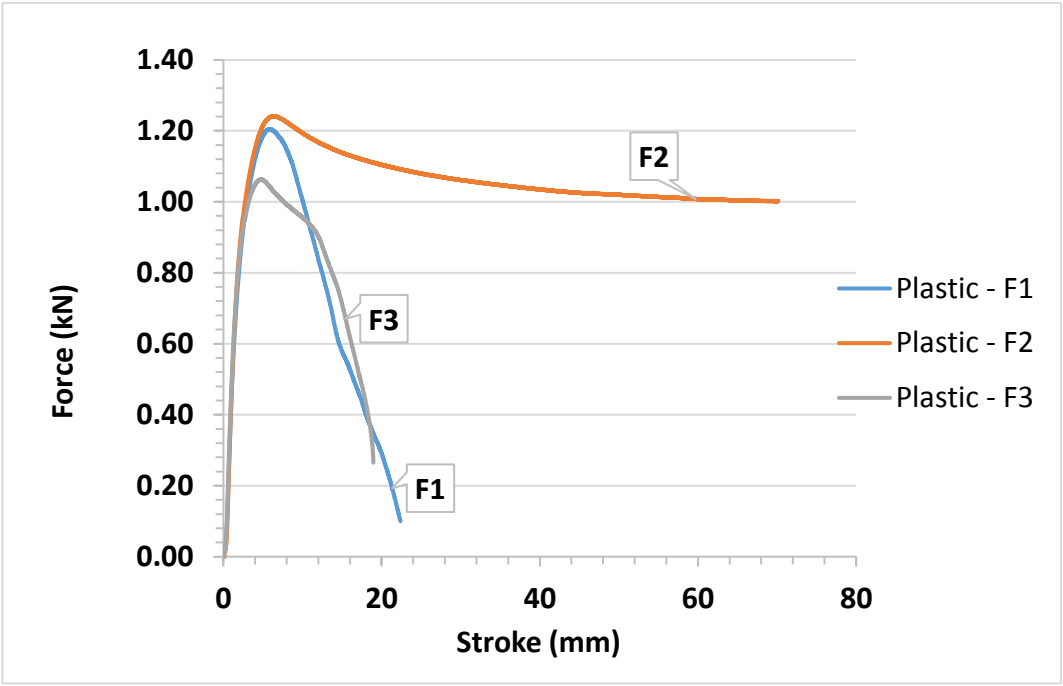


Figure 5.24: Tensile testing - Plastic frozen

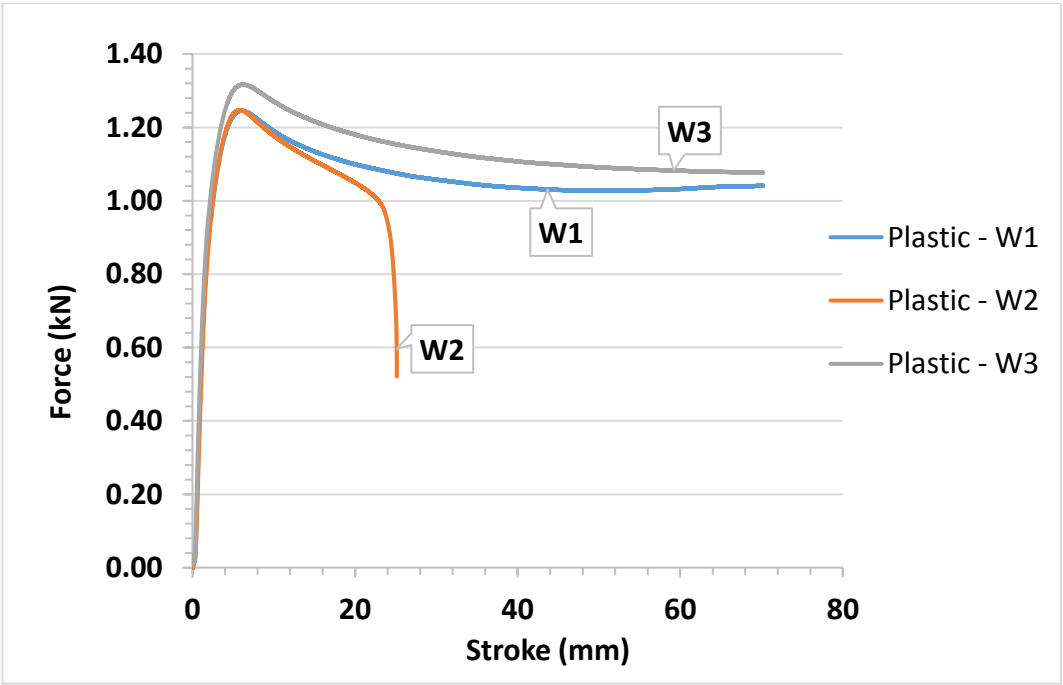


Figure 5.25: Tensile testing - Plastic weathered



Figure 5.26: Plastic test specimens

Following the use of Equations (4) – (6), some mechanical properties of the materials were calculated and are presented in Table 5.2. Unlike the wood specimens, the UTS of the polymer was not greatly affected by the operating conditions; especially from a weathered sample perspective as the normal and weathered samples had a measured UTS of 19.70 MPa and 19.54 MPa respectively. This could be due to the relatively short exposure time. In terms of the samples exposed to freezing conditions, the UTS was only marginally lower at 17.99 MPa even though two specimen samples out of the 3 experienced fracture. It should however be noted that these results may be greatly influenced if exposure time was increased.

Table 5.2: Mechanical properties of tested Plastic (Polypropylene) samples

	PLASTIC (NORMAL)	**PLASTIC (FROZEN)**	**PLASTIC (WEATHERED)**
Ultimate Tensile Strength (MPa)	19.70	17.99	19.54
Elongation at end (%)	31.34	22.50	34.32
Elastic modulus at end (MPa)	62.84	79.87	56.94

5.3 Static Pallet Property Tests

Pallet testing was important in ensuring compliance of the pallets used in the study with industry requirements as well as allowing for a brief comparison between the different pallet types. As the tests were mainly in preparation for the case study, the focus was on conducting racking and stacking tests as these are the conditions that the pallets would be exposed to within the distribution environment.

Testing conditions were noted to have varied from 32% to 44% relative humidity (RH) and 18°C to 25°C on site and were carried out in accordance with the specifications given in section 3.4.4.

5.3.1 Preparations

The pallet tests were conducted at the Jet Park Container Service Centre. Racking tests were performed on site on customised heavy-duty racking beams. Stacking tests were attempted but due to load instability concerns, these tests were outsourced to Ten-E Packaging Services.

The following documents were used as references in order to complete the pallet tests. The tests followed, as far as possible, the testing procedures and guidelines indicated in the following:

- ISO 8611-1, Pallets for materials handling — Flat pallets — Part 1: Test methods
- ISO 8611-2, Pallets for materials handling — Flat pallets — Part 2: Performance requirements and selection of tests
- ISO 8611-3, Pallets for materials handling — Flat pallets — Part 3: Maximum working loads

Due to project constraints some deviations or modifications were made to the ISO standards and are outlined in Appendix C. The performance limits that were used as reference and adhered to were as per ISO 8611-2 for both stacking and racking tests. A compliance to a maximum deflection of 2 % of L_1 (L_2) under load and 0,7 % of L_1 (L_2) after relaxation period was used, where L_1(L_2) is the distance between the pallet supports (Figure C.7).

5.3.2 Racking Tests

The racking tests were carried out on racking beams measuring 3888 mm x 160 mm IPE (I-Profile Européennes) Section, with a safe carrying capacity of 4800 kg's per level (Figure C.6). The tests were carried out as per the set-up in Figure 5.27. The use of a dead load of approximately 1000 kg in boxes was used in order to best simulate the distribution environment as opposed to a test rig as is normally used for the ISO testing.

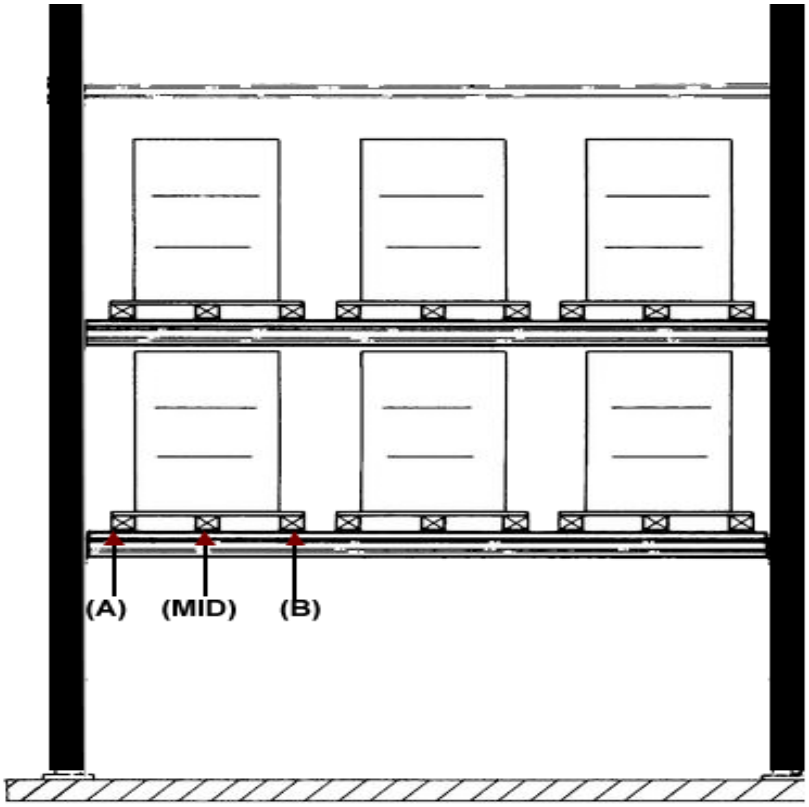


Figure 5.27: Racking test setup

All the test pallets passed the racking tests as they met the two criteria set by the standard, namely; not deflecting more than 15 mm under load or more than 5.25 mm after the relaxation period. The following tables give an indication of the deflection for each pallet under racking conditions. The measuring points (A, B and MID) indicate the far ends of the pallet (Figure 5.27) and the mid-point from which the deflection "y" was obtained as per Figure C.7 respectively. All tests were done in triplicates as indicated and further results may be found in Appendix C. The following tables and figures summarise the results from these tests.

Table 5.3: Test data for racking tests of wooden (Pallet B) pallet

Test data:	**Pallet Test Type Description: Wooden [Pallet B]**			
	Pallet: No.7	Moisture Content: 11.6%	Pallet Weight: 25.8kg	Gross Weight: 1025.2kg
	Deflection Measurement (mm)			
Measuring Point	**Empty Pallet**	**After Applying Test Load**	**After Load Test Period** (2 hours)	**After Relaxation** (1 hours)
A	136	132	131	136
MID	135	128	128	134
B	135	130	130	134
Average	135.3	130.0	129.7	134.7
Deflection (y)		**5.3**	**5.6**	**0.6**
Result (pass/fail)		**Pass**	**Pass**	**Pass**



Figure 5.28: Deflection results for wood (Pallet B) pallet

Table 5.4: Test data for racking tests of plastic (Pallet A) pallet

Test data:	**Pallet Test Type Description: Plastic [Pallet A]**			
	Pallet: No.8	Moisture Content: N/A	Pallet Weight: 26.2kg	Gross Weight: 1026.8kg
	Deflection Measurement (mm)			
Measuring Point	**Empty Pallet**	**After Applying Test Load**	**After Load Test Period** (24 hours)	**After Relaxation** (2 hours)
A	134	132	130	133
MID	134	129	129	133
B	134	131	130	134
Average	134	130.7	129.7	133.3
Deflection (y)		**3.3**	**4.3**	**0.7**
Result (pass/fail)		**Pass**	**Pass**	**Pass**

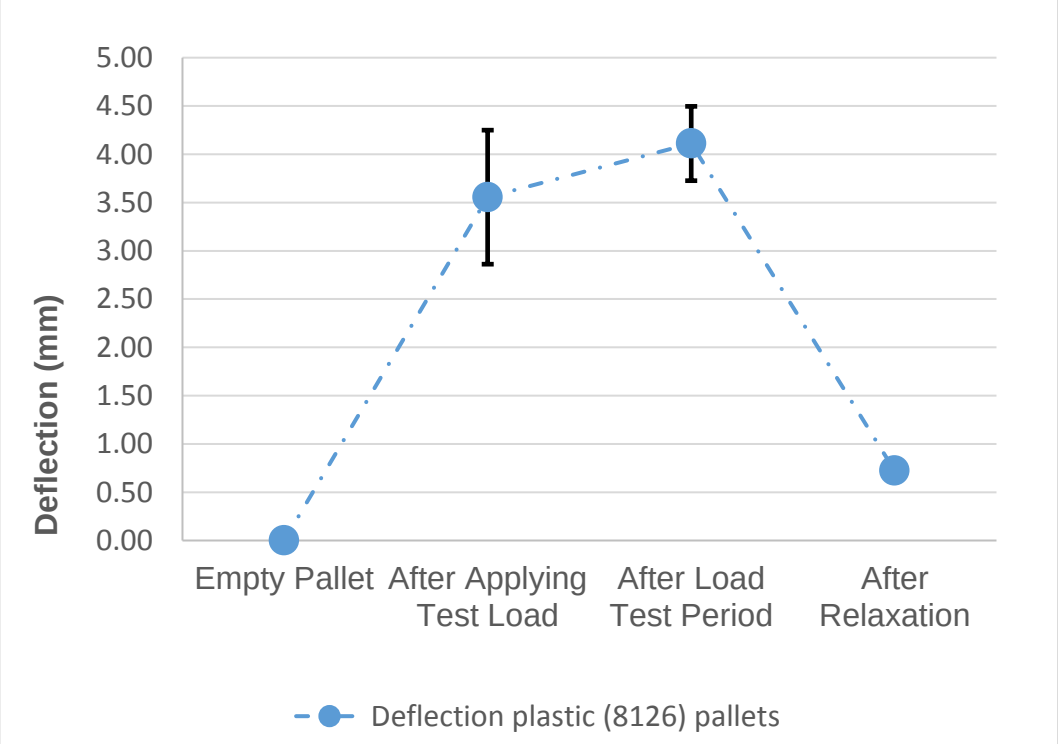


Figure 5.29: Deflection results for plastic (Pallet A) pallet

Table 5.5: Test data for racking tests of plastic (Pallet C) pallet

Test data:	**Pallet Test Type Description: Plastic [Pallet C]**			
	Pallet: No.7	Moisture Content: N/A	Pallet Weight: 22.8kg	Gross Weight: 1029.6kg
	Deflection Measurement (mm)			
Measuring Point	**Empty Pallet**	**After Applying Test Load**	**After Load Test Period** (24 hours)	**After Relaxation** (2 hours)
A	134	131	129	134
MID	134	131	129	134
B	134	131	129	133
Average	134	131.0	129.0	133.7
Deflection (y)		**3.0**	**5.0**	**0.3**
Result (pass/fail)		**Pass**	**Pass**	**Pass**

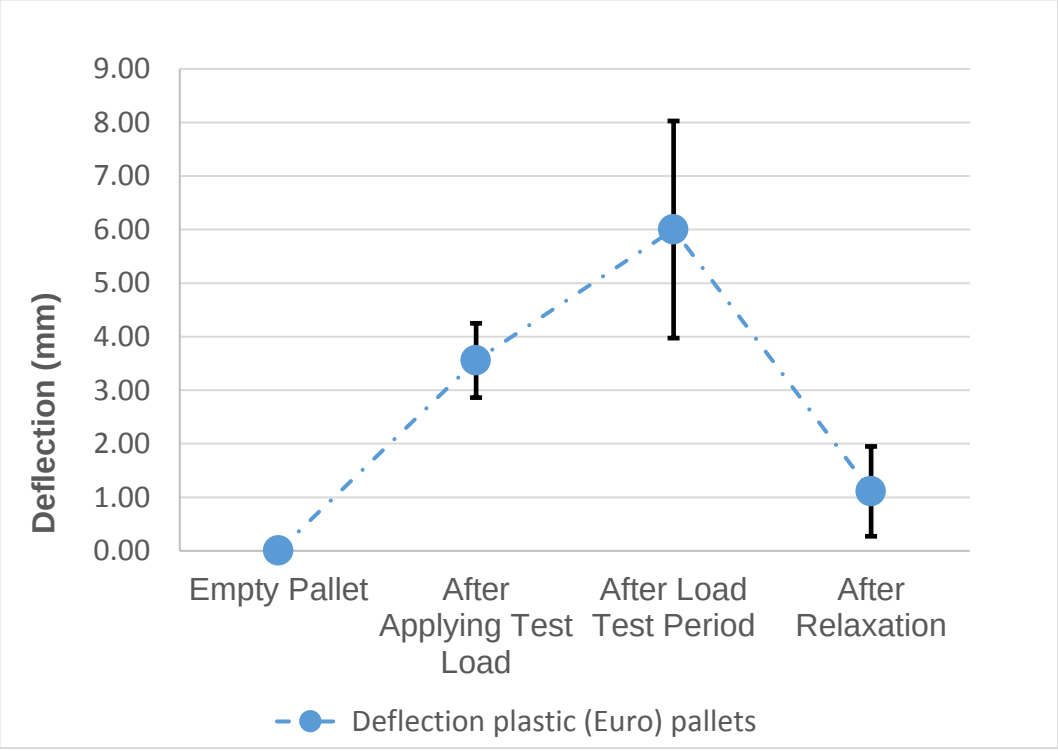


Figure 5.30: Deflection results for plastic (Pallet C) pallet

As can be noted from Table 5.3 to Table 5.5, the pallets all passed the specifications as per the ISO standard. These tables only indicate results from 1 of each type of pallet tested in order to display how data was obtained and a pass determined. For each represented data set in a table, figures have been attached to show the set-up, deflection and relaxation phases of the test conducted (see Figure C.14, Figure C.15 and Figure C.16) with average deflection results presented in Figure 5.28 - Figure 5.30. In accordance with the standard, 3 replicates of each test were done and the results thereof have been presented in Figure C.11, Figure C.12, and Figure C.13. Data used to plot the average deflection data (Figure 5.28 - Figure 5.30) with the given error bars is presented in Table C.1 - Table C.3.

Collated results permit for viewing all the average deflection measurements in one figure and show that the Pallet A plastic pallets (see Figure 5.31) were overall the best performer. This is substantiated by results in Figure 5.29 as they present the smallest deflection values after load test period with values between 3.7 mm and 4.5 mm when looking at the deviation from the average as shown by the error bars. This could be attributed to the steel reinforcement in the pallet which gives it a great load bearing capacity.

The wood (Pallet B) pallet (see Figure 5.28) presented slightly higher deflection values than the plastic (Pallet C) pallet (see Figure 5.30) after the test load period with both averaging approximately 6 mm of deflection under the given test load and testing orientation. However, it should be notes that unlike the wood (Pallet B) and plastic (Pallet A) pallets, the plastic (Pallet C) had a sharp rise (almost linear increase) in deflection values between the period after applying test load and after the load test period (Figure 5.31). This may suggest that over time, this pallet type is more susceptible to further deflection as opposed to its counterparts.

In terms of the “bounce back” after testing, all pallets were excellent in this regard as results presented were all below 2 mm which is well below the 5.25 mm as stipulated by the standard. The plastic (Pallet C) was however the weakest performer in this regard with average deflection data coming in

above 1 mm. This was not a major point of concern for the study, however, given potentially heavier loads could be encountered, this pallet type may not prove to be suitable if deflection characteristics are large.

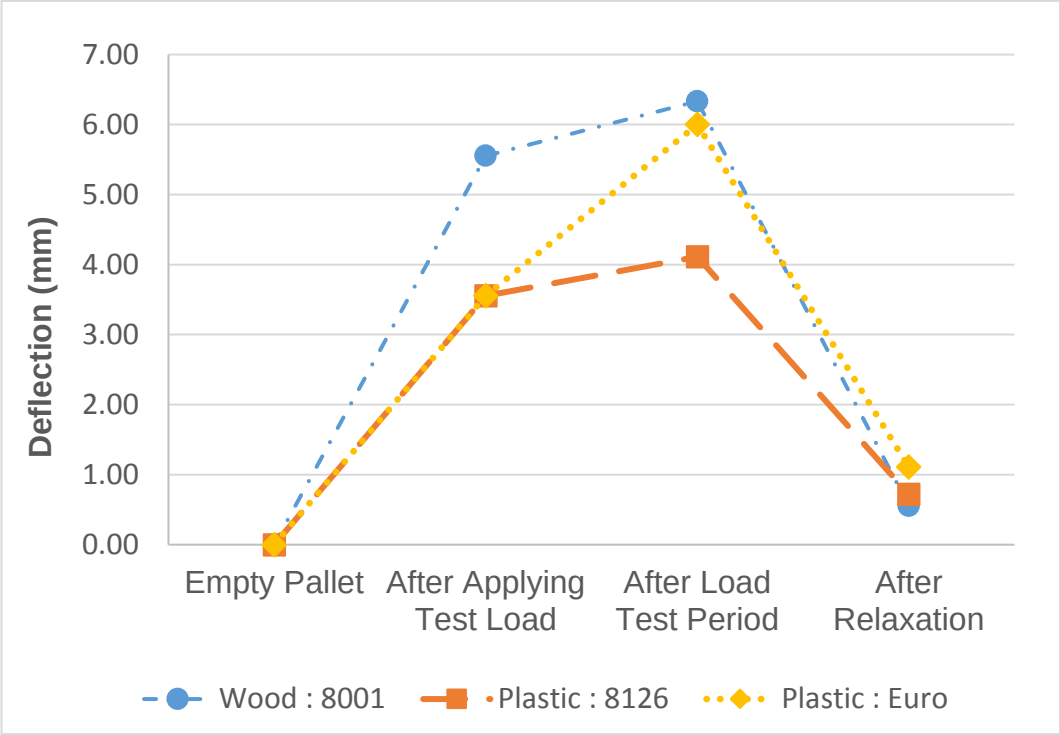


Figure 5.31: Collated deflection results for test pallets

In essence all the pallets passed the racking tests and were compliant enough with the specifications set by the standard and as such could be introduced into the live racking systems within the distribution environment.

5.3.3 Stacking Tests

The stacking tests were carried out using the set-up in Figure 5.32. This allows for deflection measurements to be taken in both the upward and downward directions unlike that shown in Figure C.9. However, $L_1(L_2)$ dimensions are well represented in this figure and are adopted in order to obtain the allowable deflection values as required by the standard.

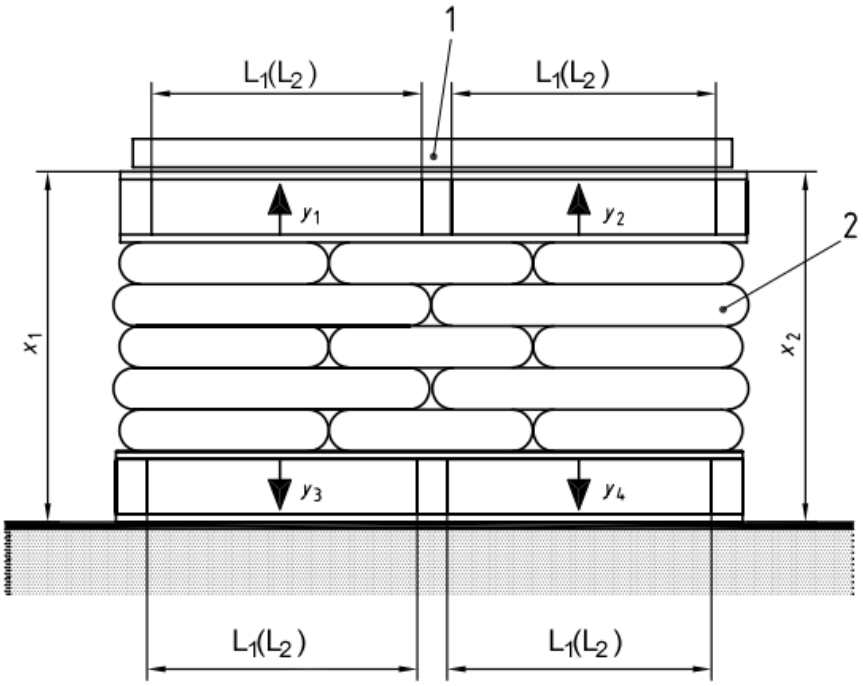


Figure 5.32: Test 4b using dead load and illustrating deflection

Key: 1 Test load, payload or test machine
2 Payload
x_1, x_2 Overall stability
y_1, y_2 Downward deflection
y_3, y_4 Upward deflection
Note: payload for illustration only

All the test pallets performed reasonably well and were compliant with the standards as they had deflection not exceeding 15 mm when under load and were well below 7 mm after the relaxation period for $L_1(L_2)$ as per the ISO standard.

The following tables and images present the results from the stacking tests that were carried out on the pallets. These tests were done at a 3rd party pallet tester and as such no replicate data was provided.

As can be seen from Table 5.6 to Table 5.8 all the test pallets passed the ISO 8611 specifications in relation to the specified test loads for each given pallet type. Deflection rates after test load period of 4.0 mm, 3.5 mm and 4.8 mm for the Pallet B: wood, Pallet A: plastic and Pallet C: plastic pallets respectively were all well within the 15 mm as specified by the standard.

Table 5.6: Test data for stacking tests of wooden (Pallet B) pallet

Test data:	**Pallet Test Type Description: Wood [Pallet B]**				
	Pallet: No.3 and 4	MC: N/A	Load applied: 1000kg		
Deflection Measurement (mm)					
Measuring Point	**Empty Pallet**	**After positioning load applicators**	**After Applying Test Load**	**After Load Test Period**	**After Relaxation**
				(2 hours)	(1 hours)
Y_1	124.4	123.5	122.6	120.3	124.2
Y_2	124.0	121.2	121.0	119.2	123.6
Y_3	124.6	123.4	122.8	121.0	124.2
Y_4	123.9	122.2	121.5	120.1	122.9
Average	124.4	123.5	122.6	120.3	124.2
Deflection		**1.6**	**2.2**	**4.0**	**0.5**
Result (pass/fail)			**Pass**	**Pass**	**Pass**

The Pallet A had the best results (see Figure 5.33), with deflections of 1.5 mm and 3.5 mm recorded for after applying test load and after test load periods respectively. Much like with the racking tests, this may also be attributed to its steel reinforced rods which give it superior strength and load bearing capabilities in comparison with the other pallet types. As a result, deflection for the applied test load was relatively low.

Table 5.7: Test data for stacking tests of plastic (Pallet A) pallet

Test data:	**Pallet Test Type Description: Plastic [Pallet A]**				
	Pallet: No.1 and 2		MC: N/A	Load applied: 1125kg	
	Deflection Measurement (mm)				
Measuring Point	**Empty Pallet**	**After positioning load applicators**	**After Applying Test Load**	**After Load Test Period**	**After Relaxation**
				(24 hours)	(2 hours)
Y_1	121	121	119	117	120
Y_2	121	121	120	118	121
Y_3	122	122	121	118	122
Y_4	122	121	120	119	121
Average	121.5	121.25	120	118	121
Deflection		**0.3**	**1.5**	**3.5**	**0.5**
Result (pass/fail)			**Pass**	**Pass**	**Pass**

For the given test load, for the stacking test, the plastic (Pallet C) pallet was again the worst performer in terms of deflection measurements. At values of 3 mm and 4.8 mm for both the deflection after applying test load and after test load periods respectively, this pallet type presented the highest deflections (Figure 5.33). These values were still well within the performance requirements however, given greater loads, this may prove to be a factor.

Table 5.8: Test data for stacking tests of plastic (Pallet C) pallet

Test data:	**Pallet Test Type Description: Plastic [Pallet C]**				
	Pallet: No.8 and 9		MC: N/A	Load applied: 1000kg	
Deflection Measurement (mm)					
Measuring Point	**Empty Pallet**	**After positioning load applicators**	**After Applying Test Load**	**After Load Test Period** (24 hours)	**After Relaxation** (2 hours)
Y_1	125	124	122	120	124
Y_2	123	123	121	119	123
Y_3	124	123	121	119	123
Y_4	124	123	120	119	123
Average	124.0	123.3	121.0	119.3	123.3
Deflection		**0.8**	**3.0**	**4.8**	**0.8**
Result (pass/fail)			**Pass**	**Pass**	**Pass**

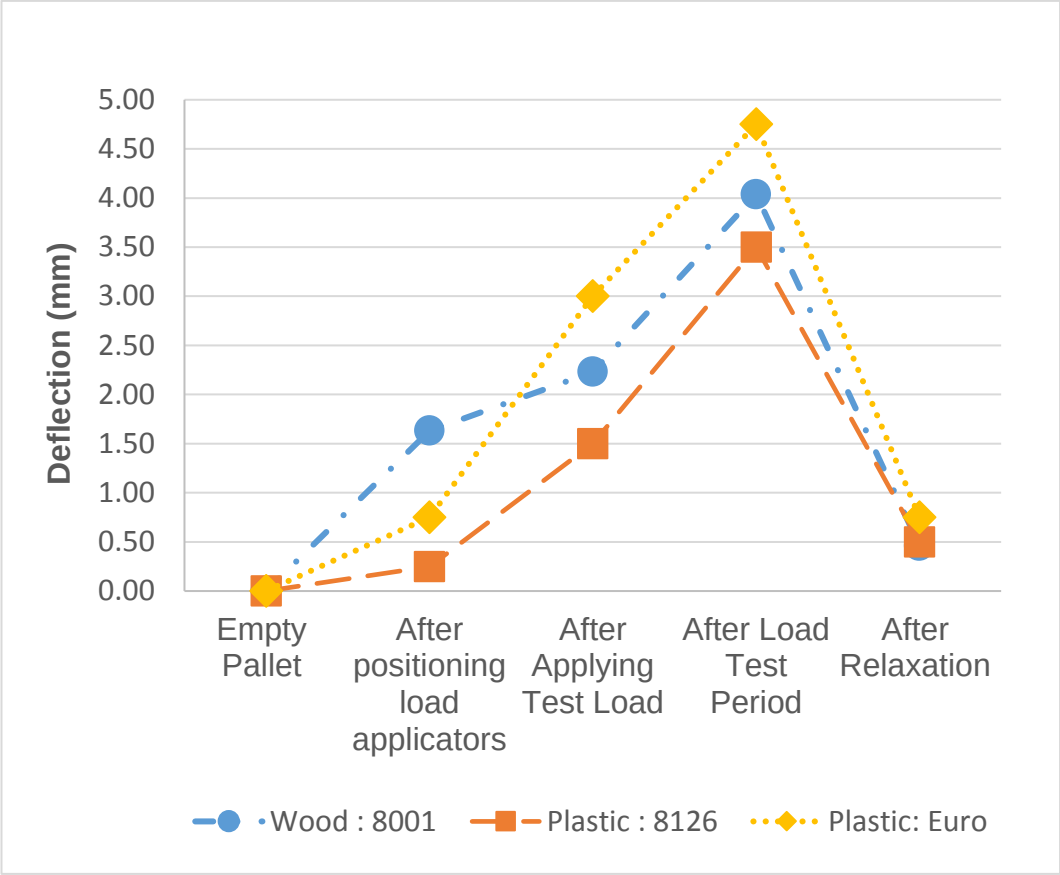


Figure 5.33: Collated deflection data for pallet stacking

In conclusion, the test pallets used for this study and the case study to follow, proved to be compliant with specifications set out in the ISO standards in terms of stacking and racking abilities and were adequate enough for the trials. It should however be noted that the tests were done on the basis of a modified protocol of the ISO tests and full compliance with the ISO specification cannot be claimed. These results did however allow for the safe implementation of the pallets within the distribution environment and provided a basis of comparison when conducting the case study.

5.4 Simulation Model

Finite element analysis (FEA) was conducted on the modelled test pallets in order to more accurately simulate a variety of test loads and conditions. This computational analysis technique reduces complex structures and interactions into more simplified units in order to model the behaviour of the complex structure (Baker, 2016). Deflection characteristics as well as areas or concentrated stress points are observed and analysed. As previously outlined, only the Pallet C plastic and the Pallet B wood pallets were modelled (see Figure 5.34 - Figure 5.37) as both were made entirely of one material unlike the steel reinforced Pallet A.



Figure 5.34: Plastic pallet (Pallet C)

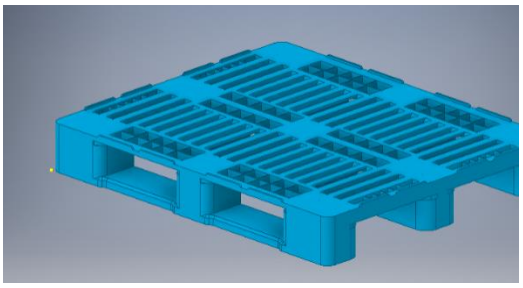


Figure 5.35: 3D model of plastic (Pallet C) pallet



Figure 5.36: Pallet B wood pallet

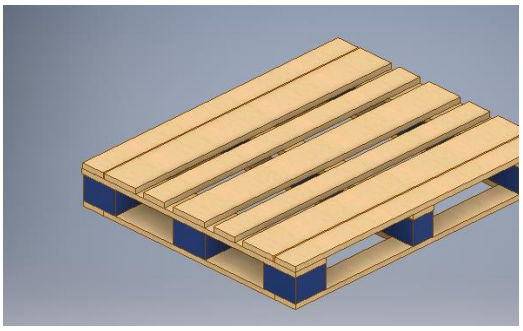


Figure 5.37: 3D model of wood (Pallet B) pallet

The goal of FEA modelling within the confines of this study is twofold. Firstly, it allows for a comparison of the simulated pallets to results obtained from the testing in order to validate the models as well as use them to predict an array of test conditions. The second is in the adaptation of these models to

predict the effect of damage on a pallet and by consequence the pallets ability to perform its task.

This was motivated by the fact that no set criteria exist as to what extent a damaged plastic pallet may no longer be considered feasible for operations within the distribution environment and also the lack of repairability of most plastic pallets. The simulation models should be able to help in this regard by allowing for the prediction of the effect that damage to a plastic pallet may have without prematurely discarding it.

Unit stacking as well as racking simulations were conducted on these two simulated models as is presented in subsequent sections. A constant and equally distributed load of 10 000 N, roughly about 1000 kg was used to simulate all the following test scenarios.

5.4.1 Model Implementation

The models were created using the test pallets as defined by Table 3.2 . In Figure 5.38 and Figure 5.39 a representation of the software (Autodesk® Inventor®) interface is shown and how the given pallets were dimensioned and modelled prior to the FEA analysis. The models were made as accurate as possible, however, some simplifying assumptions were made.

In terms of the wooden pallet, the pallet was modelled as a single part element with multiple solid bodies to cater for the nails that would ideally fasten the pallet elements. In addition to this, when conducting the FEA analysis, the material library for pine did not reflect local SA pine characteristic and as such test results from section 5.2.3 were utilised. Although wood is anisotropic, a further assumption was made to model it as isotropic due to software limitations of Autodesk® Inventor® when modelling such materials.

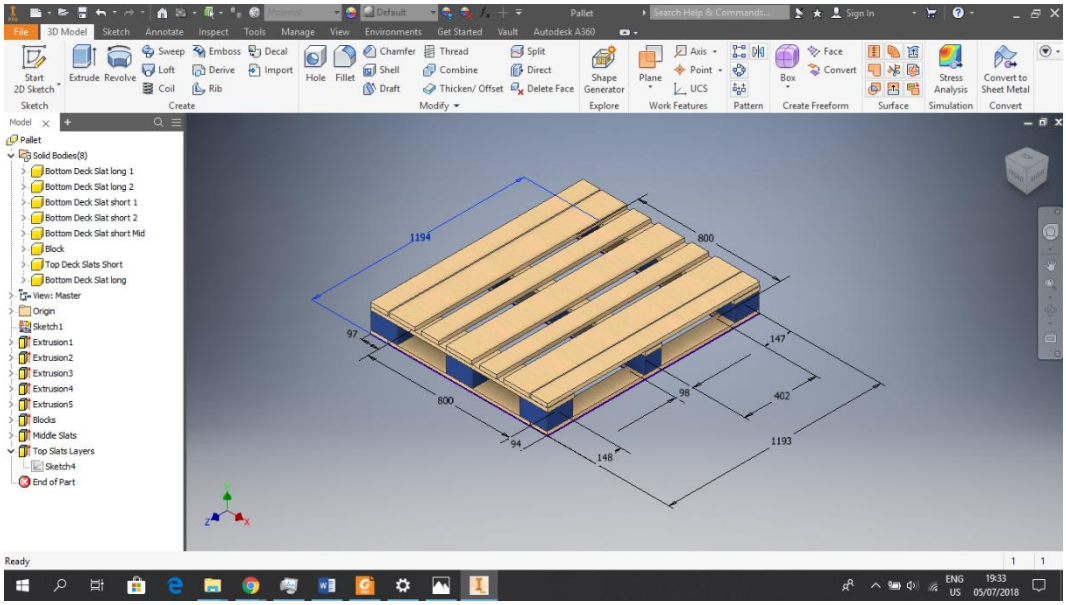


Figure 5.38: Wood pallet model dimensioning

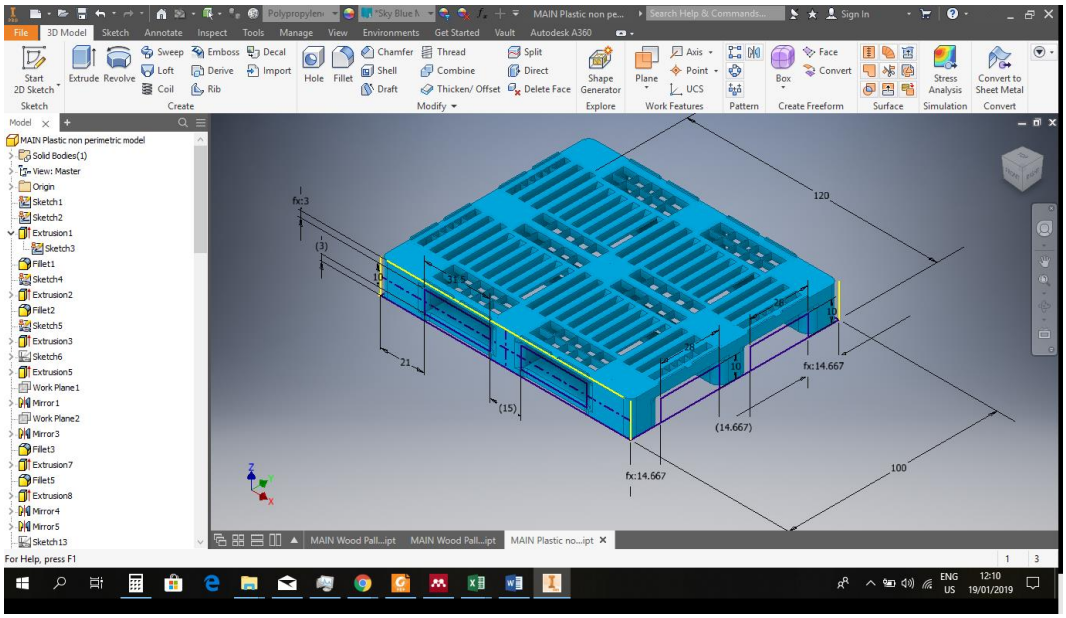


Figure 5.39: PP Plastic pallet model dimensioning

Unlike the wood, the modelling of the plastic pallet (Figure 5.39) made use of less assumptions. The pallet was modelled as a single part element containing just one solid body as would be the case when the pallet is extruded from a mould or 3D printed. The following FEA segments indicate how these models were use in terms of force application and constraint settings. Additional data is available in Appendix D.

5.4.2 FEA: Stacking Simulation

The 10 000 N force was applied on the pallet surface and equally distributed across the surface of the respective pallets (Figure 5.40 and Figure 5.42),. All surfaces beneath the pallet were considered fixed constraints (sky blue surface on bottom decks) in order to model the stacking behaviour (Figure 5.41 and Figure 5.43).

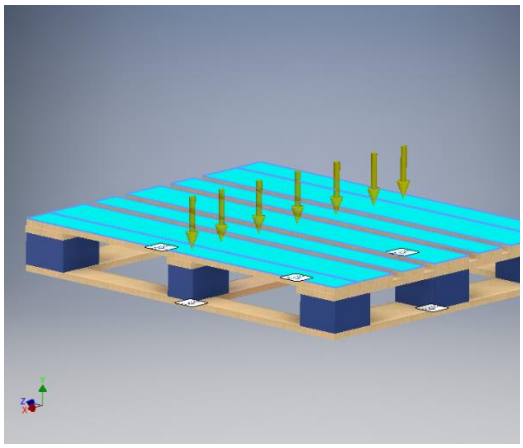


Figure 5.40: Distributed force on wood pallet- stacking

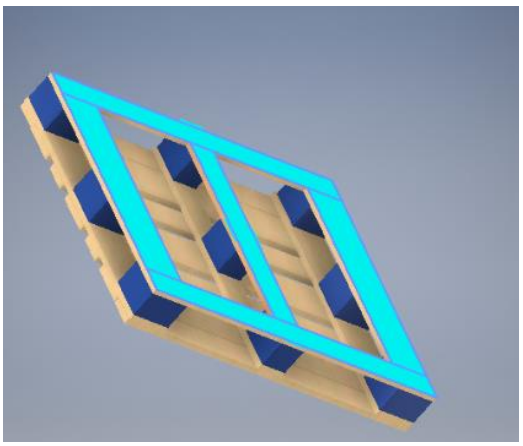


Figure 5.41: Constraint location on wood pallet - stacking

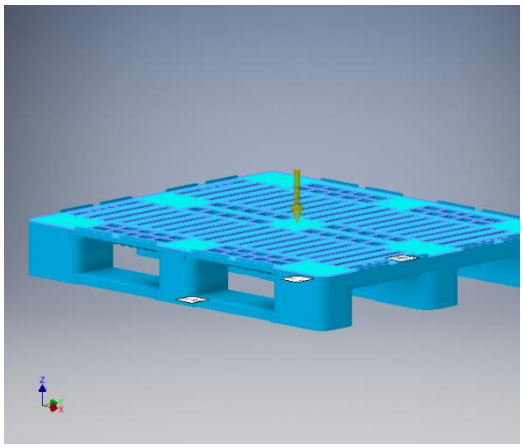


Figure 5.42: Distributed force on plastic pallet- stacking

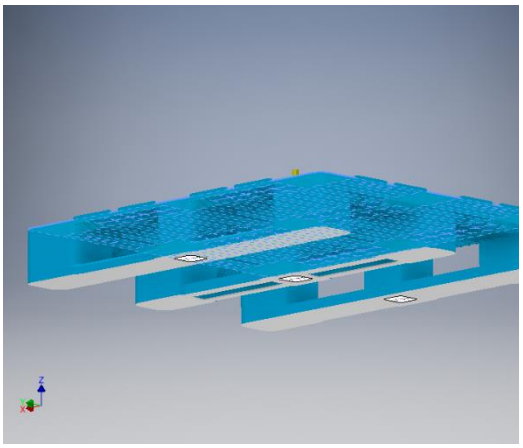


Figure 5.43: Constraint location on plastic pallet - stacking

The results from the FEA analysis as presented by Figure 5.44 and Figure 5.45, gives maximum displacement / deflection values of 0.6981 mm and 2.316 mm for wood and plastic (PP) respectively. The large discrepancy of the wooden model (~4 mm deflection from experimental data) may be attributed to the fact that the material library in Autodesk Inventor does not have the right properties for SA pine and some assumptions previously

outlined may have affected this. A better data set may improve simulation results for the stacking tests.

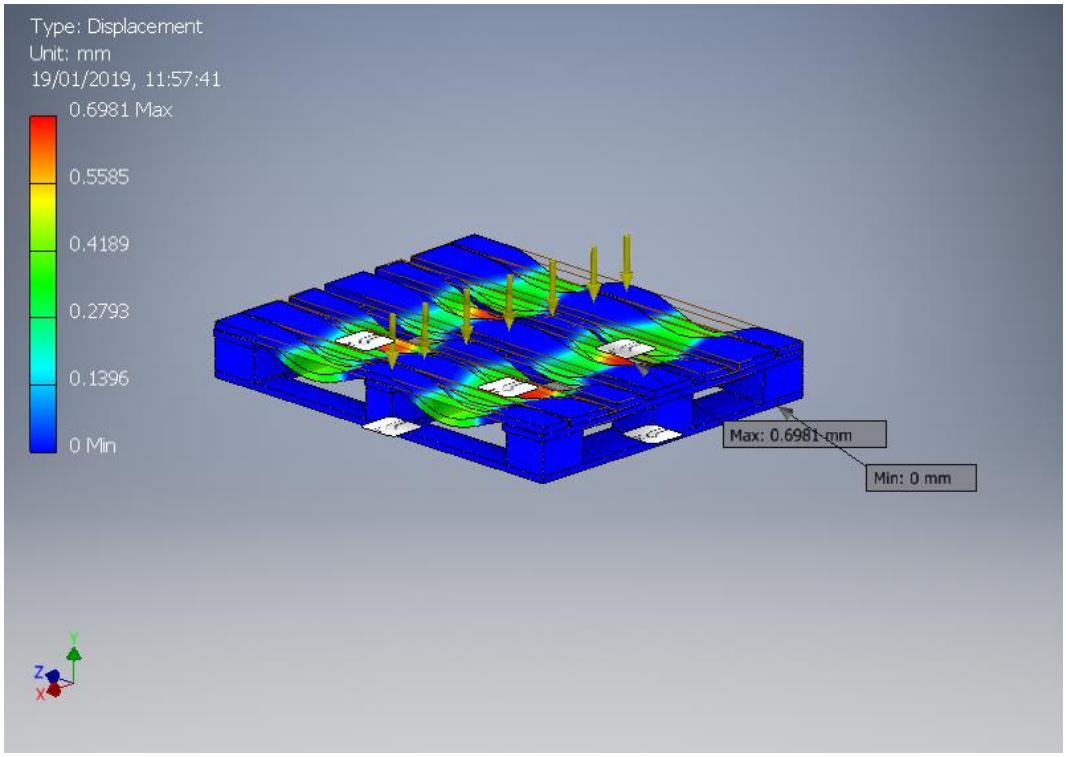


Figure 5.44: Displacement / Deflection measurement on wood pallet – stacking

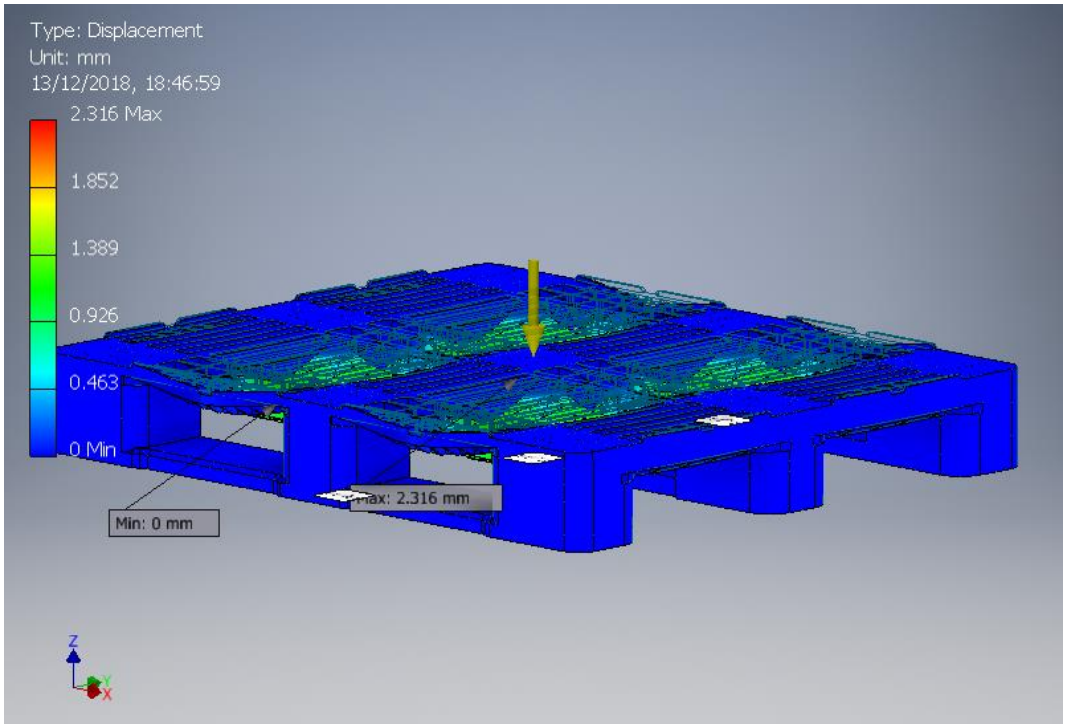


Figure 5.45: Displacement / Deflection measurement on plastic pallet - stacking

5.4.3 FEA: Racking Simulations

As with the stacking, the racking models also made use of an evenly distributed applied load across the top deck of the pallet. However, unlike the stacking test, the constraints set for the racking tests where only on the bottom deck elements that would be in contact with the racking beams as shown in Figure 5.47 and Figure 5.49.

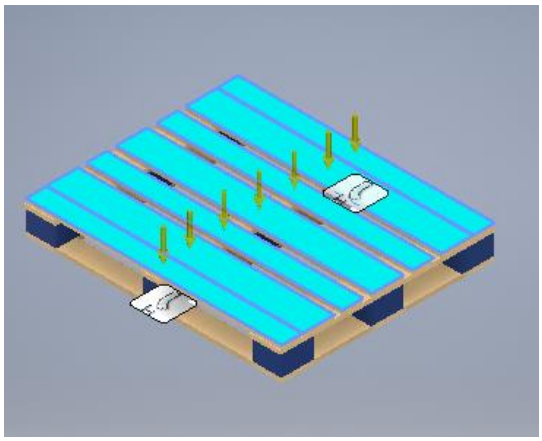


Figure 5.46: Distributed force on wood pallet- racking

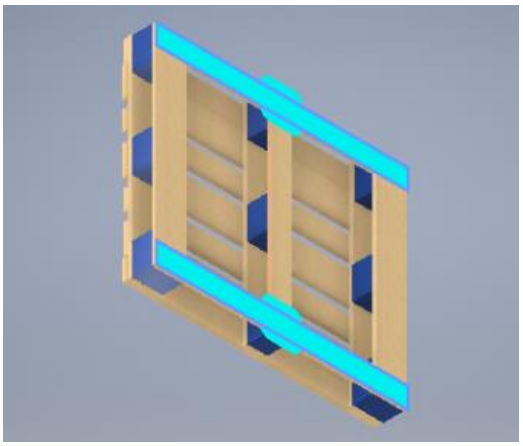


Figure 5.47: Constraint location on wood pallet - racking

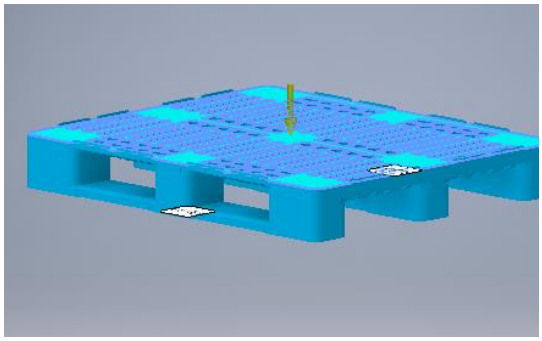


Figure 5.48: Distributed force on plastic pallet- racking

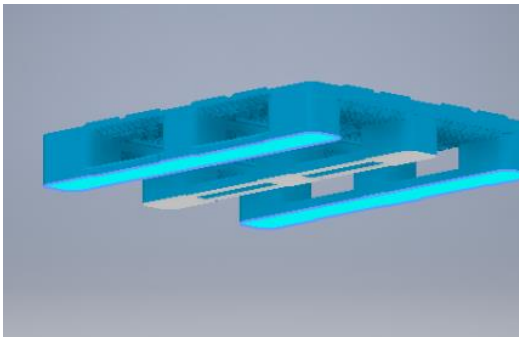


Figure 5.49: Constraint location on plastic pallet - racking

The results from modelling the wooden pallets did not correlate with experimental data (~5.7 mm deflection from experimental data vs 2.315 mm simulated) and again this can be attributed to the lack of material data or a more in-depth database and the simplifying assumptions. However, at 2.315 mm for the wood pallet, the deflection rates were comparatively much better for the racking test as opposed to the stacking configuration. The results of the plastic simulation in this test orientation proved to be a lot more consistent with experimental data from the previous section (5.3.2) as

deflection rates of 4.05 mm were presented in Figure 5.51 (~5 mm was obtained from experiments as seen in Table 5.5).

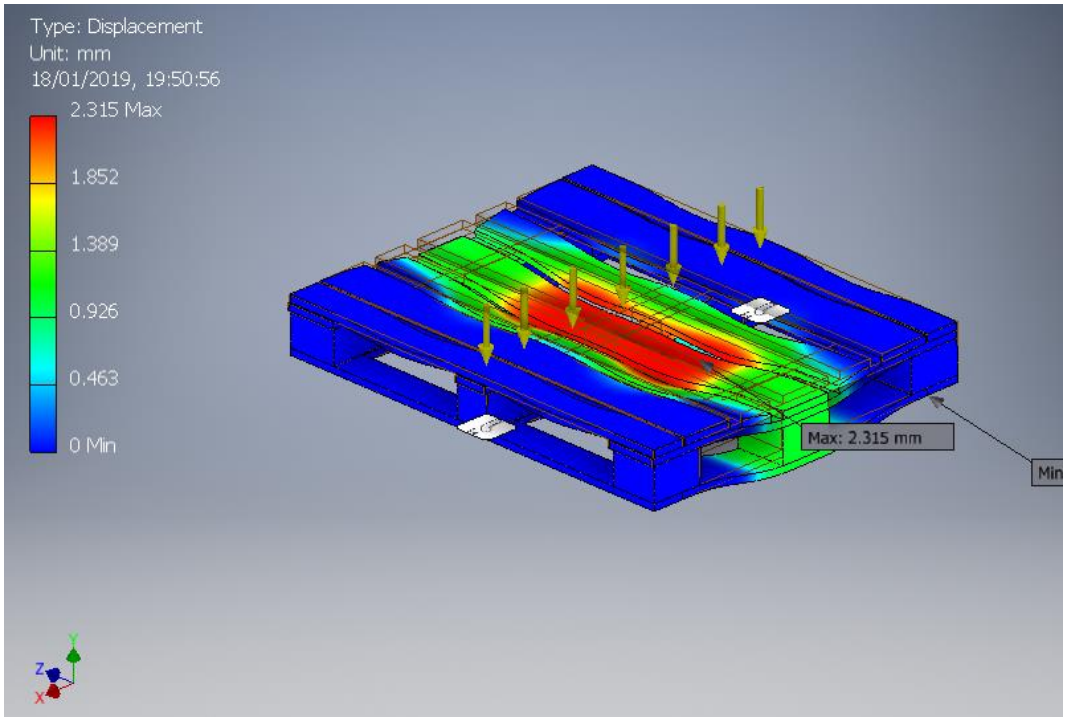


Figure 5.50: Displacement / Deflection measurement on wood pallet - racking

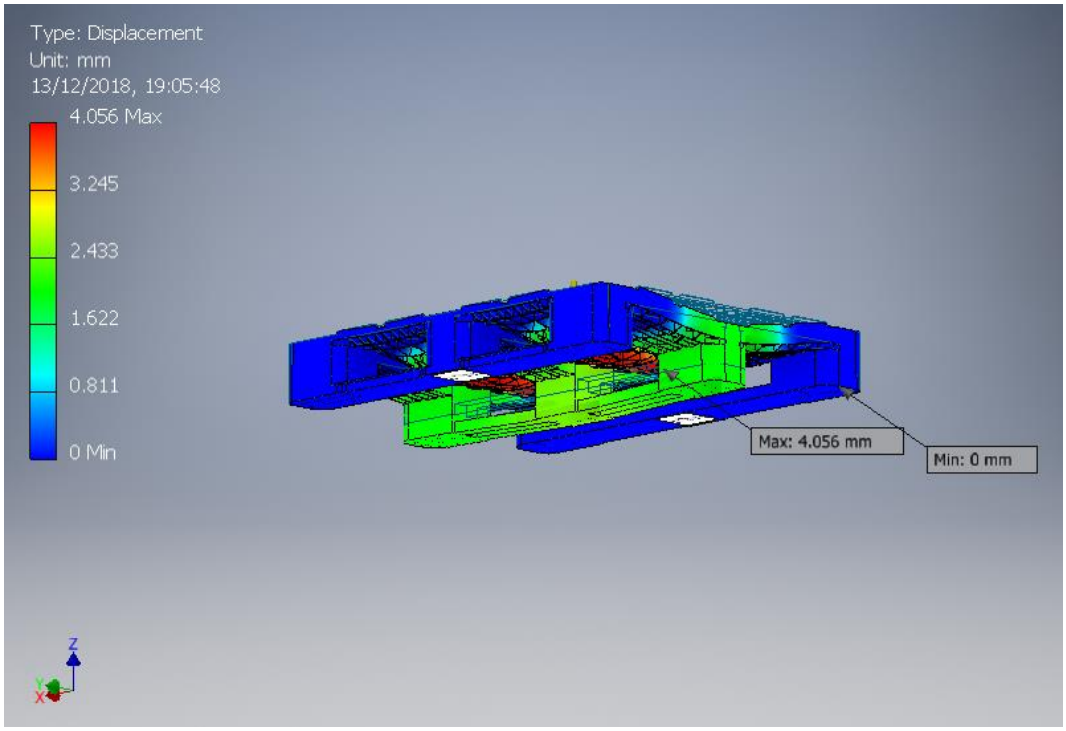


Figure 5.51: Displacement / Deflection measurement on plastic pallet – racking

These findings motivated for the use of the racking test set-up for the simulation of damaged pallets under load as opposed to the stacking method. The margin of error (19%) was much smaller in this configuration in comparison with the stacking setup.

5.4.4 FEA: Predictive modelling – Damage to elements

In order to simulate the effect that damage to a pallet can have on the deflection characteristics and by extension its structural integrity of the pallet, a worst-case scenario was adopted. As displayed in Figure 5.52 and Figure 5.53, the modelled pallets were modified to in effect “lose block support” due to damage. These scenarios are based on the assumption of forklift damage at central supporting blocks.

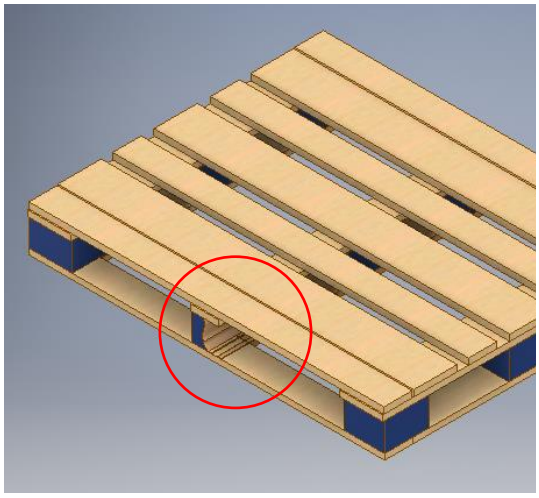


Figure 5.52: Wood pallet with simulated damage

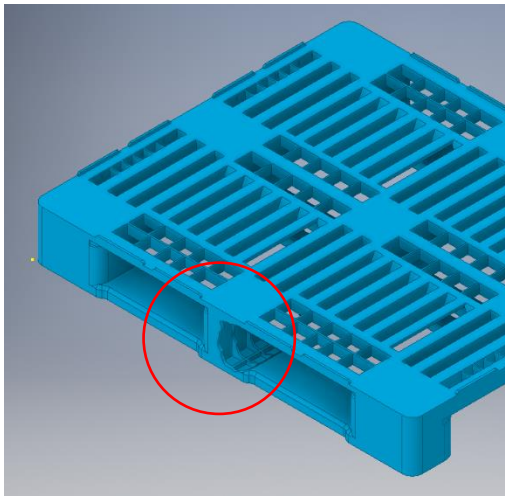


Figure 5.53: Plastic pallet with simulated damage

The force quantity and distribution pattern remained unchanged from the previous simulations and in addition, the constraints from the racking test set up were used as these models proved to be more accurate. Simulating these new “damaged” scenarios presented new elevated deflection data for both these pallet types. The plastic pallet displayed a moderate 22% increase in deflection from 4.056 mm to 4.954 mm in maximum deflection. The wooden pallet on the other hand had an increase of 7% from 2.315 mm to 2.479 mm. This data indicates the severity of the potential impact of damage to a pallet may have on its deflection characteristics and by

extension its load bearing capacity. This approach, upon optimization could be effective in further simulating common damages experienced by pallets within the distribution environment.

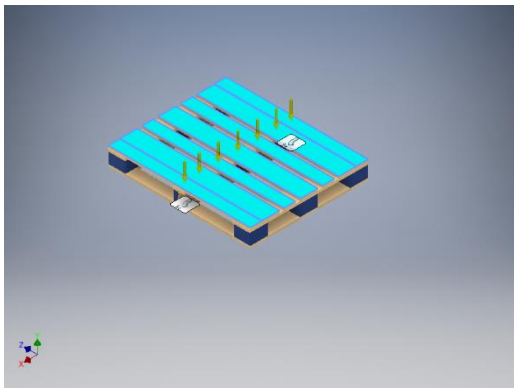


Figure 5.54: Distributed force on damaged wood pallet - racking

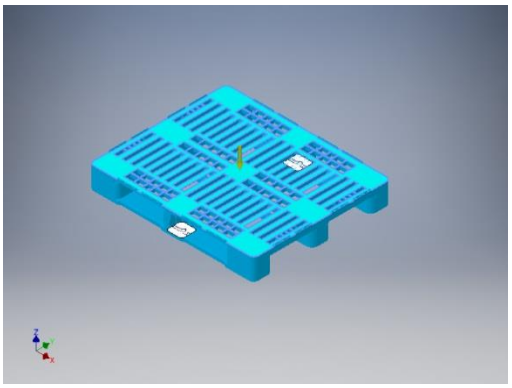


Figure 5.55: Constraint location on damaged plastic pallet - racking

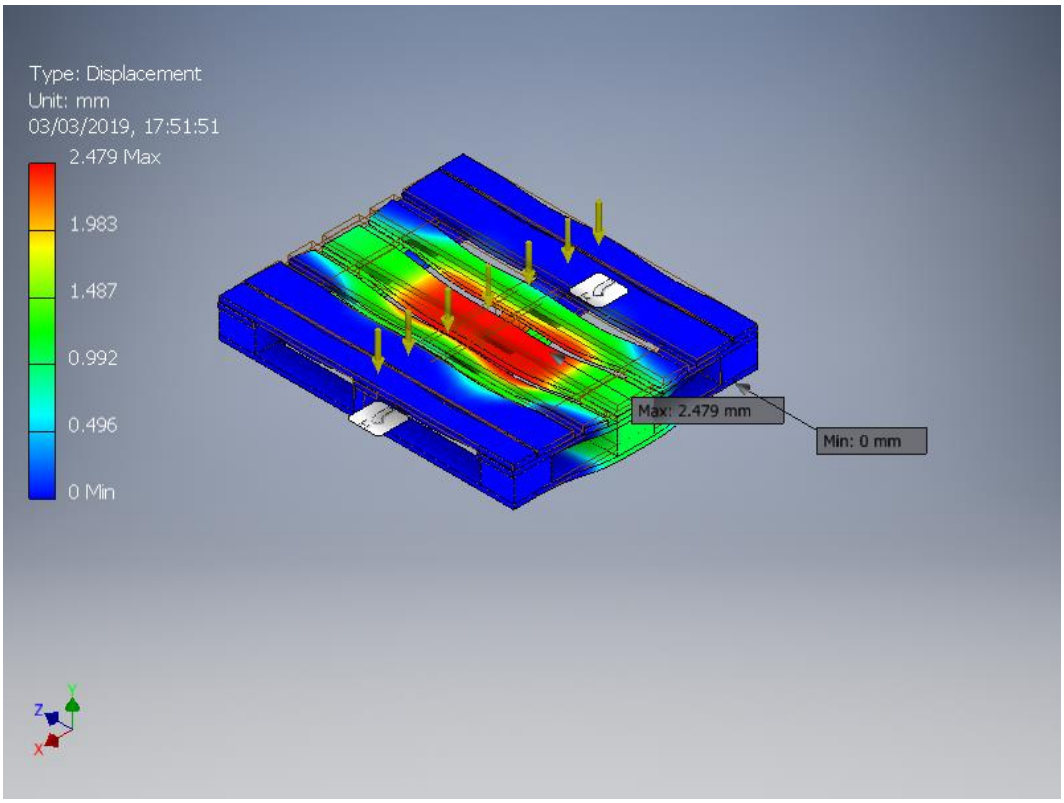


Figure 5.56: Displacement / Deflection measurement on damaged wood pallet - racking

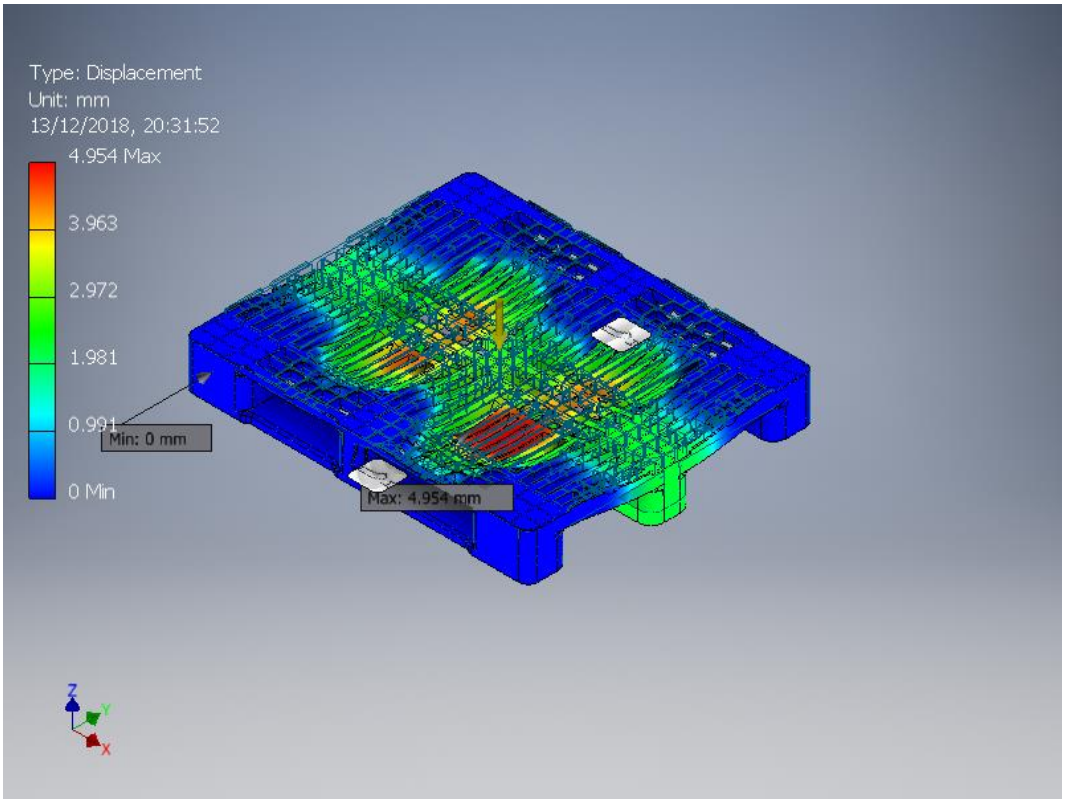


Figure 5.57: Displacement / Deflection measurement on damaged plastic pallet - racking

5.5 Summary

The main focus of this chapter was to analyse the material used as the MOC of the study pallets, test the pallets as per standards and consequently apply these results to creating a suitable simulation model.

As the pallets were manufactured by a 3rd party, material characterization (both chemical and mechanical) of the MOC was critical. By means of FTIR spectroscopy, properties of polypropylene, high density polyethylene and pine were observed during spectra analysis and validated the presented pallet materials. The morphology and topology examinations proved consistent with literature findings and gave great insight on surface properties of the given pallets.

Pallet testing in accordance with the ISO 8611 pallet standards was carried out on the trial pallets with all successfully passing the requirements set by the standard for both the stacking and the racking test scenarios. These test

results formed the basis of comparison for the simulation model that was developed in Autodesk Inventor.

The models were designed as accurately as possible with some simplifying assumptions such as modelling the wood pallet as an isotropic material. Some assumptions and lack of a material library specific to the SA pine characteristics reduced the accuracy of the FEA analysis, however, when compared with the results from the pallet testing, the margin of error was not too high (60% for wood and 19% for plastic in racking simulations).

In addition, a predictive model was proposed as a means to identify safe working conditions for damaged plastic pallets as these cannot be readily repaired and no set standard exists in this regard.

Limitations

Due to the nature of the pallet design for the Pallet A plastic pallet, there was not enough pallet material for extraction in order to test the MOC for its mechanical properties by means of tensile tests. In addition to this, because this pallet was steel reinforced, this pallet type was not modelled in section 5.4.

CHAPTER 6:

PHASE III – CASE STUDY

6.1 Introduction

This chapter serves the purpose of outlining the particulars of the case study within this research. The objective is to introduce the various key business partners of the study, the environments within which the study was conducted along with how the execution of the case study contributed to the merits of the overall study.

6.2 Case Formulation

This case study aimed to identify the benefits and drawbacks of using either wood or plastic pallets within a specified supply chain network. Justification for the choice of pallets used was outlined in Chapter 3 section 3.4.2.

6.2.1 Pallet Description and Identification

Pallets of differing specification (see Table 3.2) were marked and prepared for the commencement of the case study. All the trial pallets were numerically marked for ease of identification within the distribution environment (Figure 6.1). Prior to all preparations, tests were carried out as close as possible to ISO 8611 standards (see section 5.3) in order to ensure that the pallets met industry expectations before introducing them into the distribution environment.



Figure 6.1: Pallets used for testing and the case study

6.2.2 Industry Selection Rationale

On the basis of supporting literature and survey results, the decision was made to conduct the case study within the fast-moving consumer goods (FMCG) industry. This industry is one of the largest markets for pallets, and as such, participants were selected from this industry.

In lieu of alternative equally suitable criteria, this case study was formulated on the basis of operating temperature within the FMCG industry. Different types of supply chains with varied operating conditions were chosen in order to facilitate for a wide variety of conditions in order to best analyse the performance of each pallet type. These supply chains represented a different “case” of the study.

The following supply chains were selected for analysis:

- Case I – Ambient chain (15°C to 25°C)
- Case II – Perishables chain (0°C to 4°C)
- Case III – Cold chain (-40°C to 0°C)

6.3 Case Execution

In order to assess the pallets in the case study, each of the pallets were rated on a metric scale of 5 on the basis of performance for each key interaction along the supply chain within each case. At the top of the metric, 5 implied adequate performances with no major negative effects on the distribution environment. Points were docked from this total when pallets were considered to deviate from the ideal scenario in criteria relating to palletization, storage, transport, equipment handling and compatibility at the different sites employed.

6.3.1 Participating Companies

Although the study looked to compare performance of pallets in various industries and supply chain networks, the study focussed on the FMCG industry.

The gracious participants of the study from this industry were as follows:

- Clover
- DHL
- Natures Garden
- Pick ‘n Pay
- Sequence Logistics
- Unilever
- Vector Logistics

Pallets were put into the supply chain at manufacturer’s sites and allowed to traverse the supply chain through the distribution centres and down to the retailers or end consumers. Interactions within the distribution environment were observed between pallets, pallet handling equipment, operators and the operating environment. Additional site-specific information may be located in Appendix E.

6.3.2 Supply Chain Outline

The objective of the case study was to expose the pallets of wood and plastic MOC in supply chains of varying operating conditions. With the involvement of the participating partner companies as listed in section 6.3.1, three distinct supply chain routes were mapped out. Namely, an ambient supply chain route, a perishables products supply chain, as well as a cold chain route, all starting at manufacturer sites and endind at retail outlets (Table 6.1).

Table 6.1: Pallet flow through supply chain partners for case study

	Manufacturer	**Primary DC**	**Secondary DC**	**Retailer**
Ambient Chain	Unilever (Khanyisa)	DHL (Jozi Park)	PnP DC (Longmeadow)	PnP Stores
Chilled / Perishable Chain	Clover Dairy Plant (Queensburgh)	Clover CDC (Clayville)	PnP DC (Longmeadow)	PnP Stores
Cold Chain	Nature’s Garden (Alrode)	Sequence Logistics (Aeroton)	Vector Logistics (Midrand)	PnP Stores

6.4 Case I: Ambient Chain

In this case, Unilever was the key partner. Liquid detergents were produced on site at the Khanyisa factory (Anderbolt, Johannesburg) and transported to Kwa-Zulu Natal (PMB) via their Jozi Park warehouse / DC. The role of this phase was to conduct a long-haul transport study on the pallets and to expose them to both automated and manual palletizing.

It should be noted that the study could not incorporate a full supply chain trial to the retailers due to an oversupply of product at partner sites (during the scheduled trial period), hence making it economically infeasible. As such only the long-haul transit trial was carried out. It is possible that results would change if the entire supply chain was considered.

This supply chain operated at ambient conditions (room temperature) with no direct exposure to harsh elements. The transit trial was conducted over a 3 to 4-week period with various interactions observed and recorded along the way. Below are the monitored interactions.

Key interactions:

- Automated palletizing
- Conveyor systems
- Manual palletizing
- Pallet Stacking
- Long-haul transport

In order to understand the flow of pallets and palletised unit loads, process mapping at the relevant sites was carried out. The typical flow of pallets at the Unilever site in this supply chain is illustrated in Figure 6.2. Here it is noted how pallets were distributed to either the automated palletizing zone (APZ) or the manual palletizing zone (MPZ) (depending on production schedules) prior to being dispatched to their Jozi Park warehouse for distribution. The pallets were observed at key touch points in these zones and their performance rated.

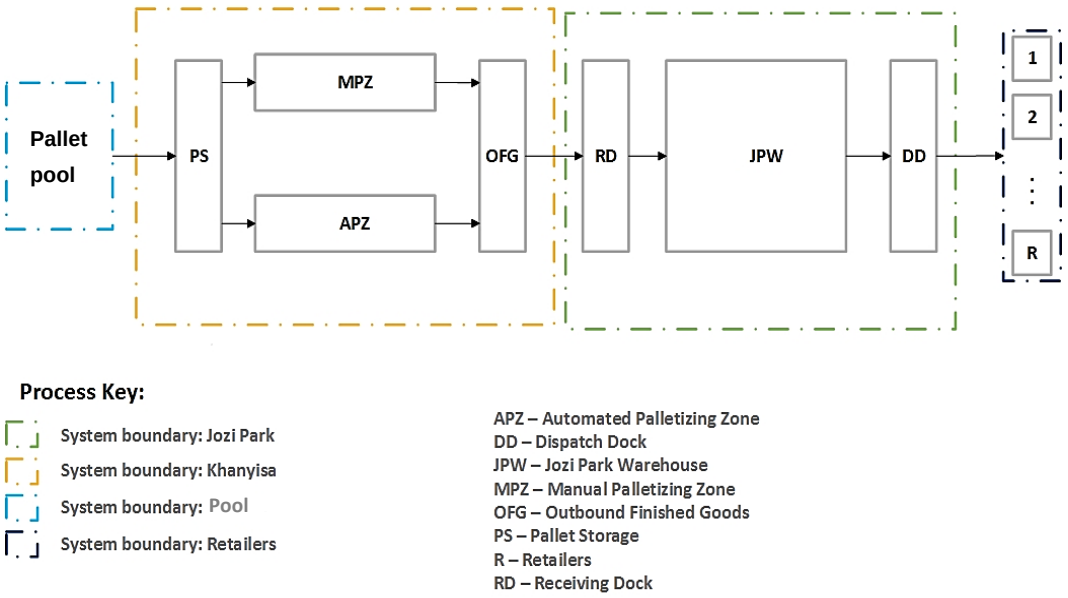


Figure 6.2: Process mapping - Unilever Khanyisa & Jozi Park block flow diagram for pallet flow

Figure 6.3 indicates the key “touch points” within the Unilever Khanyisa site that served as important observation locations. These “touch points” indicate points of interaction of the pallets with various PHE and environments within the site. The main interactions were within the manual palletising zone (MPZ) and automated palletising zone (APZ) as unit loads were prepared therein. The points labelled 1-8 are respectively the:

1. Pallet storage area
2. Manual palletizing zone
3. Robo-pack and Labelling
4. Automated Palletizing Zone Pallet Entry
5. Automated Palletizing Bay
6. Outbound Finished Goods
7. Repackaging Zone
8. Forklift Operator interaction with unit loads

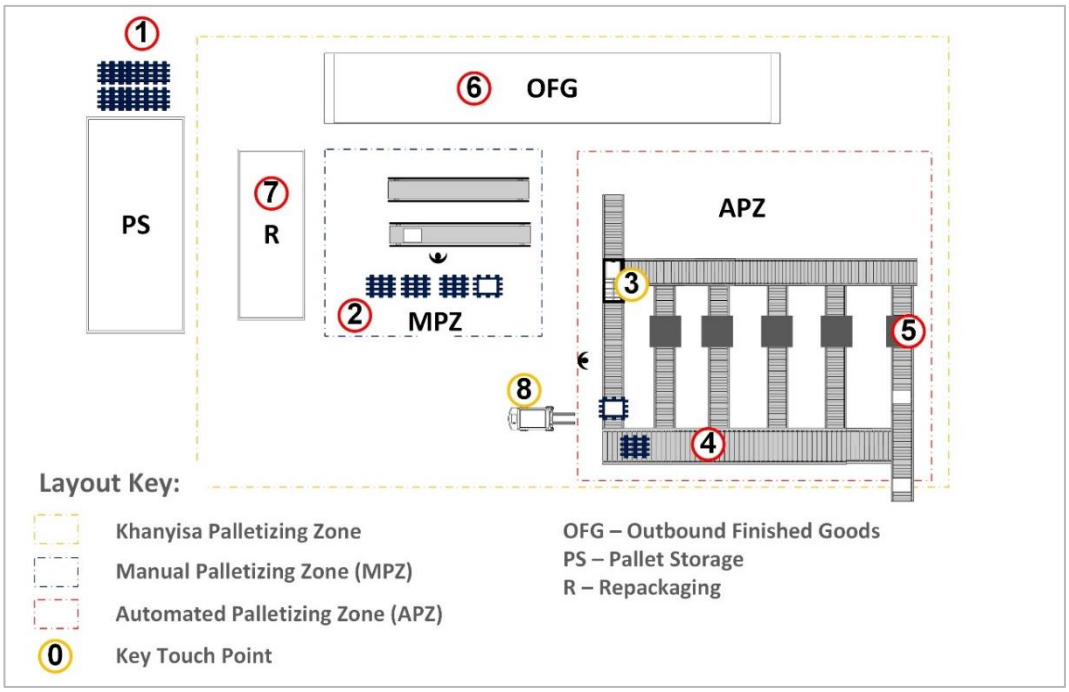


Figure 6.3: Key observational areas / "touch points" at Unilever Khanyisa site

6.4.1 Manual Palletizing

All pallets exhibited an ease of palletization in the MPZ. Boxes were loaded as per the packing configuration outlined for the given products without any problems. Figure E.14 and Figure E.15 display some test pallets in this environment with the typical load from this site.

6.4.2 Automated palletizing

Much like the MPZ, the automated palletizing was administered without any delays, disruptions, failures or damages. Smooth intake of the pallets (mixed with the traditional wooden ones), was observed as can be seen in Figure E.16 and Figure E.17. The smooth performance of the plastic pallets was captured by video and links are provided below for further engagement.

Link to video of Plastic (Pallet A) being loaded: https://tinyurl.com/y2a58tj8

Link to video of Plastic (Pallet C) being loaded: https://tinyurl.com/y5cbrs7n

6.4.3 Conveyor and Equipment Handling

All test pallets performed relatively well on the conveyor systems (in comparison with the pallets currently used in this supply chain). No issues were observed on either the chain or roller conveyor systems. It should be noted though that the plastic pallets (Pallet A) did exhibit slight slippage at the end point of the conveyor system likely due to the smooth surface.

With regards to the plastic (Pallet C) pallet, although it also has a smooth polymer surface, the top deck lips ensure that the load remained relatively fixed to the surface and the behaviour noted on the Pallet A was averted. The slippage on the smooth surface was however present when bulk transporting pallets stacked onto each other. This was highlighted by the forklift operator on site and posed a cause for concern.

6.4.4 Damage Analysis

The pallets and products were successfully transported in the long-haul transport segment given that no damage to products or pallets was reported by Unilever. All the pallets passed this transit trial as they met the minimum requirements of performance. Damage to the pallets was minimal at best. In Figure E.21 and Figure E.23 slight insignificant damage to the pallet bodies of the Wood and Pallet C pallets is notable. In terms of the Pallet A plastic pallet in Figure E.22, damage to the Anti-slip grommets was a concern as it was significant for just one cycle, however, this did not impede on the load bearing capacity of the pallets.

6.4.5 Scorecard

A summary of the assessed performance (assessed by the author) of each of the pallets is displayed in Table 6.2. This scorecard indicates that the wood pallets were the best pallets in the case, being optimal performers in terms of palletising, equipment handling, transport, durability and storage with a score of 5/5 in this case.

Table 6.2: Scorecard for pallets in ambient chain

Case 1: Ambient Pallet Score Sheet								
Pallet Type	**Manufacturer site**			**Distribution centers**			**Retailers**	**TOTAL**
	Palletizing	Equipment Handling	Storage	Transport & Durability	Equipment Handling	Processing & Storage	Durability	Avg.
Wood: Pallet B	5	5	5	5				5.00
Plastic (PP)	5	4	5	5	**Only transit trial conducted**			4.75
Plastic (HDPE + PP): Pallet A	5	4	5	4				4.50

Although this case did not incorporate a full supply chain exposure trial, the transit trial was sufficient in allowing for the deduction of the best performer under the stipulated conditions.

6.5 Case II: Perishables Chain

For the chilled goods / perishables chain, Clover was the industry partner. The pallets were introduced into the supply chain at the Clover (Clayville, Johannesburg) central distribution centre (CDC) and were further sent to Queensburgh (KwaZulu-Natal) (long-haul study) to their dairy manufacturing site. They were then sent back to the CDC and then onto the retailers for distribution.

The average temperature within this case was 2.2°C with temperatures ranging between 3.2°C and 0.8°C at different sample points within the CDC. The relevant pallet flows at the Clover CDC site were mapped and key regions identified for the study (Figure 6.4).

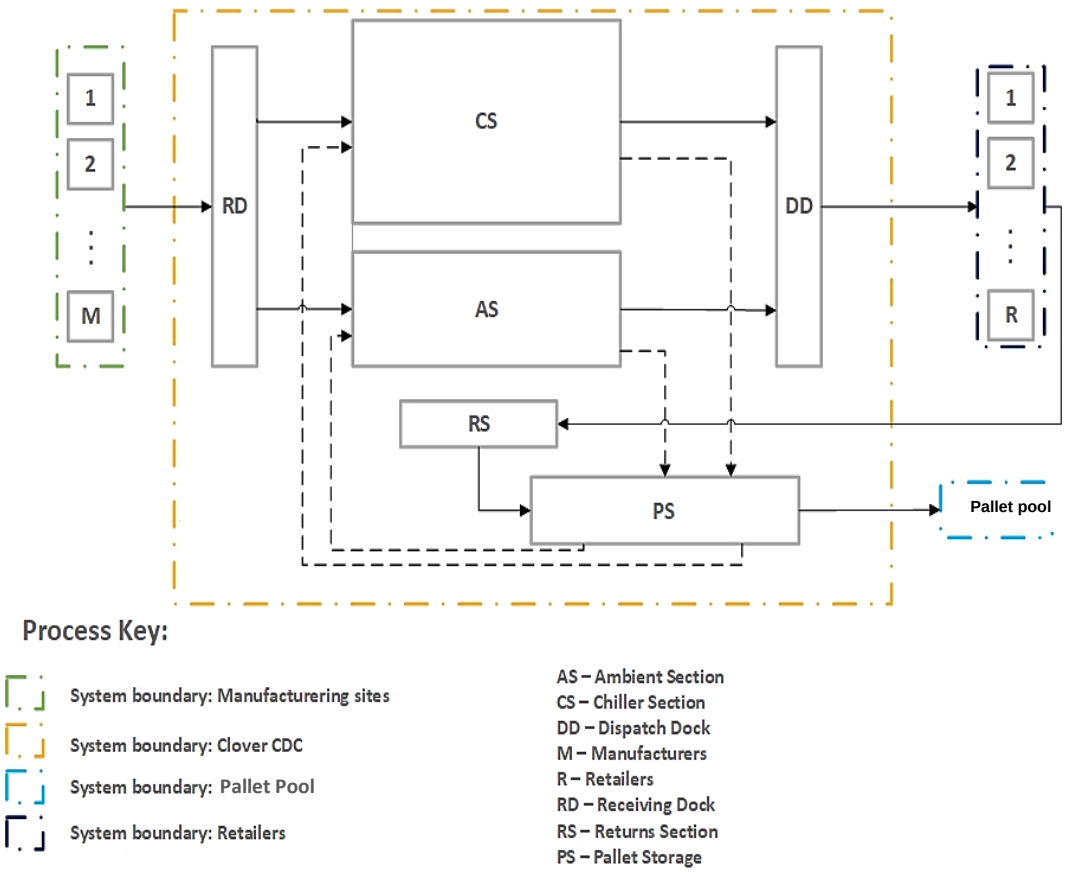


Figure 6.4: Clover CDC BFD for pallet flow

Unlike with Case I, the long-haul transport segment in this case incorporated the use of refrigerated transport trucks that were maintained at similarly

chilled temperatures as the distribution centres. Below are the monitored key interactions within this case.

Key interactions:

- Manual palletizing
- Product picking
- Product transfer
- Long-haul transport
- Refrigerated transport

As the initial point of entry into the supply chain was at the Clover CDC, layout touch points (Figure 6.5) were identified and mapped out for observation. The respective points labelled 1-6 were respectively the:

1. Receiving Bay
2. Returns Section
3. Chilled Storage Warehouse
4. Dispatch Dock
5. Outbound Finished Goods
6. Pallet Storage Bay

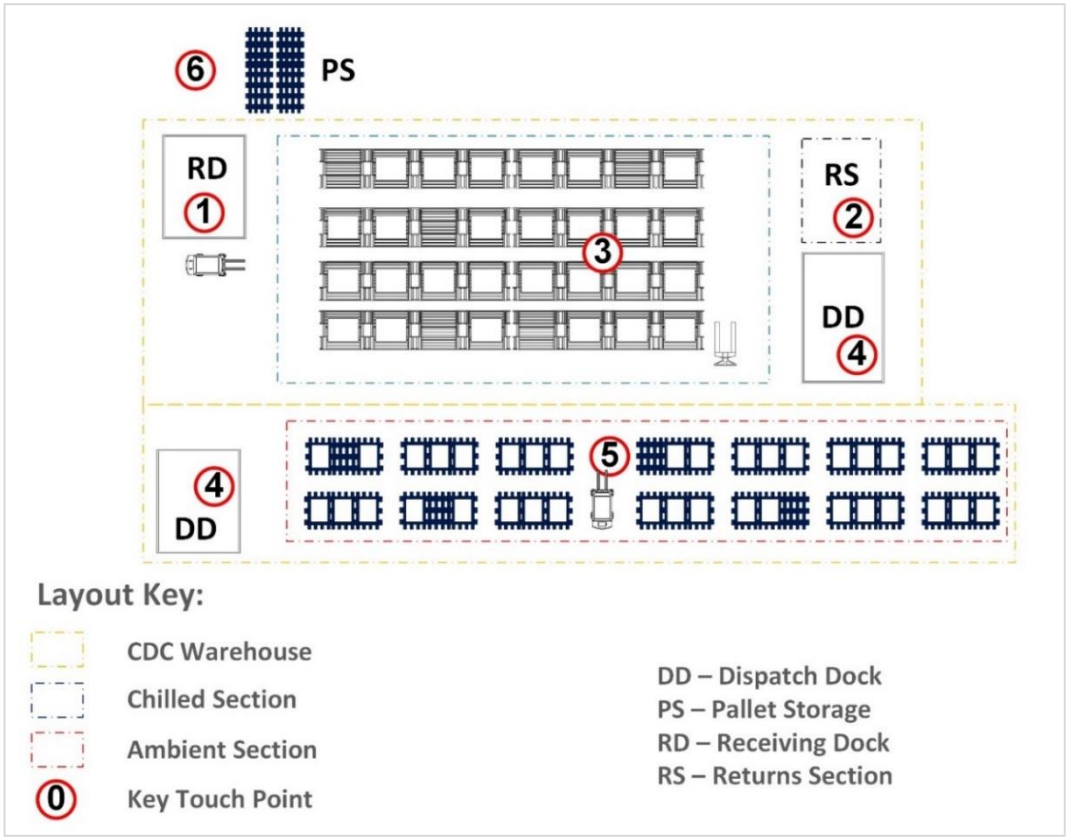


Figure 6.5: Key observational areas / "touch points" at Clover CDC pallet flow

6.5.1 Manual Palletizing

Manual palletizing was overall an adequate process. Products were transferred from existing pallet loads onto the test pallets. There is normally a concern in industry regarding slippage of product when it comes to plastic crates on plastic pallets, however, in this case the opposite occurred. The anti-slip grommets on the Pallet A pallets worked, but not as efficiently as desired. As packers needed to move a lot of crates at once on the surface, as such, the grommets effectively created resistance to this process and slowed down the palletizing process (see Figure E.25).

In terms of the Pallet C plastic pallet, the smooth surface was not a major hindrance and due to the lips on the top deck, load stability was enhanced and the crates secured (Figure E.24). Although the industry already used wood, it was important to note its performance.

With wood, it would be considered ideal due to its mechanical properties (good load bearing capability and coarse surface), however, during observations, it was noted that protruding nails or uneven elements caused a similar outcome to that of the grommets on the Pallet A pallet. These protruding nails also posed a safety concern and posed a risk to products if not for the slip sheets.

6.5.2 Transport and Storage

All pallets performed well in storage and transport as no product damage was reported by Clover after the long-haul segment of the trial to Queensburgh (approximately 587 km travel distance one way).

6.5.3 Equipment Handling

In terms of materials handling, there was excellent performance by all pallet types. Interaction with forklifts, pallet jacks, pickers and reach trucks was smooth and without disruption (Figure E.32 and Figure E.33).

6.5.4 Damage Analysis

The quick nature of the perishables supply chain took its toll on the Pallet A plastic and wooden pallets. Turnaround times within this supply chain are

considerably quick (days) and not weeks as can be seen in the ambient and frozen food chains.

Significant damage on the Pallet A plastic pallet was noted on the fastening pins (Figure E.35) and on both the top and bottom decks as seen on pallets (Figure E.34 and Figure E.36) returning from the transit trial and post retail leg. It incurred a lot of damage not only to the pallet body but also to the anti-slip grommets, that were either missing or severely worn out.

The wooden pallets also exhibited major damage to a number of elements on various pallets (see Figure E.38 and Figure E.39). Significant damage was observed predominantly on the bottom deckboards of the pallets but it should be noted that within a pooling model, these pallets could be repaired and reintroduced in the supply chain unlike with the plastic pallets.

With regard to the plastic (Pallet C) pallet, little to no damage was exhibited by these pallets (Figure E.37), neither upon return from the transit trial or return from the retail outlets at the end of the supply chain.

6.5.5 Scorecard

The results from this case are provided in Table 6.3 with the Pallet C plastic (PP) being the best performer across the board and scored 5/5. The Pallet B wood pallet was a close second at 4.43/5 leaving the Pallet A plastic pallet as the worst performer.

Table 6.3: Scorecard for pallets in perishables chain

Case 2: Perishables Pallet Score Sheet								
Pallet Type	**Manufacturer site**			**Distribution centers**			**Retailers**	**TOTAL**
	Palletizing	Equipment Handling	Storage	Transport & Durability	Equipment Handling	Processing & Storage	Durability	Avg.
Wood: Pallet B	4	5	5	4	5	5	3	4.43
Plastic (PP)	5	5	5	5	5	5	5	5.00
Plastic (HDPE + PP): Pallet A	3	5	5	3	5	5	4	4.29

These results are based on two trips to retail outlets from the CDC and one long-haul transport. No pallet repairs were considered and durability was based only on the state of the pallets at the end of the cycle in comparison to that when they were first introduced.

6.6 Case III: Cold Chain

Natures Garden was the key partner in the frozen goods supply chain. Frozen chips were produced at the manufacturers site (Alrode, Alberton) and distributed onto primary and secondary distribution warehouses prior to reaching Pick ‘n Pay (PnP) retail outlets. In this phase the key objective was to monitor the pallets performance in sub-zero conditions and rank the respective performances of the trial pallets on the basis of key interactions as with prior cases. In this chain the operating temperatures ranged from between -23°C in the cold storage warehouses and approximately 4°C in the palletising zone. This presented a critical opportunity to note how temperature fluctuation affected pallet performance.

Key interactions:

- Manual palletizing
- Racking Storage
- Refrigerated transport
- Cold Storage

From the manufacturer’s site, there was a 67% throughput of trial palletised loads as only some of the initial loaded pallets were dispatched to the DC. This was due to product recalls for reworks and as such pallets did not follow the supply chain path set out.

Uniform loads of frozen chips were loaded onto the trial pallets and stored in the DC. Due to the nature of the product and demand, the product movements were subdued as compared to the other supply chains. The trials took over 4 months execute.

This supply chain hence favoured pallet materials that were not vulnerable at temperatures below -20°C with little to no product movement for extended periods of time.

In Figure 6.6, a depiction of the pallet flow from the Natures site is outlined. The flow of pallets in and around the site is important in getting a grasp of how well pallets performed within the supply chain.

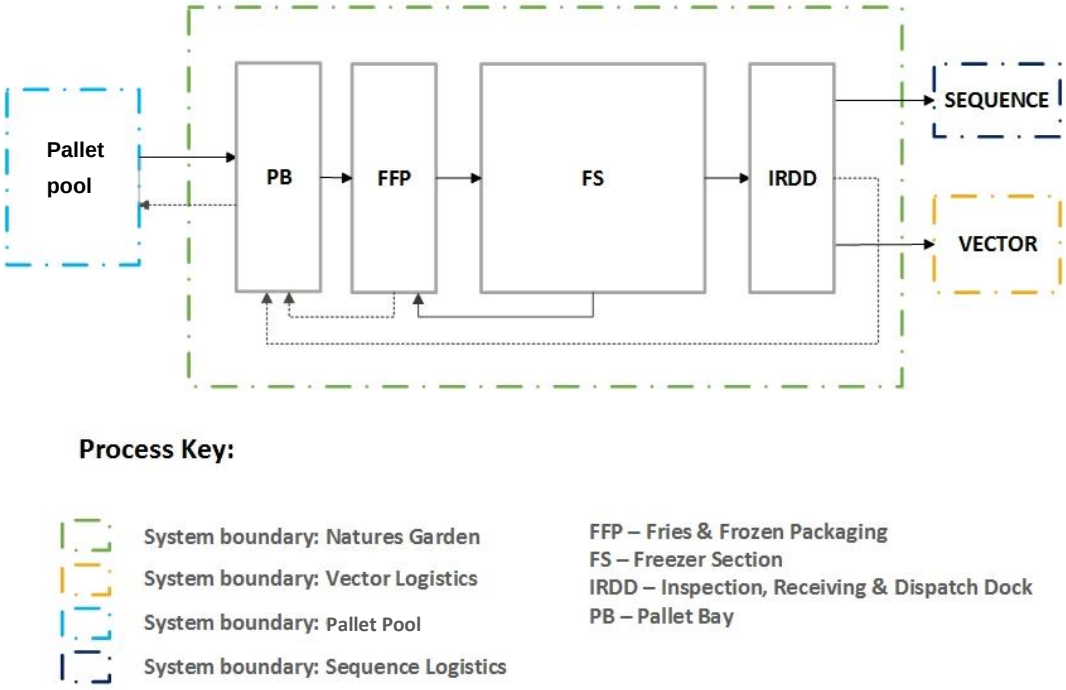


Figure 6.6: Process mapping – Natures Garden block flow diagram for pallet flow

In the Fries and Frozen packaging segment of the BFD (Figure 6.6), the section with critical pallet interaction at key observational points or "touch points" is located. This area involved manual palletizing of packaged products and unit load assembling for storage.

These layout touch points were identified and mapped out for observation as indicated in Figure 6.7. The respective points labelled 1-6 were the:

1. Pallet Storage Bay
2. Manual Palletizing Zone
3. Unit Load Wrapping Station
4. Inspections, Receiving & Dispatch Dock
5. On Site Freezer Warehouse
6. Refrigerated Transportation

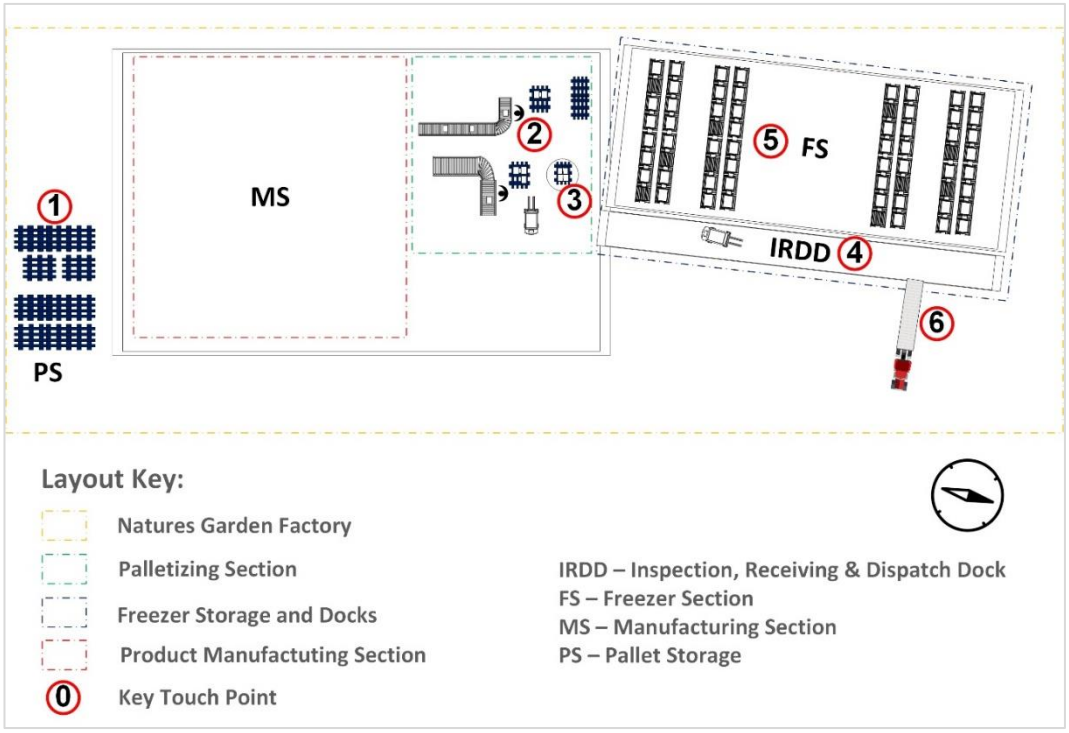


Figure 6.7: Key observational areas at Natures Garden Alrode site

6.6.1 Manual Palletizing

Due to similar dimensions, all pallets were fully compatible within the loading bay and had no major problems during the manual palletization. All pallets were loaded with the same product and no load instability issues or major problems during this process were observed.

6.6.2 Transport and Storage

Pallets were effectively transported to and stored at primary (Sequence Logistics - Aeroton, Johannesburg) and secondary (Vector logistics – Midrand) distribution centres. Figure E.40 - Figure E.42 shows the trial pallets in-situ on some racking beams.

6.6.3 Equipment Handling

All pallets performed relatively well with all pallet handling equipment. It should however be noted that upon brief interview with forklift drivers, they did highlight having extra caution due to not being accustomed to plastic pallets. This exposed the pallets to unequal treatment which may have influenced the potential for damage. Below are some video clips showing the handling of pallets on the shrink-wrap machine for further perusal.

Video link for Wood (Pallet B): https://tinyurl.com/yxecwu4l

Video link for Plastic (Pallet C): https://tinyurl.com/yyk9dyy4

Video link for Plastic (Pallet A): https://tinyurl.com/y579vfmo

6.6.4 Damage Analysis

The wooden pallet type was the only pallet to sustain damage at the manufacturers site as shown in Figure E.45 and Figure E.46 and ironically this pallet type was the only one to have made it through the entire supply chain down to retailers. As shown in Figure E.47, the pallet incurred a lot of damage along the route.

The plastic (Pallet C) showed signs of brittleness and damage as per Figure E.48 and Figure E.49. The Pallet A pallets had not exhibited any damage as inspected at the primary DC.

It should be noted that due to the low throughput levels and the lack of consistent product flow and the loss of pallets in the supply chain, some pallet types did not traverse the entire supply chain and hence results were somewhat inconclusive.

6.6.5 Scorecard

In terms of pallet performance in this case, all pallets exhibited strengths and considerable weaknesses at various points within the supply chain. From the data obtained, Table 6.4 summarised the performance ratings.

Given that this supply chain had minimal touch points and few product movements, the Pallet A plastic pallet was the better performer although it was not tracked all the way to the retailers. Minimal reported damage and smooth handling made it favourable with a score of 4.83/5. All the pallets performed reasonably well with no major interruptions to the distribution environment reported. Since not all pallets made it to the retail outlets, the score obtained by the Pallet B pallet was omitted as indicated by the brackets i.e. ‘(4).

Table 6.4: Scorecard for pallets in cold chain

Case 3: Cold Chain Pallet Score Sheet								
Pallet Type	**Manufacturer site**			**Distribution centers**			**Retailers**	**TOTAL**
	Palletizing	Equipment Handling	Storage	Transport & Durability	Equipment Handling	Processing & Storage	Durability	Avg.
Wood: Pallet B	4	4	5	5	5	5	‘(4)	4.67
Plastic (PP): Pallet C	5	5	5	4	5	4	-	4.67
Plastic (HDPE + PP): Pallet A	5	5	5	5	5	4	-	4.83

Both the wood (Pallet B) and plastic (Pallet C) pallets were rated equally with a score of 4.67/5 each respectively, the plastic (Pallet A) performed the best under the stipulated operating conditions, without considering the retail segment of the supply chain.

6.7 Summary

After considering the performance of all the pallets thus far in the case study, it was evident that the plastic (Pallet C) pallet was the best overall performer. This was in spite of its brittle nature in the cold chain.

It should also be noted that the findings are purely on the basis of a single pass within the supply chain and outcomes for multiple iterations may prove to present a different outcome especially if pallet repair is considered.

Table 6.5 below gives an overall summary of the pallet performance across all three supply chains.

Table 6.5: Overall Scorecard for pallets in all supply chains

PALLET	TOTAL AVERAGE SCORECARD
Plastic (PP): Pallet C	4.81
Wood: Pallet B	4.70
Plastic (HDPE + PP): Pallet A	4.54

Each pallet type was noted to have been the best performer in at least one of the chains. The wood (Pallet B) was the best performer in the ambient chain, the plastic (Pallet C) was the best performer in the perishables chain and the plastic (Pallet A) displayed the best performance in the cold chain. These observations assert the viewpoint that not one single pallet type can be considered as the best type for all the supply chains, however, a decision can be made once all criteria for a given set of objectives are considered. This concept is what will be assessed when dealing with the multi-criteria decision analysis procedure in the next chapter.

CHAPTER 7:
PHASE IV – MULTI-CRITERIA DECISION ANALYSIS

7.1 Introduction

Within this chapter, methods will be explored relating to multi-criteria decision analysis (MCDA) tool formulation and illustrate how this tool incorporates the results of the study by means of an illustrative example. This tool is developed as a standalone application and as such the main goal of this chapter is to illustrate how it works and showcase the relevant methods underpinning its formulation.

7.2 MCDA Tool Formulation

As previously outlined in section 2.5, there are a number of methods that are useful in solving problems that require multi-objective optimization. The first stage in tool formulation is to ensure that the tool outputs only pareto optimal solutions. In order to achieve this, the tabular method (TM) may be employed in order to eliminate all non-pareto solutions or in this case alternatives. However, since in the case of this study, there are only 3 pallets used as alternatives for a set of decision criteria, each pallet solution would be pareto optimum and as such the TM will not be used in this regard.

The second stage involves the application of a MCDM technique. With the vast literature and varied application of its use, the Analytic Hierarchy Process (AHP) as proposed by Saaty (1980) was the technique of choice as it is well documented and highly effective (Subramanian & Ramanathan, 2012). The final stage would be to review the results of any of the techniques and apply the result or refine one of the steps within the decision-making process. In this case seeing that stage one is catered for, the following sections will further elaborate on the AHP process and its implementation.

7.2.1 Analytic Hierarchy Process - Procedure

AHP applications make use of 4 steps in order to come to a decision on a given set of alternatives. The following steps are elaborated upon in the context of this study.

The steps involved are (Subramanian & Ramanathan, 2012) :

STEP 1: Structuring of the decision problem
STEP 2: Making pair-wise comparisons and obtaining the judgmental matrix
STEP 3: Computing local weights and consistency of comparisons
STEP 4: Aggregation of local weights

The first step involves formulating the decision problem into a hierarchical model which normally contains levels relating to the goal, criteria (with possible multiple sub-criteria) and alternatives (Subramanian & Ramanathan, 2012). In this tool formulation, a pallet selection framework is presented as per Figure 7.1 containing the list of suitable decision criteria as presented in section 7.2.2.

The second step incorporates the use of pairwise comparisons, which is the basis of the AHP (Saaty, 1987). Herein elements within a particular level are compared using the fundamental comparison scale in Table 7.1 on a pairwise basis to the immediate upper level within the hierarchy (Subramanian & Ramanathan, 2012). The comparison elicits the decision maker's judgements in order to select an intensity of relative importance or in the case of this study, ratings are made in relation to results from this study for each criterion (as well as the author's judgments based on experience gained while conducting the study). These ratings form the foundation of a judgemental matrix which is governed by the following rules for each entry a_{ij}:

1. $a_{ij} > 0$
2. $a_{ij} = 1/a_{ji}$
3. $a_{ii} = 1 \ \ for\ all\ i$

In order to compute the relative importance of a particular alternative in a judgemental matrix in relation to the criteria being evaluated, Saaty proposed the calculation of the right principle eigenvector of the matrix and calculating the normalised value of each element.

Table 7.1: Fundamental comparison scale used by Saaty (1995) (Fong & Choi, 2000)

Intensity of importance	**Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When a compromise is needed
Reciprocals	If activity "*i"* has one of the above nonzero numbers assigned to it when compared with activity "*j*", then activity "*j*" has the reciprocal value when compared with "*i* ".	

Due to the nature of the pairwise comparisons indicated earlier, it is possible that comparisons may prove to be inconsistent. The AHP technique caters for this by introducing a Consistency Ratio (CR) for which if the value is less than 0.1, the pairwise comparisons are said to be adequate. CR is obtained by dividing the Consistency Index (CI) as per Equation 5, by the Random Consistency index (RCI) which is provided in Table 7.2 (Triantaphyllou & Mann, 1995). This process is in essence what step 3 entails.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

Where:

n = number of elements in the row of the matrix

λ_{max} = maximum eigenvalue associated with previously calculated eigenvector

Table 7.2: RCI values for different values of n (Triantaphyllou & Mann, 1995)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The final step is an aggregation of each of the weights at each level of the hierarchy by means of an arithmetic aggregation rule for each of the criteria and alternatives i.e. for a problem has M alternatives and N criteria (Triantaphyllou & Mann, 1995) the following equation would apply:

$$A^i_{AHP} = \sum_{j=1}^{N} a_{ij} \times w_j \; for \; i = 1,2,3, \dots, M \tag{6}$$

Where:

A = decision matrix of final priorities

a_{ij} = judgement matrix of criteria being compared

w_j = local weights of the immediate upper level

7.2.2 Identification of Decision Criteria

The following are some definitions of the criteria and sub-criteria that are used in formulating the decision framework. Each criterion is given a brief description as to what it relates to in terms of pallets selection as well as comparative findings as found in literature in relation to wood and plastic pallets. In this tool data from this study (as formulated by the author) was used and were none exists; literature findings are used in order to supplement the given data.

Operational Comparison

Rack ability

(Description: This criterion relates to the ability and ease of using a pallet on racking in the distribution environment).

- Plastic pallets are more susceptible to slippage than their wooden counterparts due to the smooth nature of the polymer surface which can pose a safety concern in racking environments (Freightera, 2018).

Life Cycle/ Durability - expected useful life

(Description: This criterion defines the useful lifespan of a pallet and its durability under different use cases).

- The projected lifespan of a plastic pallet is set around the 10-year mark (Freightera, 2018).
- Wooden pallets can have a 3–5 year lifespan (Eightohtwo, 2017) although difficult to assess with repairs.

Operating Condition

(Description: This criterion indicates the types of operating conditions best suited to a pallet types as well as outlines which conditions may have adverse effects).

- Wood is known to be sensitive to water as it may warp when exposed and can potentially rot and grow fungi.

- Plastic becomes brittle when exposed to sub-zero condition and as such it may not be suitable for very cold temperatures.

Risks – pallet flammability, occupational hazards from handling of pallets

(Description: All types of equipment come with associated risks. This criterion looks to emphasize the risks associated with a particular pallet MOC).

- Smooth surfaces make them slippery which can prove to be an operational risk (Freightera, 2018).
- Broken elements from wood can pose a serious safety risk as protruding nails and sharp element can cause injury.

Consistency - variable weight with water contact, humidity or any other factors

(Description: Pallet consistency is important in predicting behaviour and expected performance. This criterion caters of this variable).

- Wood: Due to construction by different elements and material properties, pallets comprised of wood are susceptible to weight inconsistencies and may exhibit unreliable performance (Soury et al., 2009).
- Plastic: Chemical properties make these pallets more durable and effectively more resistant to weather elements.

Environmental Comparison

Recyclability and Disposal

(Description: The associated impacts of disposal and ability to recycle a product are key decision factors and this criterion caters for this).

- Wood being 100% biodegradable can be landfilled, however, other end of life (EOL) option can be undertaken such as mulch and animal bedding (Lacefield, 2008; Materials Handling, 2011). Waste to energy technologies are also options for energy recovery from waste wood pallets (Buehlmann et al., 2009).

- Plastic is non-biodegradable and has a long half-life prior to initial decomposition. Landfilling is not a sustainable option and other options such as recycling need to be administered (Lacefield, 2008; Soury et al., 2009).
- Plastic pallets may be made from recycled material and be recycled at EOL scenarios (Lacefield, 2008). This promotes a circular plastic economy that reduces landfilling and material waste.

Regulations and Hygiene - infections, parasites, mould, etc. and repercussions

(Description: Most products are regulated according to some standard and this may impact on operation or adoption of a particular pallet type. This criterion explores this potential concern).

- Regulations exist such as the ISPM 15 that requires export wood pallets to be heat treated. This is done in order to eliminate the transfer of pests between countries.
- Heat treatment of pallets is energy intensive and thus can compound CO_2 emission levels.

Manufacturing – source of materials used for pallet manufacture (local/ import)

(Description: The impact of manufacturing activities associated with the manufacture of a pallet of a type of MOC may have an impact on costs, pollution and overall sustainability).

- Plastic pallet manufacturing is highly energy intensive, up to 5 times the energy consumption of wood pallet manufacturing, thus consequently produces more CO_2 emissions (Lacefield, 2008).
- Forest depletion is a major environmental concern for pallet manufacturing from wood (Soury et al., 2009), however, major pallet manufacturers are actively engaged in reforestation.

Sustainability - sustainable benefits/ shortfalls of the various pallet types

(Description: This criterion defines the requirements for assessing a sustainable pallet type and how some may fair against one another).

- In order to quantify the sustainability of a given pallet, a full Life Cycle Analysis, from cradle to grave, of the specific pallet needs to be carried out following ISO14040 guidelines (Lacefield, 2008).
- Pallet from wood are completely biodegradable. Plastic on the other hand is non-biodegradable and must be recycled (Freightera, 2018).

Economic Comparison.

Cost – detailed cost breakdown by element

(Description: Costs are normally the driving force in many decisions taken in industry, this criterion caters for this although the option exists of carrying out a cost benefit analysis in isolation).

- Wood pallets for export require heat treatment which necessitates a larger energy input for kiln operation and thus a higher associated energy cost.
- Mechanical failure, such as broken elements and protruding nails, of wood pallets can lead to damage of goods, injuries, customer returns, legal claims or delays in material movement which ultimately decreases total efficiency and increases operating costs (Emiliani & Stec, 2005).
- Exports on wooden pallets offer a cheaper alternative to plastic ones as these pallets are rarely ever returned (Eightohtwo, 2017; Prostack, 2016).
- As fuel consumption is the most significant energy cost in unit load transportation, a reduction in either size or volume of the unit load could improve operational efficiency of goods transportation in the supply chain (White & Hamner, 2005).

Repair/ Maintenance – ability to clean, condition and repair pallets as well as the cost of repair and maintenance

(Description: Maintenance and repair costs may have a significant impact on associated economics of a decision regarding pallet selection).

- Wooden pallets are repairable however there is an associated cost for repair by transporting damaged pallets to repair facilities along with costs for elements, fasteners and labour.

Pallet Footprints

(Description: This criterion defines and caters for availability of sizes, specifications, pallet weight and other similar factors associated with a given pallet MOC).

- With more than 80% of freight moved by road in South Africa (Havenga et al., 2014), considerations need to be made to reduce the load weight of pallets. Lighter pallets reduce the load on the trucks, thus reducing the fuel requirements (and costs) and as a consequence, CO_2 emissions are reduced as well (Eightohtwo, 2017; Lacefield, 2008).
- Plastic pallets can be as much as 30 - 50 % lighter than a wooden pallet. On this assertion, plastic pallets can reduce the trailer load's weight by between 500 and 2000 lbs (230 – 900 kg) (Lacefield, 2008; Materials Handling, 2011).

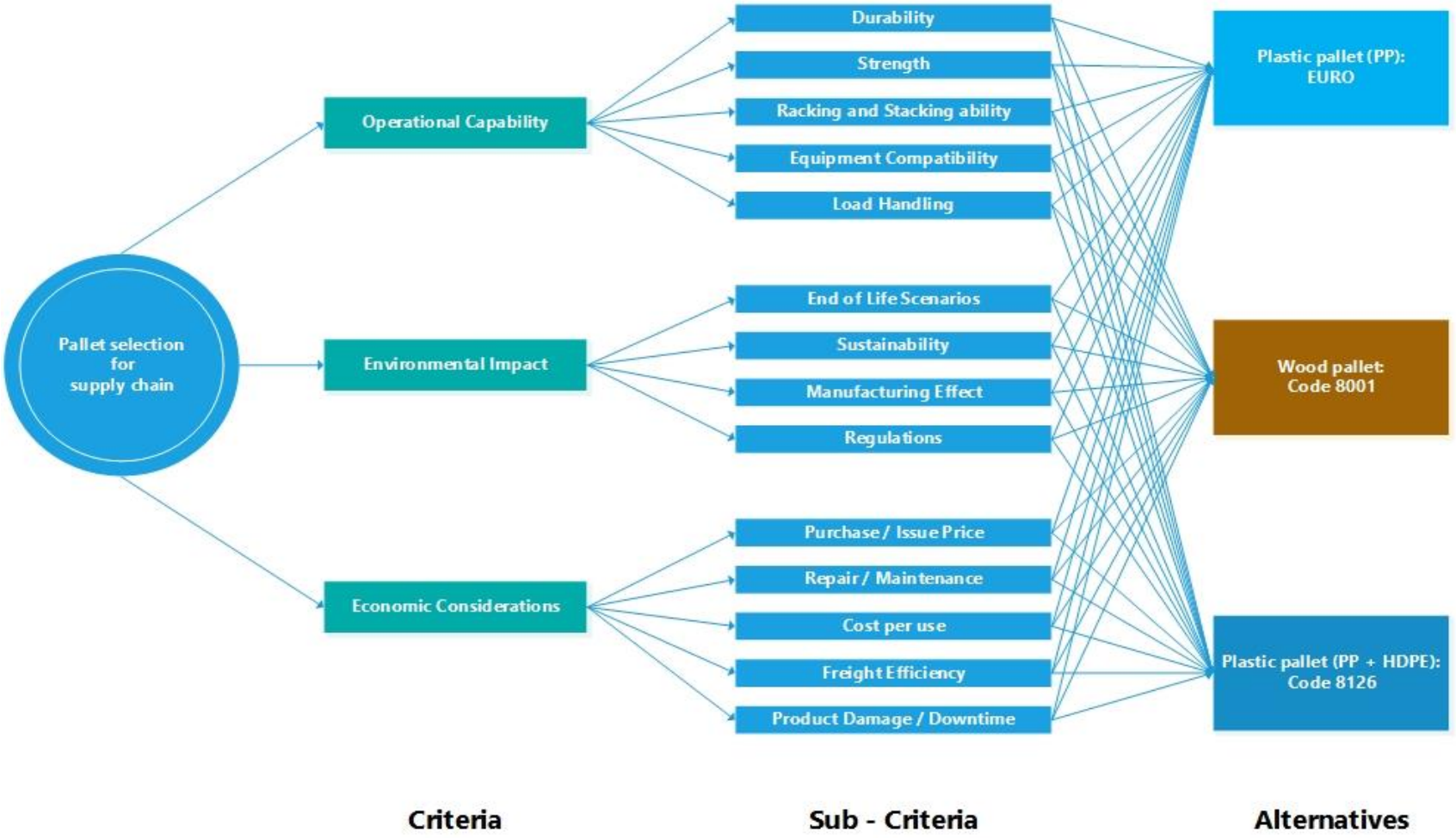


Figure 7.1: Pallet selection framework for MCDA tool

7.3 Illustrative Example

In order to adequately grasp the manner by which the MCDA tool operates, an illustrative example is presented here on the basis of the results obtained in this study as outlined in Chapters 4-6.

7.3.1 Problem Formulation

As stated from the onset, the objective is to assess pallet MOC options and select which is best for a particular SCN. For this purpose, a solution on the basis of a perishables supply chain as presented in section 6.5 is formulated. The subsequent procedure is followed for different supply chains and for each criteria and sub-criteria. For the purpose of illustration, only the operational capability criterion (see Figure 7.1) will be explored.

Three pallets are used as the alternatives, namely; the Pallet B wood pallet, the Pallet A plastic pallet and the Pallet C plastic pallet as indicated in the preceding selection framework (Figure 7.1). They will be referred to as alternatives and denoted by the letter A and a subscript indicating the MOC i.e. A_{WOOD}, $A_{PP+HDPE}$ and A_{PP} respectively. Similarly, each criterion and / sub-criterion is denoted by the letter C and a subscript that defines the element i.e. C_{DUR} for the durability sub-criteria or a suitable shorthand.

7.3.2 Solution Pathway

Each of the alternatives are pairwise compared in relation to each sub-criterion using the procedure outlined in section 7.2.1 and the framework in Figure 7.1. The results from Chapters 5 and 6 are used as the foundation for the pairwise comparisons. To illustrate this, the first sub-criteria used to assess the 3 alternatives by is durability (C_{DUR}).

Looking at the results summary of section 6.5.5, a determination of which pallet type was the best performer can be made. In terms of the judgement matrix for C_{DUR}, the fundamentals scale from Table 7.1 is used to rank each pair. Since overall in terms of durability, the Pallet C plastic (A_{PP}) pallet was the best overall performer and much better than the wood (A_{WOOD}) and Pallet A plastic ($A_{PP+HDPE}$), it received pairwise ratings of 9 and 7 against

each respectively. The Pallet A pallet was only marginally more durable than the Pallet B wood pallet and as such it scored 3 on this comparative scale. This ranking procedure is used to formulate the judgement matrix given in Table 7.3. Once the matrix is computed, the right principal eigenvector and associated eigenvalue are calculated following the aforementioned procedure in order to obtain the priority vector and supplementary CI and CR values.

Table 7.3: Comparison of alternatives in relation to sub-criteria C_{DUR}

C_{DUR}: Durability	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}		Right Principal Eigenvector	**Priority vector**
A_{WOOD}	1	1/3	1/9		0.084	**0.0658**
$A_{PP+HDPE}$	3	1	1/7		0.189	**0.1488**
A_{PP}	9	7	1		1	**0.7854**

λ_{max} = 3.0803, CI = 0.0402 and CR = 0.0692

The output gives a CR value of 0.0692 which is less than 0.1 which confirms that the comparisons were adequate and within reason. The same procedure is then followed for each of the remaining sub-criteria as follows:

To further illustrate the manner in which the AHP process works, the following matrix will explore in depth how comparisons are made. The strength (C_{STR}) sub-criterion (see Table 7.4) was slightly different from the initial matrix in that it is based predominantly on the pallet testing done in section 5.3 as data on strength cannot be obtained in the distribution environment. Using the stacking and racking deflection results, we are able to compute some pairwise comparisons for the strength criteria. In the matrix the A_{WOOD} vs A_{WOOD} comparison is given a value of 1 (for a_{11} in matrix) as they are of equal importance as per Table 7.1. For $A_{PP+HDPE}$ vs A_{WOOD} a value of 2 is assigned for a_{21} as the Pallet A although it was the best performer in the tests only had a slight advantage in this regard. As per the rules of the judgement matrix, a_{12} was subsequently assigned the value

of 1/ a_{21} i.e. 1/2. Similarly, when comparing the results of A_{PP} vs A_{WOOD} a value of 1/3 is assigned to a_{31} as wood was marginally better considering both tests when compared to the polypropylene pallet (A_{PP}). This procedure is adhered to for all other criteria as shown below.

Table 7.4: Comparison of alternatives in relation to sub-criteria C_{STR}

C_{STR}: Strength	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}		Right Principal Eigenvector	**Priority vector**
A_{WOOD}	1	1/2	3		2.621	**0.3196**
$A_{PP+HDPE}$	2	1	4		4.579	**0.5584**
A_{PP}	1/3	1/4	1		1	**0.1220**

λ_{max} = 3.01829, CI = 0.00915 and CR = 0.0157

Similarly, the sub-criterion for $C_{R\&S}$ was based on the tests performed in section 5.3 and considerations were made for the results obtained during the simulation models in terms of damage tolerance.

Table 7.5: Comparison of alternatives in relation to sub-criteria $C_{R\&S}$

$C_{R\&S}$: Racking &Stacking	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}		Right Principal Eigenvector	**Priority vector**
A_{WOOD}	1	1/3	1		0.874	**0.2098**
$A_{PP+HDPE}$	3	1	2		2.289	**0.5499**
A_{PP}	1	1/2	1		1	**0.2402**

λ_{max} = 3.01829, CI = 0.009145 and CR = 0.01577

According to the results obtained in the case study, all pallets performed equally well in the perishables supply chain and as such this sub-criterion was left out of the calculations. The load sub-criterion was based predominantly on quoted load carrying capacities of the pallet manufacturers.

Table 7.6: Comparison of alternatives in relation to sub-criteria C_{LOAD}

C_{LOAD}: Load Handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}		Right Principal Eigenvector	**Priority vector**
A_{WOOD}	1	1/4	3		2.241	**0.2255**
$A_{PP+HDPE}$	4	1	5		6.694	**0.6738**
A_{PP}	1/3	1/5	1		1	**0.1007**

λ_{max} = 3.08577, CI = 0.042885 and CR = 0.07394

Once all the alternatives (pallets) have been assessed in terms of the sub-criteria, these sub-criteria need to be given local relative weights using the same procedure as above but in relation to the overall criteria i.e. Operational capability.

Table 7.7 gives this comparison and unlike the sub-criteria, the pairwise comparison is based entirely on the decision makers experience within the perishables SCN. In this case the author used prior knowledge obtained during the case study to rank each item. As an indication of the rationale, the sub-criterion of durability (C_{DUR}) is ranked the highest in comparison to any as the SCN is fast paced and pallets spend little time in racking and stacking configurations.

Table 7.7: Comparison of sub-criteria in relation to the parent criteria C_{OPER}

C_{OPER}: Operational Capability	C_{DUR}	C_{STR}	$C_{R\&S}$	C_{LOAD}		Right Principal Eigenvector	**Priority vector**
C_{DUR}	1	5	8	9		15.605	**0.6713**
C_{STR}	1/5	1	2	5		4.125	**0.1775**
$C_{R\&S}$	1/8	1/2	1	4		2.514	**0.1082**
C_{LOAD}	1/9	1/5	1/4	1		1	**0.0430**

λ_{max} = 4.18741, CI = 0.06247 and CR = 0.06941

This final resulting priority vector is multiplied by the priority vectors obtained from the judgement matrices of each of the sub-criteria in order to obtain a final weight for each alternative on the basis of operational capability, where each row in the following matrix product relates to a particular alternative i.e. A_{WOOD}, $A_{PP+HDPE}$ and A_{PP} respectively i.e.:

$$\begin{pmatrix} 0.0658 & 0.3196 & 0.2098 & 0.2255 \\ 0.1488 & 0.5584 & 0.5499 & 0.6738 \\ 0.7854 & 0.1220 & 0.2402 & 0.1007 \end{pmatrix} \begin{pmatrix} 0.6713 \\ 0.1775 \\ 0.1082 \\ 0.0430 \end{pmatrix} = \begin{pmatrix} 0.133 \\ 0.287 \\ 0.579 \end{pmatrix}$$

From the results of this process it is noted that A_{PP} was the overall best performer in terms of operational capability with an overall weight if 0.579. This was based on the selection criteria and the associated weights attributed according to perceived significance and relevance within the perishables supply chain.

7.4 MCDA Online Platform

The pallet MCDA tool was developed as part of the study in order to assist in the decision-making process for pallet users, when selecting a pallet. The tool is accessible from https://pallet-mcda.firebaseapp.com/mcda.html directly and operates dynamically in the manner outlined in the previous illustrative example (7.3). Further illustration is presented in Appendix F.

The tool works first by eliminating non-pareto optimal solutions on the basis of operating conditions and pallet properties (Figure 7.2). This is then followed by a process whereby the end user makes pairwise comparisons based on the importance of particular criteria in relation to their supply chain (Figure 7.3), which is then aggregated with pallet rankings from the study. Once this process is complete, the algorithm then determines the best pallet solution for the consumer based on these factors (Figure 7.4).

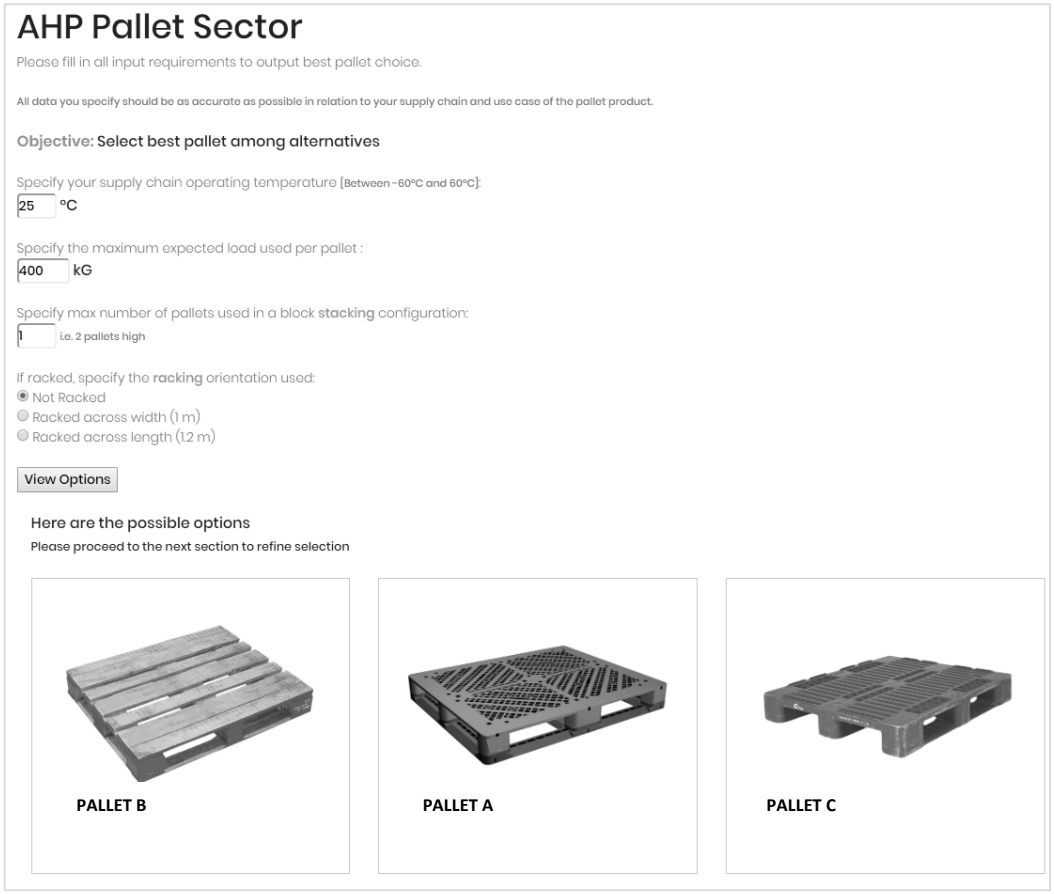


Figure 7.2: Pallet pareto selection

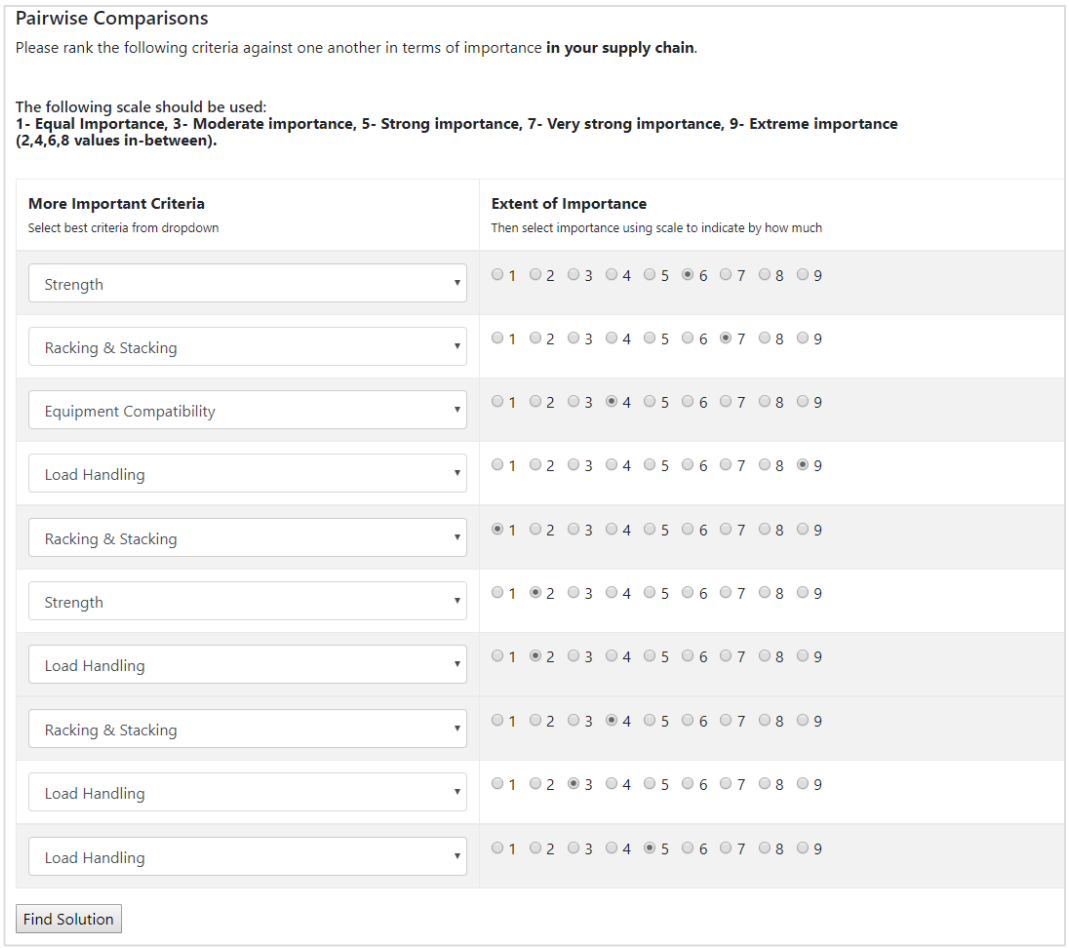


Figure 7.3: Pallet properties - pairwise comparisons

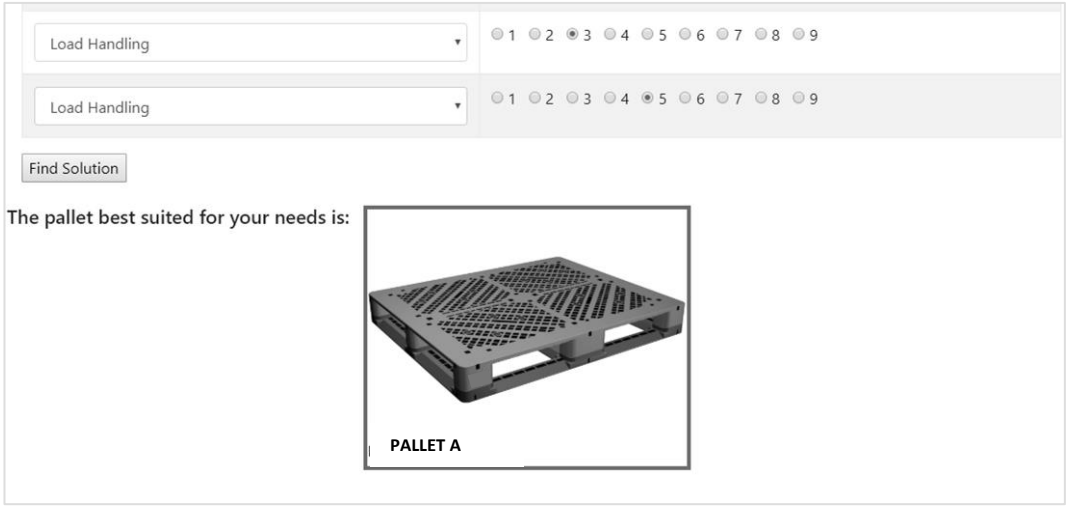


Figure 7.4: Best pallet output - MCDA tool

7.5 Summary

The outlined procedure details how the MCDA tool operates in relation to the underlying code incorporated in the web application. The calculations can be extended to all criteria and sub-criteria pending the availability of suitable data.

The developed MCDA tool as well as additional video and photo media from this study report may be found online at the following web address: https://pallet-mcda.firebaseapp.com . The tool is accessible and available for testing and use as of 07/03/2019.

CHAPTER 8:

CONCLUSIONS and RECOMMENDATIONS

8.1 Conclusions

This research work was an investigation into the relationship between packaged products, pallets and the material handling environment they are found. The impact which the material of construction of a pallet had on supply chain networks was thoroughly investigated, both from a theoretical point of view to a practical assessment by means of a case study.

In most cases, the decision between one pallet material of construction (MOC) and the next is implicitly a complex decision with a multitude of variables to consider. As such the approach taken in this work was to frame the problem not as a comparison to see which MOC is best, but rather an investigation as to which MOC may be better suited for a particular supply chain network (SCN). In order to achieve this, the investigation was structured as a multi-criteria decision analysis (MCDA) problem.

Pallet manufacturers surveys confirmed the rise of plastic pallets within the local market and soon decision makers will have to find ways to mitigate the difficulties in this decision process when faced with the option to use either wood or plastic pallets. Given that the survey also confirmed the FMCG industry as the largest pallet market, the implementation of a case study therein proved productive and yielded the following overall results for the performance of each of the pallets:

Table 8.1: Overall Scorecard for pallets in all supply chains

PALLET	TOTAL AVERAGE SCORECARD
Plastic (PP): Pallet C	4.81
Wood: Pallet B	4.70
Plastic (HDPE + PP): Pallet A	4.54

Regarding the pallet testing and modelling, all the pallets successfully passed stacking and racking tests and this then formed the basis of the

models and FEA analysis. The models had a reasonable margin of error (19% for the chosen racking setup) and as such predictive modelling for damage to plastic pallets was proposed.

Once all the parameters and phases were complete, the complexity of deciding on a pallet MOC on the basis of multiple criteria proved to be an arduous task without the use of an assistive technique. As such, the MCDA tool was formulated for this purpose.

The developed MCDA tool as well as additional video and photo media from this study report may be found online at the following web address: https://pallet-mcda.firebaseapp.com.

8.2 Areas for Further Work

No other studies have endeavoured to probe the effects of pallet type on the supply chain in the manner done here and hence, there is some room for improvement of this work with novel contributions.

For the purpose of adding to this body of work, further research can be done by looking at various types of wood and plastic as this work focussed mainly on SA pine (wood) as well as polypropylene and high-density polyethylene (plastics). An expansive array of materials may also be investigated such as paper, metal, composites and rubber pallets in order to gain a full apprehension of the most suitable pallet type beyond the market leading materials studied in this work.

Another potential aspect that could be further investigated, would be the overall sustainability aspect of the pallet type in terms of reusability and recyclability. The case study in this work looked to compare new pallets in the supply chain and did not incorporate pallet refurbishing or the concept of component recycling and remanufacture in terms of plastic pallets. This concept could be integrated in a form of Life Cycle Assessment (LCA) of the pallets in order to gain a more rounded sustainability outlook as a basis of comparison.

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APPENDIX A MATERIALS AND METHODS

A.1 Specimen Sample Preparation

Samples for characterization and mechanical testing were extracted directly from pallet specimens. As depicted in Figure A.1 and Figure A.2, samples were extracted from the deckboards of the respective pallets and resized in accordance with specification given by the ASTM standard D638.

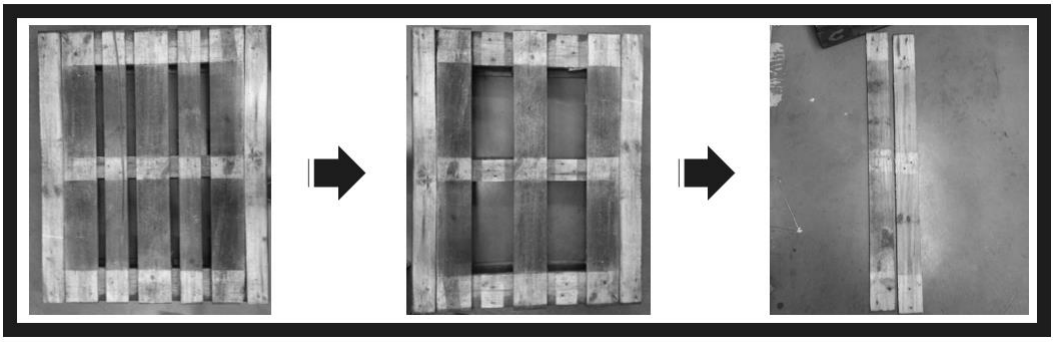

Figure A.1: Sample extraction from pallet, top deckboard slats dislodged from stringers.

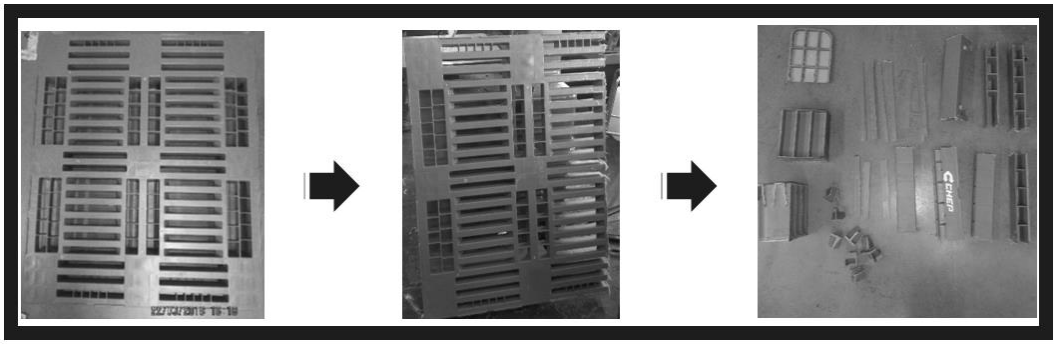

Figure A.2: Plastic pallet samples extracted from main mould by cutting with a band saw.

Figure A.3 and Figure A.4 indicate the use of the CO_2 laser for specimen sample cutting in order to meet the specifications as per the aforementioned standard. Figure A.15 shows the specimen dimensions used as per the standard.



Figure A.3: CO_2 later cutting equipment

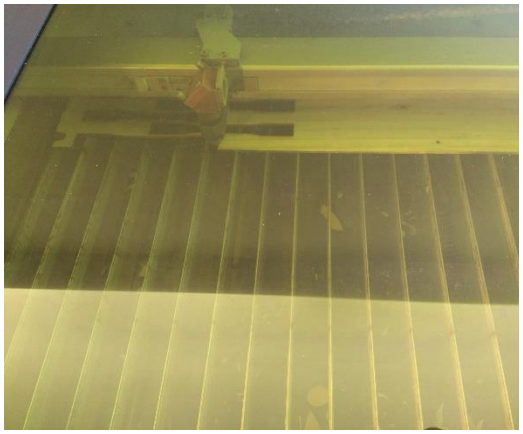

Figure A.4: Test specimens cut to specification

A.2 Characterization Equipment and Samples

Characterization and chemical identification of the materials was done using FTIR analysis. Figure A.5 shows the make and model of the equipment used for this analysis. In addition, in Figure A.6 an image is displayed showing a polypropylene sample in the process of analysis.



Figure A.5: PerkinElmer Spectrum Two FT-IR Spectrometer

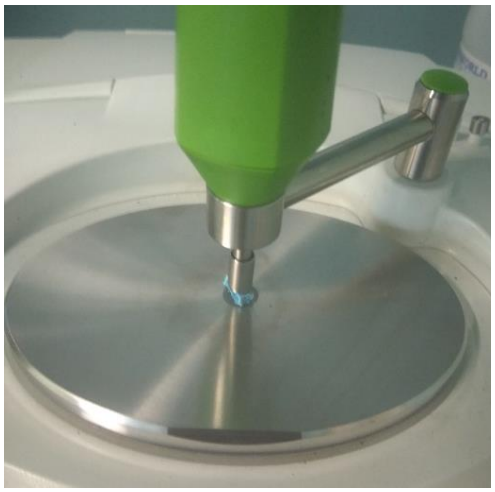

Figure A.6: Polymer sample being analysed

Morphological and Topological surface properties of the materials was obtained using a FEI Nova Nanolab 600 SEM (Figure A.8) and a Veeco Di3100 AFM (Figure A.7) respectively.



Figure A.7: Veeco Di3100 AFM

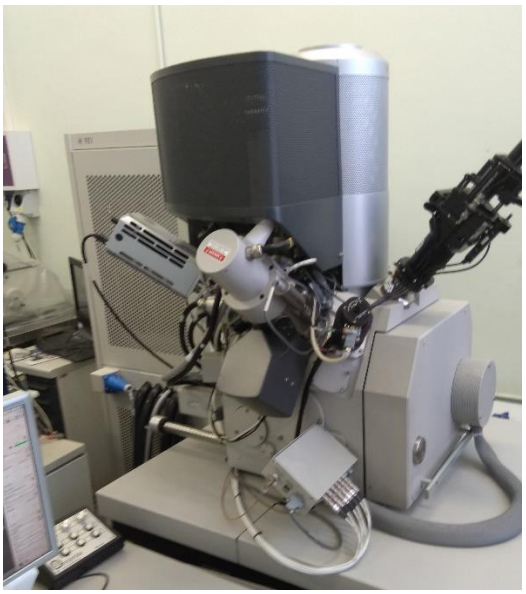

Figure A.8: FEI Nova Nanolab 600 SEM

The samples as prepared for the SEM analysis are given in Figure A.9 and Figure A.10 for the polypropylene (pp) and pine respectively. These specimens were prepared as outlined in section 3.4.3.



Figure A.9: PP plastic on SEM stub



Figure A.10: Pine wood on SEM stub

In terms of mechanical characterization by means of tensile testing, the Shimadzu universal testing machine was used to conduct the tests (Figure A.11).



Figure A.11: Shimadzu Universal testing machine



Figure A.12: Sample in grips of tensile tester.

The samples used for tensile testing were exposed to varying conditions in order to determine the effect of environmental conditions on material properties. Frozen storage as well as natural weathering of the samples as depicted in Figure A.13 and Figure A.14 respectively were used as the standard exposure conditions in addition to ambient storage.



Figure A.13: Specimen samples – Frozen



Figure A.14: Specimen samples – Weathering

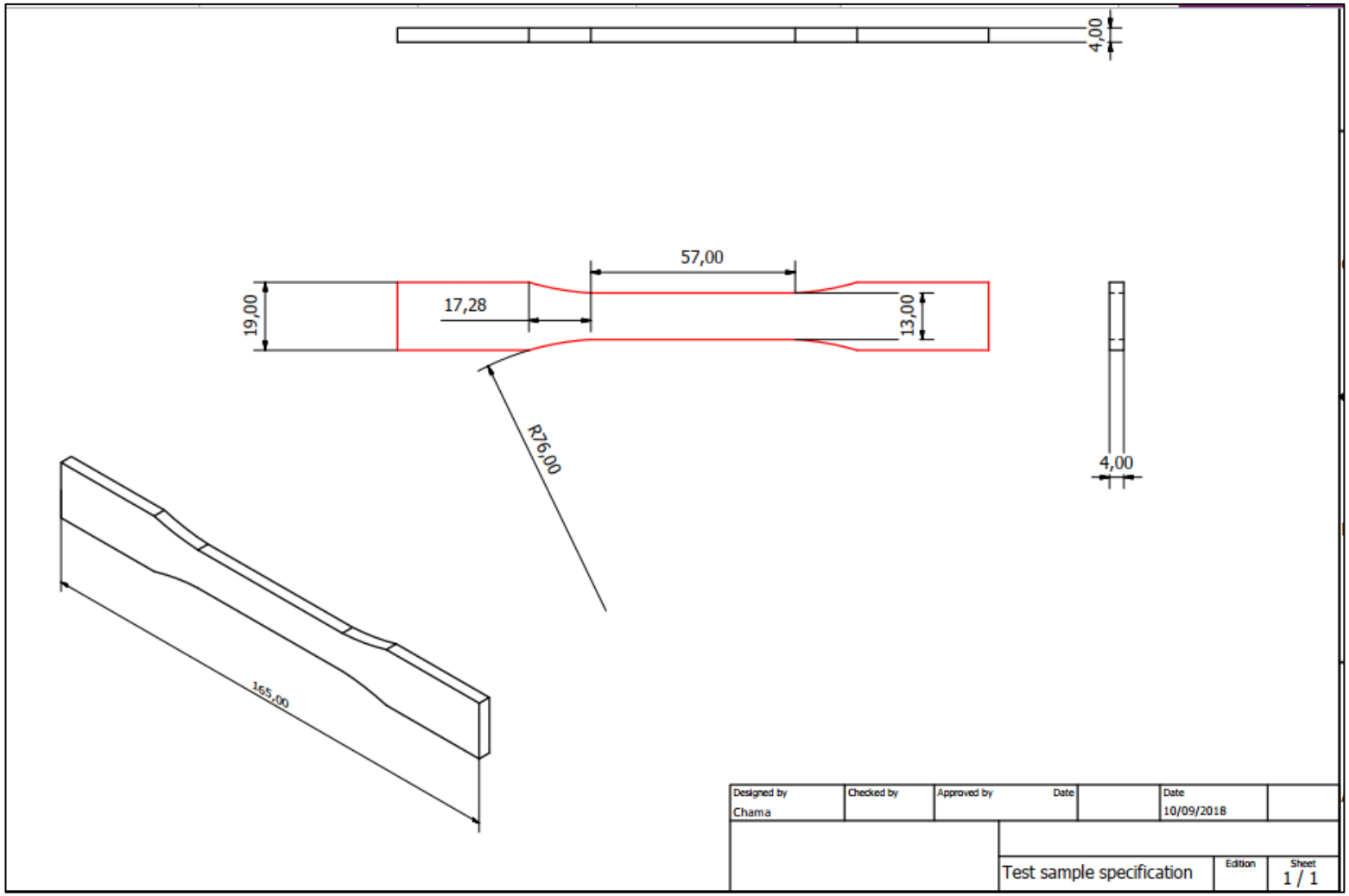

Figure A.15: Test sample specification for tensile testing

APPENDIX B PALLET SURVEYS

This section of the appendix gives additional information regarding the results found in Chapter 4 Section 4.2 of this report. The survey questions along with additional raw data for both the manufacturing and consumer surveys have been attached in the following sections.

B.1 Pallet Manufacturers Questionnaire

Project Title: A multi-criterion decision analysis (MCDA) approach to pallet material selection for varying supply chain networks

(This survey looks to probe the South African pallet industry and get a better representation of the supply chain networks within which pallets are involved)

NB: By participating in this survey you hereby grant me your consent to use the results in the scope of my research.

*Required

1. **Email address** *

2. **Your Company Name**

3. **Loacation**

4. **Are you representing the entire business or a branch?** *
   Mark only one oval.
   - Company Wide
   - Only one branch
   - Other: _____

5. **Number of employees (Company Size)**

Mark only one oval.

- ◯ 1 to 9 (micro)
- ◯ 10 to 49 (small)
- ◯ 50 to 249 (medium)
- ◯ 250+ (large)

6. **What type of business**

Tick all that apply.

- ☐ We Manufacture Pallets and other packing products
- ☐ We Import pallets and resale
- ☐ We buy second hand pallets and refurbish & resale
- ☐ We do not manufacture, refurbish or import pallets

7. **Material of Pallets Produced** *

Tick all that apply.

- ☐ Wood
- ☐ Plastic
- ☐ Steel
- ☐ Aluminium
- ☐ Composite
- ☐ Other: _____

8. **If selected more that one material, please specify the percentage (%) distribution i.e. Wood 40% Plastic 60%**

_____

9. **Are your pallets fire safety rated?**
Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Maybe

10. **What type of pallets do you produce**
Please select the pallet properties from the list below.
Tick all that apply.

- ☐ Block Pallet
- ☐ Stringer
- ☐ 4-way entry
- ☐ 2-way entry
- ☐ Reversible

11. **Pallet Dimensions - please select the dimensions you produce : W × L millimeters**
Tick all that apply.

- ☐ 800 × 1200 (31.50 × 47.24)
- ☐ 1000 × 1200 (39.37 × 47.24)
- ☐ 1016 × 1219 (40.00 × 48.00)
- ☐ 1067 × 1067 (42.00 × 42.00)
- ☐ 1100 × 1100 (43.30 × 43.30)
- ☐ 1165 × 1165 (45.9 × 45.9)
- ☐ Other: _____

12. **Which industries do you mostly supply to**
Tick all that apply.

- [ ] Aerospace
- [ ] Agriculture
- [ ] Chemical
- [ ] Construction
- [ ] Fast moving consumer goods (FMCG)
- [ ] Manufacturing
- [ ] Mining
- [ ] Other: _____

13. **Pallet retail strategy** *
Mark only one oval.

- ◯ Only Sell Pallets *Skip to question 13.*
- ◯ Only Lease / Pool Pallets *Skip to question 21.*
- ◯ Sell and Lease Pallets *Skip to question 26.*
- ◯ Do not sell or lease pallets *Stop filling out this form.*

Only Sell Pallets

This section should only be submitted by those that only retail pallets to customers

14. **How many pallets do you produce per year?**

_____

15. **How many unique customers do you sell to?**

_____

16. **Pallet function**
Tick all that apply.

- [ ] Single Use
- [ ] Reusable
- [ ] Export pallets

17. **If pallets are exported, are they heat treated?**

_____

18. **What is the average retail price of your pallets?**

19. **Do you refurbish / repair pallets**
Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Maybe

20. **Are your retail pallets**
Mark only one oval.

- ◯ Brand New
- ◯ Refurbished / Recycled

21. **Any extra comments?**
Please feel free to add links to your pallet brochures or specifications.

Stop filling out this form.

Only Lease / Pool Pallets

This section should only be answered by manufacturers that ONLY lease pallets

22. **How many pallets do you lease per year?**

23. **How many new pallets do you manufacture per year?**

24. **Do you repair pallets?**
Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Maybe

25. **Any extra comments?**

26. **Any extra comments?**
Please feel free to add links to your pallet brochures or specifications.

Stop filling out this form.

Lease and Sell Pallets

This section should be answered only by businesses that sell and lease pallets

27. **How many pallets do you lease per year?**

28. **How many new pallets do you manufacture per year?**

29. **How many pallets do you sell per year?**

30. **Do you repair pallets?**
Mark only one oval.

- Yes
- No
- Maybe

31. **Are your retail pallets**
Mark only one oval.

- Brand New
- Refurbished / Recycled

32. **Any extra comments?**

Please feel free to add links to your pallet brochures or specifications.

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B.2 Pallet Consumers / Users Questionnaire

Project Title: A multi-criterion decision analysis (MCDA) approach to pallet material selection for varying supply chain networks

This survey looks to probe the South African pallet industry and get a better representation of the supply chain networks within which pallets are involved. A pallet is a flat transport structure (normally wood), which supports goods in a stable fashion while being lifted by a forklift or transported along the supply chain

NB: By participating in this survey you hereby grant me your consent to use the results in the scope of my research.

*Required

1. **Email address** *

2. **Your company Name**
If you would like to remain anonymous please type "ANON" in this field.

3. **Are you representing the entire business or a branch**
Mark only one oval.
- Company Wide
- Only one branch
- Other:

4. **Number of employees (Company Size)**
Mark only one oval.
- 1 to 9 (micro)
- 10 to 49 (small)
- 50 to 249 (medium)
- 250+ (large)

5. **Which industry do you see yourself in**

Mark only one oval.

- Aerospace
- Agriculture
- Chemical
- Communications/Electronics
- Construction
- Fast moving consumer goods (FMCG)
- Health
- Mining
- Transportation
- Other: _____

6. **Which supply chain segment are you in?**

Mark only one oval.

- Manufacturing
- Distribution
- Retail

7. **Do you use pallets in your business**

Mark only one oval.

- Yes
- No *Skip to question 22.*
- Maybe

Pallet description

The following section allows you to specify the characteristics of the pallets used

8. **What type of material are your pallets made of**

   Please select the material of construction below
   Tick all that apply.

   - [ ] Wood
   - [ ] Plastic
   - [ ] Steel
   - [ ] Aluminum
   - [ ] Composite
   - [ ] Other: _____

9. **Why does your business use this type of pallet as opposed to other ma**

   _____

   _____

10. **What type of pallets do you use**

    Tick all that apply.

    - [ ] Block Pallet
    - [ ] Stringer
    - [ ] 4-way entry
    - [ ] 2-way entry
    - [ ] Reversible
    - [ ] Other: _____

11. **Pallet ownership**

    Please specify if you own the pallets, lease/rent the pallet
    Mark only one oval.

    - ◯ We own all pallets
    - ◯ We own and rent pallets
    - ◯ We only rent / lease pallets

12. **Pallet Management**

Please do select how your business pallets are managed
Mark only one oval.

- ◯ We manage our own pallets
- ◯ A third party manages them
- ◯ Pallets are part of a third party external pool

13. **State of pallets when purchased / leased**

Mark only one oval.

- ◯ Brand New
- ◯ Refurbished
- ◯ Second Hand

14. **How much do the following factors affect your decision on purchasing / renting pallets** *

Please rank the following items in reference to its importance to your business when selecting pallets
Mark only one oval per row.

	Very Important	Important	Moderately Important	Slightly Important	Not Important
Accessibility / Availability	◯	◯	◯	◯	◯
Ease of Automation in Supply Chain	◯	◯	◯	◯	◯
Ease of Disposal	◯	◯	◯	◯	◯
Meet customer requirements	◯	◯	◯	◯	◯
Pallet Cost	◯	◯	◯	◯	◯
Regulations & Environmental Concerns	◯	◯	◯	◯	◯
Pallet Durability	◯	◯	◯	◯	◯
Pallet Rackability	◯	◯	◯	◯	◯
Pallet Reusability	◯	◯	◯	◯	◯
Pallet Strength	◯	◯	◯	◯	◯

Pallet Usage

The objective of this section is to gain an understanding of your pallet usage statistics

15. **How many pallets does your business use per year**

_____

16. **What is the average load you place onto pallets**

Mark only one oval.

- ◯ 0-300 kg
- ◯ 301-600 kg
- ◯ 601-900 kg
- ◯ 901 - 1200 kg
- ◯ >1200kg

17. **How are you using your pallets?**

Tick all that apply.

- ☐ One-way between trading partners
- ☐ Between company facilities
- ☐ Closed-loop between trading partners
- ☐ When exporting
- ☐ Within a facility
- ☐ Other: _____

18. **What Challenges, if any, do you have with you pallets**

_____

_____

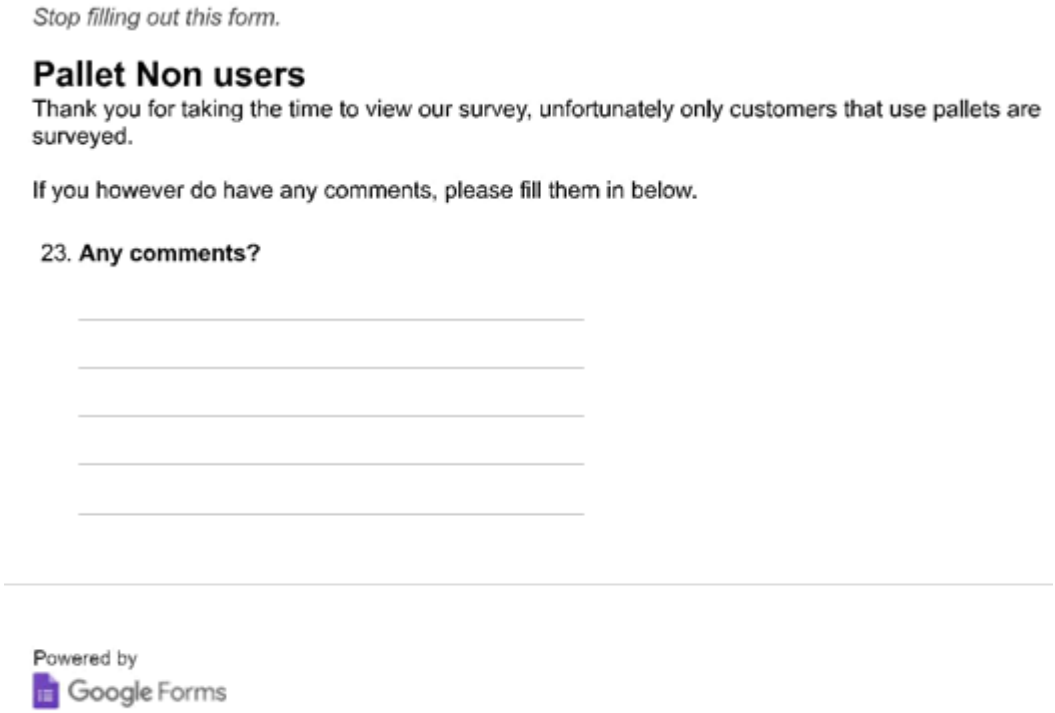
19. **How often do you repair your pallets?**

20. **What percentage (%) on average of your operating costs do you spend on pallets and their management.**

21. **How do you dispose of your pallets after use**
Mark only one oval.

- ◯ Resale
- ◯ Refurbish
- ◯ Landfill
- ◯ Incinerate
- ◯ Recycle
- ◯ Third party pallet management
- ◯ Other: _____

22. **Any further comments you would like to add?**
Thank you for your participation. Any further input or comments will be warmly welcomed.



Stop filling out this form.

Pallet Non users

Thank you for taking the time to view our survey, unfortunately only customers that use pallets are surveyed.

If you however do have any comments, please fill them in below.

23. **Any comments?**

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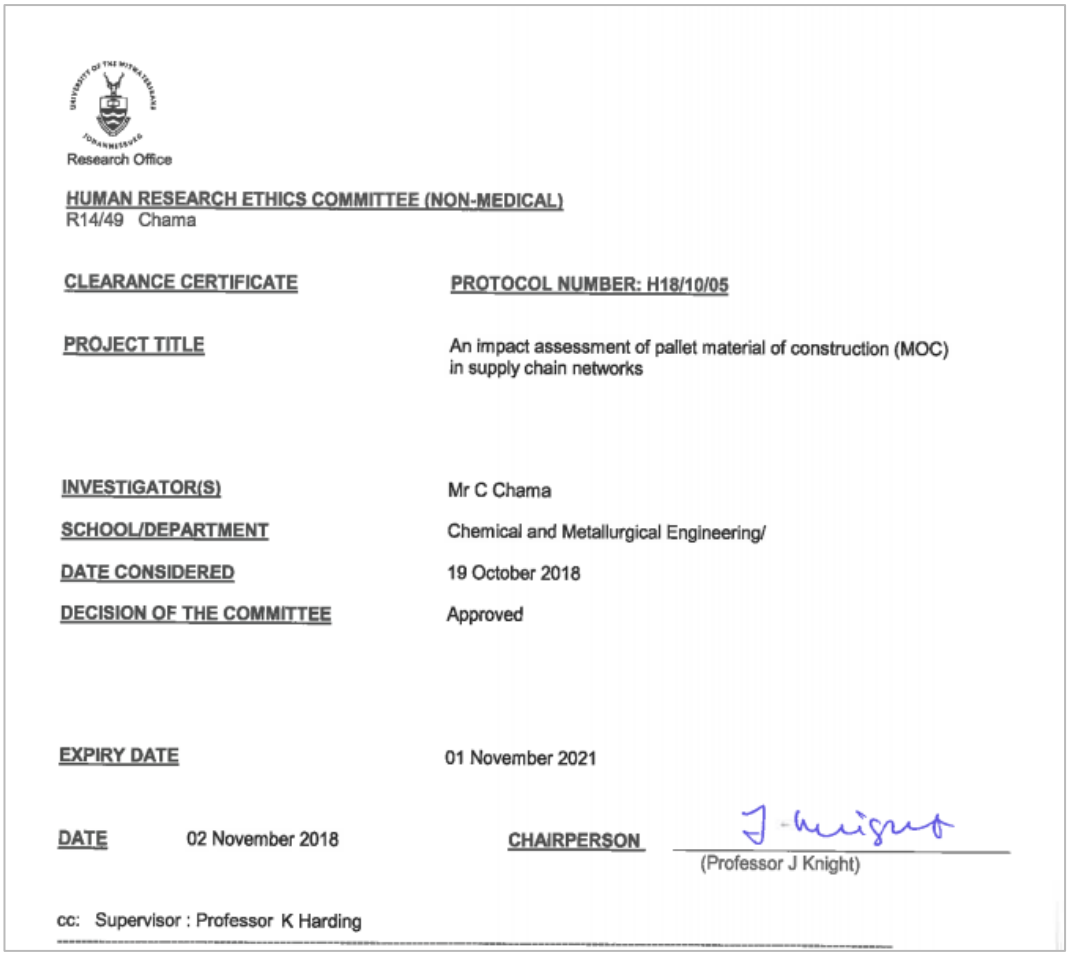
It should be noted that although the pallet surveys were distributed to well over 100 recipients within industry, the response rate was low and as such only results from the manufacturers survey is reported extensively.

B.3 Ethics Clearance Certificate

Figure B.1 is the ethics certificate issued by the University of the Witwatersrand's Human Research Ethics Committee (Non-Medical). This was issued to the current project presented in this dissertation with the only alteration being the change in project title since the issue of the certificate.



Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Chama

CLEARANCE CERTIFICATE	PROTOCOL NUMBER: H18/10/05
PROJECT TITLE	An impact assessment of pallet material of construction (MOC) in supply chain networks
INVESTIGATOR(S)	Mr C Chama
SCHOOL/DEPARTMENT	Chemical and Metallurgical Engineering/
DATE CONSIDERED	19 October 2018
DECISION OF THE COMMITTEE	Approved
EXPIRY DATE	01 November 2021

DATE 02 November 2018 CHAIRPERSON J Knight (Professor J Knight)

cc: Supervisor : Professor K Harding

Figure B.1: Ethics clearance certificate

APPENDIX C PALLET TESTING

C.1 Deviations from ISO Standard

As the given trial pallets had already been tested prior in terms of compliance with the standard and had been implemented in various supply chains, this testing was done primarily as a way of conducting “field tests” to verify load capacity and deflection characteristics as outlined in the standard. However, further notes are made herein to outline the deviations from the standard that these testing procedures made use of.

The ISO 8611 standard was used as an additional guideline as it contains the relevant test methods for evaluating new flat pallets for materials handling. The standard itself states that its test procedures as described in the first part of ISO 8611-1:2011, are “approximate simulations of pallet use”. The use of racking beams in this work was to circumnavigate this and ensure a more accurate approximation of the environment that pallets would be exposed to during the case study.

C.1.1 Load Type and Packaging Configuration

As per clause 6 of ISO 8611-1:2011 the option to utilise a “dead load” was opted for. This was in the form of boxes (± 43 boxes per unit load) of nails at approximately 23.2 kg per box as shown in Figure C.1 and Figure C.2.



Figure C.1: Individual box load weight



Figure C.2: Box of nails used as load

A load of 1000 kg was used in all the tests as this was within the safe working load capacity as quoted on the pallet brochures of the test pallets. The StackBuilder software tool was used for product stack configurations

(Figure C.3) in order to maximise load placement and distribute the loads evenly.Final unit loads were wrapped in cling wrap to ensure load stability during testing (see Figure C.4 and Figure C.5).



Figure C.3: Load stacking configuration



Figure C.4: Unit load on Richter scale



Figure C.5: Wrapped unit load

C.1.2 Racking Tests

The pallet racking tests were done in approximation of typical storage conditions found in the distribution environment. In order to achieve this, racking tests were carried out on heavy duty racking as indicated by Figure C.6. As per the diagram, each racking beam could accommodate three test pallets as the beams had a safe carrying capacity of 4800 kg's UDL (Uniform distributed load) and measured 3888 mm x 160 mm IPE Section.

This specification was slightly modified in that the beams were adjusted (dropped) approximately 640 mm lower in order to allow for better access by the forklift, and only the bottom two levels were racked on as the top beam was used purely for support.

In terms of the ISO 8611-1:2011 test specifications for the racking handling activity, two test methods are outlined, namely; the bending strength (test 1a) and bending stiffness (test 1b). Test 1a is used for determining the bending strength of the pallet. This is done by testing the pallets until

breakage of one of the pallet components in order to obtain an ultimate load. Due to the limited quantity of trial pallets available and the prior testing of pallets for this, this test method was disregarded. Test 1b was better suited for the application in this study as it enables for the determination of the bending stiffness of a pallet.

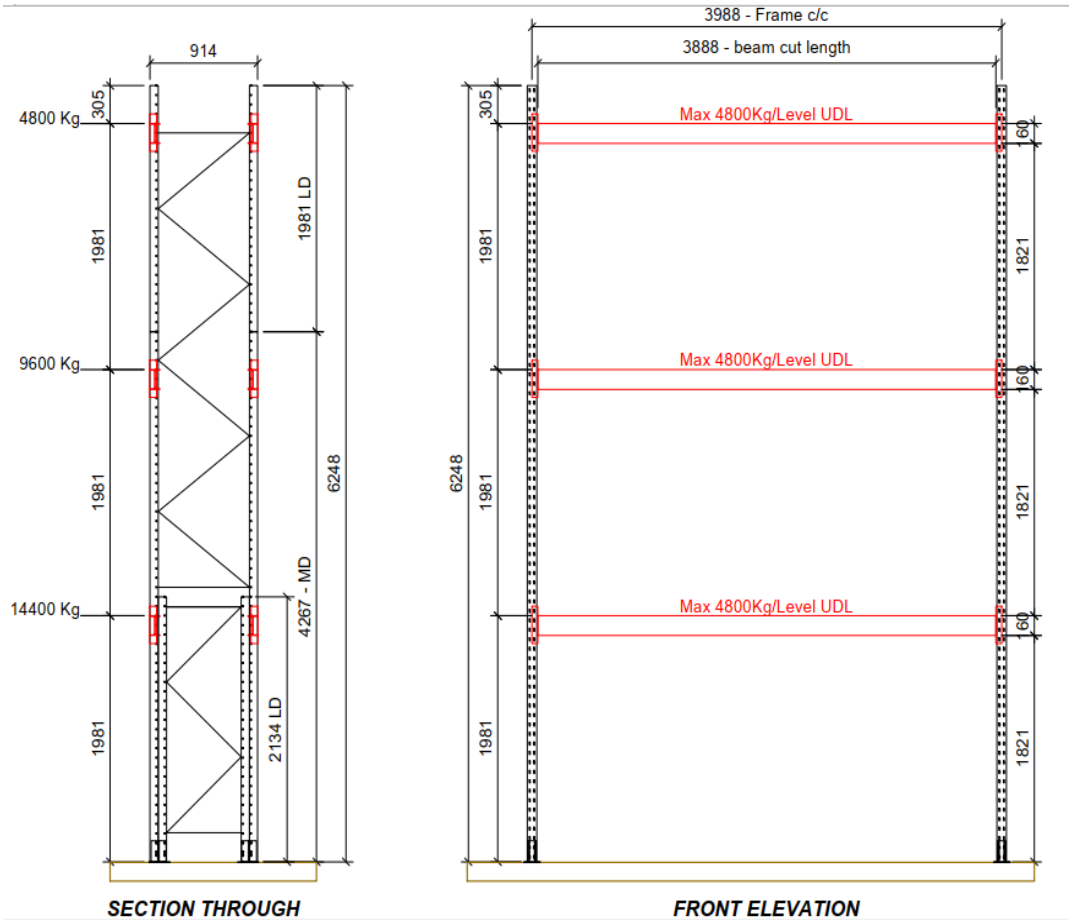


Figure C.6: Racking beams manufactured for pallet testing (dimensions in mm)

The test setup for the ISO 8611 Test 1b is given in Figure C.7 with additional dimensioning data given in Figure C.8. From these, the deviations from the standard may be noted when comparing with the outlined test setup shown in Figure 5.27. Instead of a test rig for dynamic application of loads, manual palletization was used for the racking. The standard makes provision for the use of a “dead load” and this is what was opted for. In terms of load applicators, the objective was to simulate the distribution environment as closely as possible and as such, no load applicators were used. As

discussed, the support used was the heavy duty racking beams as used in industry, and as such they did not fully comply with the support dimensions required as set in the standard (see Figure C.7 and Figure C.8). The beams had a width of approximately 81 mm (50 mm specified by standard). The overhang over the support was much greater than 25 mm as the pallet width was 1000 mm and the racking depth was 914 mm. The deflection, y, was measured at points A [maximum of y at A1 (B1), A2 (B2), A3 B3] as per Figure C.8 and was recorded. No datum load was applied during testing. The compliance requirements for passing the deflection tests were however maintained and are discussed in section 5.3.2.

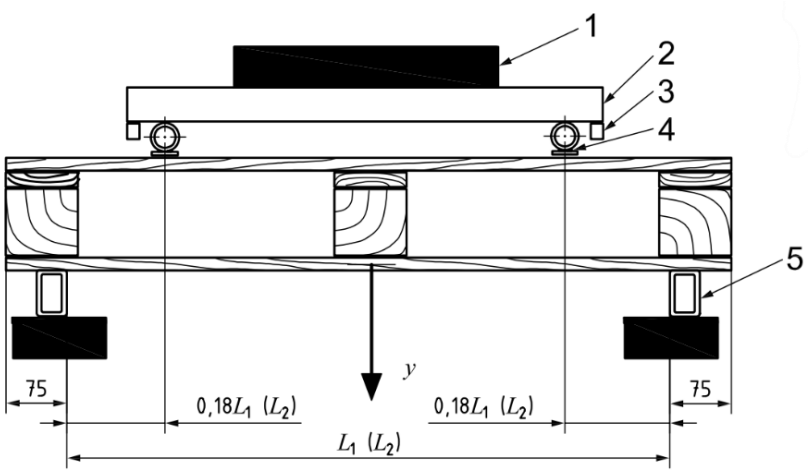


Figure C.7: Test for racking conditions – Test 1b – Bending Stiffness

Key:	1 Test load	4 Load applicators
	2 load board	5 Support
	3 Safety stops	y deflection

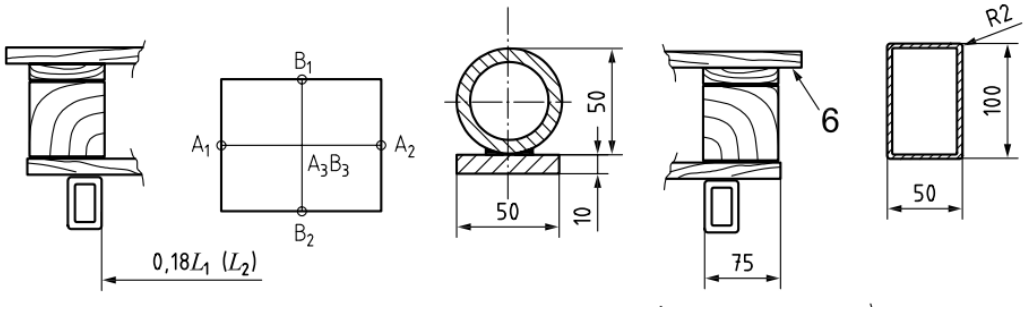


Figure C.8: Dimensions for test 1b

C.1.3 Stacking Tests

Tests 4a and 4b of the ISO 8611-1:2011 standards specify the methods for testing pallets for the stacking handling activity. The purpose of the test is to determine the ability of the pallet top and bottom decks to withstand the local effects of widely varying payloads as may be found in a block stacking situation within the distribution environment.

The tests outlined in the standard are, namely; deck strength (test 4a) and deck stiffness (test 4b). Test 4a is used for determining the deck strength of the pallet and requires testing the pallet until breakage or excessive deflection is encountered. Much like the racking test, this is done in order to obtain an ultimate load. This part of the testing was similarly disregarded. Test 4b (deck stiffness) (see Figure C.9) was better suited for the purposes of this study in that it allows for the measurement of local deflection on the pallet during stacking tests for a given payload.

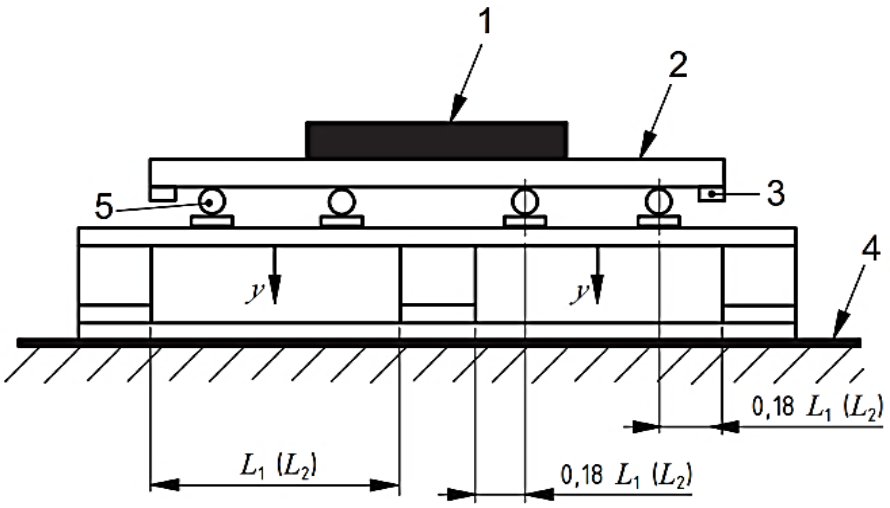


Figure C.9: Test for stacking conditions – Test 4b – Bending Stiffness

Key:	1 Test load	4 Solid support
	2 load board	5 Load applicators
	3 Safety stops	y deflection

Similarly, to the racking tests, the objective with the testing done with regard to stacking was to simulate the distribution environment as closely as possible and note the performance of the pallets prior to the case study. The

aforementioned test setup was attempted but with the use of a dead load as opposed to a testing rig and also not making use of load applicators. During the course of testing, load instability (Figure C.10) concerns were realised and as such an alternative testing configuration was opted for.



Figure C.10: Load instability during bulk stacking

ISO 8611-1:2004 was therefore used in terms of the stacking test (Test No. 6). This test is done by using a load similar to the actual load the pallet would support. A second pallet is then placed on top of the actual load, using platens of a universal testing machine. This testing was outsourced to TEN-E Packaging solutions as no test rig was available for use during the study. The test setup is presented in Figure 5.32 for the bulk stacking tests.

C.2 Replicate Racking Test Results and Test Setups

In terms of the racking tests, 3 replications were conducted for each pallet type. These results for the deflection data are presented in Table C.1 - Table C.3. Each data set for the respective test run was plotted in order to see how the deflections varied for each individual test run (Figure C.11 - Figure C.13)

Table C.1: Deflection data for replicate test runs - Wood (Pallet B)

DEFLECTION (WOOD PALLET B)					
Pallet Number / Run Number	**Run 1: No. 5**	**Run 2: No. 7**	**Run 3: No. 8**	**Average**	**Std. Dev**
Empty Pallet	0	0	0	0.0	0.0
After Applying Test Load	6.7	5.3	4.7	5.6	1.0
After Load Test Period	8.3	5.7	5.0	6.3	1.8
After Relaxation	1.7	0.7	-0.7	0.6	1.2

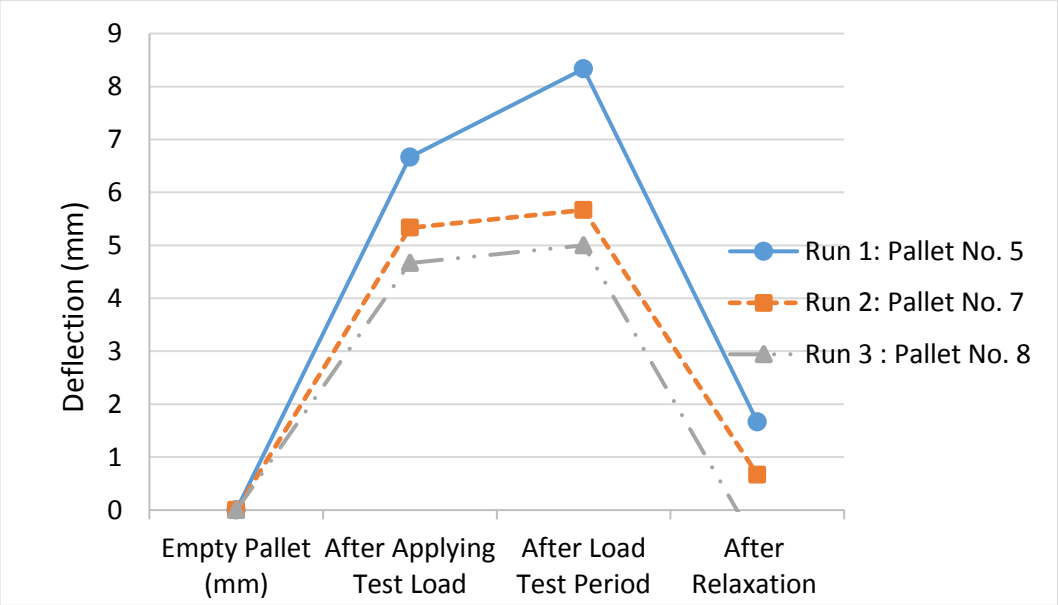


Figure C.11: Wood racking test results for each replication for Pallet B Pallets

Table C.2: Deflection data for replicate test runs - Plastic (Pallet A)

DEFLECTION (PLASTIC PALLET A)					
Pallet Number / Run Number	**Run 1: No. 5**	**Run 1: No. 7**	**Run 1: No. 8**	**Average**	**Std. Dev**
Empty Pallet	0	0	0	0.0	0.0
After Applying Test Load	3.0	4.3	3.3	3.6	0.7
After Load Test Period	4.3	3.7	4.3	4.1	0.4
After Relaxation	0.7	0.8	0.7	0.7	0.1

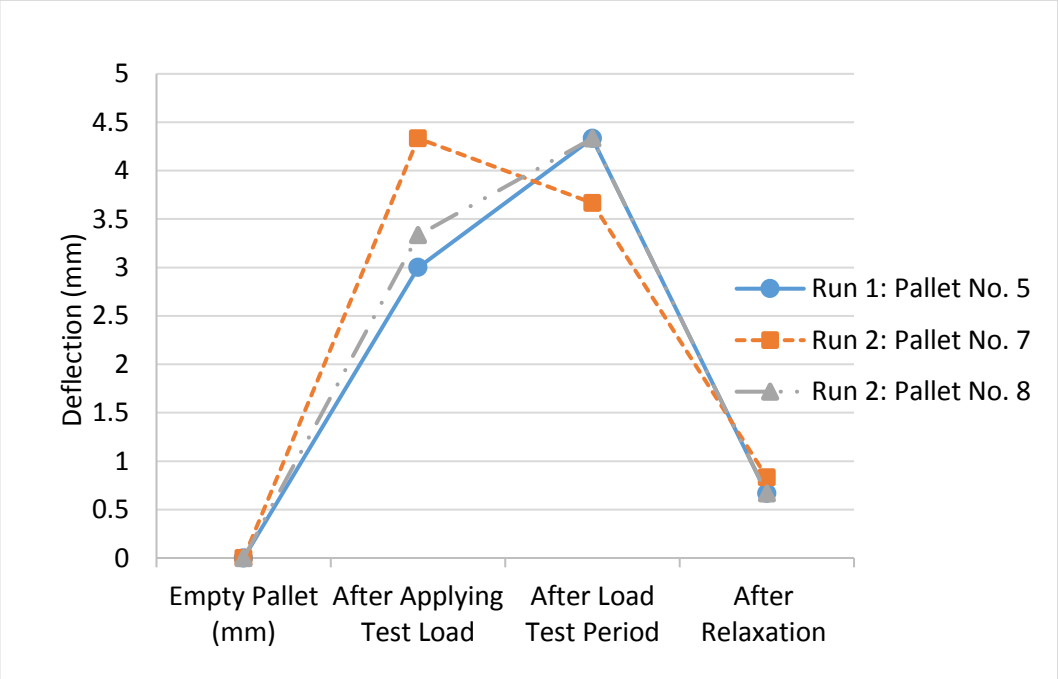


Figure C.12: Plastic (Pallet A) racking test results for each replication

Table C.3: Deflection data for replicate test runs - Plastic (Pallet C)

DEFLECTION (PLASTIC PALLET C)					
Pallet Number / Run Number	**Run 1: No. 5**	**Run 1: No. 7**	**Run 1: No. 8**	**Average**	**Std. Dev**
Empty Pallet	0	0	0	0.0	0.0
After Applying Test Load	4.3	3.0	3.3	3.6	0.7
After Load Test Period	8.3	5.0	4.7	6.0	2.0
After Relaxation	2.0	0.3	1.0	1.1	0.8

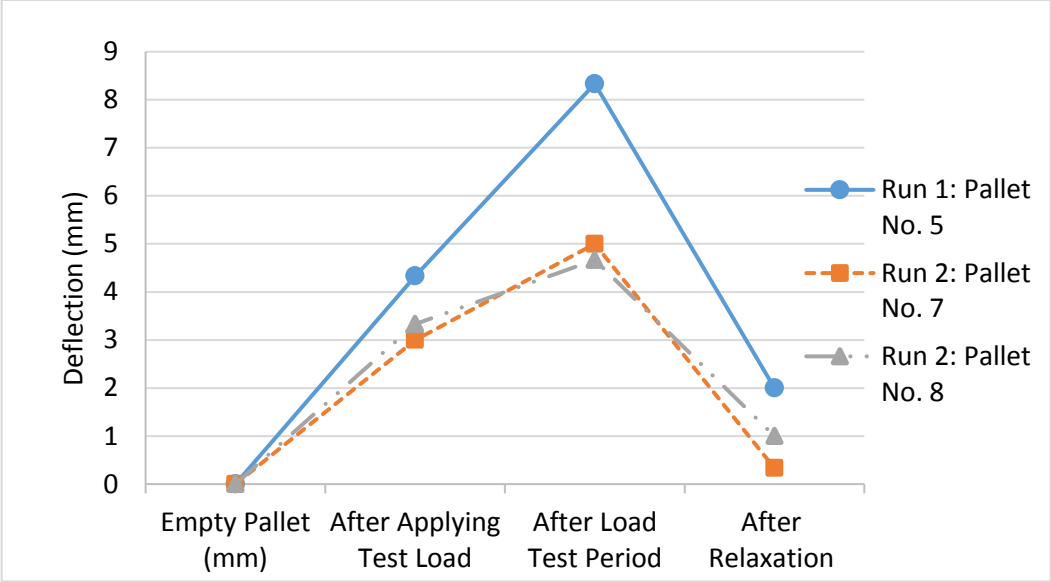


Figure C.13: Plastic (Pallet C) racking test results for each replication

The test setup for the racking tests was outlined in preceding section with deviations from the ISO 8611 standard noted in section C.1. Images that portray the test set-up, the deflection as well as the relaxation phases of the testing are presented in Figure C.14, Figure C.15 and Figure C.16 for the wood (Pallet B), plastic (Pallet A) and plastic (Pallet C) respectively.

(a) Test set-up (b) Deflection (c) Relaxation



Figure C.14: (a)Test set-up, (b) deflection and (c) relaxation images of wooden pallet racking

(a) Test set-up (b) Deflection (c) Relaxation



Figure C.15: (a)Test set-up, (b) deflection and (c) relaxation images of plastic (Pallet A) pallet racking

(a) Test set-up (b) Deflection (c) Relaxation



Figure C.16: (a)Test set-up, (b) deflection and (c) relaxation images of plastic (Pallet C) pallet racking

C.3 Stacking Test Setups

Similarly, the test set-up, deflection as well as relaxation phases of the bulk stacking testing are displayed in Figure C.17, Figure C.18 and Figure C.19 for the wood (Pallet B), plastic (Pallet A) and plastic (Pallet C) respectively.

(a) Test set-up **(b) Deflection** **(c) Relaxation**

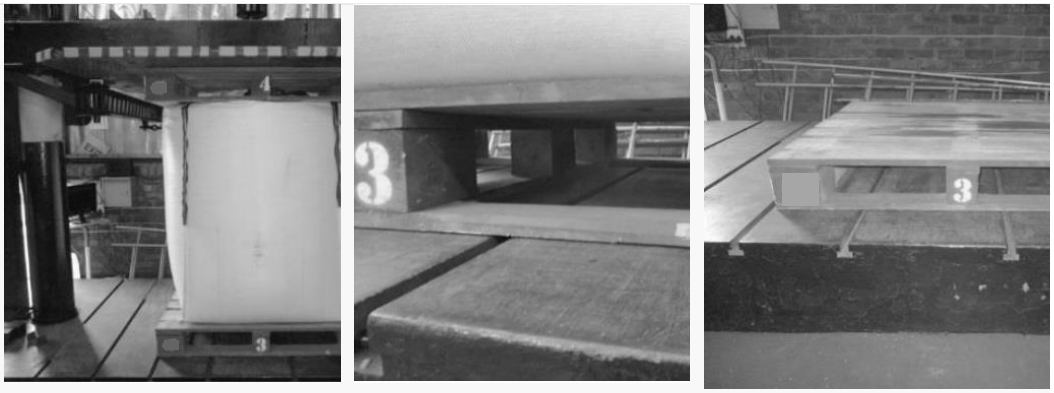


Figure C.17: (a) Test set-up, (b) deflection and (c) relaxation images of wood (Pallet B) pallet stacking

(a) Test set-up **(b) Deflection** **(c) Relaxation**



Figure C.18: (a) Test set-up, (b) deflection and (c) relaxation images of plastic (Pallet A) pallet stacking

(a) Test set-up **(b) Deflection** **(c) Relaxation**



Figure C.19: (a) Test set-up, (b) deflection and (c) relaxation images of plastic (Pallet C) pallet stacking

APPENDIX D PALLET SIMULATION MODEL

D.1 Simulation Model Parameters

The following images provide more detailed views of the modelled test pallets from all sides of the models.

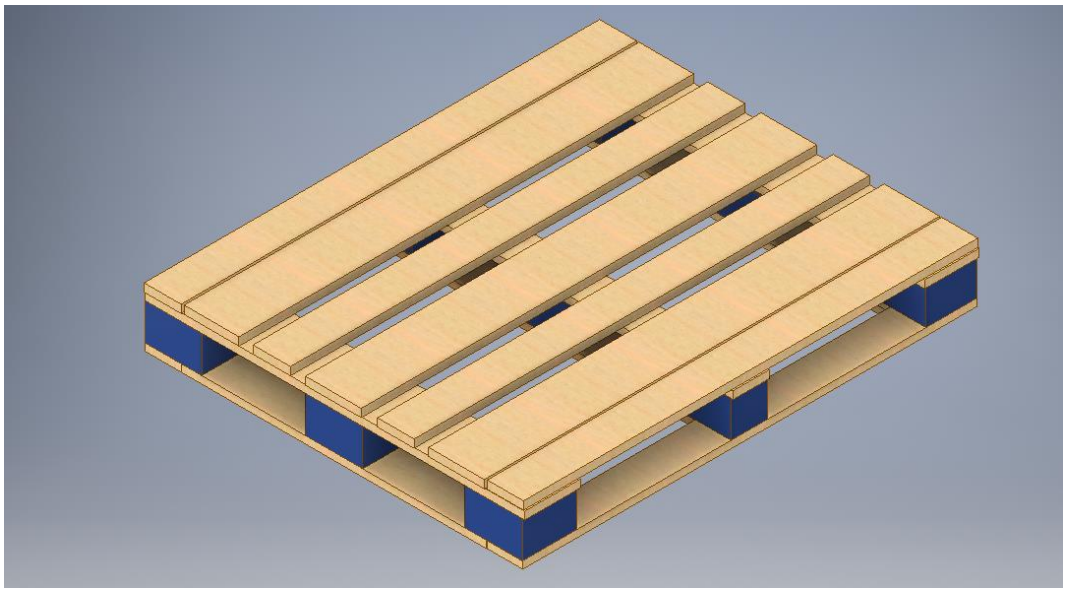


Figure D.1: Wood (Pallet B) pallet model overview

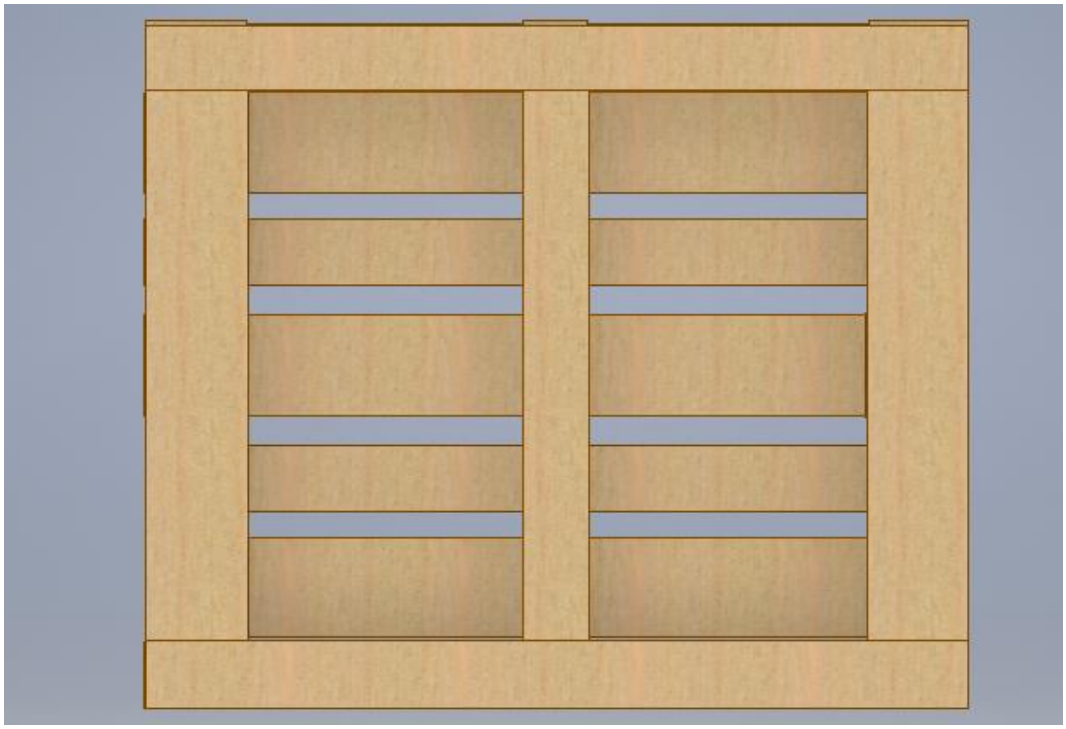


Figure D.2: Wood (Pallet B) pallet model bottom view

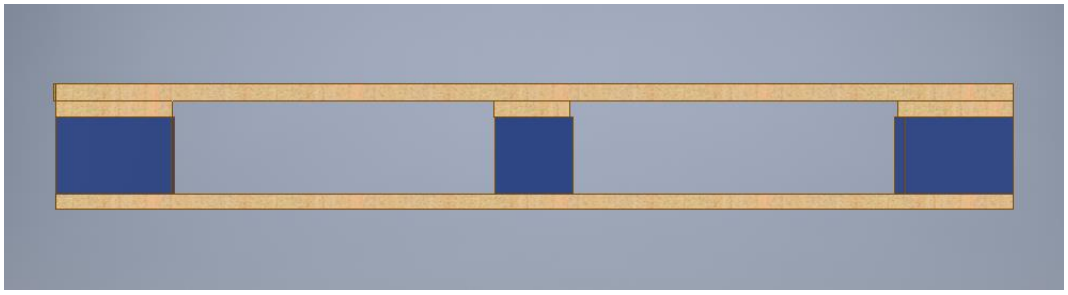


Figure D.3: Wood (Pallet B) pallet model side view - length

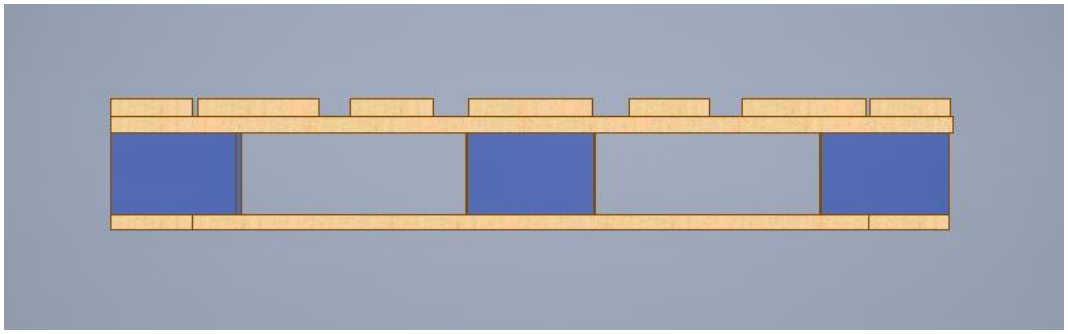


Figure D.4: Wood (Pallet B) pallet model side view - width

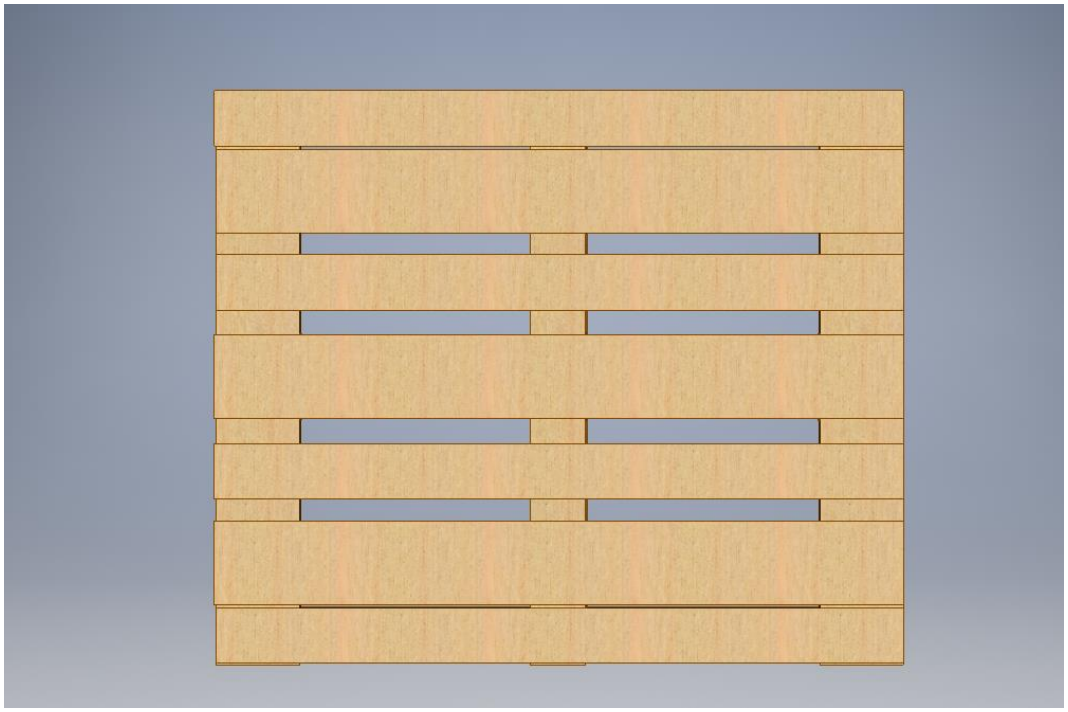


Figure D.5: Wood (Pallet B) pallet model top view

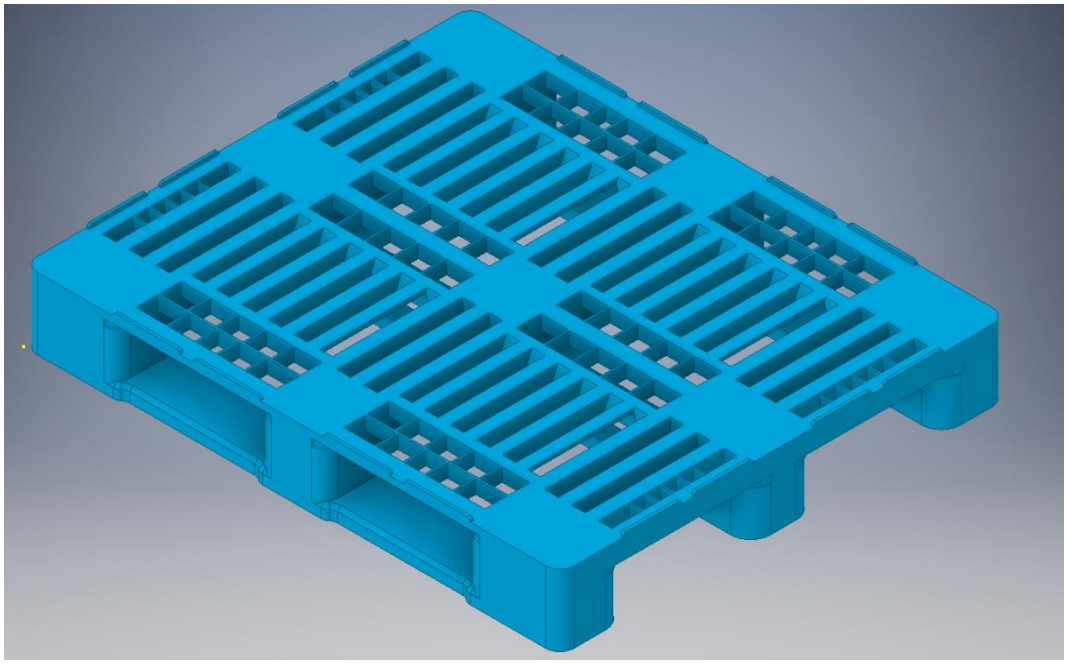


Figure D.6: Plastic (Pallet C) pallet model overview

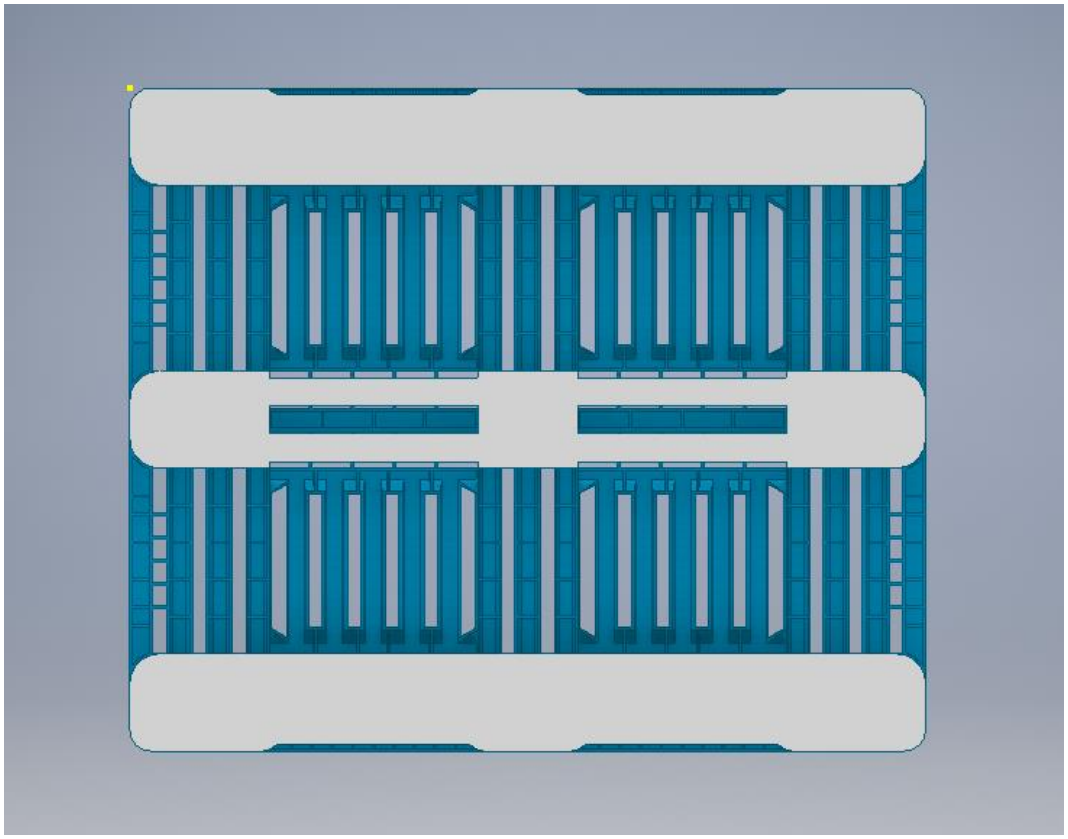


Figure D.7: Plastic (Pallet C) pallet model bottom view

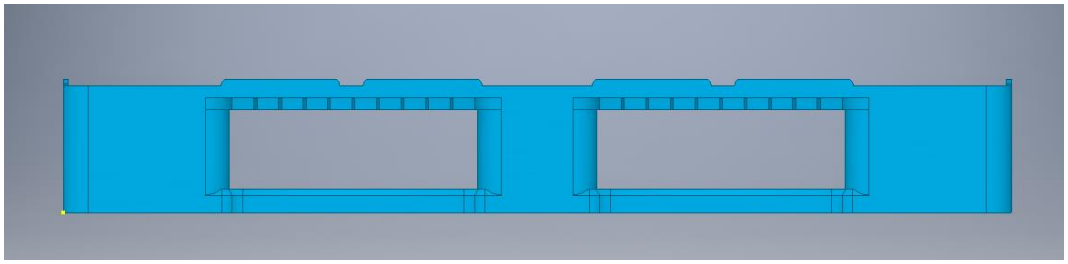


Figure D.8: Plastic (Pallet C) pallet model side view - length

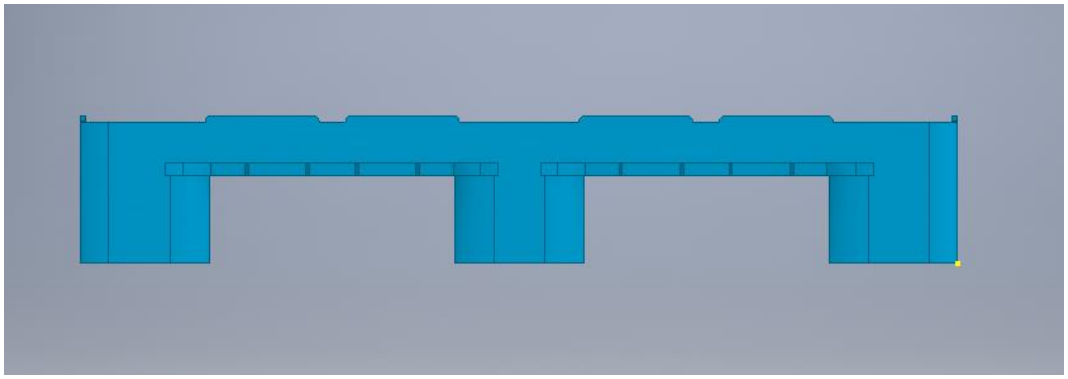


Figure D.9: Plastic (Pallet C) pallet model side view - width

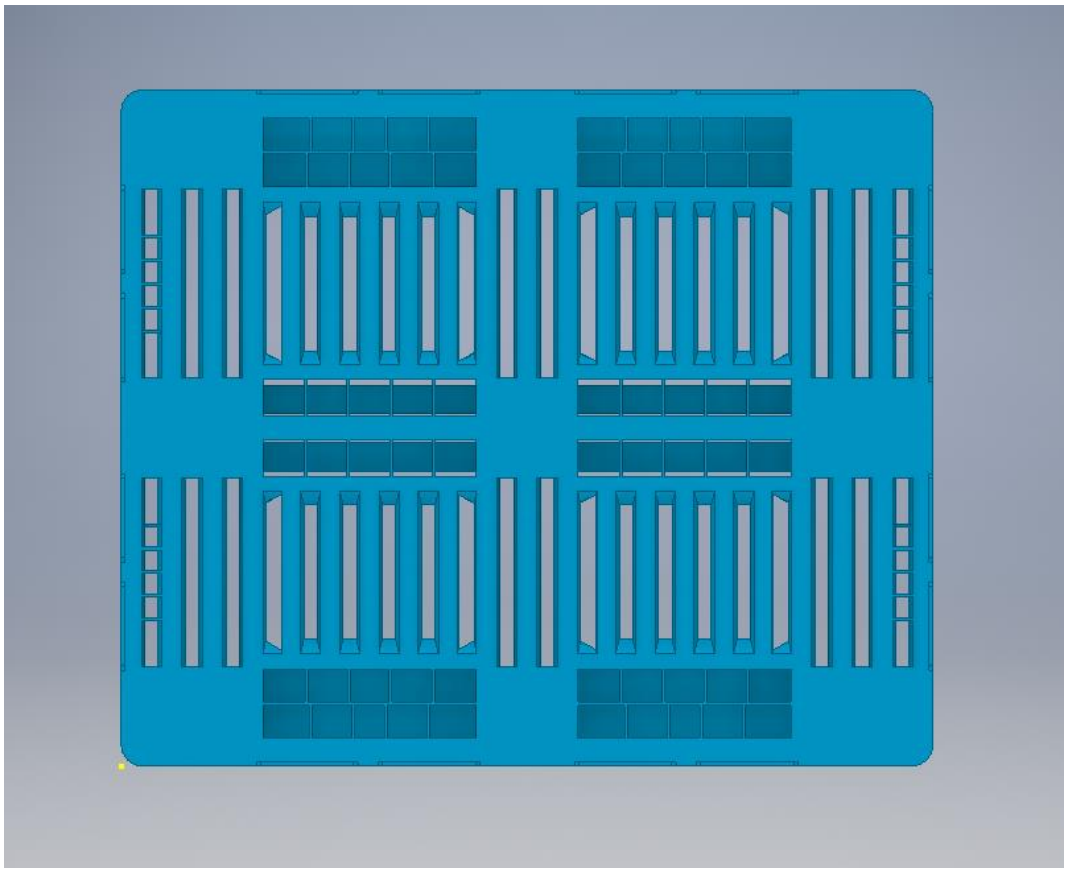


Figure D.10: Plastic (Pallet C) pallet model top view

D.2 Model Parameters

The physical parameters used to conduct the FEA analysis for the pallet material is presented in Figure D.11 and Figure D.12 for the wood and plastic pallet simulation models respectively.

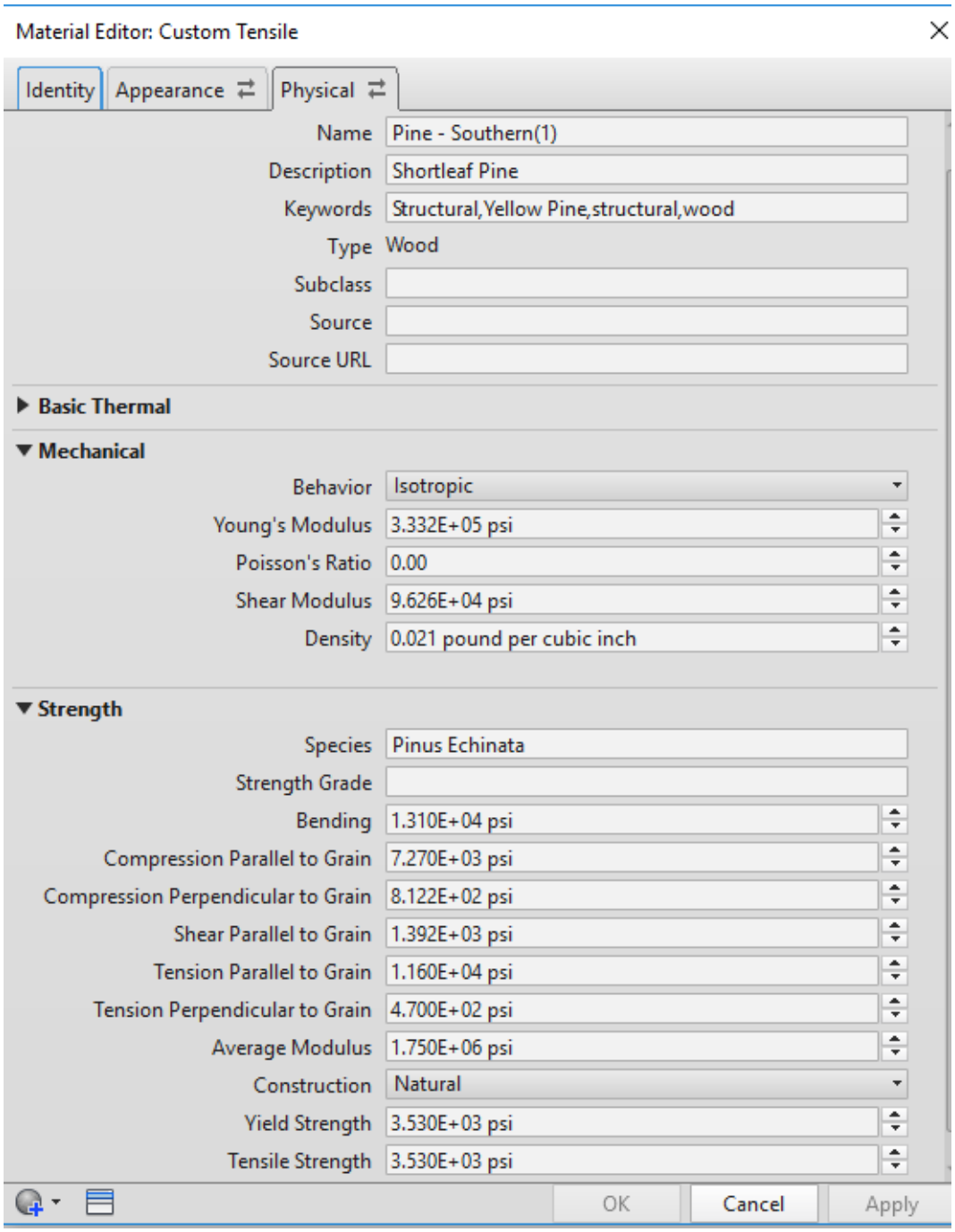


Figure D.11: Simulation model physical parameter for wood (Pallet B) pallet

In terms of the wood pallets, the material data properties of the Pinus Echinata species were adopted and modified to include tensile test data obtained from section 5.2.3. This was done in order to account for the lack of material property data in the Autodesk Inventor library for SA Pine. On the other hand, the plastic pallet models were modelled using the generic Polypropylene physical database as presented in Figure D.12.

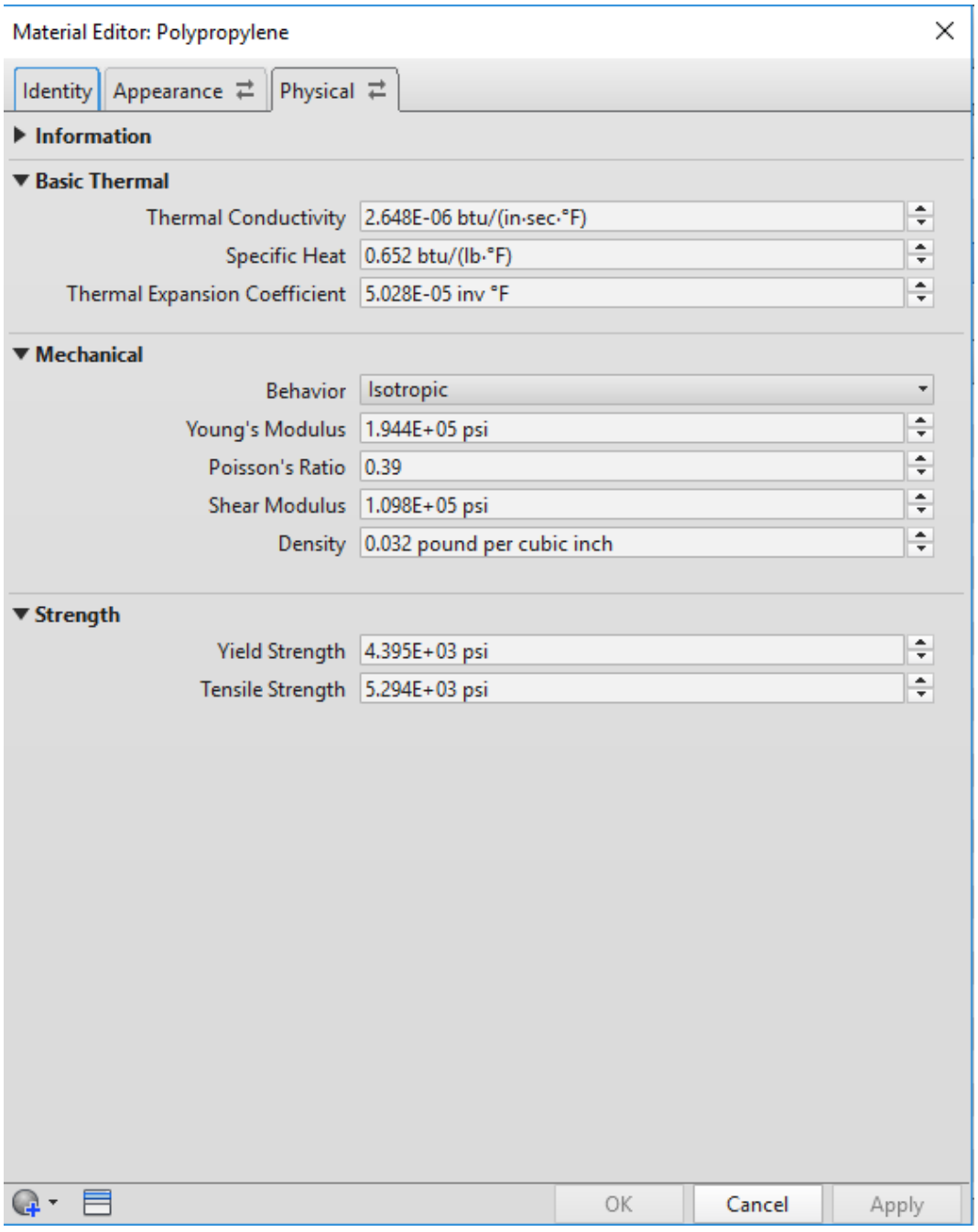


Figure D.12: Simulation model physical parameter for plastic (Pallet C) pallet

D.3 FEA Model Results

The following tables present the of results of the FEA on the modelled pallets for both stacking and racking cases as presented in section 5.4.

Table D.1: Wood (Pallet B) pallet 10000 N stacking simulation results summary

Name	Minimum	Maximum
Volume	55350500 mm^3	
Mass	31.564 kg	
Von Mises Stress	0.000000581925 MPa	2.41843 MPa
1st Principal Stress	-0.239665 MPa	1.4186 MPa
3rd Principal Stress	-2.50793 MPa	0.124252 MPa
Displacement	0 mm	0.698132 mm
Safety Factor	13.6452 ul	15 ul
Stress XX	-1.57853 MPa	1.40307 MPa
Stress XY	-0.794713 MPa	0.704453 MPa
Stress XZ	-0.334913 MPa	0.354014 MPa
Stress YY	-2.04911 MPa	0.419647 MPa
Stress YZ	-0.589144 MPa	0.627033 MPa
Stress ZZ	-1.91362 MPa	1.29076 MPa
X Displacement	-0.0455225 mm	0.0482536 mm
Y Displacement	-0.697399 mm	0.00506629 mm
Z Displacement	-0.0467795 mm	0.0488399 mm
Equivalent Strain	0.0000000001743 ul	0.000894553 ul
1st Principal Strain	-0.000104338 ul	0.000617588 ul
3rd Principal Strain	-0.00109183 ul	0.0000540933 ul
Strain XX	-0.000687215 ul	0.000610829 ul
Strain XY	-0.000345979 ul	0.000306684 ul
Strain XZ	-0.000145805 ul	0.00015412 ul
Strain YY	-0.000892081 ul	0.000182693 ul
Strain YZ	-0.000256484 ul	0.000272979 ul
Strain ZZ	-0.000833097 ul	0.000561931 ul
Contact Pressure	0 MPa	5.46432 MPa
Contact Pressure X	-1.97931 MPa	1.57464 MPa
Contact Pressure Y	-0.860884 MPa	5.18813 MPa
Contact Pressure Z	-0.978776 MPa	1.1941 MPa

Table D.2: Wood (Pallet B) pallet 10000 N racking simulation results summary

Name	Minimum	Maximum
Volume	55350500 mm^3	
Mass	31.564 kg	
Von Mises Stress	0.00000269685 MPa	5.47088 MPa
1st Principal Stress	-0.436193 MPa	4.96518 MPa
3rd Principal Stress	-5.54567 MPa	0.217512 MPa
Displacement	0 mm	2.31546 mm
Safety Factor	6.03194 ul	15 ul
Stress XX	-5.53541 MPa	4.9644 MPa
Stress XY	-1.9308 MPa	1.83676 MPa
Stress XZ	-0.60884 MPa	0.609435 MPa
Stress YY	-4.24769 MPa	1.14869 MPa
Stress YZ	-1.15213 MPa	0.888988 MPa
Stress ZZ	-2.52293 MPa	1.29567 MPa
X Displacement	-0.361171 mm	0.352964 mm
Y Displacement	-2.31545 mm	0.0252428 mm
Z Displacement	-0.129346 mm	0.132751 mm
Equivalent Strain	0.000000000786717 ul	0.00198377 ul
1st Principal Strain	-0.000189897 ul	0.00216159 ul
3rd Principal Strain	-0.00241431 ul	0.0000946939 ul
Strain XX	-0.00240984 ul	0.00216125 ul
Strain XY	-0.000840573 ul	0.000799635 ul
Strain XZ	-0.000265059 ul	0.000265318 ul
Strain YY	-0.00184923 ul	0.000500083 ul
Strain YZ	-0.000501581 ul	0.000387021 ul
Strain ZZ	-0.00109836 ul	0.000564071 ul
Contact Pressure	0 MPa	12.4031 MPa
Contact Pressure X	-5.77103 MPa	5.32662 MPa
Contact Pressure Y	-5.21656 MPa	11.5264 MPa
Contact Pressure Z	-1.13466 MPa	1.52245 MPa

Table D.3: Plastic (Pallet C) pallet 10000 N stacking simulation results summary

Name	Minimum	Maximum
Volume	27668000 mm^3	
Mass	24.8736 kg	
Von Mises Stress	0.0000145891 MPa	11.6557 MPa
1st Principal Stress	-6.68587 MPa	5.39933 MPa
3rd Principal Stress	-14.3033 MPa	1.461 MPa
Displacement	0 mm	2.3156 mm
Safety Factor	2.59958 ul	15 ul
Stress XX	-11.3131 MPa	5.38083 MPa
Stress XY	-3.11719 MPa	3.39103 MPa
Stress XZ	-5.21719 MPa	5.34332 MPa
Stress YY	-8.77656 MPa	4.04408 MPa
Stress YZ	-2.32482 MPa	2.3756 MPa
Stress ZZ	-7.4677 MPa	2.1831 MPa
X Displacement	-0.313955 mm	0.316282 mm
Y Displacement	-0.220809 mm	0.221989 mm
Z Displacement	-2.31553 mm	0.00426254 mm
Equivalent Strain	0.0000000111989 ul	0.00821842 ul
1st Principal Strain	-0.00011856 ul	0.00462917 ul
3rd Principal Strain	-0.00891338 ul	0.00000925927 ul
Strain XX	-0.00729108 ul	0.00379637 ul
Strain XY	-0.00323815 ul	0.00352262 ul
Strain XZ	-0.00541965 ul	0.00555067 ul
Strain YY	-0.00485126 ul	0.00334265 ul
Strain YZ	-0.00241504 ul	0.00246779 ul
Strain ZZ	-0.00376656 ul	0.00212161 ul

Table D.4: Plastic (Pallet C) pallet 10000 N racking simulation results summary

Name	Minimum	Maximum
Volume	27668000 mm^3	
Mass	24.8736 kg	
Von Mises Stress	0.0000420475 MPa	17.2766 MPa
1st Principal Stress	-6.34641 MPa	15.8058 MPa
3rd Principal Stress	-21.5574 MPa	5.83476 MPa
Displacement	0 mm	4.05563 mm
Safety Factor	1.75382 ul	15 ul
Stress XX	-12.3892 MPa	6.38795 MPa
Stress XY	-4.00141 MPa	3.95822 MPa
Stress XZ	-5.96122 MPa	5.98242 MPa
Stress YY	-19.2663 MPa	14.258 MPa
Stress YZ	-6.05809 MPa	6.10562 MPa
Stress ZZ	-11.7842 MPa	8.96941 MPa
X Displacement	-0.338936 mm	0.339033 mm
Y Displacement	-0.419583 mm	0.418916 mm
Z Displacement	-4.05526 mm	0.0293724 mm
Equivalent Strain	0.0000000405678 ul	0.0121254 ul
1st Principal Strain	-0.000010358 ul	0.00946026 ul
3rd Principal Strain	-0.0132364 ul	0.0000170454 ul
Strain XX	-0.00774801 ul	0.0058816 ul
Strain XY	-0.00415669 ul	0.00411183 ul
Strain XZ	-0.00619255 ul	0.00621457 ul
Strain YY	-0.0114648 ul	0.00825302 ul
Strain YZ	-0.00629318 ul	0.00634256 ul
Strain ZZ	-0.00690192 ul	0.00413378 ul

APPENDIX E CASE STUDY

E.1 Case Study outline

This section of the appendix gives additional information regarding the pallet case study. Site locations along with detailed analysis of the focus areas are illustrated. Additional photographic inserts from the case study may be found in the following sections.

As noted in section 6.2, three distinct supply chains were trailed for the case study, namely; an ambient chain, a perishables chain and a cold chain. Unilever was the main partner company for the ambient chain, Clover similarly for the perishables chain and Natures Garden for the cold chain. Intermediary companies such as Sequence Logistics, Vector Logistics, DHL (Jozi Park) played crucial roles in the distribution segment of the study. All trials concluded at Pick ‘n Pay outlets as the they were the main partner company for the retail segment of the supply chain.

E.2 Site Maps

The following site maps and additional site detail gives further insight to the audience on the preparations done prior to the commencement of the case study as well as outlines the conditions for the testing and locations considered when transporting the palletised products between sites.

E.2.1 Clover

Site Location

Clover (Pty) Ltd has a branch located at 25 Axle Rd, Clayville Industrial, Midrand. Furthermore, the CDC may be found at the following GPS locations [GPS: -25.9659621, 28.228752]. Figure E.1 depicts the site location.

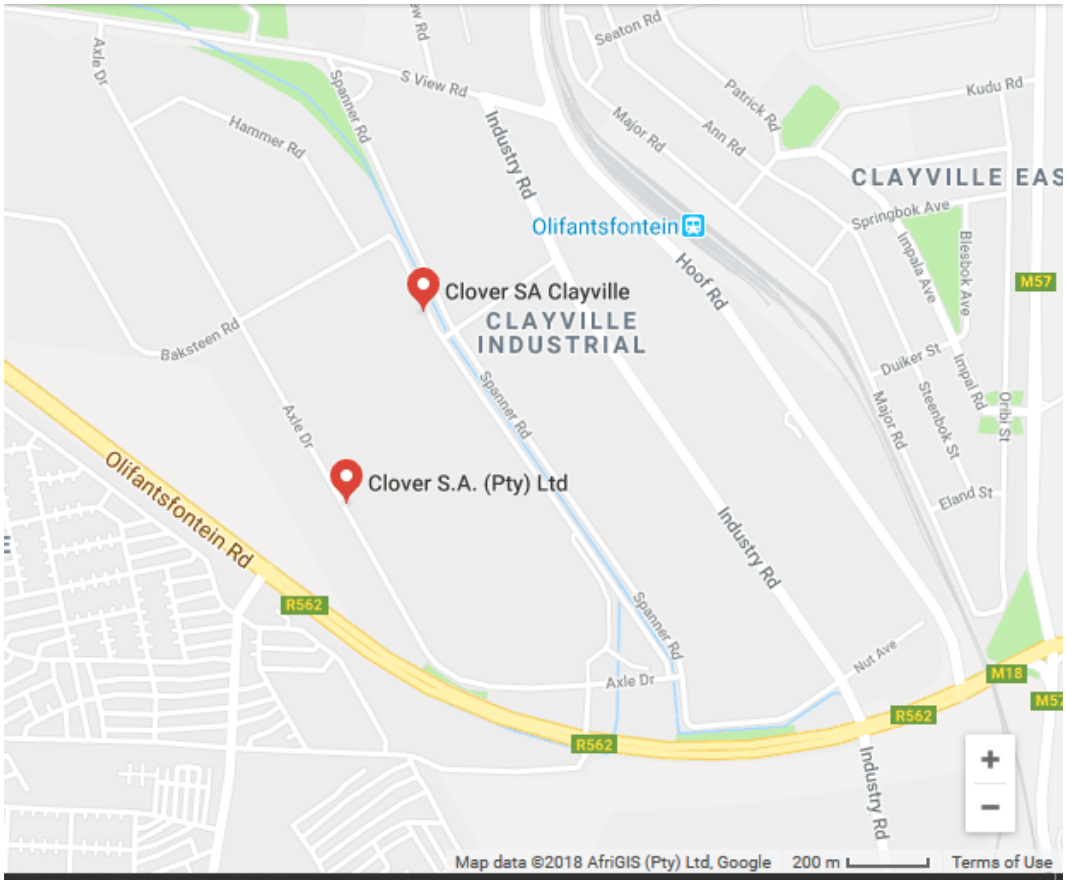


Figure E.1: Clover CDC site location (Google Maps, 2018a)

1.3 Site Details

Clover is South Africa's largest dairy producer and produces milk and other value-added dairy products such as yoghurt and custards for the Southern African market space (Mahlangu & Gernetzky, 2018). The Clayville site serves a central distribution centre for Clover products and services local sites such as those in Queensburgh, Cape Town, Port Elizabeth, Bloemfontein, Rustenburg and some other satellite sites, as well as other countries such as Namibia, Botswana and Swaziland (Mokabane, 2018).

Below are some notable points considered during field-testing of pallets (Mokabane, 2018):

1. Operating temperature:
    - Chiller: Approximately between 0.8 ˚C and 3.7 ˚C
    - Ambient: Room temperature
2. Level of automation: none
3. Products mainly racked:
    - Chiller: 4 - 7 Racks high
    - Ambient: 3 Racks high
4. Main products: Milk and other dairy products.
5. Predominantly wooden pallets
6. Fully electric fleet of pallet handling equipment

Site Aerial Images

The aerial shot depicted in Figure E.2 gives an indication of the relative positioning of the Clayville CDC site. The letters A-G, indicate the key locations for pallet movements, namely:

A. Receiving Dock
B. Returns Section
C. Chiller Storage Section
D. Dispatch Dock
E. Ambient Storage Section
F. Ambient Dispatch Dock
G. Pallet Storage Yard

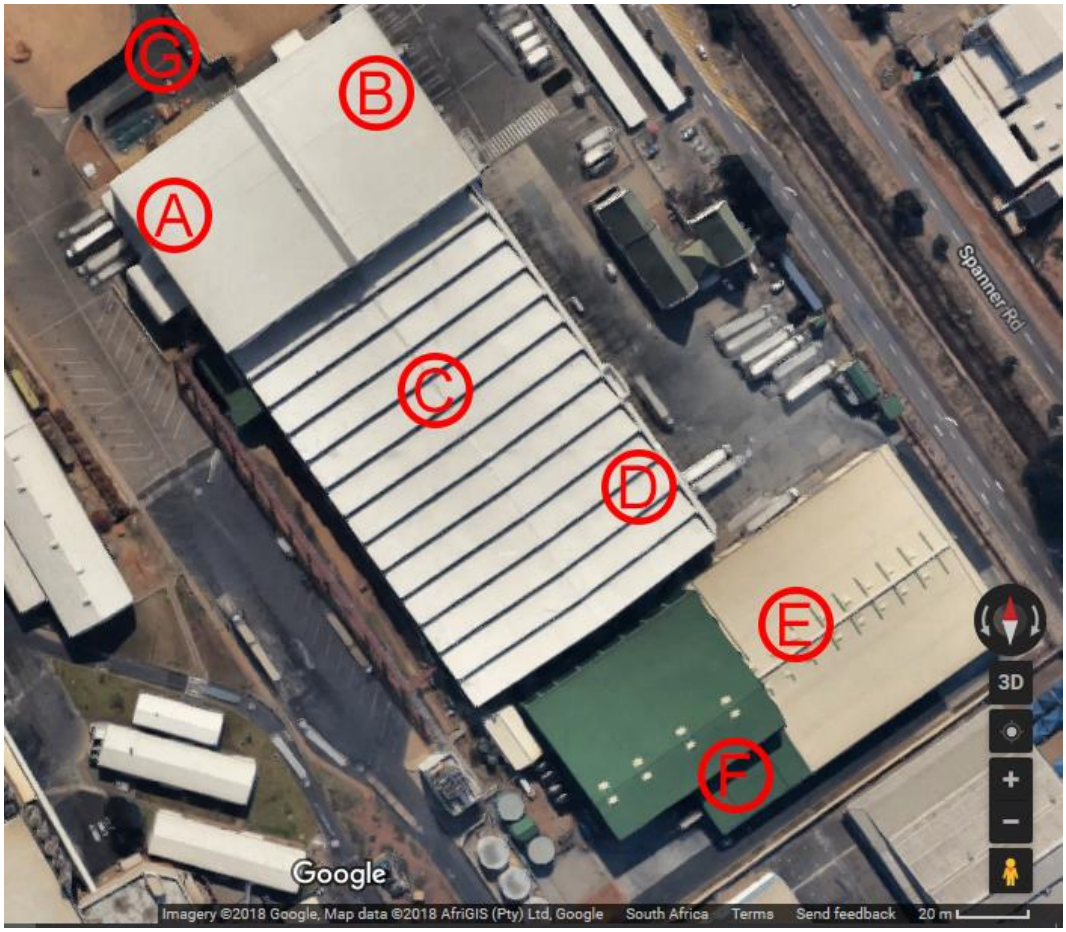


Figure E.2: Clover CDC aerial view with key sectors (A-E) for pallet flow analysis (Google Maps, 2018b)

These key areas served as the primary locations of observation. Locations A, D and F are the Receiving and Dispatch zones respectively with some inspection phases. Locations C and E are the stock storage sections at chilled and ambient storage conditions respectively. Section B is a dedicated bay for product returns. Pallets are stored in the yard at location G and are returned to the pooling company if damaged or cleaned and reused for picking within the warehouse.

E.2.2 Natures Garden

Site Location

The Natures Garden site is located at 24 Berryllium Road, Alrode. The site can be found at the following GPS locations [GPS: -26.31895, 28.12514]. Figure E.3 shows the site location.



Figure E.3: Natures Garden site location (Google Maps, 2018c)

Site Details

Natures Garden is a producer of Frozen Vegetables and Chips. The site produces a number of products for retailers such as Golden Harvest, Pick 'n Pay, Makro and Spar. Within the fast foods sector, the site produces for well-known brands such as KFC, Spur and Nando's (Natures Garden, 2018). The site is approximately 28 100 m^2 (Davies, 2016) and has a cold storage warehouse with a capacity for 6500 pallets.

Site Aerial Images

The aerial shot depicted in Figure E.4 gives an indication of the relative positioning of the Natures Garden Alrode site. The letters A-D, indicate the key locations for pallet movements, namely:

A. Pallet Storage Bay
B. Frozen Vegetables and Fries Packaging
C. Freezer Section
D. Receiving Dock, Inspection Floor and Dispatch Dock

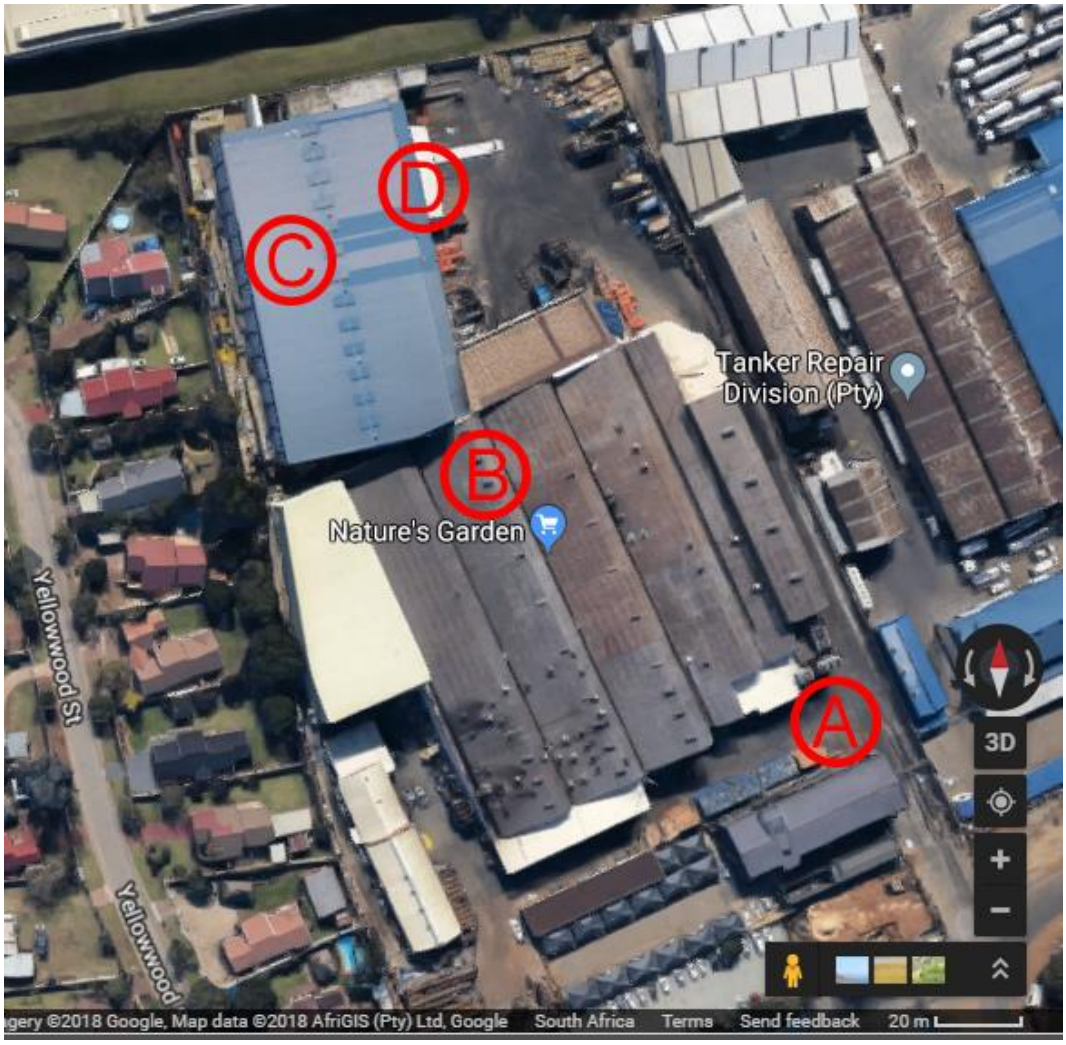


Figure E.4: Natures Garden aerial view with key sectors (A-D) for pallet flow analysis (Google Maps, 2018c)

These key areas served as the primary locations of observation. Locations A is the pallet storage section on site, Location B is the Fries and Frozen Vegetables packaging. Location C is the cold storage warehouse on site whereas location D is the Receiving and Dispatch zones with some inspection phases.

E.2.3 Pick ‘n Pay Longmeadow

Site Location

The PnP Longmeadow DC is located at the Longmeadow Business Estate, Cnr. Longmeadow Boulevard & Hereford Drive, Modderfontein, Edenvale, 1609 [GPS: -26.107273,28.1347604] (Figure E.5).

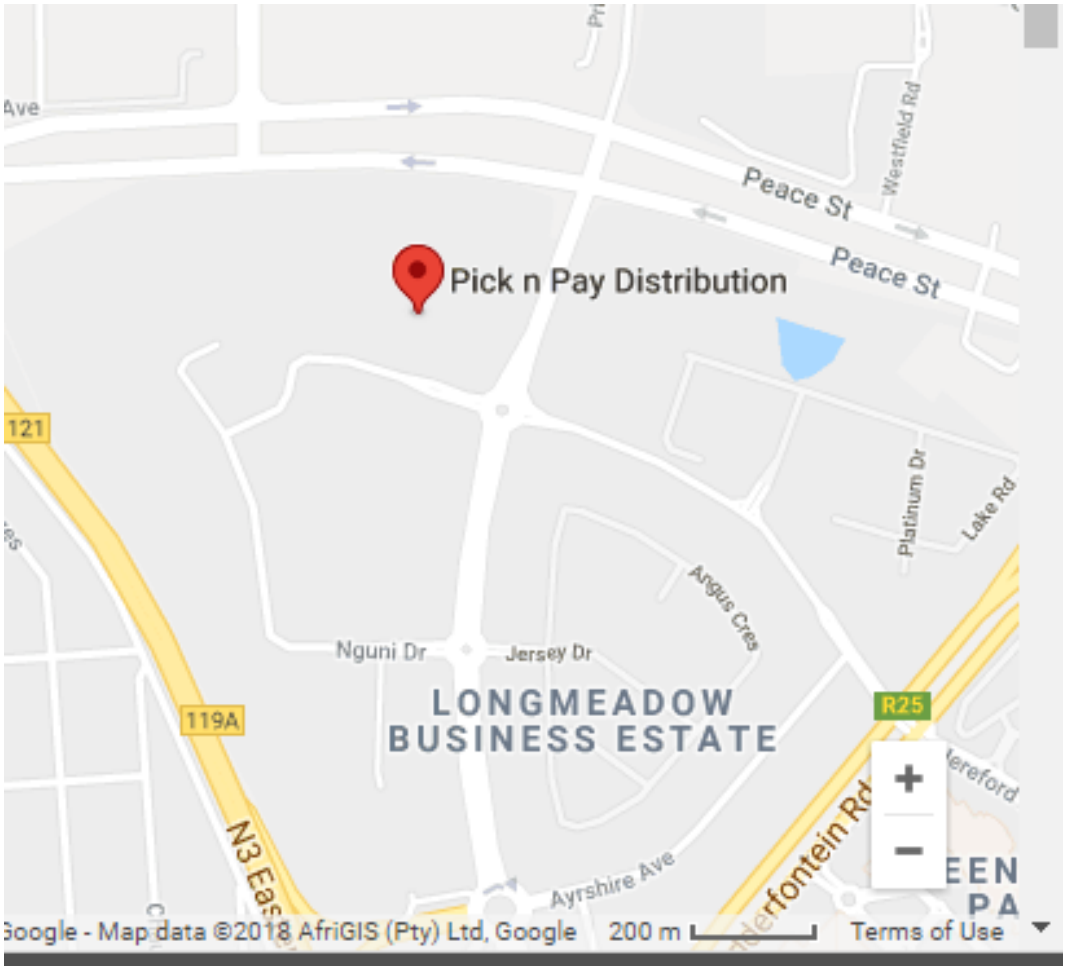


Figure E.5: PnP Longmeadow DC site location (Maps, 2018)

Site Details

The PnP Longmeadow site is the largest DC in Gauteng for Pick ‘n Pay. The site itself is believed to have a footprint of about 273 000 m^2 with the DC occupying 100 000 m^2 (Sikhakhane, 2014; Trade Intelligence, 2009). PnP is in the Fast-Moving Consumer Goods (FMCG) Industry and hence the majority of products on site fall into this category.

Non-Perishable Goods (NPG) Warehouse

Below are some notable points considered during field-testing of pallets in the NPG section (some factors are common to PG section as well, indicated by an asterisk i.e. *) (Odendaal, 2018):

1. Operating temperature: ambient
2. Level of automation: 0%*
3. Products mainly racked: Up to 7 racks high
4. Products stack height: 1.4 -1.7m max*
5. Unit load stacking: 2 pallet loads max*
6. 150 product lanes: High volume environment
7. Pallet damage: mostly caused by human error (dropped pallets approx. twice a week) *
8. Product storage duration in DC: 7 – 40 days max
9. Target products: OMO (quick moving line in non-perishables approx. 1 day)

Perishable Goods (PG) Warehouse

Below are some notable points considered during field-testing of pallets in the PG section (Odendaal, 2018):

1. Operating temperature: Chill Chamber [0 – 4°C], General Perishables [12 – 16°C]
2. Vendors transport on own low-cost pallets or deliver in crates
3. Temperature fluctuations: Instant Temperature change from ambient environment
4. Target products: Chill Chamber [apples], General [bananas] or UHT milk

Recovery Unit

Below are some notable points to consider during field-testing of pallets in the RU section (Odendaal, 2018):

1. Pallets returned mixed with other equipment i.e. roll cages, crates etc.
    - Pallets used to carry undesignated items

- Higher damage affinity due to absence of “valuable cargo / product”

2. Only 8 inbound lanes from all stores
3. C-stock ready for redistribution. Stored exposed to elements as can be seen in the region marked D-2 in Figure E.7
4. Pallets should be assessed as they return from retailers, prior to any repairs or redistribution

Site Aerial Images

The aerial shot depicted in Figure E.6 indicates the relative spacing and location of the units that make up the distribution centre. The letters A-D, indicate the key locations for pallet movements, namely:

A. Inbound Gate (First entry of pallet from supplier / vendor into the DC)
B. Non-Perishables Warehouse (Product storage + redistribution)
C. Perishables Warehouse (Product storage + redistribution)
D. Onsite pallet recovery and repair unit (Managed by a pooling company)



Figure E.6: PnP aerial view with key sectors (A-D) for pallet flow analysis (Maps, 2018)

These key areas served as the primary locations of observation. Location A gives an indication of the state that the pallet (and its goods) enters the DC (it is noted that there are inspection bays, which can be used for this

purpose). Locations B & C presented an in-situ observation of the rest state of pallets within the two warehouses at the respective operating conditions as pallets are first racked then dispatched. Lastly, location D as seen in Figure E.7 is in essence the end-point of the pallet flow system as used pallets return from stores and are either repaired or prepared for redistribution.



Figure E.7: Close Up of onsite recovery unit at PnP Longmeadow (Maps, 2018)

E.2.4 Sequence Logistics

Site Location

The Sequence Logistics warehouse is a brand-new facility, located at the corner of O'Connor Road and Aerodrome Road, Aeroton. The Sequence Logistics site can be found at the following GPS location [GPS: -26.256075, 27.971684]. Figure E.8 depicts the site location.

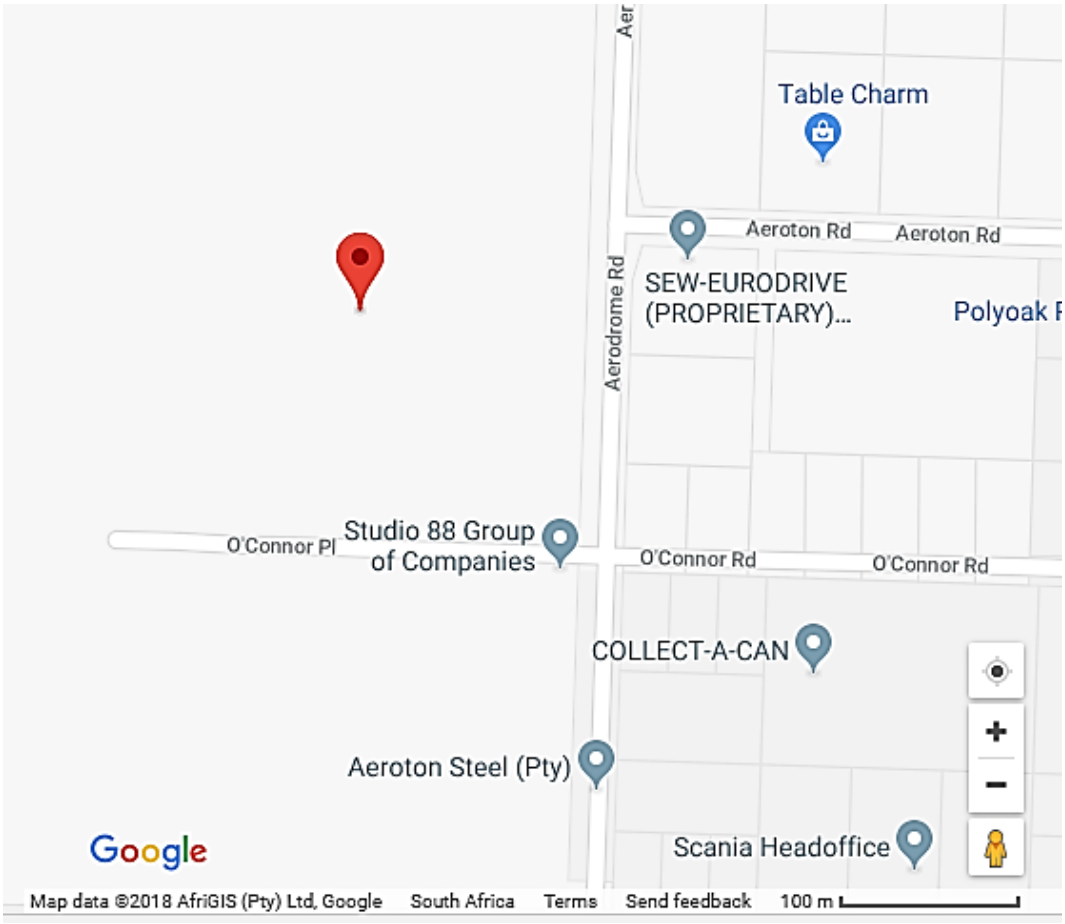


Figure E.8: Sequence Logistics site location (Google Maps, 2018d)

Site Details

Sequence Logistics provides temperature-controlled supply chain solutions in South Africa and Sub-Saharan Africa. These services include refrigerated warehousing and refrigerated transportation (Sequence Logistics, 2018). The Aeroton site is believed to be one of the highest in South Africa with a total capacity of over 19 000 pallets (RPP, 2018).

Below are some notable points considered during field-testing of pallets in the Sequence Logistics Aeroton DC (Kali, 2018):

1. Operating Temperature:
    - Inspection Bay: Approx. 2˚C
    - Freezer: -21˚C to -25˚C
2. Level of automation: Mobile Racking System
3. Products mainly racked: 5 Racks high
4. Main products: Raw material for Natures Garden, cold meat, frozen vegetable, ice cream.
5. Predominantly wooden pallets.
6. Warehouse Management System (WMS) assigns product stacking location.
7. Size: 4 Chambers, Approx. 22 700 pallets total capacity.
8. Product Durations:
    - FIFO System employed: First in First out system used but consideration made towards product expiry date
    - Slow products spend 4 – 5 months on site
    - Fast products spend 1 – 1.5 months on site

E.2.5 Unilever

Site Location

Both the Unilever Khanyisa and Jozi Park sites are located in Boksburg, Johannesburg. The Khanyisa site is located at 24 Francis Road, Boksburg [GPS: -26.1904596,28.2691695] whereas Jozi Park is located at 1 King Austin Road, Boksburg [GPS: -26.189693,28.2692686]

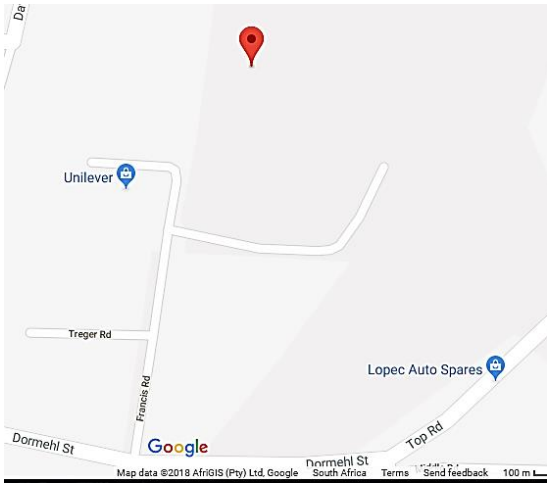


Figure E.9: Unilever Khanyisa site (Google Maps, 2018e)

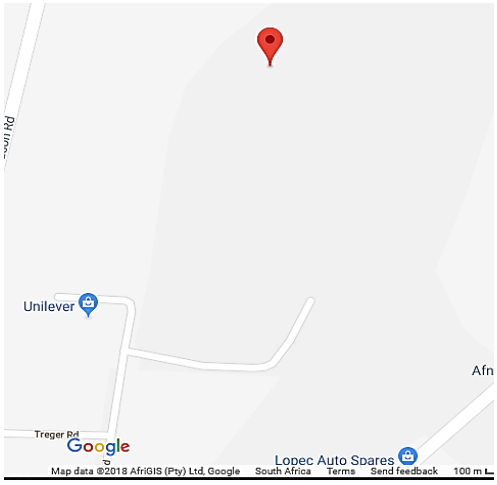


Figure E.10: Unilever Jozi Park site (Google Maps, 2018e)

Site Details

Unilever Khanyisa is a modern Home Care factory officially commissioned in June 2015. It has an estimated 150 000 tons per annum production capacity (Unilever - Press, 2015). The Unilever Jozi Park warehouse houses products and raw materials for the Unilever Khanyisa site and serves as a general Distribution Centre (DC) for Unilever in Gauteng. The Jozi Park warehouse occupies approx. 85 000m^2 with about 105 000 pallets therein (Niemann, 2018). Unilever South Africa (Pty Ltd) is one of the largest Fast-moving consumer goods (FMCG) companies in South Africa.

Below are some notable points considered during field-testing of pallets in the Khanyisa palletizing section(Dalton, 2018):

1. Operating Temperature: ambient
2. Level of Automation: 5 Automated product lines for palletizing, coupled with one for manual palletizing

3. Products mainly stacked: Max stacking: 2 pallet unit loads
4. Pallet damage: mostly from supplier, little damage on site
5. Main products: Handy Andy, Sunlight Dish, OMO, Domestos and Comfort.
6. Pallet problems: Line stoppages on automated palletizing lines mainly due to damaged pallets.

Site Aerial Images

The aerial shot depicted in Figure E.11 gives an indication of the relative positioning of the Unilever Khanyisa and Jozi Park sites. The letters A-C, indicate the key locations for pallet movements, namely:

A. Automated and Manual Palletizing zones for Khanyisa Factory
B. Pallet Storage and offloading bay at Khanyisa
C. Jozi Park Warehouse (Unilever Storage and Distribution Centre)



Figure E.11: Unilever aerial view with key sectors (A-C) for pallet flow analysis
(Google Maps, 2018e)

These key areas served as the primary locations of observation. Location A gave an indication of how well the pallets fair within the manual and automated palletizing environments at Unilever. Both sections were critical in comparing the relative performance of the pallets to one another. Location B was the primary entry point for the pallets within the supply chain. Location C was used as an in-situ observation location of the rest state of pallets within the Jozi Park warehouse at the respective operating conditions as pallets are racked then dispatched.

E.2.6 Vector Logistics

Site Location

The Vector Logistics DC is located at 80 Olievenhoutbosch Avenue, Louwlardia, Centurion. The Vector site can be found at the following GPS locations [GPS: -25.916596, 28.1686500]. Figure E.12 depicts the site location.

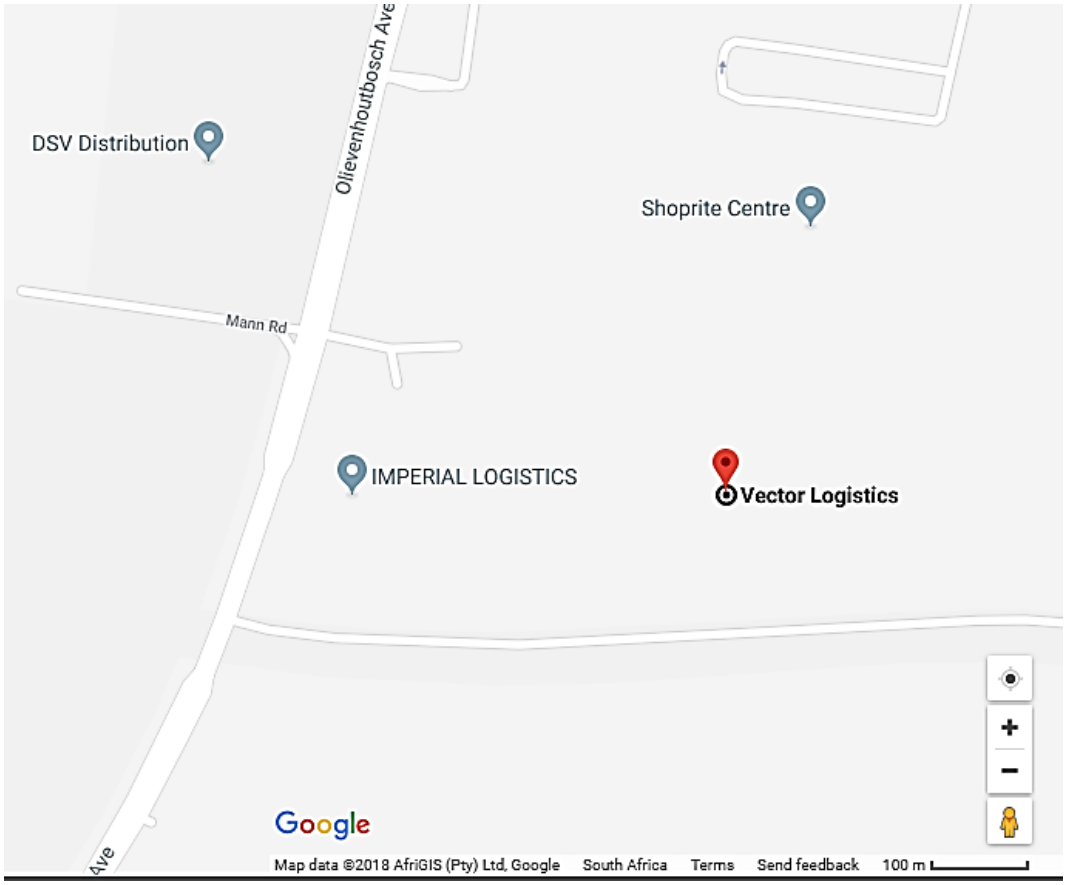


Figure E.12: Vector Logistics site location (Google Maps, 2018f)

Site Details

Vector Logistics is a third party logistics (3PL) service provider that provides supply chain solutions across retail, wholesale and food service sectors in the Southern African market space (RCL Foods, 2018). The Centurion site directly services retail outlets such as those for Pick ‘n Pay and Shoprite within Gauteng as well as Nelspruit and Polokwane (Padayachee, 2018).

Below are some notable points considered during field-testing of pallets in the Vector Logistics Centurion DC (Padayachee, 2018):

1. Operating Temperature:
    - Chiller: Approx. -8˚C
    - Freezer: Approx. -38˚C
2. Level of Automation: none
3. Products mainly racked:
    - Chiller: 2 Racks high
    - Freezer: 4 Racks high
4. No plastic pallets have been trialled in freezer section
5. Main products: Cold meats, spreads etc.
6. Predominantly wooden pallets, low cost wooden pallets tend to break under extreme freezing temperature.

Site Aerial Images

The aerial shot depicted in Figure E.13 gives an indication of the relative positioning of the Vector Logistics Centurion site. The letters A-E, indicate the key locations for pallet movements, namely:

A. Receiving Dock and Inspection Floor
B. Chiller Section
C. Freezer Section
D. Dispatch Dock
E. Pallet Storage yard



Figure E.13: Vector Logistics aerial view with key sectors (A-E) for pallet flow analysis (Google Maps, 2018f)

These key areas served as the primary locations of observation. Locations A and E are the Receiving and Dispatch zones respectively with some inspection phases. Locations B and C are the stock storage sections, within the Chiller as well as the Freezer sections respectively at below freezing conditions. Pallets are stored in the yard at location E once they return from the various retailers

E.3 Site Observations

The following images outline some of the observations encountered during the duration of the case study (as referred to in sections 6.4 - 6.6). Interactions with PHE, operators, product and machinery are displayed along with the resulting observed damage.

E.3.1 Case I



Figure E.14: Pallet C plastic pallet in manual palletizing zone



Figure E.15: Pallet A plastic pallet in manual palletizing zone



Figure E.16: Mixed cartridge into palletizer



Figure E.17: Plastic pallets compatible in automated palletizer



Figure E.18: Wood on conveyor



Figure E.19: Pallet A on conveyor



Figure E.20: Pallet C on conveyor



Figure E.21: Damage from transit on wood



Figure E.22: Damage from transit on Pallet A



Figure E.23: Damage from transit on Pallet C

E.3.2 Case II



Figure E.24: Crates on Pallet C plastic pallet



Figure E.25: Crates on Pallet A plastic



Figure E.26: Mixed order load



Figure E.27: Stored and ready to transit



Figure E.28: Double stacked load



Figure E.29: Wood in load bay



Figure E.30: Pallet C in load bay

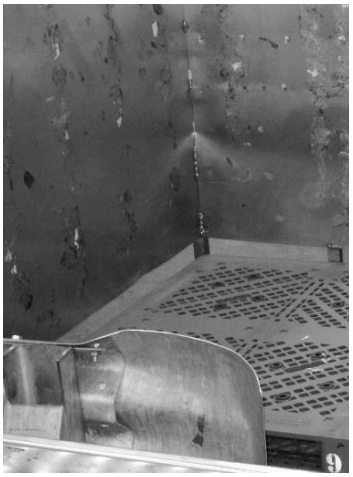


Figure E.31: Pallet A in load bay



Figure E.32: Pallets on reach truck



Figure E.33: Pallets with forklift truck



Figure E.34: Central pins damaged

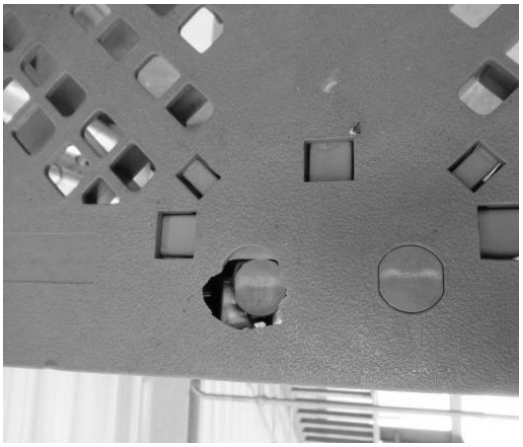


Figure E.35: Damaged pins



Figure E.36: Shredded plastic pallet base



Figure E.37: No damage on Pallet C



Figure E.38: Damage to elements on wood



Figure E.39: Bottom deck damages

E.3.3 Case III



Figure E.40: Wood in racking



Figure E.41: Plastic (Pallet C) in racking



Figure E.42: Plastic Pallet A in racking



Figure E.43: Wood getting shrink-wrap



Figure E.44: Plastic getting shrink-wrap



Figure E.45: Damaged pallet in load bay



Figure E.46: Broken element from wood pallet



Figure E.47: Damaged pallet after retailers



Figure E.48: Slight pallet damage



Figure E.49: Plastic pallet damage to central block

APPENDIX F MCDA TOOL

F.1 Tool formulation

The following section gives some insight on the manner in which the tool was formulated by showcasing the supplemental data used and the code used on the online platform. Screenshots of the tool in a use case scenario have been attached to further outline its operation. In addition to the pallet selector model, an AHP Matrix calculator was also developed than can be used as a standalone tool or in addition to the pallet selector as the user may see fit.

F.1.1 MCDA Tool Backbone

This web application / tool was developed using HTML, CSS and JavaScript with VueJS being the framework of choice for carrying out the calculations. Using Analytic Hierarchy Process (AHP) techniques embedded within the code, the tool allows for the selection of the best pallet for a particular supply chain based on operating conditions and importance of properties/criteria to the end user.

As illustrated in section 7.3, the underlying principle is to couple the results of the study, that rated each pallet performance for varying conditions, with the selection criteria and importance ranking of the end user. A similar process is followed to that of the illustrative example.

Decision matrices for the various criteria for each pallet were formulated based on performance in the study and have been presented here (Table F.1 and Table F.2) for the ambient and cold chains much like with the perishables presented in the body of the work. These form the basis for the comparison with the importance ranking of the criteria by the end user of the tool.

F.1.2 Decision Matrices for Supply Chains

Ambient Chain

Table F.1: Pallet pairwise comparisons - ambient chain

C_{DUR}: Durability	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	3	4	**0.6300**
$A_{PP+HDPE}$	1/3	1	1/2	**0.1514**
A_{PP}	1/4	2	1	**0.2184**

C_{STR}: Strength	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/2	3	**0.3196**
$A_{PP+HDPE}$	2	1	4	**0.5584**
A_{PP}	1/3	1/4	1	**0.1220**

$C_{R\&S}$: Racking &Stacking	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/3	1	**0.2098**
$A_{PP+HDPE}$	3	1	2	**0.5499**
A_{PP}	1	1/2	1	**0.2402**

C_{EH}: Equip Handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	3	2	**0.5396**
$A_{PP+HDPE}$	1/3	1	1/2	**0.1634**
A_{PP}	1/2	2	1	**0.2969**

C_{LOAD}: Load Handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/4	3	**0.2255**
$A_{PP+HDPE}$	4	1	5	**0.6738**
A_{PP}	1/3	1/5	1	**0.1007**

Cold Chain

Table F.2: Pallet pairwise comparisons - cold chain

C_{DUR}: Durability	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/2	4	**0.3233**
$A_{PP+HDPE}$	2	1	6	**0.5876**
A_{PP}	1/4	1/6	1	**0.0889**

C_{STR}: Strength	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/2	3	**0.3196**
$A_{PP+HDPE}$	2	1	4	**0.5584**
A_{PP}	1/3	1/4	1	**0.1220**

$C_{R\&S}$: Racking &Stacking	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	2	4	**0.5584**
$A_{PP+HDPE}$	1/2	1	3	**0.3196**
A_{PP}	1/4	1/3	1	**0.1219**

C_{EH}: Equip Handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/3	1/3	**0.1396**
$A_{PP+HDPE}$	3	1	2	**0.5278**
A_{PP}	3	1/2	1	**0.3325**

C_{LOAD}: Load Handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	**Priority vector**
A_{WOOD}	1	1/4	3	**0.2255**
$A_{PP+HDPE}$	4	1	5	**0.6738**
A_{PP}	1/3	1/5	1	**0.1007**

F.1.3 Online Pallet MCDA Tool – Pareto Example

In order to illustrate how the pareto optimisation step works in terms of pallets selection, a test set of conditions were set up. From Figure F.1, a presentation of the tool interface is given which would meet the user after viewing pallet options for the specified operating conditions. However, once these conditions are altered, i.e. changing the supply chain temperature from 25°C to -35°C, there is a visible change in the displayed pallet options for the user (Figure F.2). This is due to the given properties of the pallets and non-pareto optimal solutions are eliminated.

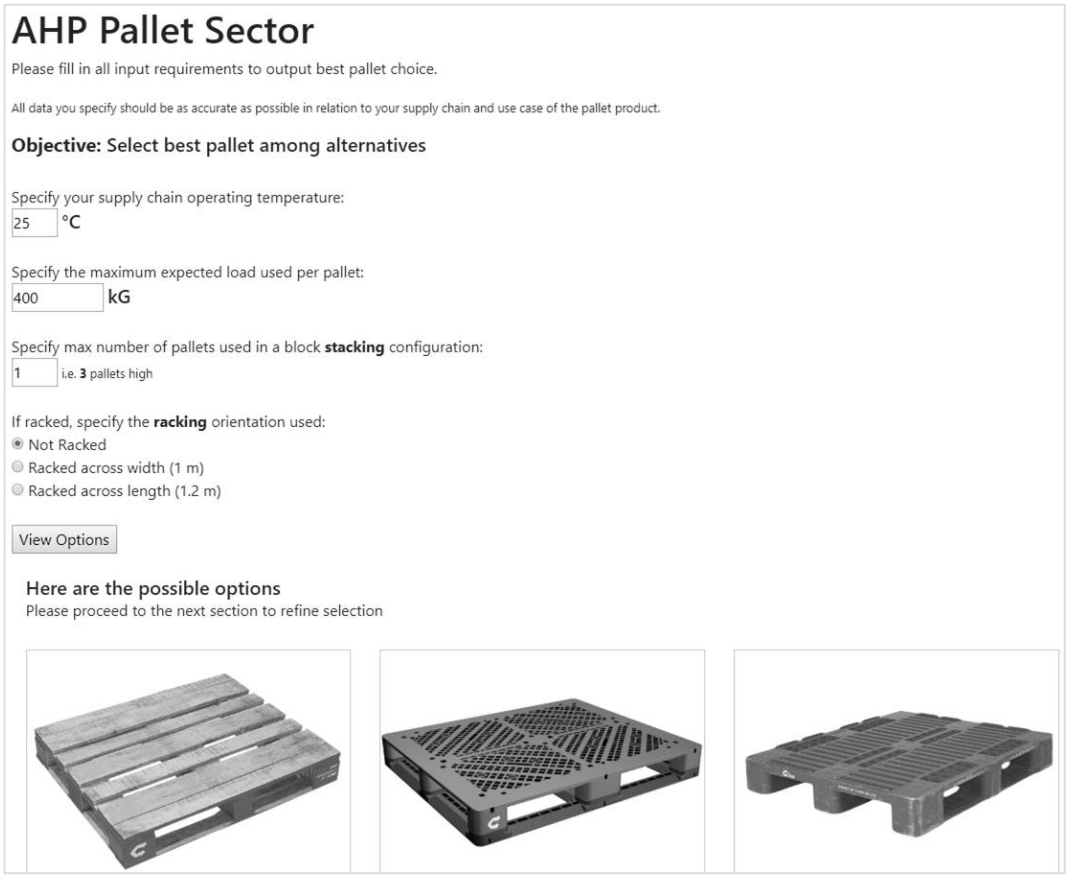


Figure F.1: MCDA tool interface - pallet selector



Figure F.2: MCDA tool interface - pareto optimisation

Once this is done, the algorithm the allows the user to make pairwise comparisons and outputs the most suitable solution for their purpose from the remaining pareto optimal solutions. The tool also allows for an error to be displayed if the pairwise comparisons are inconsistent as per the criteria set when using this MCDA technique (Figure F.3).

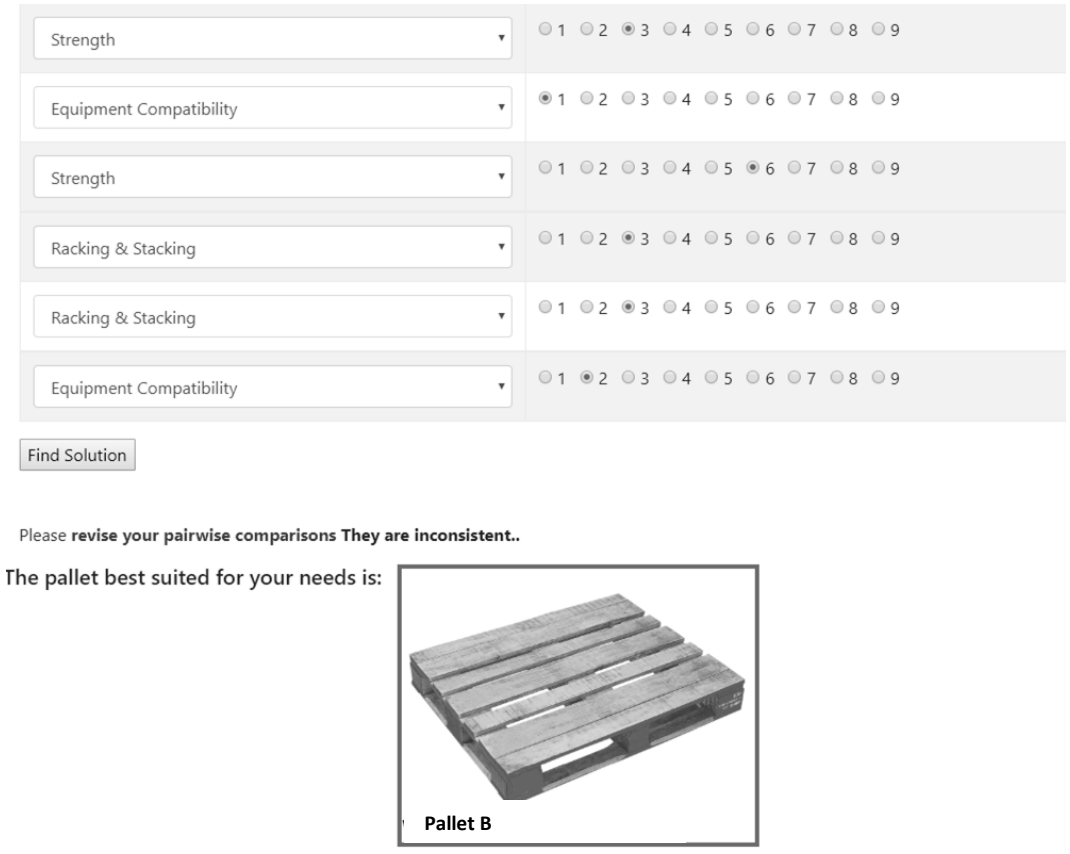


Figure F.3: MCDA tool interface - pallet choice output

F.1.4 AHP Matrix Calculator

An Analytic Hierarchy Process (AHP) calculator was developed in addition to the MCDA tool as an easier way to obtain the priority vector and check the consistency on the comparison matrix. The developed AHP calculator is available at : https://pallet-mcda.firebaseapp.com/ahp-matrix-calc.html (Figure F.4).

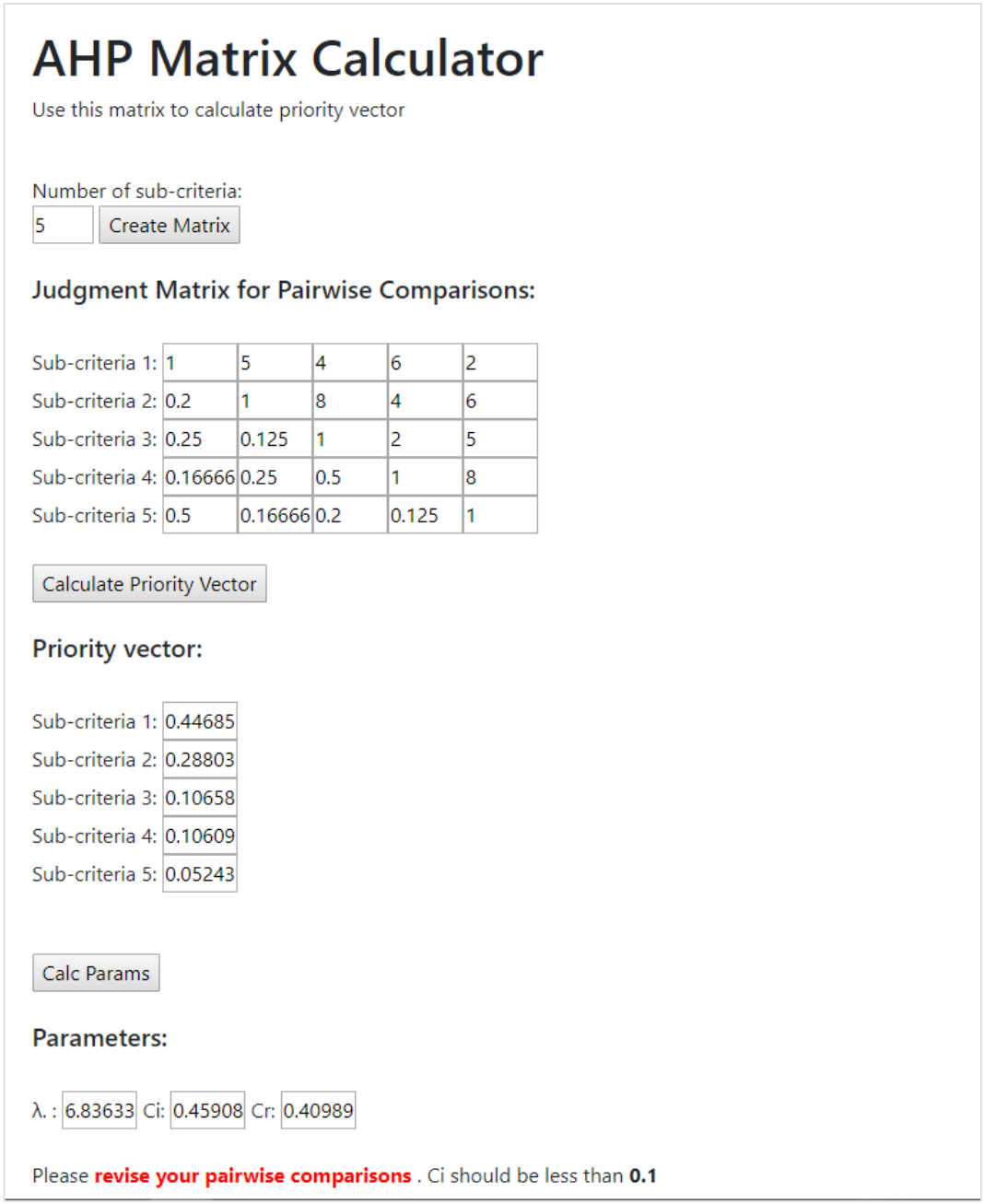


Figure F.4: AHP Matric calculator interface

F.2 Sample Code

F.2.1 VueJS Methods:

```
var app2 = new Vue ({
  el: '#app-2',
  data: {
    ahpMtrx : [[1,0],[0,1]], // AHP matrix
    ahpCriteriaMtrx:
[[1,0,0,0,0],[1,0,0,0,0],[1,0,0,0,0],[1,0,0,0,0],[1,0,0,0,0]],
    ambientChain:
[[0.6300,0.3196,0.2098,0.5396,0.2255],[0.1514,0.5584,0.5499,0.1634,0
.6738],[0.2184,0.1220,0.2402,0.2969,0.1007]],
    perishChain:
[[0.0658,0.3196,0.2098,0.3333,0.2255],[0.1488,0.5584,0.5499,0.3333,0
.6738],[0.7854,0.1220,0.2402,0.3333,0.1007]],
    coldChain:
[[0.3233,0.3196,0.5584,0.1396,0.2255],[0.5876,0.5584,0.3196,0.5278,0
.6738],[0.0889,0.1220,0.1219,0.3325,0.1007]],
    //dummy: [[1,0,0],[4,1,0],[9,6,0]],
    criteria: ["Durability","Strength","Racking &
Stacking","Equipment Compatibility","Load Handling"],
    currentBestPal:0, //Random current best pallet option
    matrixSize: 2,
    inptj: 1,
    prVctor:[1,2,3], //Priority vector initialiser
    prVctorPar: [0,0,0], //Priority vector parameters
    invalidCi: false, // Checks to see if Ci is invalid or not
    palletOrder: [0,1,2], // Order of pallets in the pallets object
    palletOptionExist: true, //shows pallet options if true, hides
if false
    parTemp: 25,
    parLoad: 400,
    parStack: 1, // if Stacked more than 3 high, wood and plastic
Pallet A eliminated, Pallet C stacked 4 high max
    parRack : "notRacked", // If pallets are racked across width
i.e. "acrossWid", Pallet C eliminated
    pallets: [
      {
          id : 0,
          name: 'wood (Pallet B)',
          image: 'img/wood.png'
      },
      {
          id : 1,
          name: 'plastic (Pallet A)',
          image: 'img/plastic.png'
```

```
      }
      ,
      {
          id : 2,
          name: 'plastic (Pallet C)',
          image: 'img/euro.png'
      }
    ],
    stepTwo: false, // Shows pallets and next step after "view
options clicked" - if true
    showsoln: false


  },
  methods: {
    tester: function () {
      alert('Hello !')
    },
    ahpFit: function (a,b,v) {
      var temp2 = math.string(v);
      var temp3 = math.eval(temp2);
      //var temp4 = math.number(temp3)
      this.ahpMtrx[a][b] = temp3;
    },
    myAhpInit: function (svar) {
      var tempVar = math.identity([svar, svar]); //create square
array and not matrix of ones [matrix causes issues] NOTE: array
input = array output
      this.ahpMtrx = tempVar; //math.matrix([[0, 1], [2, 3], [4,
5]]);
      this.inptj = tempVar;

      var temparr = [];

      for (var i = 0; i < svar+1; i++) {
        temparr.push(i);
      }

      this.prVctor = temparr; // Also creates temporary identity
array in prVctor slot
      //this.ahpMtrx[0][1] = svar;
     // alert(this.ahpMtrx);
    },
    alertva: function (varName) {
      alert(varName)
    },
    alertMath: function (strng) {
```

```
      var temp2 = math.string(strng)
      var tempvar4 = math.eval(temp2);
      //alert(tempvar4);
    },
    priorVector: function (ary) {
      var prVcGiv = [];
      prVcGiv = getPriorVector(ary);
      var temp5 = math.string(prVcGiv);
      var temp6 = math.eval(temp5)
      this.prVctor = temp6;
      //alert(temp6);
    },
    extractArv: function(arr,indx){
      var xtract = math.subset(arr, math.index(indx)) //gets array
value from matrix using index. See mathjs for subset definition
      return xtract;
    },
    paramsF: function (arrry) {
      var temp7 = [];
      temp7 = getLambdaCiCr(arrry);
      this.prVctorPar = temp7;
      var myCi = checkCi(temp7[1]);
      this.invalidCi = myCi;
    },
    viewOptions: function (temp, load, stack, rack) {
      var palOrder = [];
      var tempVaryb = checkTemp(temp);
      palOrder = tempVaryb;

      var tempVaryb = checkLoad(load,palOrder);
      palOrder = tempVaryb;

      var tempVaryb = checkStack(stack,palOrder);
      palOrder = tempVaryb;

      var tempVaryb = checkRack(rack,palOrder);
      palOrder = tempVaryb;


      var currentPalLen = palOrder.length;
      var solns =  solunExist(currentPalLen); //Checks if there are
pallet solutions
      this.palletOptionExist = solns; // updates state of pallet
solutions
      this.palletOrder = palOrder; // Sets the pal order variable to
latest version
      this.stepTwo = true; // shows the second step and pallets
```

```
    },
    findSoln: function () {
      var alertvar = gtFormInputs();//this.ahpCriteriaMtrx;
      this.priorVector(alertvar); //sets new priority vector bases
on selected importance criteria
      this.paramsF(alertvar) //calculates the parameters
      var prvrctr = this.prVctor;

      var ci = this.invalidCi; //checks to see if ci is valid
      var selTemp = this.parTemp;


      if (selTemp<-2) {
          arry1 = this.coldChain;
          //alert(mychain);
      } else if (selTemp<16) {
          arry1 = this.perishChain;
          //alert(mychain) ;
      } else if (selTemp<60) {
          arry1 = this.ambientChain;
          //alert(mychain) ;
      }

      var arry2 =  prvrctr;//[[7,8],[9,10],[11,12]]; //priority
vector for pallets on the basis of study results

      var prodValMtrx = mtrxprod(arry1, arry2);

      let indxBestPal =
prodValMtrx.indexOf(Math.max(...prodValMtrx)); //gets index of best
pal


      var currentOptions = this.palletOrder;
      var bestPal = spliceNon(currentOptions,prodValMtrx);
      this.currentBestPal = bestPal;
      this.showsoln = true;

    }
  }
})
```

F.2.2 Generic JS Functions

```
// Prerequisistes are math.js and numeric-1.2.6.js


function crtMtrixOnes(size) {
    math.ones(size, size); //create square matrix of ones
}

function rghtPrincEigVal(arr) {
    var Aeig = numeric.eig(arr);
    var valueMx = -500000000000000; //Max neg eig val esti
    var indexMx = 0; //O max index. i.e smallest possible index

    var indexA = Aeig.lambda.x;

    indexA.forEach(function (value, index, matrix) {//Function to
get the max eigen value and the index of where it is located
        if (value>valueMx) {
          valueMx = value;
          indexMx = index;
        }
    })

    return [indexMx, valueMx ]; //Function returns array with max
eigen value of arr (array) and the index where it is at

    /** The values can be accessed by saying : var getValVar =
rghtPrincEigVal(inoutArr); getValVar[0] will give you indexMx*/
}

function rghtPrincEigVec(arr,indMX) {
    var Aeig = numeric.eig(arr); // function returns matrices of
both eig vectors and values
    var dax = math.matrix(Aeig.E.x); // Eigenvectors from the Aeig
matrix

    var daxSize = dax.size()[0];
    var eigVector = []; // Empty Subset for Eig Vector

    for (let i = 0; i < daxSize; i++) {
        var indexinRow = math.subset(dax, math.index(i,indMX));
        eigVector.push(indexinRow);
        //var eigVectorF = math.matrix(eigVector); // This would
make it a matrix
    }
```

```
    return eigVector;
}

function crPriority(arry) {
    var totArr = arry.reduce(add, 0);

    function add(a, b) {
        return a + b;
    }

    for (var i = 0, length = arry.length; i < length; i++){
        arry[i] = arry[i]/totArr;
    }

    var arry =math.matrix(arry);
    return arry;
}

function RCIcalc(n_in) {
    var x = n_in; // set x to input n variable
    var rci = 0; //Initialise RCI (Random Consistency index)

    switch (x) {
        case 3:
            rci = 0.58;
            break;
        case 4:
            rci = 0.90;
            break;
        case 5:
            rci = 1.12;
            break;
        case 6:
            rci = 1.24;
            break;
        case 7:
            rci = 1.32;
            break;
        case 8:
            rci = 1.41;
            break;
        case 9:
            rci = 1.45;
            break;
        default:
            rci = 0;
    }
```

```
    return rci;
}

function CIcalc(lambda, n) {
    var Ci = (lambda-n)/(n-1);
    return Ci;
}

function CRcalc(Ci, RCi) {
    var Cr = Ci/RCi;
    return Cr;
}

function getPriorVector(comArr) { // function takes in array and
outputs Priority vector
    var n_EigValIndx = rghtPrincEigVal(comArr)[0]; //Outputs the
Right Principle EigenVal Index Loc
    var n_EigVec = rghtPrincEigVec(comArr,n_EigValIndx); //Gives the
Eig Vector associated with the Right Principle EigenVal
    var n_PrVec = crPriority(n_EigVec); // Gets priority vector,
take array as param from right principle eig vec

    return n_PrVec;
}

function getLambdaCiCr(comArr) { //Function creates Lambda, Ci and
Cr from array
    var n_sizeArr = comArr.length; // assumption is it is an nxn
array therefore number of col = num of rows
    var n_EigValB = rghtPrincEigVal(comArr)[1]; //Outputs the Right
Principle EigenVal
    var n_Ci = CIcalc(n_EigValB, n_sizeArr); // Gets the Ci value
using (lambda, n)
    var n_RCi = RCIcalc(n_sizeArr); // Gets Rci using the n value
    var n_Cr = CRcalc(n_Ci, n_RCi); // Gets the Cr value using (Ci,
RCi)

    return [n_EigValB, n_Ci, n_Cr];
}


function print(value) {
    var precision = 5;
    document.write(math.format(value, precision) + '<br>');
}
```

```
function alertme(nom) {
    alert("This is an alert..number is.. "+nom);
}

function makeMtrx(a,b,valIndx) {
    ahpMtrx[a][b] = valIndx;
}

function checkCi(Ci) {

    if (Ci > 0.1) {
        return true;
    }

}


/**** Functions for pallet selector AHP */

function checkTemp(t) {
    var myAr = [0,1,2];


    if (t<-35) {
        myAr = [0];
    } else if (t<-30) {
        myAr = [0,2];
    } else if (t<45) {
        myAr = [0,1,2];
    } else if (t<50) {
        myAr = [0,1];
    }else if (t<70) {
        myAr = [0];
    }
    else {
        myAr = [];
    }
    return myAr
}

function cutArrayElm(arry, valRem) {

}

function checkLoad(l,arry) {
    var myNewArr = arry;
```

```
    if (l>1000 ) { //check that the load capacity is less that 1250
but greater than 1000

        if (l<1251) {
            if (myNewArr.includes(1)) { // Checks if array already
contains the Pallet A i.e id=1 as a pallet solution
                myNewArr = [1];
            }else{
                myNewArr = [];
            }
        }else{
            myNewArr = [];
        }
    }

   return myNewArr;
}

function checkStack(s,arry) {
    var myNewArr = arry;

    if (s>3 ) { //check that the stack height is greater than 3 but
less than 5

        if (s<5) {
            if (myNewArr.includes(2)) { // Checks if array already
contains the Pallet C i.e id=2 as a pallet solution
                myNewArr = [2];
            }else{
                myNewArr = []; //returns empty array as no pallets
may be stacked more that 4x
            }
        }else{
            myNewArr = [];
        }
    }

   return myNewArr;
}

function checkRack(r,arry) {
    var myNewArr = arry;

    if (r=="acrossWid" ) { //check racked across width as Pallet C
pallet should be eliminated
```

```
        if (myNewArr.includes(2)) { // Checks if array already
contains the Pallet C i.e id=2 as a pallet solution
            var index = myNewArr.indexOf(2);

            if (index > -1) {
                myNewArr.splice(index, 1);
            }

        }
    }

   return myNewArr;
}

function solunExist(valu) {
    var solns = true;
    if (valu==0) {
        solns = false;
    }
    return solns;
}

function arryCrtAhpfil(array) {// makes all aij = 1/aji and vice
versa
    var arlngth = math.size(array);
    var newAry = array;

    for (let x = 0; x < arlngth[0]; x++) {

        for (let y = 0; y < arlngth[1]; y++) {
            var currentIndx = newAry[x][y];
            if (currentIndx!=0) {
                newAry[y][x] = 1/newAry[x][y];
            }

        }

    }

    return newAry;

}

function addfunc(a, b) {
    return a+b;
}
```

```
function gtFormInputs() {

    var  myImporArr =
[[1,0,0,0,0],[0,1,0,0,0],[0,0,1,0,0],[0,0,0,1,0],[0,0,0,0,1]];
//Initialise array with importance pairwise comparisons

    var matches = document.querySelectorAll(".tableRow .critVal");
// selects all items that have class tableRow and then critVal
    var lenSelector = matches.length;

    for (let i = 0; i < lenSelector; i++) {
        var valCrit12 = matches[i].value;
        var indxImprt = caseHC(i,valCrit12);
        var matchesb = document.querySelectorAll(".tableRow
.radVal:checked"); //selects checked value for importance rank
        var imprVarValu = matchesb[i].value;

        myImporArr[indxImprt[0]][indxImprt[1]] = imprVarValu;
//Outputs comparison array without inverse
    }

    var finalAhpImportance = arryCrtAhpfil(myImporArr);
    return finalAhpImportance;
}

function caseHC(index,valu) {
    var var1 = ""+index+"";
    var var2 = ""+valu+"";
    var arIndx = [0,0]

    switch(var1 + "|" + var2) {//determines which index to insert
value into depending on criteria selected
        case "0|1":
            arIndx = [0,1] //array index to insert
            break;
        case "0|2":
            arIndx = [1,0]
            break;
        case "1|1":
            arIndx = [0,2] //array index to insert
            break;
        case "1|2":
            arIndx = [2,0]
            break;
        case "2|1":
            arIndx = [0,3] //array index to insert
            break;
```

```
        case "2|2":
            arIndx = [3,0]
            break;
        case "3|1":
            arIndx = [0,4] //array index to insert
            break;
        case "3|2":
            arIndx = [4,0]
            break;
        case "4|1":
            arIndx = [1,2] //array index to insert
            break;
        case "4|2":
            arIndx = [2,1]
            break;
        case "5|1":
            arIndx = [1,3] //array index to insert
            break;
        case "5|2":
            arIndx = [3,1]
            break;
        case "6|1":
            arIndx = [1,4] //array index to insert
            break;
        case "6|2":
            arIndx = [4,1]
            break;
        case "7|1":
            arIndx = [2,3] //array index to insert
            break;
        case "7|2":
            arIndx = [3,2]
            break;
        case "8|1":
            arIndx = [2,4] //array index to insert
            break;
        case "8|2":
            arIndx = [4,2]
            break;
            case "9|1":
            arIndx = [3,4] //array index to insert
            break;
        case "9|2":
            arIndx = [4,3]
            break;
```

```
    }

    return arIndx;
}

function mtrxprod(arry1, arry2) {
    var newAr = [];
    var prdct = math.multiply(arry1, arry2);
    var lngth = prdct.size();

    for (let y = 0; y < lngth; y++) { //converts matrix into array
        newAr[y] = math.subset(prdct, math.index(y))
    }
    return newAr;
}

function spliceNon(arrya, arryb) {//gets max index of pallets and
leave in array
    var lngth = arrya.length;
    var newAr = [];

    for (let y = 0; y < lngth; y++) { //converts matrix into array
        newAr[y] = arryb[arrya[y]];
    }

    let indxBestPal = arryb.indexOf(Math.max(...newAr)); //gets
index of best pal
    return indxBestPal;
}
```