An investigation to evaluate the impact of quality-controlled logistics on food waste and food quality with the assistance of Internet of Things

by
Lélani Joubert

Thesis presented in fulfilment of the requirements for the degree of Master of Engineering (Industrial Engineering) in the Faculty of Engineering at Stellenbosch University

Supervisor: Prof. Louis Louw

April 2019

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: April 2019

Acknowledgements

The author wishes to acknowledge the following people for their various contributions towards the completion of this study:

- Professor Louis Louw for his exceptional guidance and supervision over the past two years.
- Prof. Dr.-Ing Vera Hummel for her contributions towards this study and also providing the opportunity to visit the ESB Business School in Reutlingen, Germany.
- The LLF team at the ESB Business School for their assistance, friendliness and the unforgettable moments in Germany.
- Friends and family for their emotional support and encouragement during the past two years.
- Our Lord for providing unconditional strength, wisdom and success.

Abstract

Fresh food is mainly wasted due to overproduction and the natural decay of food quality, which cannot be prevented but is accelerated by poor supply chain management. Therefore, actors in the fresh produce supply chain are responsible for monitoring and controlling logistic activities that influence the quality of fresh food. The emergence of new technologies such as the Internet of Things provides the ability to collect real-time food quality information, which may be used to assist and adapt logistic activities to ensure that food quality remains within the accepted quality limits. However, limited literature is available to gain sufficient understanding on how Internet of Things technologies and quality-controlled logistics can be combined to potentially reduce food waste along the fresh produce supply chain and to improve overall food quality. The purpose of this research study is to investigate the impact of quality-controlled logistics on food waste in the fresh produce supply chain. Thereafter, the study will explore how quality-controlled logistics can be implemented with the use of Internet of Things technologies.

Expert insights regarding quality-controlled logistics and the Internet of Things were collected to determine (i) how traditional logistics could be adapted to implement quality-controlled logistics in the fresh produce supply chain; and (ii) to identify whether the experts believe that Internet of Things technologies could assist supply chain planning in the fresh produce industry. Simulation modelling was used to evaluate the impact of several quality-controlled logistics activities on food waste and food quality. It was found that the implementation of the Least-Shelf-life-First-Out with dynamic pricing replenishment strategy at the retail stores, would result in a significant reduction in food waste throughout the supply chain; however, it slightly reduced the remaining shelf-life of the purchased fresh produce. An Internet of Things prototype application was also developed to illustrate how emerging technologies could assist the implementation of quality-controlled logistics in the fresh produce supply chain, and to highlight the practical challenges that should be considered before implementing such applications. The findings from this study contribute towards research on food supply chain management, by documenting how quality-controlled logistics and the Internet of Things can contribute to the reduction in waste in the fresh produce supply chain.

Opsomming

Vars voedsel produkte word hoofsaaklik vermors weens oorproduksie en die natuurlike verval van die kwaliteit van die produk wat nie voorkom kan word nie, maar eerder versnel word deur swak voorsieningskettingbestuur. Daarom is rolspelers in die voedselvoorsieningsketting verantwoordelik om logistieke aktiwiteite wat die kwaliteit van vars produkte beïnvloed, te monitor en te beheer. Nuwe tegnologieë soos die Internet van Voorwerpe skep die geleentheid om inligting rakend die kwaliteit van vars produkte in reële tyd in te samel. Dit kan gebruik word om logistieke aktiwiteite aan te pas om te verseker dat die kwaliteit van die vars produkte steeds in die aanvaarde gehalte perke bly. Daar is egter nog beperkte literatuur beskikbaar om voldoende insig te kry oor hoe Internet van Voorwerpe tegnologieë saam met kwaliteit-gedrewe logistieke aktiwiteite kombineer kan word sodat voedselvermorsing kan verminder en om die kwaliteit van vars produkte te verbeter. Die doel van hierdie navorsingstudie is om die impak van kwaliteit-gedrewe logistieke aktiwiteite op voedselvermorsing asook die kwaliteit van vars produkte te evalueer. Daarna sal die studie ondersoek instel om te bepaal hoe kwaliteit-gedrewe logistieke aktiwiteite geïmplementeer kan word saam met die gebruik van Internet van Voorwerpe tegnologie.

Kenners wat in die vars produksiebedryf werk se kennis oor kwaliteit-gedrewe logistiek asook die Internet van Voorwerpe was ingesamel om te bepaal (i) hoe tradisionele logistieke aktiwiteite aangepas kan word om kwaliteit-gedrewe logistieke aktiwiteite in die vars voedselvoorsieningsketting te implementeer; en (ii) om die kenners se opinie te kry ten opsigte van die gebruik van Internet van Voorwerpe in die vars produksiebedryf. Simulasie modellering was gebruik om die impak wat verskeie kwaliteit-gedrewe logistieke aktiwiteite op voedselvermorsing asook voedselkwaliteit het, te evalueer. Daar is bevind dat die implementering van die Minste-Rakleeftyd-Eerste-Uit met 'n dinamiese prysbepaling strategie by kleinhandelaars 'n beduidende vermindering van voedselvermorsing tot gevolg sal hê, maar die oorblywende rakleeftyd van die vars produkte tydens verkope sal effens verminder word. 'n Internet van Voorwerpe toepassings prototipe was ontwikkel om te illustreer hoe nuwe tegnologieë die implementering van kwaliteit-gedrewe logistiek kan bevoordeel en om die praktiese uitdagings wat oorweeg moet word, uit te lig. Die bevindinge van hierdie navorsingstudie maak 'n bydra tot die navorsingveld voedselvoorsieningskettingbestuur, deur bewustheid te skep oor hoe kwaliteit-gedrewe logistieke aktiwiteite en die Internet van Voorwerpe 'n bydra lewer tot die vermindering van voedselvermorsing.

Contents

List of Figures

List of Tables

Nomenclature

Acronyms

CCP Critical Control Point

CSIR Council of Scientific and Industrial Research

DSC Digital Supply Chain

FEFO First-Expiry-First-Out

FFSC Fresh Food Supply Chain

FFV Fresh Fruits and Vegetables

FSC Food Supply Chain

GHG Greenhouse Gas

I4.0 Industry 4.0

ICT Information and Communication Technology

IoT Internet of Things

IWF Internet of Things World Forum

QCL Quality-controlled Logistics

RFID Radio-Frequency Identification

SCM Supply Chain Management

TPL Third-Party Logistics

Chapter 1

Introduction

This chapter serves as an introduction to this research study. The chapter commences with brief background information to this study which leads to the problem statement, the formulation of the research aim, questions and objectives. Following that, the proposed research methodology as well as the contribution of this study are given. Finally, the chapter concludes with the proposed outline of this study.

1.1 Background and rationale of the research

Roughly one third of edible fresh produce is wasted because the quality has dropped below acceptable limits (FAO, 2013; Quested *et al.*, 2011). Food waste is therefore a global issue as it has an impact on (i) food security for poor people, (ii) food quality and safety; and (iii) economic development and the environment (Gustavsson *et al.*, 2011). Food is wasted throughout the supply chain, from the initial harvesting stage down to the final consumption stage (Parfitt *et al.*, 2010). In developed countries, more than 40% of food waste occur at the consumption stages, but in developing countries more than 40% of food waste occur during post-harvest and processing stages (Gustavsson *et al.*, 2011).

In South Africa it is estimated that the fruit and vegetable commodity group have a significant contribution towards food waste, as it contributes 44% to the total food waste (Oelofse & Nahman, 2013). The World-Wide Fund (WWF, 2017) estimated that 50% of fruit and vegetables are wasted during the post-harvest stage, 25% is wasted during process and packaging, and 20% is wasted during the distribution and retailing stages. Sciortino *et al.* (2016) mention that the two main factors contributing to food waste are (i) overproduction of produce; and (ii) the natural decay of food quality which cannot be prevented but is accelerated by poor supply chain management.

Fresh produce supply chains (FPSC) are classified complex due to various reasons. Although most FPSC normally consists of four stages, it does not necessarily mean that there are only four actors involved. The number of actors involved depend on the size and strategy of the supply chain (Trienekens *et al.*, 2012). Van der Vorst *et al.* (2011) explain that actors in FPSCs usually participate in different supply chain processes which means that they may collaborate with partners that are competitors in other chains. Jonkman *et al.* (2017) further argue that FPSCs are complex because the supply design and performance measurements are highly dependent on product integrity. The reason is that fresh produce are perishable by nature, meaning that the products deteriorate rapidly once they have been harvested (Chen *et al.*, 2009). Perishability influences the value and the quality of the products, and according to Aramyan *et al.* (2006) food quality should be considered as a key performance measurement since it is one of the main characteristics that makes FPSCs complex.

Food quality is becoming increasingly important to measure and monitor throughout the FPSC. This is in part due to consumers' expectations on food quality which are becoming a key influence during their purchase decision (Van der Vorst *et al.*, 2005). It is difficult to measure food quality because (i) each actor in the supply chain has their own perception of quality; and (ii) there are various product and environmental factors involved that influences food quality (Heising *et al.*, 2017; Luning & Marcelis, 2007).

To address the challenge of measuring and monitoring food quality, researchers in food science developed the concept of shelf-life. Shelf-life is defined by Jedermann *et al.* (2014) as the "time span for which fresh produce can be stored at a certain reference temperature until they are no longer suitable for human consumption or when the food quality does not meet the freshness requirements of consumers". Shelf-life models can be used to predict the time span that is left in total for transport, storage and display in the shop as a function of the environmental conditions to which fresh products may have been exposed to, if such information is available (Sciortino *et al.*, 2016). The accuracy of the shelf-life model depends on the number of quality attributes that are available to monitor and measure, but Jedermann *et al.* (2014) mention that even the simplest shelf-life model provides great insights on product quality and estimated remaining shelf-life.

Van der Vorst *et al.* (2007) suggest that product quality should be considered when determining the required logistic strategies to implement throughout the supply chain, hence they developed the concept of "quality-controlled logistics" (QCL). QCL is defined as "part of supply chain management that plans, implements, and controls the efficient, effective flow and storage of food products, services and related information between point of origin and the point of consumption in order to meet customers' requirements with respect to availability of specific product qualities in time and using time-dependent product quality information in the logistics decision process". Figure 1.1 illustrates the essence of QCL.

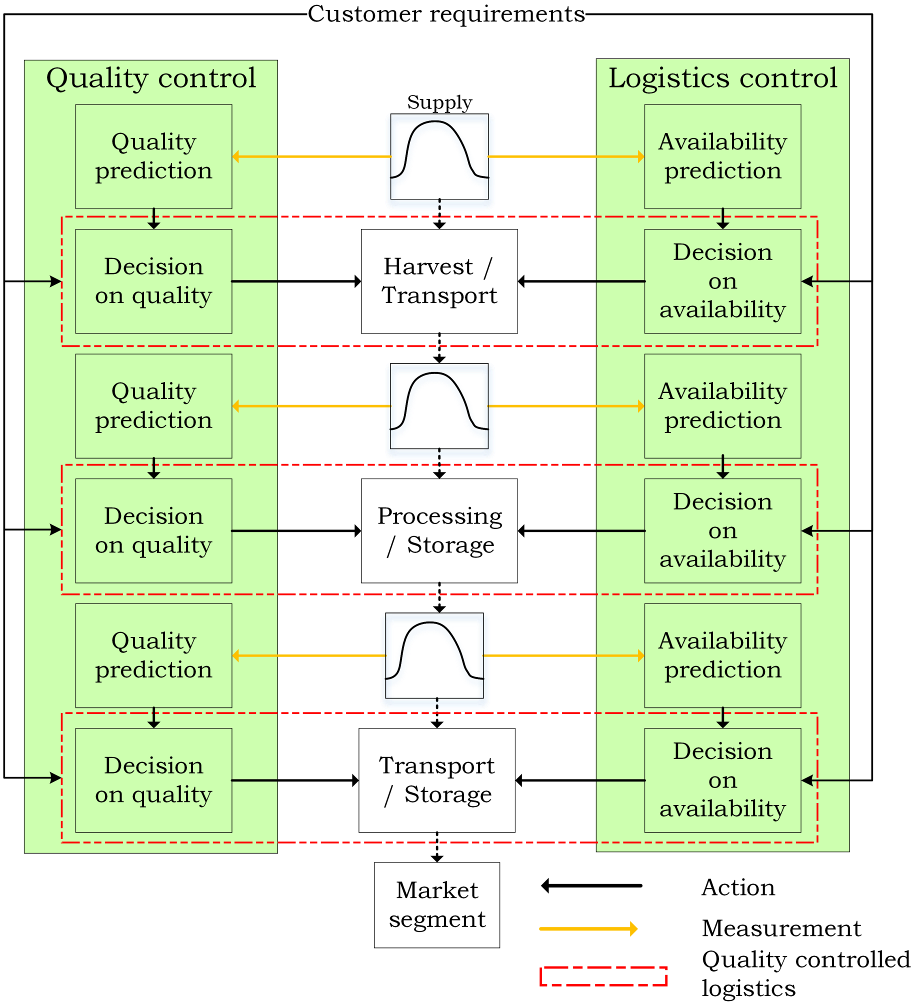


Figure 1.1: Overview of the quality-controlled logistics concept (adapted from Van der Vorst *et al.* (2007))

Appropriate strategies for logistics management are developed based on dynamic product quality attributes to improve product maximisation. The QCL starts with obtaining knowledge on customer requirements in market segments. At the harvest stage products are collected based on various quality parameters. QCL then makes use of quality distribution profiles and batch products of the same quality at the beginning of the supply chain. At each supply chain stage, comparable decisions have to be made between customer demand for specific products and price with the available supply of products with variations in quality prediction. Thereafter, activities are required to either direct the products to the market, or to influence the quality level of the products using technological equipment.

Additionally, there is a growing interest in using emerging technologies to collect the relevant information regarding food quality attributes. Researchers are investigating the use of Internet of Things (IoT) technologies within the food industry, as they believe that IoT will create numerous benefits for the FPSC (Zhou *et al.*, 2015). Sundmaeker *et al.* (2016) mention that IoT in the supply chain might create the following capabilities:

1. Better sensing and monitoring of production, crop development, and food processing;
2. Better understanding of environmental conditions, and gaining knowledge about appropriate management actions;
3. More sophisticated processing and logistics operations by actuators and robots;
4. Improving food quality monitoring and traceability of the location and conditions of shipment and products by remote control; and
5. Increasing consumers' awareness of sustainability and health issues by personalised nutrition and wearables.

It is estimated that the implementation of IoT-technologies will create opportunities to tackle food waste as well. Smart sensors may be used to monitor temperature, freshness, respiration and ethylene gas to detect food spoilage. This information may then be used to determine accurate shelf-life and redirect products to closer locations depending on the remaining shelf-life. Thus, it reduces the chance of food becoming wasted before it reaches the consumers (Shacklett, 2018). Additionally, Vasseur (2016) explained that IoT sensor data and analytics is a promising start to gain insights on identifying elements that contribute to food waste. It may allow supply chain actors to take the necessary actions to control or mitigate these elements to reduce food waste.

Previous studies investigated the impact of QCL in FPSCs within developed countries, since they have more resources available such as infrastructure and funding, and because there are greater cooperation between research institutions and food organisations (Shukla & Jharkharia, 2013). Additionally, most studies mainly evaluated the impact of QCL strategies at the distribution stages and not across the entire supply chain. Trienekens *et al.* (2012) mention that there is still a need for integrated information systems to make fresh produce quality information visible across the supply chain. Researchers believe that IoT-technologies may overcome this need, but it is still in an experimental stage of development and there is still uncertainty whether all actors within the FPSC will reap the full benefit and value from these technologies (Sundmaeker *et al.*, 2016). This research study will explore how QCL activities could be implemented in a South African fresh produce supply chain. The impact of QCL on food waste as well as on overall food quality will be evaluated throughout the entire supply chain. The research study will investigate opportunities and challenges to implement IoT-technologies within the FPSC, and also illustrate how these technologies may assist the implementation of QCL.

1.2 Research problem statement and questions

From the background and rationale of this research study, it was identified that (i) the impact of quality-controlled logistics on fresh produce supply chains are researched less in developing countries; and (ii) the use of Internet of Things technologies in the fresh produce supply chain is still a novel idea. Also it is clear from the background and rationale that there is still limited understanding of how Internet of Things technologies may assist quality-controlled logistics activities within the fresh produce supply chain, thereby helping to reduce food waste. Therefore, the primary research question was developed:

How can Internet of Things technologies assist quality-controlled logistic activities within the fresh produce supply chain, thereby reducing food waste?

In order to answer the primary research question, the following sub-questions have been defined:

1. What are the main components, characteristics and challenges within fresh produce supply chains?
2. What are the various logistic activities to consider within fresh produce supply chains?
3. To what extent is food wasted in the fresh produce supply chain, and in which stage (e.g. harvesting, processing, packaging or distribution) does the most wastage occur?
4. How can quality-controlled logistic activities be implemented in the fresh produce supply chains?
5. Will quality-controlled logistic activities contribute to the reduction of food waste and improve fresh produce quality, and if so how?
6. What is the Internet of Things and can it contribute to improved logistics activities?
7. What are the benefits and challenges to implement Internet of Things technologies within the fresh produce supply chain?
8. How can Internet of Things technologies be implemented within the fresh produce supply chain to assist quality-controlled logistics?

1.3 Research purpose and objectives

The purpose of this research study is twofold. Firstly the study will investigate the impact of quality-controlled logistics on food waste in the fresh produce supply chain. Thereafter the study will explore how quality-controlled logistics could be implemented with the use of Internet of Things technologies. The following objectives have been developed to potentially fulfil the research purpose.

1. Awareness of the problem should be highlighted by defining the nature and contribution of this research study. Fresh produce supply chains will be investigated to identify the reasons for food waste, which stage in the supply chain contributes the most to food waste, and to determine the impact of food waste.

2. It will be necessary to understand the concept of quality-controlled logistics, to identify the critical quality control points in the supply chain and to determine quality measurements that need to be measured throughout the fresh produce supply chain, that could assist logistic activities.

3. Research on digitisation will be necessary to identify whether opportunities exist to implement emerging technologies within the fresh produce supply chain, and to identify how they can assist with quality measuring and monitoring to implement quality-controlled logistics.

4. A fresh produce supply chain will be selected as a case study for the development of a simulation model to evaluate and quantify the impact of quality-controlled logistics on food waste and to identify whether these logistics can increase food quality for end consumers.

5. Information and requirements will be gathered to develop an Internet of Things application prototype to illustrate how emerging technologies could be used assist the implementation of quality-controlled logistics.

1.4 Research contribution

This research study will contribute to research within the field of fresh produce supply chain management, with specific focus on how Internet of Things can assist the implementation of quality-controlled logistics to potentially reduce food waste. Research already exists on Internet of Things technologies and quality-controlled logistics within food industries in developed countries, therefore this research will focus on the benefit South African fresh produce industries will receive by merging these concepts in their current logistic activities. This research will also highlight practical challenges that need to be addressed before fresh produce industries can implement Internet of Things technologies within their supply chains.

1.5 Research design and methodology

Blaxter (2010) defines the philosophy of research as the belief about the way which data about a phenomenon should be gathered, analysed, and used. The research philosophy shapes how a research question is understood and influences the research design (Saunders *et al.*, 2009). There exist various philosophical viewpoints such as (i) positivism; (ii) interpretivism; and (iii) pragmatism. Positivism adheres to the view that only 'factual' knowledge gained through observations and measurements, is trustworthy (Van Boekel, 2005). Interpretivism refers to the views of writers from various intellectual traditions who are critical of the application of the scientific model to study the social world (Mouton, 2001). Pragmatism is a viewpoint that accepts concepts to be relevant only if they support action, since the importance of the concept lies in its finding's practical consequences (Saunders *et al.*, 2009).

This research study adopted the **pragmatism** research philosophy. The reason for this is because this study attempted to identify the practical effects of implementing quality-controlled logistics and thereafter it focused to determine whether quality-controlled logistics could be considered as an acceptable concept by analysing and evaluating the findings gathered from this concept. This research study followed an **inductive** approach, as it aimed to form a theory out of the proposed research question, rather than testing a theory to determine whether it fitted the research question. The approach started by making specific observations and measurements, after which they were analysed to detect significant patterns. Thereafter, a tentative research question was formulated and explored. Finally some general conclusions were developed that could be viewed as new theories.

The research study followed a **mixed methods** research design, since both **qualitative** and **quantitative** research strategies were used. Figure 1.2 illustrates the research design steps. A qualitative research strategy was used to explore and gain knowledge on quality-controlled logistics and the Internet of Things in order to create **awareness** of the researched problem and to develop **objectives** that needed to be achieved throughout the study. **Data collection** and the **interpretation** thereof were also qualitative in nature. A quantitative research strategy was used to **analyse** and **evaluate** the impact of quality-controlled logistics, and to assist the **development** of an Internet of Things application **prototype**.

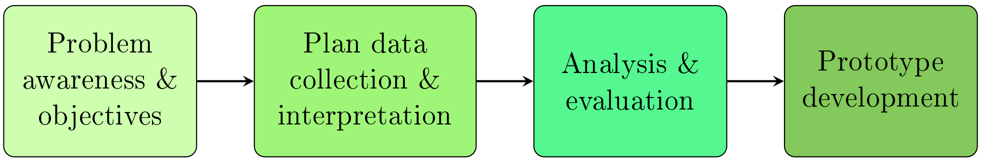


Figure 1.2: Research design steps

Various tasks and methods were required to accomplish each step defined in the research design strategy. Table 1.1 shows the selected research methods that were used within this research study and each method is separately described.

Table 1.1: Proposed research methodology

Research steps	Research methods
Problem awareness & objectives	Literature review
Plan data collection & interpretation	Literature review Interviewer questionnaires Semi-structured interviews
Analysis & evaluation	Simulation modelling Expert opinion validation
Prototype development	Design science

Literature review

The purpose of a literature review is to create awareness of the problem or idea to be studied, and to define key terminology, concepts and frameworks. It was important to investigate and evaluate the problem to ensure that the proposed research solution would be feasible and contribute to the defined research field. Literature was reviewed on food waste to identify which commodity group contributed the most to wastage. The reason therefore was to select a commodity group that would gain significant benefit from this research study, and to contribute towards waste reduction. Next, fresh produce supply chains and the key logistic activities were reviewed to understand why food supply chains differ from generic supply chains. The influence of digitisation within fresh produce supply chains was reviewed to identify whether it could contribute to improving current challenges the food industry faces and to assist current logistic activities. The use of the Internet and Online databases such as Google Scholar, Scopus, and Elsevier were the main search tools to conduct the literature review, and books and journal articles were the main sources of information. Mouton (2001) provided tips on literature review and was used to guide the researcher towards conducting a good literature review.

Interviewer questionnaires

Questionnaires are a popular data collection method to use when the research study requires feedback and opinions from participants based on their experience. Using questionnaires as a data collection technique has its strengths, as it provides an efficient way to collect data quickly, and it is usually a cost effective approach. Questionnaires can be divided into self-administered questionnaires and interviewers' questionnaires (Saunders *et al.*, 2009). Interviewer questionnaires with the purpose of asking semi-structured questions were used to gain insights regarding quality-controlled logistics and

Internet of Things from experts working in the fresh produce industry. Interviewer questionnaires refer to those questionnaires where the interviewer physically met the participants and asked the questions face-to-face. Semi-structured questions are a mix of open and closed questions, meaning the participant had the opportunity to provide feedback based on a predetermined selection of answers, as well as providing answers based on the participant's freedom. Participants collaborating within fresh produce supply chains were asked to complete the questionnaires.

Semi-structured interviews

Semi-structured interviews are used as a data collection method to gain insights into an issue from the perspective of participants. Generally a list of questions and topics are developed that need to be covered during a conversation. Semi-structured interviews were conducted with an expert within a South African fresh produce industry to gain insights on how general logistical decisions were made in practice, and to explore complex issues the company faced regarding logistics and quality related activities. An initial face-to-face meeting was arranged with the expert, to explain the purpose of the study. Thereafter semi-structured interviews were held with the expert via meetings at the company and via email conversations. The information that was obtained from the expert, was used to guide the analysis and the evaluation of the impact of implementing quality-controlled logistics and to compare the results with the company's current logistic activities.

Simulation modelling

Simulation modelling is often used as an analysis tool in research when experimentation with the actual system is not possible, and when the system is too complex to analyse analytically (Bekker, 2016). Discrete-event simulation modelling was used in this research study as it provided the researcher with the ability to analyse the impact of implementing quality-controlled logistics within a fresh produce supply chain. The simulation model was used to evaluate various logistic alternatives without disrupting the actual supply chain. The simulation model and results were validated by the expert who participated in the semi-structured interviews. This was done to ensure that the work that was completed in this study would contribute towards both the academia and the industry.

Design science

Design science is a research method that seeks to create innovations that define the ideas, practices and technical capabilities through which the analysis, design and implementation of an artefact can be accomplished (Hevner *et al.*, 2004). Design science was used in this research study to gain the knowledge to create an artefact that would have to satisfy a given set of functional requirements. The artefact that was developed in the research study are an Internet of Things application prototype to illustrate how emerging technologies could assist the implementation of quality-controlled logistics.

1.6 Delimitations and limitations

Food supply chains can be categorised into (i) food supply chains for fresh agricultural products (such as fresh fruits and vegetables); and (ii) food supply chains for processed food products (such as portioned meats, snacks, deserts and canned food products). This research study will only focus on the fresh produce supply chain because fresh fruit and vegetables are highly perishable meaning that product quality should be closely monitored to ensure optimal quality and food safety. Additionally, majority of South Africa's food waste occur within the fruit and vegetable commodity group, hence providing multiple improvement opportunities. The fresh produce supply chain will be analysed from the postharvest stage until before the consumption stage. This is in part due to (i) multiple factors such as weather conditions, soil degradation and fertility, and production planning that should be considered in the preharvest and harvest stages; and (ii) it was defined in literature that food is not predominately wasted at the consumption stage in South Africa.

The Internet of Things application developed in this research study is only a prototype to illustrate that opportunities exists to implement emerging technologies in the fresh produce supply chain. The prototype has not been fully tested and still requires development before it can be tested with the use field experiments.

1.7 Research study outline

The outline of this research study is illustrated in Figure 1.3. Chapter 1 will introduce the rationale of this study, the research questions and the objectives that will be achieved during the study. It will discuss the research philosophy and design as well as the various methods that will be used throughout the study. Chapter 2 will provide an overview of relevant literature that will be reviewed. Topics such as food waste, fresh produce supply chains, food quality and Internet of Things will be addressed in this chapter. Chapter 3 will identify current knowledge on quality-controlled logistics from experts working in the fresh produce industry and also determine whether the experts believe that Internet of Things technologies could provide opportunities to improve the industry. Chapter 4 will describe key traditional logistic activities that are currently implemented in most fresh produce supply chains, as well as the impact they have on produce quality. Thereafter several strategies will be discussed to potentially implement quality-controlled logistic activities.

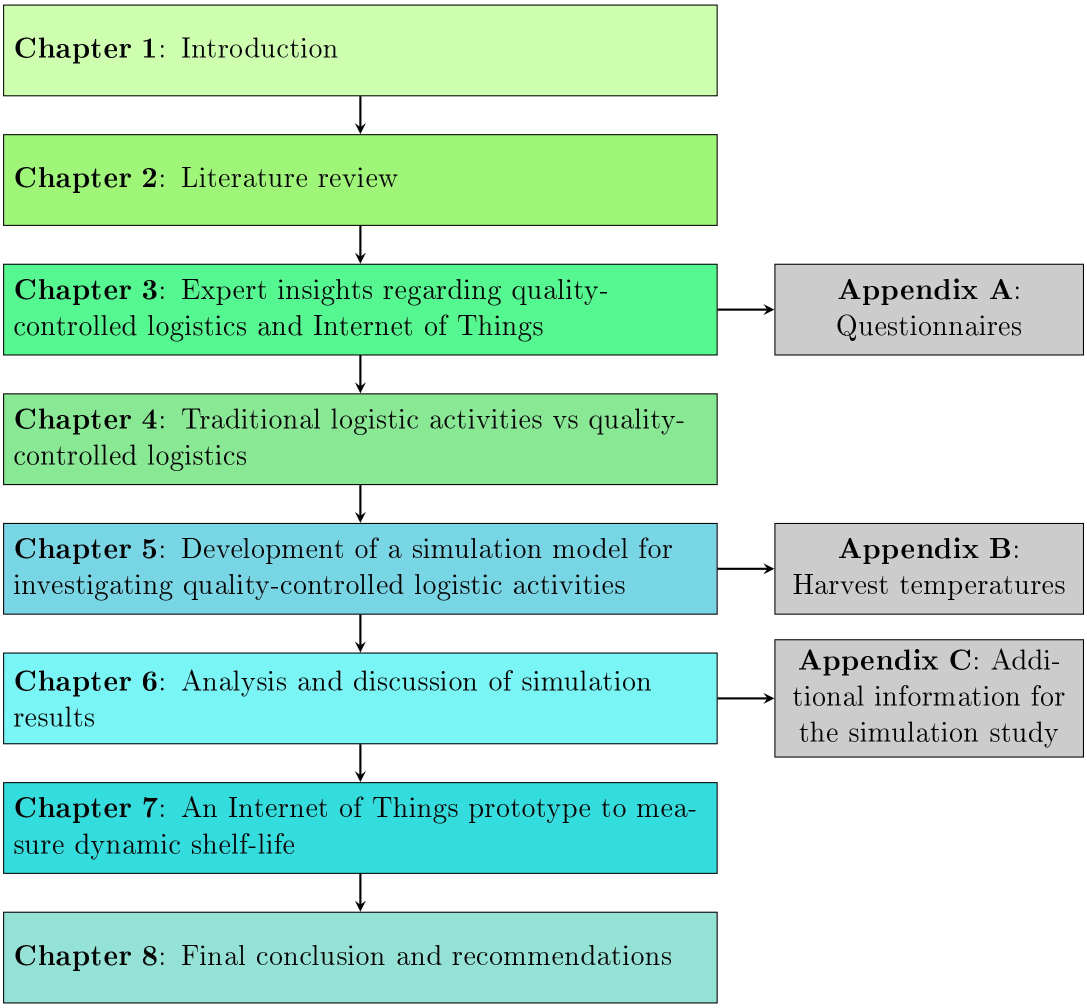


Figure 1.3: Outline of the research study

Chapter 5 will investigate the impact of quality-controlled logistic activities on food waste as well on food quality. This will be done by means of a simulation study based on a fresh produce supply chain. Chapter 6 will analyse the results that were obtained from the simulation study and will discuss trends that have been identified during the analysis. Chapter 7 will discuss how emerging technologies such as Internet of Things can be used to dynamically predict the shelf-life of produce. Thereafter an Internet of Things application will be proposed and a prototype of this application will be developed. Chapter 8 will summarise this research study and briefly discuss the key findings and contributions of this study. This chapter will conclude this study by providing suggestions for future research.

Chapter 2

Literature review

This chapter provides an overview of relevant literature that was reviewed to assist this research study. First the chapter will explore the magnitude of food waste and identify where the majority of food is wasted within food supply chains. Next a description on fresh food supply chains and the various components that distinguish them from general supply chains will be provided. Components such as food supply chain characteristics, performance measurements, and quality-controlled logistics will be discussed. Thereafter literature regarding digitisation within supply chains will be explored, with specific focus on the Internet of Things. Lastly literature will be reviewed to identify how digitisation could be implemented in the food industry and how the Internet of Things could contribute towards the reduction of food waste.

2.1 Food waste

Many definitions exist to define food loss and food waste but according to Parfitt *et al.* (2010), food waste refers to 'the decrease in edible food mass throughout the supply chain that specifically leads to edible food for human consumption'. Food is wasted throughout the food supply chain, from the initial harvesting stage down to the final consumption stage (Parfitt *et al.*, 2010). The following section will emphasise the extent of global food waste and then focus on the amount of food being wasted in South Africa. Thereafter the impact of food waste will be discussed.

2.1.1 Global food wastage

According to Gustavsson *et al.* (2011), approximately one-third of the edible parts of food produced for human consumption is lost or wasted. The distribution and magnitude of food waste differs between developed and developing countries (Gustavsson *et al.*, 2011; Hodges *et al.*, 2011). Stroecken (2017) did a study to identify some factors that cause food waste along the food supply chain and these factors are illustrated in Table 2.1.

Table 2.1: Factors that cause waste along the food supply chain (reproduced from Stroecken (2017)).

Stages	Factors causing wastage
(1) Postharvesting	Incorrect harvesting time Careless handling Distance to warehouse Temperature in warehouse
(2) Transport	Careless handling Temperature during transport & transhipment Vibration & equipment failure
(3) Shipment rejections	Different food safety standards Lack of enabling environment Lack of skilled workforce Cost of certification
(4) Processing	Various processing steps Package damages Technical malfunctions Demand sizes
(5) Retail level	Labelling Flaws in products Discounts Overfull shelves
(6) Consumer	Discounts Lack of planning Improper storage Big dinner plates and over preparation

In developed countries (Europe, North America and Oceania and Industrialised Asia) 40% of food is wasted by the consumer, as it is thrown away even if it is still suitable for human consumption. Food is thrown away for reasons such as (i) it was left on the plate after a meal; or (ii) it passed its expiry date (Hodges *et al.*, 2011). In developing countries (sub-Saharan Africa, North Africa, West & Central Asia, South & Southeast Asia and Latin America) more than 40% of food waste occurs during the production-to-processing stages in the food supply chain. This is due to poor harvesting technologies, lack of transport and poor storage in combination with extreme weather conditions (Gustavsson *et al.*, 2011). Figure 2.1 shows the per capita food losses and waste in developed and developing countries.

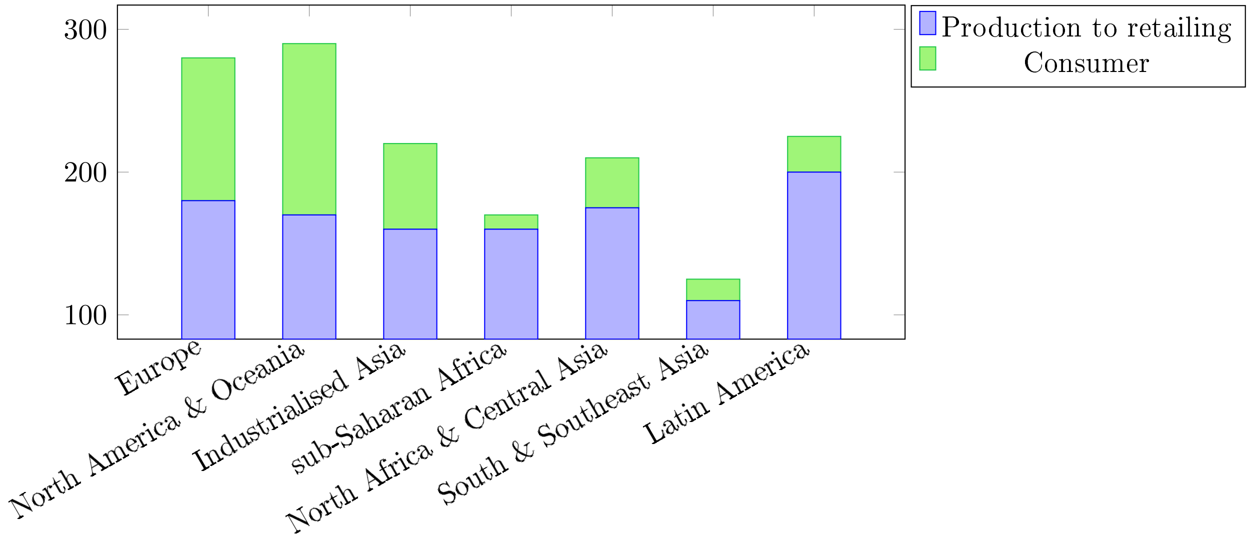


Figure 2.1: Per capita food losses and waste (kg/year) (reproduced from Gustavsson *et al.* (2011)).

Gustavsson *et al.* (2011) did a study to quantify the extent of food waste in developed and developing countries. The study examined the amount of food waste in the following commodity groups: (i) dairy products; (ii) fish production; (iii) fruits and vegetables; and (iv) meat. The amount of food waste for each commodity group will be separately discussed.

Dairy products

Figure 2.2 shows percentage waste that occurred in each stage of the dairy supply chain, in developed and developing countries. In developed countries, dairy products mostly waste during the consumption stage and makes up approximately 40 to 65% of the total food waste. For developing countries, waste of dairy products mainly occurs during postharvest handling, storage and distribution.

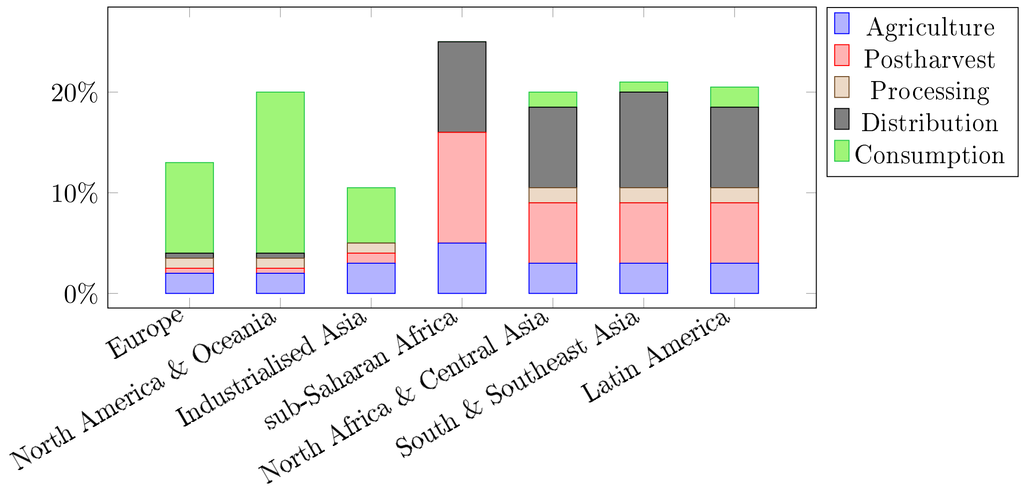


Figure 2.2: Part of the initial milk and dairy production for each country at different stages in the supply chain (reproduced from Gustavsson *et al.* (2011)).

Fish and seafood products

Figure 2.3 shows percentage waste that occurred in each stage of the fish and seafood supply chain, in developed and developing countries. Waste of primary fish and seafood produce are significant during the consumption stage in developed countries. In developing countries, large wastage occurs at the distribution stage of the supply chain, possibly due to high levels of deterioration during distribution.

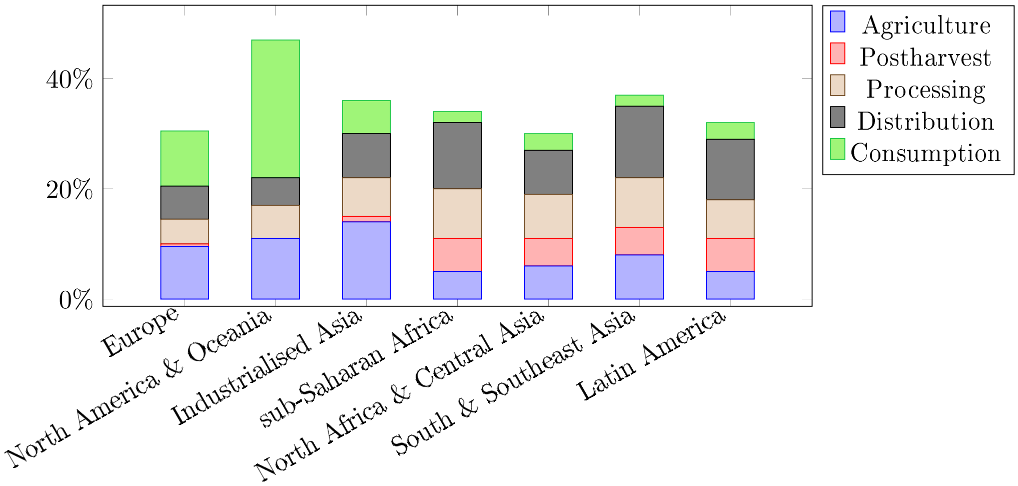


Figure 2.3: Part of the initial fish and seafood harvest discarded for each country at different stages in the supply chain (reproduced from Gustavsson *et al.* (2011)).

Fruits and vegetables

Figure 2.4 shows percentage waste that occurred in each stage of the fruit and vegetable supply chain, in developed and developing countries. In developed countries, fruit and vegetable waste dominates at the agricultural production stage. The main reason is because of the high quality standards set by retailers. Waste of this commodity group is also relatively high at the consumption stage as 15 to 30% of purchases are discarded by consumers. Waste in developing countries occurs significantly at agricultural production and during processing.

Meat products

Figure 2.5 shows percentage waste that occurred in each stage of the meat supply chain, in developed and developing countries. Waste of meat and meat products is most severe at the consumption stage of the supply chain in developed countries, especially in Europe and the US. The levels of waste during agricultural production, postharvest handling and storage are relatively low due to the low animal mortality rate during breeding and transportation to slaughter. In developing countries, meat waste is distributed throughout the supply chain. In sub-Saharan Africa, it is noted that large losses occur during agricultural production. This is explained by the high animal mortality rate, caused by diseases in livestock breeding.

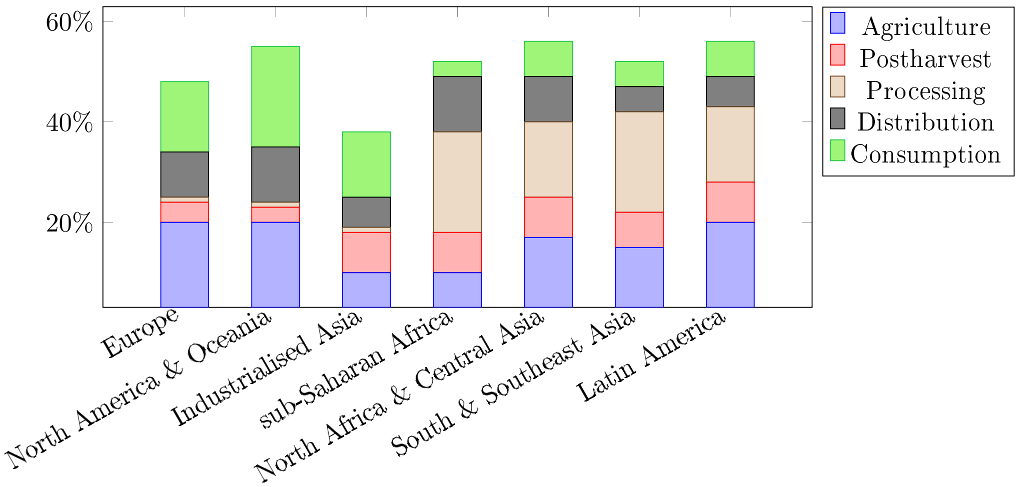


Figure 2.4: Part of the initial production lost or wasted at different stages of the supply chain for fruits and vegetables in different regions (reproduced from Gustavsson *et al.* (2011)).

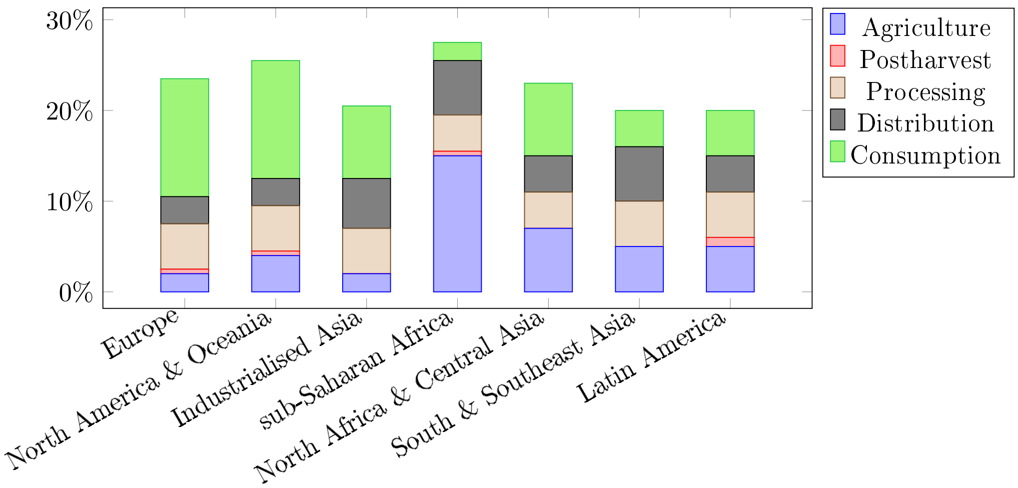


Figure 2.5: Part of the initial production wasted for meat for each country at different stages in the supply chain (reproduced from Gustavsson *et al.* (2011)).

2.1.2 Food waste in South Africa

South Africa is a developing country that forms part of sub-Saharan Africa. Research was done by Oelofse & Nahman (2013) with the assistance of the Council for Scientific and Industrial Research (CSIR), to estimate the magnitude of food waste generated in South Africa. The CSIR estimated that food waste for edible and inedible food generated is 12.6 million tonnes per year (CSIR, 2013).

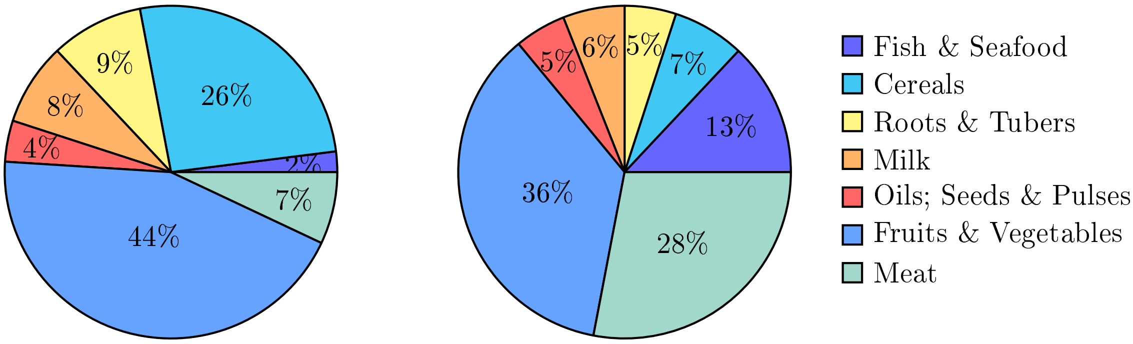


Figure 2.6: The left pie-chart illustrates the relative cost contribution towards food waste and the right pie-chart illustrates the relative waste contribution, for each commodity group (reproduced from Oelofse (2013)).

From Figure 2.6 it is noted that the fruit and vegetables commodity group has the largest impact (44%) on the total food waste in South Africa and results in the largest cost (36%) associated with it. It is interesting to notice that the meat commodity group only contributes 7% to the total food waste, but has the second largest (28%) cost contribution to the total cost of food waste. It is observed from Figure 2.7 that the processing and packaging of the fruits and vegetables commodity group, adds a large contribution to the cost of food waste in South Africa. The distribution of fruits and vegetables and meat produce also has a significant contribution to the total cost of food waste.

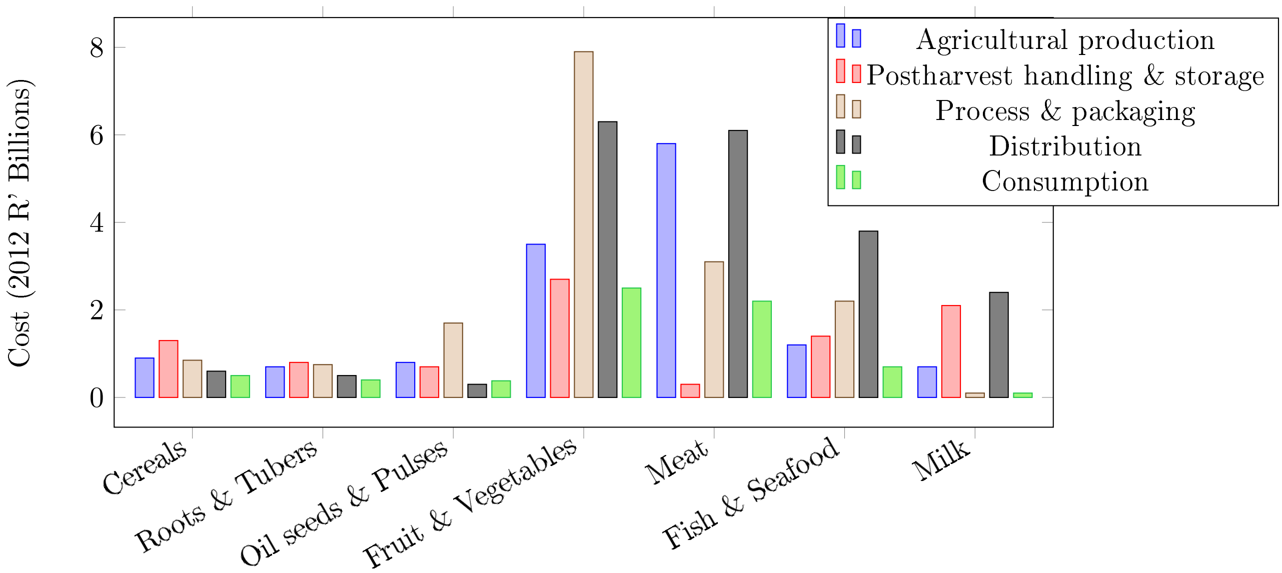


Figure 2.7: Cost of food waste in each stage of the supply chain for each commodity group in South Africa (reproduced from Oelofse (2013)).

A study done by the Word Wide Fund (WWF, 2017) estimated that 50% of food waste occurs during the agricultural and postharvest stages due to damaged harvests and overproduction. At the processing and packaging stage 25% of the food is wasted, 20% is wasted at the distribution and retail stage, and only 5% at consumer level. A key challenge this research highlighted is that there are currently not accurate and actual data available on the amount of food waste generated and why food is wasted. Although stakeholders in the food supply chain are aware of the large amount of food wasted, little action has been taken to quantify the amount of food waste and to identify the causes thereof.

2.1.3 Impacts of food waste

Food waste has substantial economic impact on both farmers' and consumers' income (Gustavsson *et al.*, 2011; Lundqvist *et al.*, 2008). For smallholders living on the margins of food insecurity, a reduction in food waste could have an immediate and significant effect on their livelihood. For consumers affected by food poverty, the ideal is to have access to food products that are nutritious, safe and affordable. Improving the efficiency of the food supply chain has the potential to bring down the cost of food to the consumer and increase access to quality food (Papargyropoulou *et al.*, 2014). Food producers, retailers and the food services sectors have been encouraged to reduce food waste in order to achieve cost savings (Papargyropoulou *et al.*, 2014).

The disposal of food waste in landfills creates an environmental concern as methane and carbon dioxide are produced during the natural decomposition process. Methane and carbon dioxide are greenhouse gases (GHG), contributing to climate change (Papargyropoulou *et al.*, 2014). Another environmental concern is that activities in the food supply chain such as agricultural production, processing, manufacturing, transportation, storage, refrigeration, distribution and retail also have an embedded GHG impact (Lundqvist *et al.*, 2008; Padfield *et al.*, 2012). Food waste disposal throughout the food supply chain also results in environmental pollution (Lundqvist *et al.*, 2008).

Food waste has a social impact which tends to focus around the ethical and moral dimension of wasting food. As the issue of global food security is becoming increasingly important, the reduction of food waste throughout the food supply chain, as well as alternative diets, are considered to be the first step towards achieving food security (Papargyropoulou *et al.*, 2014). Lastly, it is important to consider the time dimension of food waste analysis and to identify the parameters that have contributions to food waste challenges. Two parameters were identified by Papargyropoulou *et al.* (2014), namely: (i) the growing world population; and (ii) climate change. As the global population is rising, food waste generation is not diminishing and food security is becoming an urgent issue (Gustavsson *et al.*, 2011; Lundqvist *et al.*, 2008). It is estimated by Haberl *et al.* (2011) that up to 25% of world food production may become 'lost' during this century because of climate change, water scarcity, invasive pests and land degradation.

2.2 Fresh food supply chains

According to Trienekens *et al.* (2012), a supply chain refers to 'companies that are vertically linked and collaborate to put products on a market'. Van der Vorst *et al.* (2005) define supply chain as 'a series of activities connected by material and information flows, and associated flows of money and property rights that cross organisational boundaries'. In a supply chain, many processes can be identified, and these processes can operate either dependently or independently operate of one another (Lazzarini *et al.*, 2001). During the last decade, the food industry became an interconnected system with increased communication and relationships between organisations within the supply chain. According to Van der Vorst *et al.* (2009), a food supply chain consists of organisations that are responsible for the production and distribution of either vegetable commodities, or animal commodities. Food supply chains are classified as complex, because the supply chain design and performance is highly dependent on product integrity (Bourlakis & Weightman, 2008; Jonkman *et al.*, 2017; Tsolakis *et al.*, 2014). This section will discuss the components and characteristics of fresh food supply chains (FFSC) after which focus will be shifted to key performance measurements and logistic management in the FFSC.

2.2.1 Fresh food supply chain actors

Supply chains usually include manufacturers, suppliers, transporters, warehouses, retailers, service organisations and consumers, and they are defined as the supply chain actors. These supply chain actors may participate in different supply chain processes and therefore collaborate with several partners who may be their competitors in other chains (Van der Vorst *et al.*, 2009). Figure 2.8 illustrates the network between different supply chain actors in the FFSC. Each actor is positioned in a network layer and belongs to at least one supply chain.

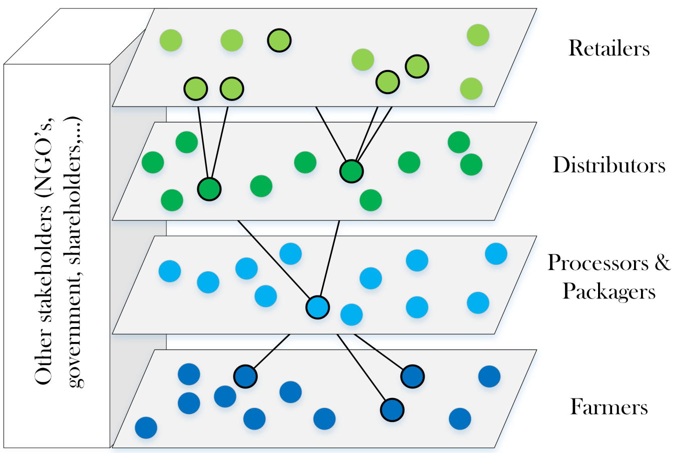


Figure 2.8: A general food supply chain (reproduced from Van der Vorst *et al.* (2005)).

It is important to realise that actors in the network influence the performance of the entire chain (Van der Vorst *et al.*, 2005). Literature from Trienekens *et al.* (2012) state that food security and high-quality products are not the sole responsibility of individual organisations, but of the entire FFSC. Each actor has their own role in quality assurance and safety of the end product, thus the activities should be closely coordinated. Dani (2015) and Entrup (2006) discuss the role of each actor within the FFSC.

Farmers

The FFSC starts with the producer (usually farmers) that supplies food in its raw form (e.g. grains, fruit, vegetables, meat and fish). Each country requires strong food production sectors, as it ensures food availability for the population, and economic sustainability for the food sector. Farming can range from small-scale family farms to large corporate farms. Input entities such as seeds, farming machinery, pesticides and fertilisers are necessary to work the raw material into useful food produce. Farmers constantly deal with challenges including the increasing uncertainty of weather conditions, scarcity of water, land-grabbing (mostly in developing countries) and soil degradation caused by industrialisation and urbanisation.

Processors and packagers

Processors and packagers receive raw material from the farmers. They decide whether the fresh produce is sent to cold storage for later processing or whether it should be directly processed. Processing usually involves washing, quality checks, and packaging in different ways depending on their customers' preferences (Blanco *et al.*, 2005). After the fresh food are packaged, they are stored in refrigerated chambers until they need to be dispatched for transportation to the required customers.

Distributors

Distributors are companies that act as links between farmers, processors and retailers. They can source either fresh produce or processed food from the processors and distribute it through various channels (retail companies or other processing companies) to reach the final consumer. Distributors will generally buy in bulk and use infrastructures such as warehouses and distribution centres to deliver products as required downstream in the supply chain. According to Akkerman *et al.* (2010), food distribution is different from the distribution of other products. The reason is that food products show continuous quality changes throughout the supply chain. Hence, a key characteristic for food distribution systems is temperature control, because for a wide variety of foods, temperature control is essential for controlling food quality and safety.

Retailers

Retailers provide consumers with a variety of products that the food sector has to offer. Retailing is a highly competitive industry because food processors compete for shelf space in the retailer's environment, and retailers compete among themselves to attract consumers. Retailers try to differentiate themselves from their competitors by developing innovative business models (e.g. e-retailing) to provide good-value propositions based on price, quality and service. The retail environment in developing countries has transformed from unorganised corner shops to organised supermarkets. These transformations force distributors to innovate and change their processes to respond to retailers' requirements.

2.2.2 Fresh food supply chain characteristics

A number of authors have highlighted the complexity of FFSCs, and according to Bourlakis & Weightman (2008); Tsolakis *et al.* (2014) and Trienekens *et al.* (2012), FFSCs have certain characteristics that distinguish them from the generic supply chain. Kirezieva *et al.* (2013b) categorise these characteristics as: (i) product; (ii) process; (iii) organisation; and (iv) chain characteristics. Product characteristics refer to the inherent properties of initial materials and final products, and are also known as quality attributes of products (e.g. colour, flavour, appearance and perishability). Process characteristics apply to conditions during production, processing and handling (e.g. brand, origin and history of produce, and resources used during production). Organisation characteristics involve administrative conditions such as employee competences, assignment of tasks and responsibilities, as well as rules and procedures which affect decision-making. Chain characteristics refer to the conditions during supply, and relationships between organisations within the chain. Examples of FFSC characteristics are listed by Van der Vorst *et al.* (2009) as:

- unique nature of the products as in most cases they refer to short life-cycle goods;
- high product differentiation;
- seasonality in harvesting and production operations;
- variability of quality and quantity on farm inputs an processing yields;
- specific requirements regarding transportation, storage conditions, quality and material recycling;
- need to comply with national and international legislation;
- need for specialised attributes, such as traceability and visibility;
- need for high efficiency and productivity of expensive technical equipment, despite long production times;
- increased complexity of operations; and
- the existence of limited capacity constraints.

Dani (2015) further mentions that the following attributes should be considered when designing the FFSC:

Perishability

The perishability of food products is one of the most vital characteristics that distinguish FFSCs from the generic supply chain (Aung & Chang, 2014; Ghaani *et al.*, 2016; Heising *et al.*, 2014). Perishable foods include fresh fruits and vegetables (FFV), fresh meat, food purchased from chill cabinets and freshly cooked food stored for later. These are usually stored in a refrigerator; however, some FFV do not have to be stored in refrigerators but need to be stored in a cool environment (Arora, 2007; CSIRO, 2015). A key attribute of perishable foods is that these food products deteriorate rapidly once they are produced, which influences the value and quality of the food products (Chen *et al.*, 2009). Other conditions such as freshness, temperature, humidity, characteristics of the food item, and the type of storage or packaging also have an immense influence on the quality and shelf-life of perishable food products (Heising *et al.*, 2014; Van Boekel, 2008).

Literature emphasises that temperature-control in the supply chain of perishable food is of extreme importance, as it prolongs the shelf-life and quality of food products and reduces food waste (Aung & Chang, 2014; Marija *et al.*, 2005). The shelf-life of food is determined in part by microbial activities, and the impact of these activities is heavily influenced by storage temperature. Freshness is almost exclusively a function of time and temperature (Zhang *et al.*, 2009). Thus, supply chain design relies heavily upon logistics and warehousing functions that provide temperature-controlled transport and storage (Dani, 2015).

Seasonality in production

Food production is seasonal and variable due to product characteristics and environmental conditions such as unpredictable climatic conditions. This affects the quality and quantity of produce, and makes operational and logistical planning more difficult. Hence, supply chain actors need to integrate the planning of supply and deliveries to ensure short lead times and efficiency across the supply chain (Dani, 2015).

Heterogeneity of the product

Food products are heterogeneous in nature which means that the same food product may have different features (i.e. different taste, smell, appearance, colour and size). The heterogeneous nature of food is often complex to control as consumers have different requirements in relation to taste, appearance and smell (Dani, 2015).

Edible nature of the product

Food inspections and regulations are vital in the supply chain design to ensure that the food is safe for consumption once it reaches the consumer. Any breakdown or delay within the supply chain can result in unacceptable food quality, which forms the basis of food logistics and design. Therefore quality assurance and control, and traceability make a large contribution toward supply chain design (Dani, 2015).

Information asymmetry

Information asymmetry occurs when one actor in the supply chain has more or better information than the other supply chain actors. A common example of information asymmetry is when each actor in the supply chain has their own perception of quality, which results in the lack of information sharing as actors may have different quality measurements. This may also occur when the buyer cannot identify a good product whilst the seller knows the history and condition of the product (Dani, 2015; Van Boekel, 2005).

2.2.3 Performance measurements in fresh food supply chains

Supply chain management (SCM) refers to the integration of business processes and relationships at different stages within the supply chain (Chopra & Meindl, 2014). A key criteria of successful SCM is the evaluation of the performance of various processes and activities within the supply chain. Unfortunately, the presence of multiple supply chain actors makes it difficult to measure overall supply chain performance because each actor has their own goals and interests (Aramyan *et al.*, 2006; Chopra *et al.*, 2017). Performance measurement plays an important role in SCM as it provides essential information for decision-making and activities (Chopra *et al.*, 2017). Gunasekaran & Kobu (2007) state that a well-developed performance measurement system enables transparency and clear communication among different supply chain actors.

Aramyan *et al.* (2006) did a study to identify the main performance measurements of food supply chains, and developed a conceptual framework as shown in Figure 2.9. The framework was developed using the characteristics of FFSCs. The performance measurements of FFSCs are classified into four main categories namely: (i) efficiency; (ii) flexibility; (iii) responsiveness; and (iv) food quality. The first three categories were identified from previous literature reviews on supply chain performance studies that were not based on FFSCs (Aramyan *et al.*, 2006). According to Luning *et al.* (2002), food quality should also be a performance measurement, since it is one of the main characteristics that differentiate FFSCs from the generic supply chain.

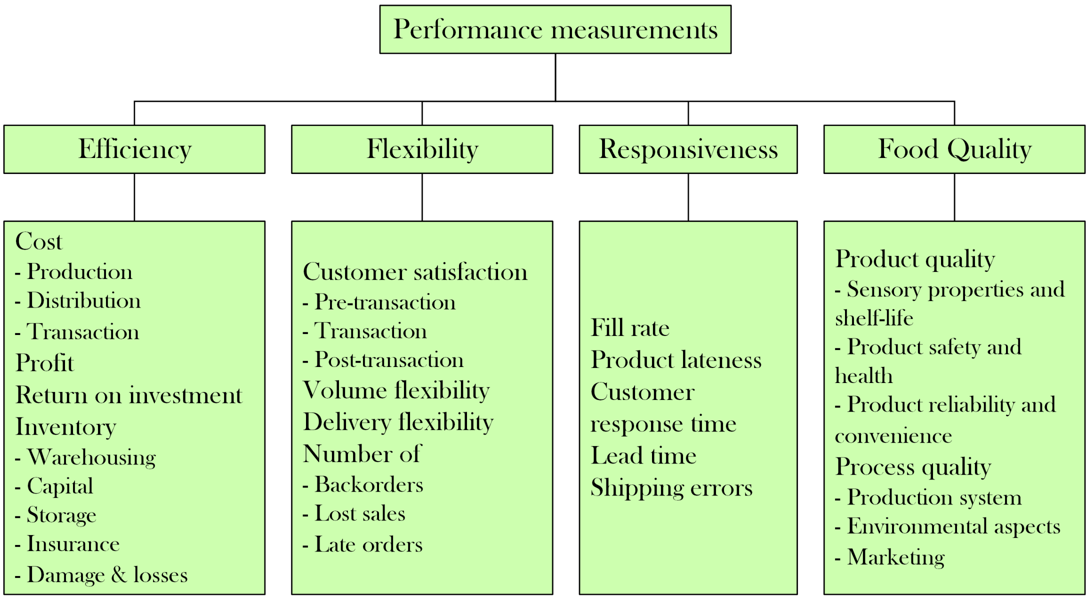


Figure 2.9: Conceptual framework of food supply chain performance indicators (reproduced from Aramyan *et al.* (2006)).

Efficiency

Efficiency measures how well resources are utilised and includes measurements such as cost of production, inventory and distribution, transaction costs, profit and return on investments (Aramyan *et al.*, 2007).

Flexibility

Flexibility indicates the degree to which the supply chain can respond to a changing environment and extraordinary customer service requests. It may include customer satisfaction, volume and delivery flexibility, reduction in the number of backorders and lost sales (Aramyan *et al.*, 2007).

Responsiveness

Responsiveness refers to a supply chain that has a short lead time for a product. It includes measurements such as fill rate, product lateness, customer response time, lead time shipping errors and customer complaints (Aramyan *et al.*, 2007).

Food quality

Food quality is defined by Luning *et al.* (2002) as 'meeting or exceeding customer's expectations' and it is the performance category that is the most relevant to FSCs (Chopra *et al.*, 2017). According to Luning & Marcelis (2007), causes such as consumer behaviour and lifestyles, environmental conditions and changes in food production systems influence the quality of food products, hence, it is becoming a necessity to measure and monitor food quality through the entire supply chain. It is difficult to measure food quality, but to make it more tangible, food scientists use intrinsic and extrinsic attributes of food products to measure quality performances (Aramyan *et al.*, 2006; Van Boekel, 2005).

Intrinsic attributes (also known as product quality) are directly related to the physical product properties and involve food safety, nutritional value, shelf-life, microbial composition and respiration rate (Aramyan *et al.*, 2006). Extrinsic attributes (also known as process quality) refer to production system characteristics, environmental conditions and the influence of marketing. These attributes might not have direct influence on the physical properties but have an effect on consumer acceptability due to consumer culture, emotional reasons and affordability (Aramyan *et al.*, 2006; Luning & Marcelis, 2007; Van der Vorst *et al.*, 2005). Table 2.2 lists several factors that influence intrinsic and extrinsic quality attributes of food products.

Supply chain design and management are complicated due to the intrinsic quality attributes of food, therefore it is suggested by Van Boekel (2005) to break it down into quality performance indicators. These performance indicators can then be measured and controlled when food passes through the FFSC as shown in Figure 2.10. For example, colour is a food quality attribute; the colour can be monitored to identify chemical changes within the food product that result in a deterioration in quality. The quality of food products changes during their life cycle because food is perishable by nature. Product properties and related intrinsic attributes of food are related to various deterioration processes and quality defects that may be due to the type of food product, packaging and conditions in the supply chain (Heising *et al.*, 2014).

Table 2.2: Factors affecting food quality and shelf-life (reproduced from Coles & Kirwan (2011)).

Intrinsic attributes	**Extrinsic attributes**
Water activity	Time-temperature profile
Total acidity (pH) or type of acid	Temperature control during storage and distribution
Production formulation	Relative humidity during storage and distribution
Availability of oxygen	Exposure to light during storage and distribution
Natural biochemistry of the product	Consumer handling
Added preservatives	Composition of gas atmosphere within packaging
Packaging interaction	

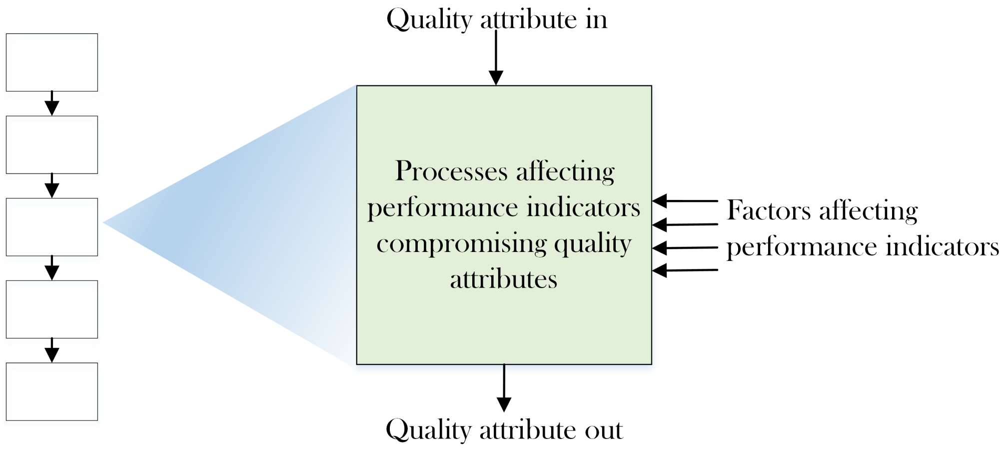


Figure 2.10: Schematic depiction of the change of quality attributes as food passes through the supply chain (reproduced from Van Boekel (2005)).

When considering the supply chain design, it is important to understand that foods are dynamic systems which are affected by the wide range of intrinsic and extrinsic attributes of food quality (Luning & Marcelis, 2007). A substantial problem is that various actors in the supply chain have different perceptions of quality (Van Boekel, 2005). Hence, each supply chain actor should realise that their activities can affect the overall quality attributes of food. For example, during harvesting, farmers should use harvesting methods which ensure that fresh produce is not bruised once harvested, as it results in increased quality degradation further along the chain. Furthermore, processors should use appropriate handling and processing conditions to maintain desired quality attributes. Therefore, it is important to identify the critical points in the supply chain that either improve or reduce quality attributes. Recent technological developments such as time-temperature indicators, biosensors, freshness sensors and indicators, measure quality related compounds formed in the product and are good direct indicators of food quality attributes (Ghaani *et al.*, 2016; Heising *et al.*, 2014; Vanderroost *et al.*, 2014).

Another aspect to consider when defining food quality, is the consumer's expectations on food quality. It is necessary to identify what the consumer expects from food quality and how these expectations can be met (Van Boekel, 2005). Food is a necessity for people, thus food has a large emotional value and people want to trust what they eat. Therefore, marketing and consumer behaviour play an important role in developing quality performance measurements. Grunert (2005) conducted a study to analyse how consumers perceive food quality and how it changes consumption experience. They identified that demographical changes, age and food habits are some of the factors that influence perceived quality. A recent trend developed where consumers are becoming very critical about their food because of increasing availability of information via technological innovations. Further literature on consumer behaviour relating to food quality can be found in Jongen & Meulenberg (2005). Food quality is vital in the FFSC, and since it consists of many attributes and is partially influenced by the consumers' perception, the food industry is forced to implement quality control systems to ensure continuous improvement of quality within the food products and various processes along the FFSC (Luning & Marcelis, 2007).

2.2.4 Temperature control in the supply chain

The movement of products within the FFSC should be in a safe and tamper-free environment to ensure that food quality is retained. An important requirement for the food industry is the management of fresh, chilled and frozen food items, therefore, temperature control is an important consideration in food logistics (Aung & Chang, 2014). Maintaining the desired holding temperature is a major factor in protecting perishable food against quality loss and wastage. Temperature control requires products to be maintained in a controlled environment, rather than exposing the products to variable ambient temperatures through the stages of the supply chain (Bourlakis & Weightman, 2008). According to Aung & Chang (2014), temperature control in a food supply chain is the most important factor to prolong the shelf-life of food products, as it preserves both sensory and nutritional qualities of food, and protects perishable food against quality loss, for example, a short period of exposure to hot or cold temperatures can decrease the shelf-life and loss of quality. Jobling (2000) states that temperature requirements vary among food items and even differ across types of food. Retail food supply chains will generally distribute multiple types of food products with different temperature requirements within the same shipment, and this creates further complexity (Dani, 2015). FFSCs that have a narrow range of products can set the temperature level that is required for that product. If a FFSC is handling a broad range of food products, an optimum temperature or a limited number of temperature setting are used (Bourlakis & Weightman, 2008; Dani, 2015). However, when designing the FFSC, product characteristics need to be considered due to the risk of product interaction, for example, bananas produce ethylene which accelerates the ripening of other fruits (Dani, 2015).

A common way to ensure temperature control in the FFSC, is to use multi temperature composite warehouses and multi-temperature delivery vehicles (Aung & Chang, 2014; Dani, 2015). Facilities such as refrigerated containers, cold stores and display cabinets are required to store and preserve perishable goods in a proper state. However, due to limited storage capacity, warehouses are restricted to provide the optimum temperature levels and conditions for each product type. Shipments to large retailers are made in separate trucks for chilled, frozen and ambient foods, while smaller retailers usually use combined loads (Aung & Chang, 2014). Furthermore, temperature control is vital during the harvesting stage since fresh produce needs to be cooled straight after harvesting, and packaging is important to prevent the exchange of temperature between produce and the external environment (Bogataj *et al.*, 2005). Figure 2.11 illustrates several technologies that can be used to control temperature at various stages in the FFSC.

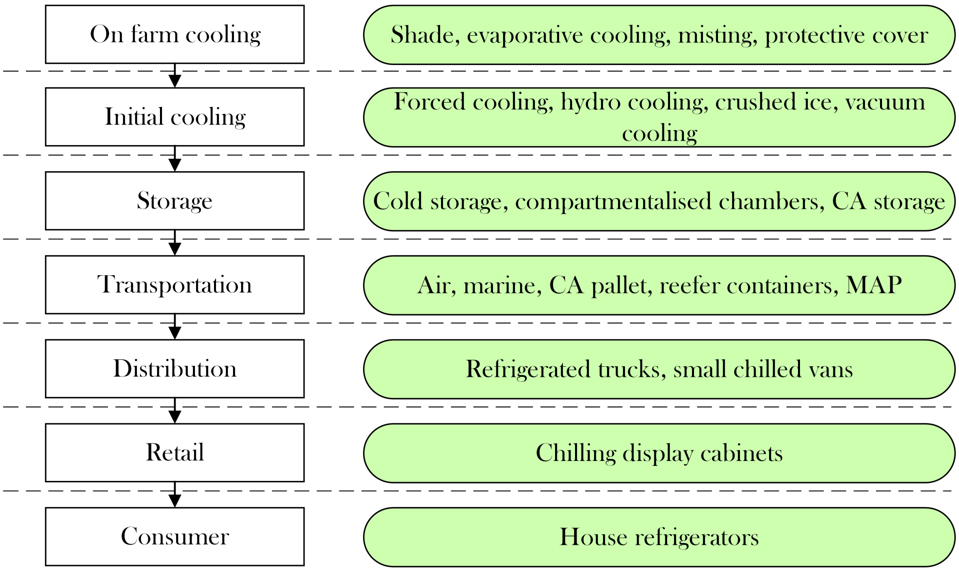


Figure 2.11: Temperature control at each stage in the food supply chain (reproduced from Bigaj & Koliński (2017)).

Bigaj & Koliński (2017) further mention the importance of collection of temperature data through the FFSC, as it ensures efficient information flow and the safety of food products. Many temperature recording systems exist such as, time-temperature indicators and radio-frequency identification (RFID) tags to monitor the temperature along the supply chain (Heising *et al.*, 2014; Vanderroost *et al.*, 2014). These technologies have the ability to assist with quality traceability and data transparency (Trienekens *et al.*, 2012).

2.2.5 Inventory management and replenishment policies

Chopra *et al.* (2017) mention that inventory exists in the supply chain to control the mismatch between supply and demand. Inventory decisions are high-risk because they commit to support future sales and drive a number of anticipatory supply chain activities such as required assets, costs incurred and the responsiveness of the supply chain (Bowersox *et al.*, 2007). According to Taylor & Fearne (2009); Wang & Li (2012), inventory management of perishable food is challenging because of the following reasons:

- variability in consumer demand;
- misalignment between supply and demand;
- fresh foods are perishable in nature; and
- poor collaboration between supply chain actors because required data are usually not available or accessible.

Most inventory models assume that items can be stored indefinitely to meet future demands, but the problem with perishable foods is that their quality changes during storage and in time they become partially or entirely unfit for consumption (Nahmias, 1982). Inventory management is an important logistic operation, especially when products have limited shelf-life. It is necessary to keep the right amount of inventory levels without incurring unnecessary holding or spoilage costs (Coelho & Laporte, 2014). Hence, numerous research studies were devoted to determining inventory policies for perishable products to assist management regarding inventory-related decisions.

Coelho & Laporte (2014) discuss three types of inventory policies namely (i) fresh first; (ii) old first; and (iii) optimised priority. The **fresh first** policy refers to fresher products that are sold first to consumers. This policy ensures that products have a longer shelf-life, but often yield a higher spoilage rate. This policy is effective if fresh products' deterioration rate greatly affects the price. The **old first** policy refers to older products that are sold first, which generates less spoilage but also less revenue. This policy is useful when the deterioration rate of products does not affect the price. Lastly, the **optimised priority** policy focuses on determining which product to sell at any given time period to maximise revenue. It means that this policy depends on parameters inserted into the model to ensure that the right amount of inventory is available at the right place to meet customer acceptance and revenue goals.

Qin *et al.* (2014) further mention that most inventory policies assume that the quality of perishable products does not decay before their expiration date. Quality plays an important role in influencing the demand for products, hence they developed an inventory policy that considers the deterioration rate of quality and physical quantity to be time-proportional to determine pricing and control inventory levels.

Replenishment policies consist of decisions regarding when to reorder product and how much to reorder (Chopra & Meindl, 2014). Literature offers numerous replenishment policies for perishable products, but according to Romsdal (2014), the most favourable policy for fresh produce is the periodic review policy, because the perishability aspect restricts the chance to have buffer inventories. It is difficult to have fixed stock levels for food products due to the age and variety of products, hence finding an optimal replenishment policy is challenging. According to Duan & Liao (2013) the most suitable policies for perishable inventory are (i) order-up-to-level policy; (ii) aged-based policy; and (iii) old-inventory-ratio policy.

With the **order-up-to-level policy**, each supply chain actor determines the amount to order and the amount to produce, and then replenishes the inventory according to their own order-up-to-level target. Replenishment decisions are made by the actors without prior knowledge of the demand for the next time period, other than statistical demand distribution.

The **aged-based policy** was first introduced by Broekmeulen & van Donselaar (2009) and works similar to the order-up-to-level policy, but takes into account the full age distribution of the inventory. The inventory position is corrected for the estimated amount of outdating or expiration, and an order is placed if this revised inventory drops below the order-up-to level. The estimated outdating or expiration amount is used to determine the production levels.

The **old-inventory-ratio policy** developed by Duan & Liao (2013), is another age-based policy where the production decisions are based on an old inventory ratio (the proportion of old items to the total items on hand) at a certain period. The definition of old items could also be subjected to optimisation with respect to length of shelf-life. The production quantity should be quantified first according to the original order-up-to-level, which accounts for the number of items on stock. Next the proportion of old items on hand is calculated. If it exceeds a certain threshold level, an additional replenishment is triggered to account for the possible outdated products.

2.2.6 Quality-controlled logistics

Macheka *et al.* (2017) explain that FFSC characteristics have an influence on quality and logistics control activities. **Quality control activities** are activities that evaluate and modify the quality system to ensure that fresh produce stays within acceptable quality or minimising quality decay, for example controlling temperature along the chain (Kirezieva *et al.*, 2013a; Luning & Marcelis, 2007). **Logistic control activities** are activities aimed at ensuring supply of the right quantity of fresh produce to the right place at the right time, and at an appropriate cost. It focuses on gathering information to reduce uncertainty within the FFSC (Luning & Marcelis, 2007). Van der Vorst *et al.* (2007) also highlighted the fact that product and process characteristics have an immense influence on logistical activities in the FFSC, and developed Table 2.3 that summarises a list of typical product and process characteristics, in various stages of the FFSC, that may influence logistical decisions.

FFSCs are characterised by heterogeneous batches of products, which means that product quality differs in the batches and between batches, and products are delivered by a diversity of producers to multiple retailers that have different demand (Van der Vorst *et al.*, 2007). Long supply chains of perishable products suffer from quality degradation. Storage, handling, transport, and distribution conditions have strong impacts on the freshness and shelf-life of products. The common strategy to deal with the variability of quality, is using an 'average' quality measurement throughout the supply chain. This might not be an effective approach, since there are quality differences for specific market outlets. Hence, Van der Vorst *et al.* (2007) developed a concept called **quality-controlled logistics** (QCL), that makes use of variation in product quality and to possibly manage product quality development in the distribution of products.

Table 2.3: Overview of main FFSC characteristics in their influence on logistics (adapted from Van der Vorst *et al.* (2007)).

Supply chain actors	**Product and process characteristics**	**Impact on logistics**
Farmers	• Long production throughput times (producing new or additional products are time consuming). • Seasonality in production.	• Return flows • Responsiveness
Food industry and processors	• High volume, low variety (although variety of products is increasing). • Highly sophisticated capital-intensive machinery focusing on capacity utilisation. • Variable process yield in quality and quantity due to biological variations, seasonality, weather conditions, pests, other biological hazards. • Waiting for the results of quality tests. • Storage buffer capacity is restricted, when material or finished products can only be kept in special storage facilities i.e. tanks or containers. • Necessity for lot traceability of work in process due to quality and environmental requirement.	• Flexibility in process and planning. • Importance of production planning and scheduling focusing on high capacity utilisation. • Flexibility of recipes. • Timing constraints, ICT possibility to confine products. • Flexible production planning that can handle this complexity • Need for configurations that facilitate tracking and tracing.
Auctions / wholesalers / retailers	• Variability of quality and quantity of supply of farm-based inputs. • Seasonal supply of products requires global sourcing. • Requirements for conditioned transportation and storage means • Demand for high quality food products, convenience and sustainability.	• Pricing issue • Timing constraints, ICT possibility to confine products. • Need for conditioning. • Pre-information on quality status of products.
Overall	• Shelf-life constraints for raw materials, intermediate and finished products and changes in product quality level while processing the supply chain (due to quality decay) • Recycling of materials required.	• Timing constraint. • Information requirements. • Return flows.

QCL is defined as 'part of supply chain management that plans, implements, and controls the efficient, effective flow and storage of food products, services and related information between point of origin and the point of consumption in order to meet customers' requirements with respect to availability of specific product qualities in time and using time-dependent product quality information in the logistics decision process'. The essence of QCL was discussed in Chapter 1, and Table 2.4 illustrates the difference between generic logistical decisions and QCL decisions.

Table 2.4: Generic logistical decisions versus QCL decisions (reproduced from Van der Vorst *et al.* (2011)).

Generic logistical decisions	**Specific QCL decisions**
Determine generic customer standards: 1. Customer needs such as quantity, quality, etc. 2. Customer service levels such as lead time, reliability, etc. 3. Determine requirements on supply of products in each stage of the chain.	Determine customer acceptance levels and periods for specific market segments using accepted and measurable quality standards. Translate these into product quality requirements for each stage in the supply chain.
Determine facility network design: 1. Number, location of stocking points 2. Equipment selection, capacity planning.	Use customer requirements data and information on supply qualities and volumes and transport scenarios with quality predictions to determine the required network design and equipment.
Determine inventory management: 1. Position Customer-Order-Decoupling-Point. 2. Push-pull strategies 3. Warehousing policies	Use supply chain data to determine the optimal position of inventory points in the network taking predicted quality changes as well as environmental conditions into account.
Determine information flows and order processing: 1. Ordering rules 2. Order inventory interface procedure 3. Order picking procedures	Determine critical control points (CCPs) to monitor quality changes. Use quality prediction models and product quality information to apply optimal picking policies. Re-sort batches if needed, and aim for homogeneous batches for specific market segments.
Plan order fulfilment: 1. Allocate harvested produce to customer orders and deliver the products without dealing with quality changes and differences that occur in supply process. A batch is not re-sorted or reallocates unless serious issues arise. 2. Determine transport management such as mode and scheduling.	Dynamic logistics planning in the complete chain based upon real-time product-quality information (using predictive models and CCPs). If needed, batches are re-sorted into homogeneous batches, re-allocated to different market segments, transported with different modes and environmental conditions are adapted to meet customer requirements. Technologies such as data loggers, RFID and GPS are used to capture relevant information and are translated into meaningful information.

Further research was done by Van der Vorst *et al.* (2011) to improve on the concept of QCL, as they identified the following features that contribute to enhance QCL activities and decision-making within the FFSC.

Consumer preference and acceptance period of product quality attributes

This feature refers to: (i) the quality attributes that consumers prefer as well as the target values of each attribute; and (ii) the acceptance period, which is the time period when consumers find all attributes of a product acceptable and will buy the product (Grunert, 2005). By consumer research it becomes possible for a specific consumer group to determine the limits of acceptability for specific attributes like colour, freshness, or taste. If this is known, it becomes possible to aim for these specific characteristics for the product in retail stores.

Critical control points

A critical control point refers to a point where there is loss of control in a process, or variation in product properties and processes outcomes are unacceptable or irreversible in the required quality attribute of the final food product (Fellow, 2015). Relating insights in chain conditions to dynamic behaviour profiles of quality attributes enables the determination of different chain configurations on the final quality of food products. This supports the necessary points in the supply chain where certain measurements need to be done and where logistical and quality control activities should be taken. As a result, one can change conditions such as temperature, storage time, and order-picking procedures, as well as the positioning of products on retail shelves.

Product measurement and prediction

There are several techniques and technologies in development, such as intelligent packaging, that enables the measurement and prediction of the dynamics of quality of food products in the FFSC (Heising *et al.*, 2014; Trienekens *et al.*, 2012; Yam & Lee, 2012). They improve the ability to predict ripening or quality decay under environmental conditions, which provides the relevant information to supply chain actors in order to take precautions. It allows food products to be placed on retail shelves within the optimum quality window, to ensure safe food consumption and consumer acceptability.

Logging and exchange of information

This features relates to data logging and exchange of information among supply chain partners. Quality of fresh food products is highly dependent on its temperature-exposure history, from production through to distribution and storage up until consumption (Aung & Chang, 2014; Trienekens *et al.*, 2012). Monitoring and exchanging critical parameters, such as temperature history through the product life cycle is of utmost importance, and it allows for more accurate prediction of shelf-life models. Emerging technologies like RFID and GPS provide innovative means to capture data. Furthermore, data on demand, inventory, and supply could also be exchanged among supply chain actors.

Local dynamic or adaptive logistics and quality control

QCL comes down to adaptive control based upon consumer demands and product quality (Van der Vorst *et al.*, 2011). Therefore, it is necessary to consider new strategies regarding to the flow of products and the environmental conditions the food products are exposed to. For example, instead of completing order-picking and stock rotation based on First-In-First-Out or Last-In-First-Out, it should rather be based on First-Expired-First-Out or Right-Quality-First-Out (Heising *et al.*, 2017; Vanderroost *et al.*, 2014).

Supply chain management

Supply chain management practices can be applied in the complete supply chain to: (i) match supply and demand using advanced product information and logistics decision policies; (ii) shorten production and distribution lead times; (iii) fully create information transparency; and (iv) reduce wastes and costs. Van der Vorst *et al.* (2011) combined these six features into a diagnostic tool, as illustrated in Figure 2.12, that indicates the operational requirements of each QCL feature. It is then required to develop performance levels to assess specific supply chains and to analyse the relationship between the QCL features and the actual supply chain performances.

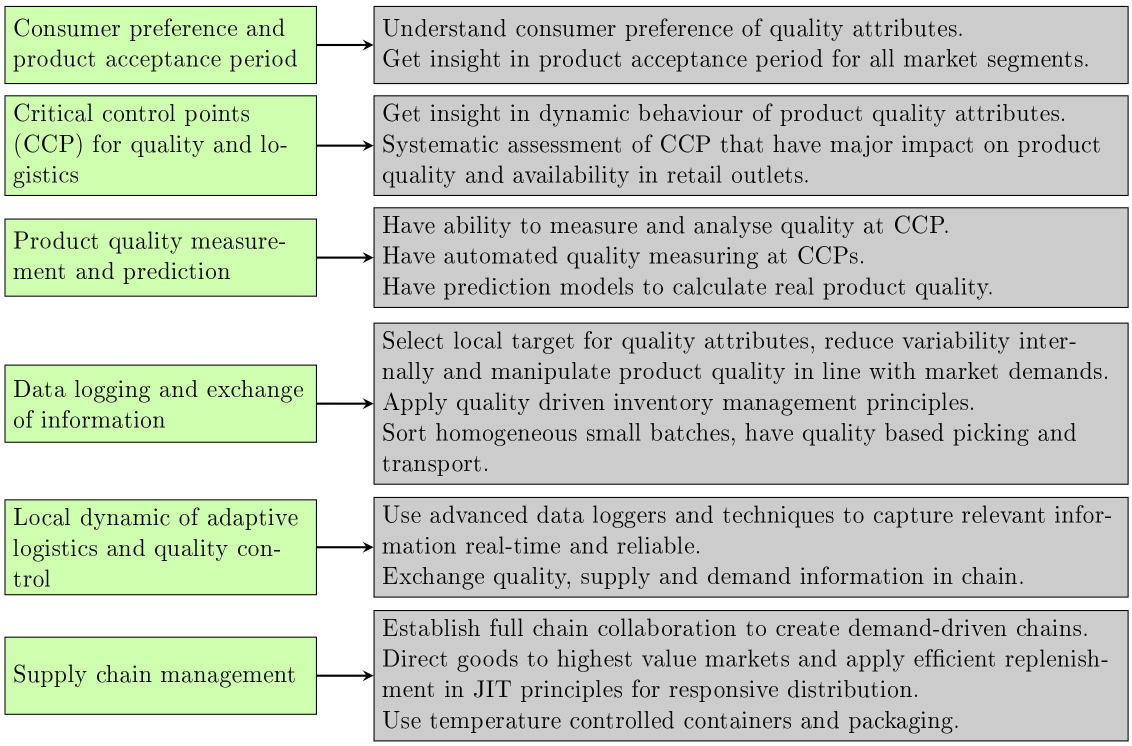


Figure 2.12: Operational requirements of QCL features (adapted from Van der Vorst *et al.* (2011)).

2.3 Digitisation

The economic environment is changing rapidly today as supply chains need to cope with increased dynamic customer demands, improved product-service innovation, product variety, quality standards, and immediacy of order satisfaction (Erol *et al.*, 2016; Pflaum *et al.*, 2017). Improved flexibility and agility are required, processes need to be accelerated and made transparent or visible in order to enhance the supply chain (Pflaum *et al.*, 2017). Organisations are increasingly focused on digitising their supply chains as research proposes that digitisation promises a higher level of supply chain visibility and improves overall efficiency (Scrauf & Berttman, 2016).

Digitalisation is the use of digital technologies to transform business models and operations to provide new revenue and value-producing opportunities. It is the process of moving to a digital business and to gain insight from digitised data and processes (i SCOOP, 2016). The rapid developments and widespread deployment of digital technologies, specifically within Information and Communication Technologies (ICT), have created digital innovation to assist with the newly known concept called **digital supply chains** (Hartmann & Halecker, 2015). A digital supply chain (DSC) is characterised by the strategic and operative exchange of information to enhance communication between actors within the supply chain (Chen & Paulraj, 2004). This can be achieved via electronic links between information systems, enabling automated and digitalised processes among the supply chain actors.

The benefits of DSC are considerable as Neubert *et al.* (2004) state that information-sharing reduces costs and allows more accurate data to be processed along the supply chain. When these information systems are correctly automated, they can eliminate manual data entry and reduce human error (La Londe & Masters, 1994). DSC has the ability to create competitive advantages to competition, reduce supply chain lead times and increase flexibility within the supply chain design (Segars & Grover, 1995). It enhances the effectiveness of information-sharing and improves traceability, transparency and visibility to assist logistical decision-making (Dinter, 2013).

Digitalisation forms part of the new technological disruptive concept **Industry 4.0**, also known as the new industrial revolution (Burmeister *et al.*, 2015; Erol *et al.*, 2016; Hermann *et al.*, 2016). Industry 4.0 (I4.0) focuses on the end-to-end digitisation of all physical assets and integration into digital ecosystems with value chain partners (Scrauf *et al.*, 2016). Furthermore, Scrauf *et al.* (2016) reported that I4.0 is driven by: (i) digitisation and integration of vertical and horizontal value chains; (ii) digitisation of product and service offering; and (iii) digital business models and customer access.

Digitisation and integration of vertical and horizontal value chains

I4.0 digitises and integrates processes along the entire supply chain, from purchasing, product development, logistics and customer services. All data about operations, efficiency, quality management and planning are available in real time, and is supported by augmented reality and optimised in an integrated network.

Digitisation of product and service offering

Digitisation of products includes the expansion of existing product features with devices such as smart sensors, communicating devices and data analytic tools. It also includes the creation of new digitised products which focus on completely integrated solutions. Integrating data collection and analysis, companies can generate useful information on product use to refine the products features so that they can meet the needs of the customer.

Digital business models and customer access

Industrial companies can expand their offering by providing disruptive digital solutions such as data-driven services and integrated platforms. Disruptive digital business models are often focused on generating additional digital revenues and optimising customer interaction and access. Digital products and services frequently look to serve customers with complete solutions in a distinct digital ecosystem.

Koch *et al.* (2014) conducted a study to establish the maturity of I4.0 within European companies. The study suggested that approximately 80% of the surveyed companies will have digitised their value chain by 2020. Industries that are actively digitising their value chains include: manufacturing and engineering, automotive suppliers, processing industry, electronic and electrical systems, and information and communications. Digitisation is finding its way into vertical and horizontal value chains. The digitisation of horizontal value chains integrates and optimises the flow of information and goods from the customer through their own companies to the supplier and back, also known as the supply chain actors. Vertical digitisation refers to securing a consistent flow of information and data from the internal departments within the company such as purchasing, manufacturing, logistics and planning.

According to Pfohl *et al.* (2017) and Brettel *et al.* (2014) many innovative technologies and concepts exist to enhance the I4.0 vision. Rüßmann *et al.* (2015) mention that there are nine technologies that form the foundation of I4.0 namely: (i) autonomous robots; (ii) system integration; (iii) Internet of Things; (iv) simulation; (v) additive manufacturing; (vi) cloud computing; (vii) augmented reality; (viii) big data; and (ix) cyber security, and these technologies are shown in Figure 2.13. For the purpose of this research study, literature was reviewed on Internet of Things technologies.

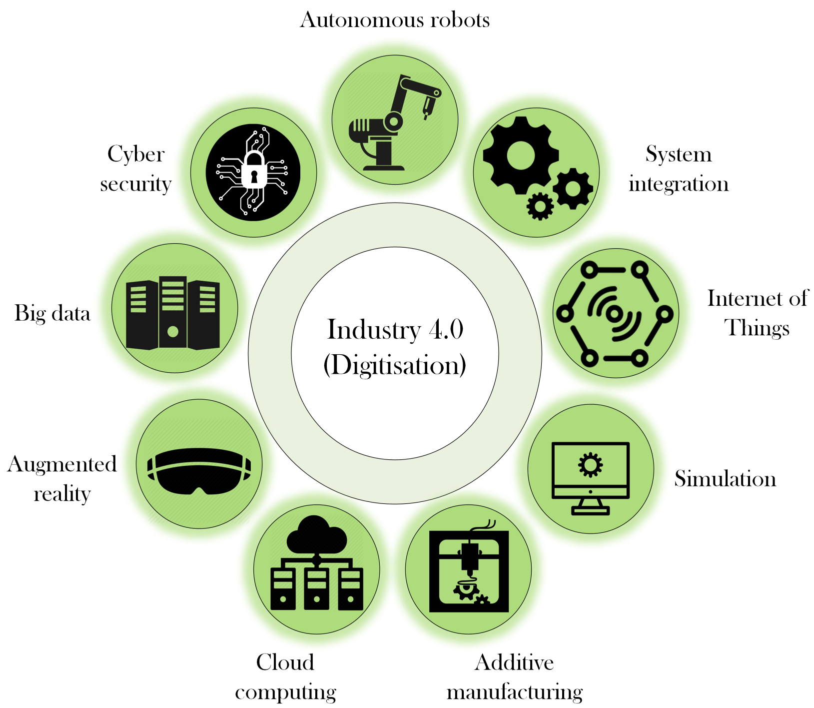


Figure 2.13: Contributing digital technologies

2.4 Internet of Things

There is a growing interest in using Internet of Things (IoT) technologies in various industries, as it is an emerging technology that is expected to offer promising solutions such as tracking, monitoring and data accessibility to transform the operations within these industries (Zhou *et al.*, 2015). IoT can be defined as "a dynamic global network infrastructure with self-configuring capabilities based on standards and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into an information network" (Sundmaeker *et al.*, 2010). Hence, IoT is a paradigm where objects are able to interact and cooperate with one another through wired and wireless connection, as shown in Figure 2.14. The main goal of IoT is to interconnect unique addressable things to generate and share information across diverse platforms and applications, considering security and privacy issues (Hartmann & Halecker, 2015; Sundmaeker *et al.*, 2010).

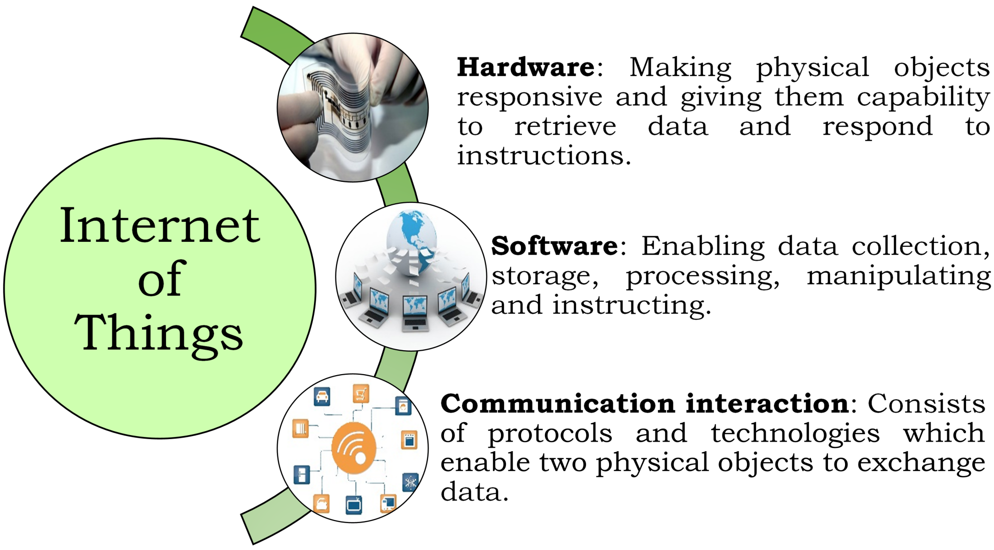


Figure 2.14: The paradigm of the Internet of Things

2.4.1 Components

Stallings (2015) discussed five components that need to be considered when developing any IoT system. An IoT device may have one or more of these components:

1. **Sensors**

   Sensors measure some parameter that is a physical, chemical or biological entity and delivers an electronic signal proportional to the observed characteristic, either in the form of an analogue voltage level or a digital signal. In both cases the sensors output is the micro-controller input. The communication between the sensor and the micro-controller can be either active of passive. Active means that the sensor periodically sends data to the microcontroller, or when a threshold has been met or exceeded. Passive means that the microcontroller requests data from the sensor.

2. **Actuators**

   Actuators are devices that receive electronic signals from the microcontroller and respond by interacting with the environment to produce an effect on some parameter of a physical, chemical or biological entity. Actuators can be in either direct mode, or callback mode. Direct mode is when the microcontroller sends a signal that activates the actuator, and callback mode is when the actuator responds to the micro-controller to report completion or a problem.

3. **Microcontrollers**

   A microcontroller is usually a single chip that contains a core (processor), non-volatile memory for programming, volatile memory for input and output, a clock, and an I/O (input-output) control unit. Microcontrollers are programmed to complete specific tasks that are embedded in its device, and executes the tasks once they are required.

4. **Means of communication**
   The means of communication is an important component, otherwise the device cannot participate in a network. Usually transceivers are used for communicating. Transceivers are electronic devices that are capable of transmitting and receiving data. Most IoT devices use wireless transceivers that can communicate using WiFi or other wireless connectivity.

5. **Means of identification**
   Identification devices refer to the tracking and identifying of objects. This is important since there are billions of devices already connected in some way to the Internet. Some identification means include unique IP addresses or RFID devices.

2.4.2 Reference architecture

Due to the growing interest but also the complexity of IoT, world leading telecommunication and networking companies such as IBM, Cisco and Intel decided to develop an IoT reference architecture to define the main elements for IoT systems and to discuss the interrelationship between the elements IoT World Forum (2017). They released the IoT reference architecture to serve as a framework for IoT deployment. Figure 2.15 shows the IWF reference architecture that consists of seven levels, and each level is described separately.

1. **Devices**
   Level one consists of physical devices that interact with physical things, such as sensors and actuators. There are two types of device namely: (i) data-carrying devices; and (ii) data-capturing devices. Data-carrying devices are attached to a physical thing to indirectly connect to a physical thing with communication networks. Data-capturing devices are read/write devices with the capability to interact with physical things. The interaction can happen indirectly via data-carrying devices or via data carriers attached to the physical things. Other capabilities of devices are the conversion from analogue-to-digital and vice-versa, data generation, and the ability to be queried or controlled remotely.

2. **Network connectivity**
   Level two enables the communication between devices as well as the communication between devices and low-level processing that occurs at the following level. It consists of physical networking devices such as routers, switches or gateways to construct local or wireless internet connectivity. This level enables devices to communicate with one another via application platforms such as smartphones, laptops and remote control devices.

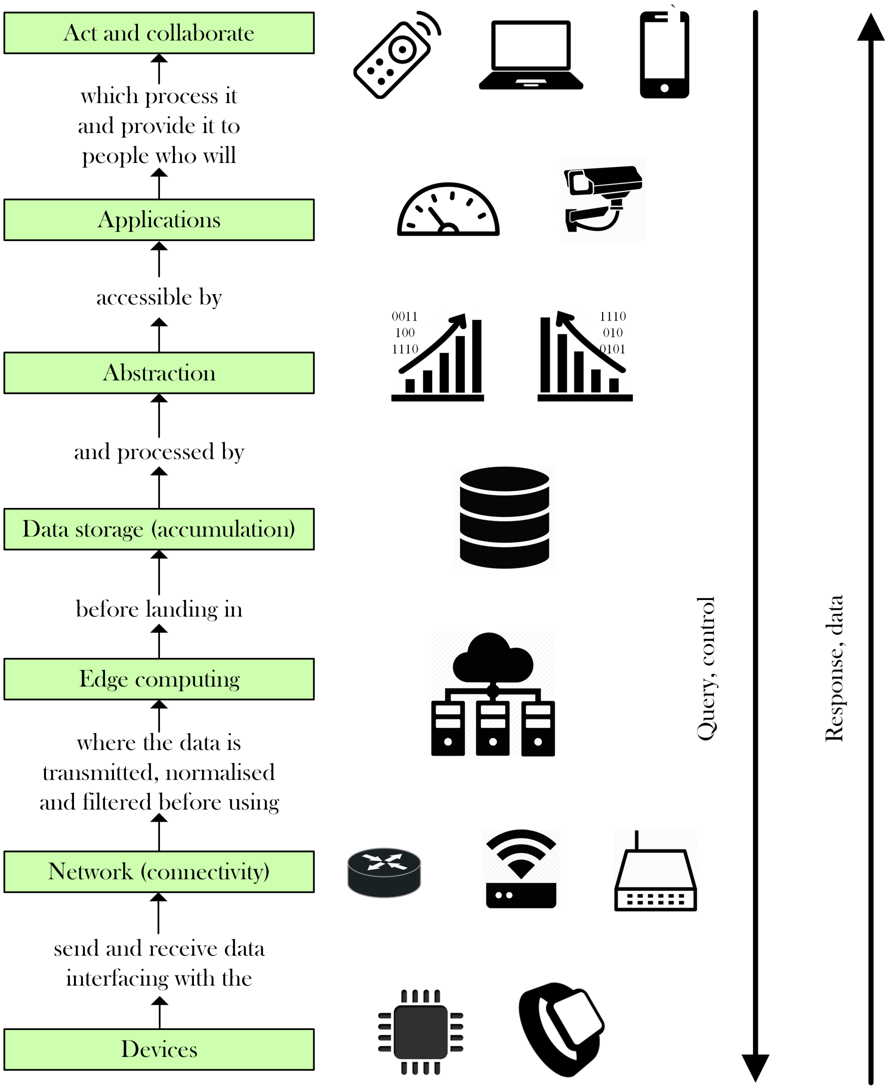


Figure 2.15: Internet of Things reference model developed by the IWF (reproduced from Stallings (2015)).

3. **Edge computing**

   Many IoT deployments result in large amounts of data that may need to be generated by various sensors. Rather than to store the large amount of data permanently, it is often desirable to process as much data as possible close to the sensors. This means that sensor data is converted into useful information that is suitable for storage and higher-level processing. Therefore, the third level referred to as the computing edge, processes high volumes of data and performs data transformation operations to reduce the amount of data to be stored. The following are examples of how edge computing operates:

   Evaluation: Evaluating the data for criteria as to whether it should be processed at higher levels.

Formatting: Reformatting the data for consistent higher-level processing.

Reduction: Reducing data to minimise the impact of data and traffic on the network and higher-level processing systems.

Decoding: Handling cryptic data with additional context.

Assessment: Determining whether data represents a threshold or alert and redirecting data to additional data.

4. **Data storage (accumulation)**
   Data moving through a network is called data in motion. The rate of data in motion is determined by the devices that generate data and this is usually event-driven. This means that data generation is either periodically or by an event in the environment. To deal with data in some way, it is necessary to respond in real time but most application platforms would struggle to keep up with the volume of data generated by various IoT devices. Therefore, applications deal with data at rest, which means that the data is in some way readily accessible at the storage facility. Applications can access data as needed, or on a 'non real-time' basis. This allows the upper levels to operate on a query basis. Hence, level four is where the filtered data from numerous devices is placed into storage that will be accessed by higher level processes.

5. **Abstraction**
   The previous level stores large quantities of data with little or no changes made to the data in order to meet specific application requirements. Data are mostly stored as different types and in varying formats. Therefore, the fifth level aggregates and formats data into ways that allow applications to access the data in a meaningful and efficient manner.

6. **Applications**
   Level six contains any type of application that uses IoT input or controls IoT devices. Usually the applications interact with the fifth level and the data at rest, hence they do not have to operate at network speeds.

7. **Act and collaborate**
   Level seven recognises the fact that people must be able to communicate and collaborate with IoT devices. This may involve application and exchange of data and control information across the Internet or an enterprise network.

2.4.3 Creating new capabilities

The idea of IoT-technologies is to embed information technologies in the product itself to make the product more intelligent, and to create additional value for companies. Porter & Heppelmann (2015) mention that IoT-technologies provide new capabilities to enhance the competitiveness of companies.

The new capabilities are:

Monitoring: Products can monitor themselves and their environment in real time, creating new data and insights.
Control: Products can be controlled through software embedded within them or that resides in the cloud.
Optimisation: Algorithms and analytics can optimise product operation, capacity utilisation, and predictive maintenance.
Autonomy: The above-mentioned capabilities can assist product autonomy which enables autonomous operations such as self-coordination, and self-diagnosis.

These capabilities can provide opportunities to improve profitability and growth for the company by: (i) discovering new approaches to differentiate new market segments; (ii) improving component standardisation which can lower costs, since functionality will be driven by software rather than hardware; and (iii) increasing the barrier for new market entries since it becomes more difficult for competitors to keep up with change. But the implementation of IoT-technologies does have its challenges such as: (i) high initial costs to invest in software development and building the product cloud; (ii) going overboard with additional features which increases costs and decreases profitability; and (iii) reducing product demand if consumers are not satisfied with the product.

Porter & Heppelmann (2015) and McBeath (2015) further developed a roadmap for companies considering IoT deployment. It consists of ten strategic questions which were categorised into four broad groups, as shown in Figure 2.16. These questions provide meaningful guidelines when planning IoT deployment within the company and they highlight important requirements to consider before investing in an IoT solution. McBeath (2015) provides a detailed discussion on each of these questions.

IoT is an integrated part of Future Internet, which is based on standard communication protocols that merges computer networks, Internet of Media, Internet of Services, and Internet of Things into a global IT platform of seamless networks (Sundmaeker *et al.*, 2010). Communication in IoT will not only take place between people, but also between people and the environment. Communication will be seen more among data centres such as home data centres or cloud computing, than current nodal networks (Sundmaeker *et al.*, 2010). IoT are expected to become actively involved in business, information and social processes where they are enabled to interact and communicate among themselves and the environment by exchanging data and information sensed from the environment, while reacting to the real world (Sundmaeker *et al.*, 2010).

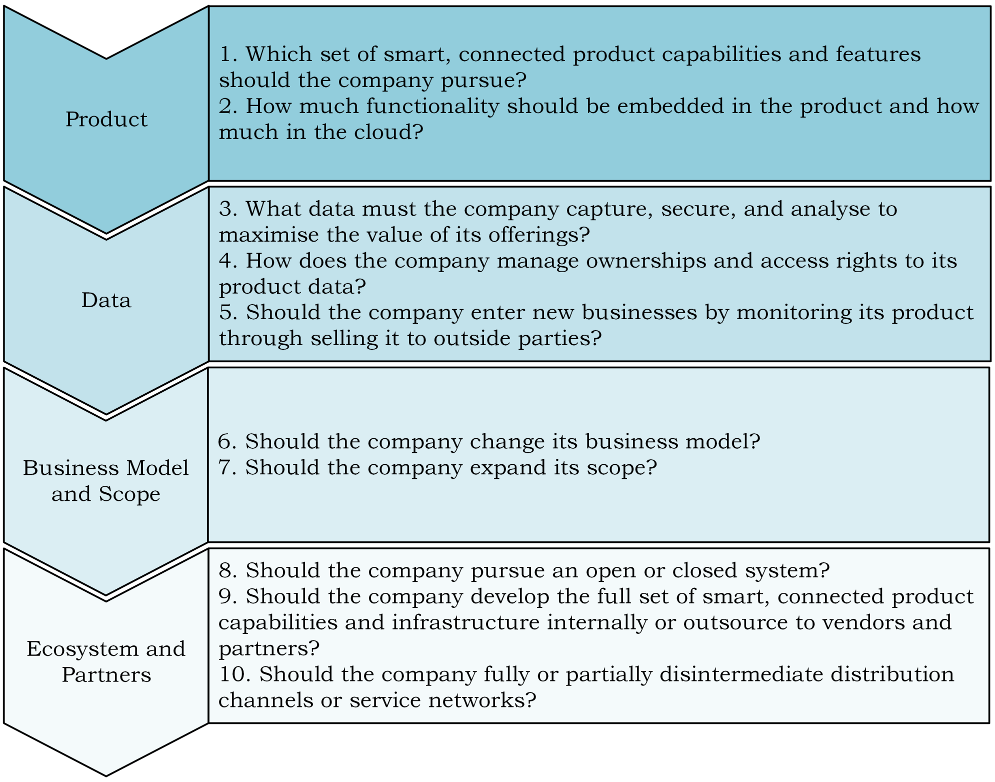


Figure 2.16: Ten strategic questions (reproduced from McBeath (2015)).

Many countries have invested in IoT initiatives the UK government has launched a project to develop IoT, and China aims to take the leading role in setting IoT standards and technologies (Voigt, 2012). In the US companies such as IBM and ITIF (The Information Technology and Innovation Foundation) reported that IoT can effectively be used to improve traditional physical and information technology infrastructure, and will have a positive impact on innovation and productivity (Da Xu *et al.*, 2014).

2.5 Digitisation within the food supply chain

Food supply chain management has to deal with some great challenges such as high dynamics and uncertainty of supply and demand, the variability of fresh product quality, and to ensure that the correct volume is available on time at the right place (Verdouw *et al.*, 2013). As result, logistical activities need to be flexible, allow last minute changes and reallocations as well as provide a robust planning (Verdouw *et al.*, 2010). Logistic decisions need to be based on the underlying fact that quality is changing over time and due to environmental conditions (Sundmaeker *et al.*, 2016). Hence, the use of ICT is important in the food industry to deal with these dynamics and uncertainties, but Verdouw *et al.* (2013) state that current ICT systems show a poor level of integration and the support of intelligent use of data is insufficient. Dani (2015) and Sundmaeker *et al.* (2016) argue that future internet technologies can provide the means to overcome these challenges. The following subsections introduce a view of how to deal with these challenges by introducing smart-agri-food logistics and the use of Internet of Things to improve data transparency across the food supply chain.

2.5.1 Smart agri-logistics

Smart agri-logistics derives from the enhancements of new types of efficient and responsive networks with flexible chain-encompassing tracking systems and decision support based on the tracking information (Dani, 2015; Verdouw *et al.*, 2013). These systems effectively virtualise the logistics flow from farm-to-fork, and support the exchange of logistics information and provide functionality for intelligent analyses and reporting (Verdouw *et al.*, 2013). The smart agri-logistics system is comprised of real-time virtualisation, logistics connectivity and logistic intelligence, as presented in Figure 2.17.

Figure 2.17: Smart agri-logistics (reproduced from Verdouw *et al.* (2013)).

There are several technological developments to envisage the smart agri-logistic system which are discussed by Dani (2015):

- **Internet of Things (IoT):** IoT is a system in which various types of sensors are embedded into the FFSC network to communicate with each other and share information. Using communication technologies such as RFID, wireless sensors and near-field communication, data on temperature and relative humidity can be captured and used to control logistical decisions. Some challenges are that this technology can only work if the signals are strong, and communication breaks occur especially when transport units or ownership is changed.

- **Telematics systems:** Sensors to react to ambient parameters such as temperature, light and ethylene concentration are already used in some parts of food logistics. The vision is to merge further information about speed, location, and context with these parameters to assist effective forecasting. It is a challenge to integrate systems across the supply chain and it will need governance to maintain data integrity and privacy.

- **Tracking and tracing:** To create better control over the products in the supply chain, the level of traceability should focus on the whole supply chain. There are already some holistic approaches available, but a challenge is to apply a centralised system to compile all the information. Another problem is that supply chain actors are reluctant to share data to such a centralised system.

- **Autonomous systems:** These systems focus on enhancing logistical processes to take decisions autonomously and communicate with other entities.

- **Business Intelligence:** Business intelligence systems analyse company, competitors, and market-related electronic accessible data and process models to support strategic and functional decisions. However, business intelligence can only become beneficial as soon as the above-mentioned technologies are exploited.

Identification of individual food items is complicated in terms of labelling, costs in relation to its value and real-world handling of food in cases, pallets and shipment. Therefore, the above-mentioned technological developments are combined with packaging units to enable proper logistic management and to virtualise the shipment and storage conditions of food items (Sundmaeker *et al.*, 2016). The use of IoT-technologies provides opportunities to monitor, control, plan and optimise business processes in real time through the Internet, based on virtual objects instead of on-site observations, as illustrated in Figure 2.18. The use of sensor technologies such as humidity, light and ethylene indicators are increasingly used to manage food quality, and temperature sensors are used to monitor the conditions in packing and cold storage facilities, and transportation (Heising *et al.*, 2014; Sundmaeker *et al.*, 2016).

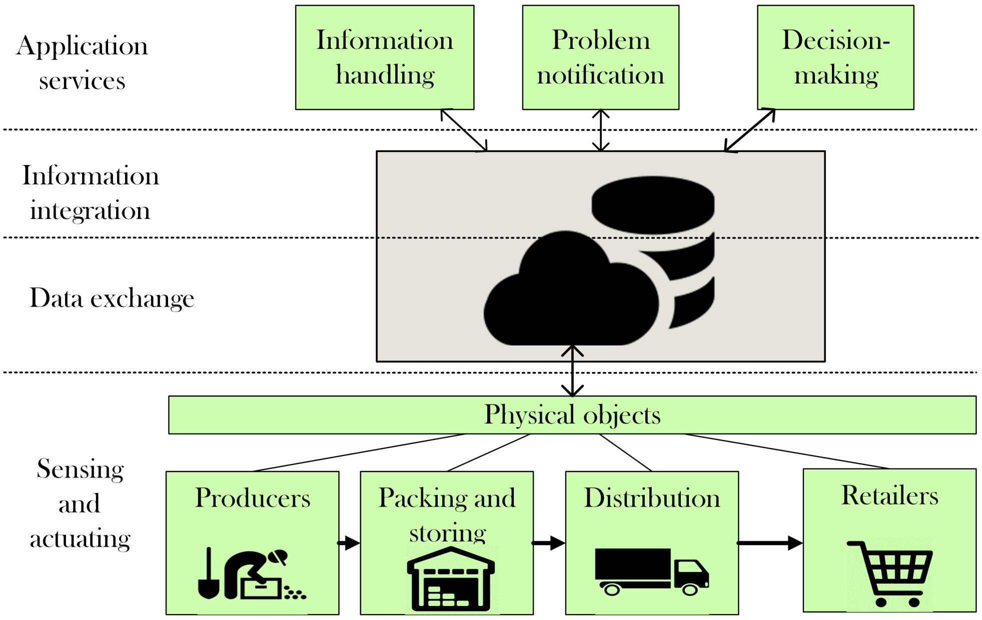


Figure 2.18: An information system architecture for the food supply chain (adapted from Verdouw *et al.* (2016)).

2.5.2 Sensing technologies in emerging food packaging

Traditional packaging has contributed greatly to the development of food distribution, but according to Yam & Lee (2012), it is no longer sufficient since society is becoming increasingly involved with the FFSC decision. Packaging has changed and improved significantly. Coles & Kirwan (2011) discuss key developments of packaging during the past 200 years. Food protection, hygiene, quality and convenience have been major drivers of food technology and packaging innovation. Although traditional packaging has contributed greatly to the development of food distribution, it is no longer sufficient because modern society is becoming increasingly complex (Vanderroost *et al.*, 2014). This requires that appropriate technologies need to be integrated in the food packaging system to extend shelf-life, monitor and improve food quality and safety (Dobrucka & Cierpiszewski, 2014; Kuswandi *et al.*, 2011). Recent research developed a concept called intelligent packaging (Dobrucka & Cierpiszewski, 2014; Ghaani *et al.*, 2016; Kuswandi *et al.*, 2011; Vanderroost *et al.*, 2014), and is discussed below.

2.5.2.1 Intelligent packaging

A definition for intelligent packaging is derived from the synthesis of definitions formed by several authors, as listed in Table 2.5. Intelligent packaging can be defined as a system that monitors and responds to external or internal conditions. Furthermore, it has the ability to facilitate decision-making, and can communicate and share information on food quality and safety throughout the FFSC. According to Barska & Wyrwa (2017); Ghaani *et al.* (2016); Vanderroost *et al.* (2014), experts forecast that emerging technologies such as intelligent packaging are the future of food packaging and mention that it will contribute to a rapid growth of sales in subsequent years.

Intelligent packaging does not directly act to extend the shelf-life of food products, but rather aims to convoy information to the stakeholders of the food supply chain (Restuccia *et al.*, 2010). The uniqueness of intelligent packaging originates from the fact that the package is the food's closest companion. Since the two move together through the supply chain, the package is in a favourable position to communicate the conditions of the food (Yam & Lee, 2012). Intelligent packaging creates the possibility to acquire continuous information on the food conditions, which enables the detection of possible abuse through the entire supply chain. This results in a safer and more efficient supply chain, reducing food waste and preventing unnecessary transport and logistic from an early stage (Mohebi & Marquez, 2015; Vanderroost *et al.*, 2014).

Table 2.5: Definitions of intelligent packaging

Definitions	**References**
The science and technology that uses the communication function of the packaging system to facilitate decision-making so that appropriate actions may be taken to achieve desired benefits in food quality and safety enhancement by, among other things, monitoring and improving the distribution and storage conditions.	(Yam & Lee, 2012)
Considered as packaging that monitors conditions of food during its life cycle to communicate information related to the quality of the product.	(Heising *et al.*, 2014)
It is a control system inside packaging which can perform intelligent functions such as standby, detection, tracking, recording, and communicating in order to provide individual links in the packaging chain, i.e. producers, distributors, and sales representatives and consumers, with certain parameters.	(Ucherek, 2011)
It is a system that provides the user with reliable and correct information on the conditions of the food, the environment and/or the packaging integrity. It is an extension of the communication function of traditional food packaging, and communicates information to the consumer based on its ability to sense, detect, or record changes in the product or its environment.	(Vanderroost *et al.*, 2014)
It is packaging that in some way senses some properties of the food it encloses or the environment in which it is kept and which is able to inform the manufacturer, retailer and consumer of the state of these properties.	(Dobrucka & Cierpiszewski, 2014)

Intelligent packaging plays an important role in facilitating the flows of both material and information in the FFSC and can be a useful tool to assist supply chain management (Heising *et al.*, 2014; Yam & Lee, 2012). In Figure 2.19, the outer circles represent the supply chain cycle. The package is traditionally used to facilitate the flow of materials by performing basic functions of containment and protection of the product. Furthermore, the package can facilitate the flow of information (represented by the links between the outer circles and inner circle), although this communication function has been overlooked in the past. The package can be a highly effective communicator as it has the ability to: (i) carry actual information in the direction of material flow (e.g. via truck, train, ship); (ii) transmit information visually (e.g. via an indicator); and (iii) electronically (e.g. via a barcode or the Internet) throughout each phase in the supply chain.

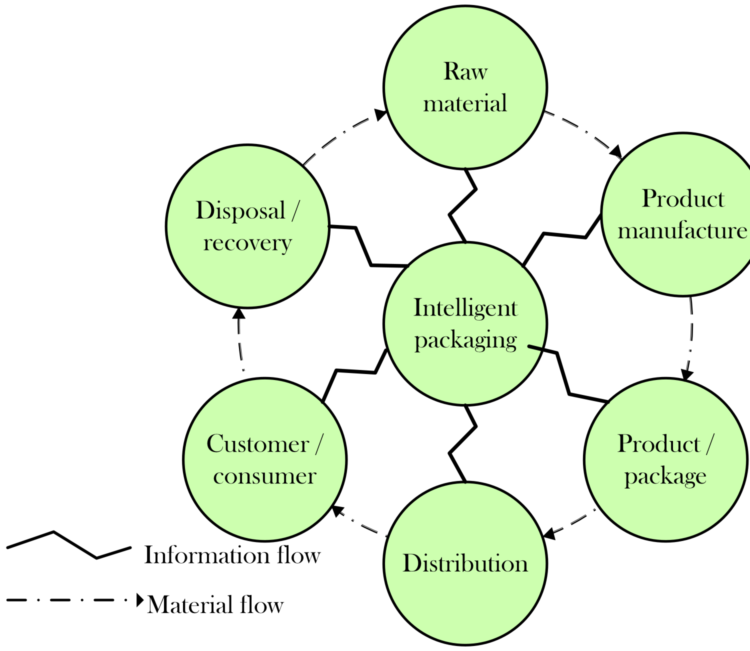


Figure 2.19: Material flow and information flow in the food supply chain cycle (reproduced from Yam & Lee (2012)).

2.6 Impact of Internet of Things on food waste

Internet of Things (IoT) technology provides the ability to collect and exchange data via connected 'things', and allows the capability to monitor and control environments as well as processes in real-time. Researchers suggest that this capability creates the opportunity to tackle food waste along the supply chain. GreenMatch (2017) and Shacklett (2018) mentioned that implementing smart sensors to monitor temperature, freshness, respiration and ethylene gas can improve food spoilage monitoring. This information can be used to determine accurate shelf-life, and redirect products to closer locations depending on the remaining shelf-life. Thus, it reduces the chance that food is wasted before it reaches the consumer.

Zestlabs (2016a) mentioned that pallet-level monitoring provides real-time feedback on remaining shelf-life based on temperature. This creates the ability to make accurate and prompt decision, for example, if produce is 'ageing' too quickly, it can be re-routed to a closer store to ensure it retains a decent shelf-life. Zestlabs implemented an initial application of their technology in a strawberry supply chain, and the result was that the retailers saved roughly half of the 18% of produce that previously went to waste. Retailers can use the data from the sensors to track the shelf-life of products and send the results to the responsible suppliers and transporters. This gives them visibility on who is providing them with the freshest produce with the lowest spoilage rate.

Additionally, Vasseur (2016) and Shacklett (2018) explained that IoT sensor data and analytics is a promising start to gain insights on identifying elements that contribute to food waste. It allows stakeholders to take the necessary action to control or mitigate these elements to reduce food waste. Vasseur (2016) also discussed that linking IoT monitoring with task management encourages behavioural change and efficiency to minimise food waste. Integrating IoT monitoring with mobile devices and apps, allows staff to take just-in-time actions to protect food and minimise waste. Notifications and alerts via email, SMS, or automated phone calls can be used to notify staff about anomalies in the supply chain.

2.7 Synthesis of literature review

As mentioned previously, the CSIR estimated that 12.6 million tonnes of food are being wasted each year, and that the fruit and vegetable commodity group contributes 44% of food wasted in South Africa. Furthermore, it was mentioned that fresh food is mainly wasted due to overproduction and the natural decay of food quality which cannot be prevented but is rather accelerated by implementing the wrong logistic activities due to poor supply chain planning. Therefore, the research will focus on investigating how logistic activities could be adapted to consider the quality of food within the fresh produce supply chain. The fresh produce supply chain will only be investigated from the postharvest to the retailing stages.

The concept of intelligent packaging together with the IWF Internet of Things reference architecture will be used to develop a concept for a proposed prototype application to assist with the prediction of the shelf-life for fresh produce. The idea is that this application might be used in the future to assist the implementation of quality-controlled logistics. Ideally, the application should assist the relevant stakeholders in adjusting logistic activities based on remaining shelf-life, as well as to provide insights to identify elements that contribute to food waste.

2.8 Conclusion

This chapter discussed the literature that was reviewed for this research study. The first section explored the extent of food waste globally, as well as in South Africa. The different food commodities were evaluated to identify where most food waste occurs. Thereafter an overview of fresh food supply chains was provided that discussed several components such as characteristics, performance measurements, and quality controlled logistics. The literature review further focused on digitisation and the Internet of Things, after which research was done on understanding how Internet of Things technologies could be implemented in the food industry and whether it would contribute to the reduction of food waste. Lastly, a synthesis of the reviewed literature was provided which will guide the remainder of the research study.

Chapter 3

Expert insights regarding quality controlled logistics and Internet of Things

The aim of this chapter is to identify current knowledge on quality-controlled logistics within the fresh produce industry as well as to receive experts' opinions and feedback on the use of Internet of Things technologies in the fresh produce industry. The chapter starts with the data collection technique that was used to gain feedback from fresh produce industry experts, after which the setting and sample size of the data collection will be described. Thereafter, the feedback will be analysed and key information extracted from the analysis will be discussed.

3.1 Data collection technique and approach

There exist various data collection techniques and methods to assist research, and it can be challenging to select an appropriate technique. Selecting the most suitable technique often depends on the: (i) purpose of data collection; (ii) type of information required; (iii) resources available; and (iv) evaluation of the collected data (Saunders *et al.*, 2009). The purpose of data collection within this chapter is to gain relevant information from the feedback of experts within the fresh produce industry, on the following topics:

- identifying essential logistics decisions regarding fresh produce quality and necessary inputs for these decisions;
- establishing ways to use IoT-technologies to enhance quality-controlled logistics; and
- identifying essential requirements and considerations to implement IoT in the fresh produce supply chain.

Questionnaires are a popular data collection technique to use when the research requires feedback from participants based on their experience. Questionnaires can be divided into self-administered questionnaires and interviewers' questionnaires. In order to decide on the design of the questionnaire, aspects that should be considered are the: (i) size of the sample that is required for analysis; (ii) types of questions that need to be asked; and (iii) number of questions that should be asked to collect data (Saunders *et al.*, 2009).

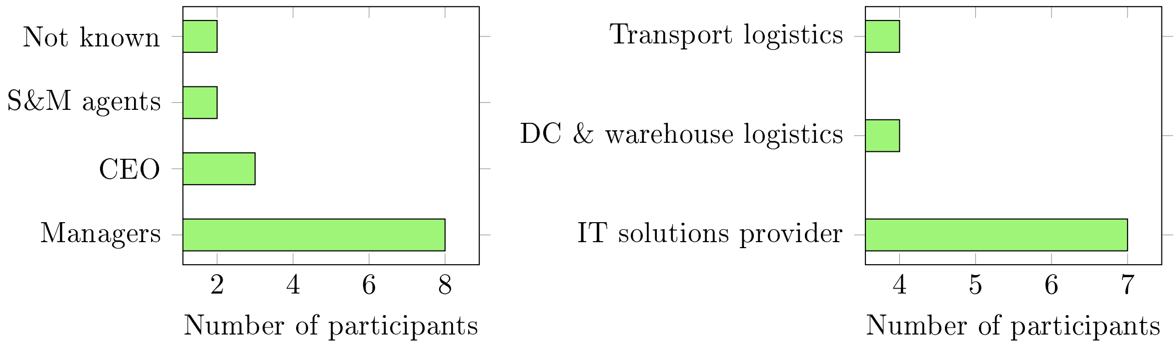
Using questionnaires as a data collection technique has its strengths, as it provides an efficient way to collect data quickly, and it is usually a cost-effective approach. Feedback provided by participants is mostly anonymous, which ensures that the data is more likely to be honest and reliable. However, some limitations of using questionnaires include (i) questions being interpreted differently by respondents due to the style of the questionnaire; (ii) forced choices may miss additional feedback from participants; and (iii) motivating respondents to complete questionnaires can be difficult.

For the purpose of this research study it was decided to design an interviewer questionnaire with the purpose of asking semi-structured questions. Interviewer questionnaires refer to those questionnaires where the interviewer physically meets the participants and asks the questions face-to-face. Semi-structured questions are a mix of open and closed questions, meaning the participant has the opportunity to provide feedback based on a predetermined selection of answers, as well as providing answers based on the participant's freedom. The questionnaire was validated by experts within the field of digital supply chain and logistics management.

3.2 Setting and sampling

FRUIT LOGISTICA is a fresh produce exhibition held annually in February in Berlin, the capital of Germany. It covers every sector of the fresh produce industry, provides the latest innovations, and offers networking and contact opportunities to global companies. From the 7^{th} until the 9^{th} of February 2018, companies from multiple countries presented their products and services such as: (i) multiple fresh products; (ii) technical systems; (iii) logistics; and (iv) other services. Further information and a list of all exhibitors can be found on the FRUIT LOGISTICA website: `https://www.fruitlogistica.de/en`.

During the exhibition, participants were asked to complete the questionnaire provided in Appendix A. The participants who completed the questionnaires were mainly from companies that provided: (i) logistic solutions for transportation and warehousing management; and (ii) technical solutions that can be integrated with transport, warehouse and quality management, as shown in Figure 3.1b. The 15 participants who were willing to partake in this study were either sales and marketing (S&M) agents, managers within their field of expertise, or the company CEO, as shown in Figure 3.1a.



(a) Role within the company

(b) Company type

Figure 3.1: Participants' feedback profile in terms of the company type and the role within the company

3.3 Analysis of feedback

The questionnaire was designed to collect feedback regarding two themes: (i) quality-controlled logistics; and (ii) Internet-of-Things (IoT). The first set of questions was designed to identify whether companies consider quality within their logistic activities in the supply chain, and what logistic activities can influence fresh produce quality reaching the end consumer. These questions were designed to receive feedback based on predetermined answers, meaning the participants were able to select the answers that they believed were most-suited for the question. Each time a specific answer was selected, it was counted to determine the most popular answers.

The second set of questions was designed to determine whether companies within the fresh produce industry believe that IoT-technologies can create value within the supply chain, and to determine what they believe are the requirements and challenges to implement IoT-technologies throughout the supply chain. These questions were designed to receive feedback based on the participant's knowledge and opinion on the topic. Similar feedback from the participants was clustered together and the most frequent responses were included in the feedback analysis.

3.3.1 Feedback regarding quality-controlled logistics

The first question related to identify general types of logistic-decisions that need to be considered in the fresh produce industry. From the feedback shown in Figure 3.2, it is observed that temperature management, and transport modes and route scheduling were general logistics-decisions to consider within the fresh produce industry since more than half of the participants responded that they consider it as general logistic-decisions. Managing inventory and stock levels, and considering storage practices can also be noted as general logistic-decision within the fresh produce industry, as more than five participants responded that they also focus on these logistic-decisions within their companies.

Less than five participants responded that they consider order picking, shelf space allocation, layout design, and replenishment policies were general logistics decisions within their company.

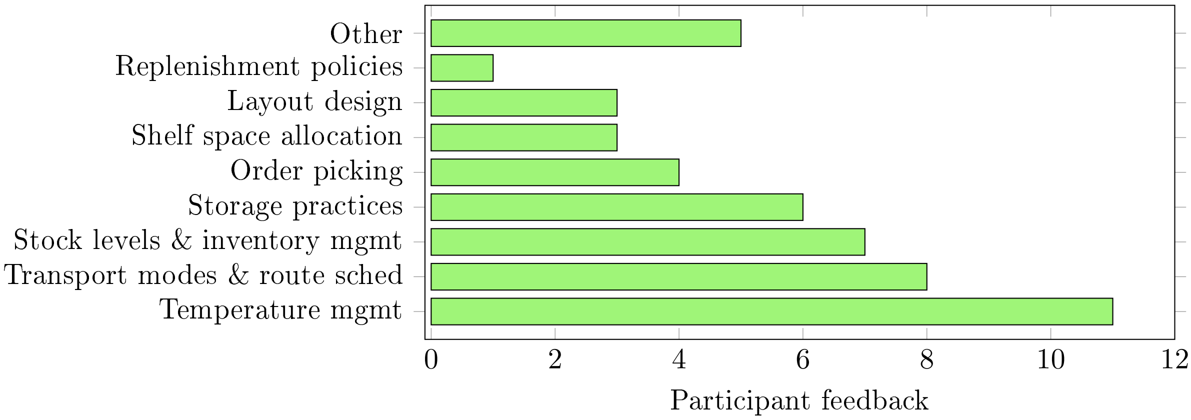


Figure 3.2: General logistic-decisions to consider within the participant's company

Questions two and three were asked to identify key logistic-decisions that influences fresh produce quality after harvest, as well as acknowledging critical quality control points provided by the participants feedback. From Figure 3.3, the feedback provided by the participants was approximately equal. This suggests that all four decisions mentioned in the question, had influence on fresh produce quality once it has been harvested. Figure 3.4 illustrates that the participants believed that the conditions during transportation as well as storage conditions in either the warehouses or the distribution centres were critical quality control points in the fresh produce supply chain.

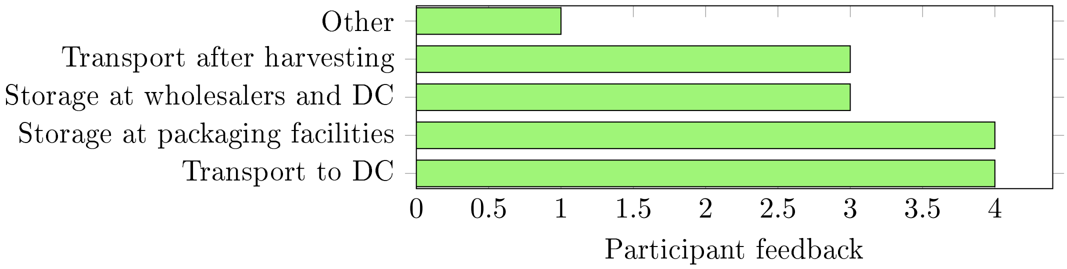


Figure 3.3: Logistic-decisions with the most influence on quality after harvesting

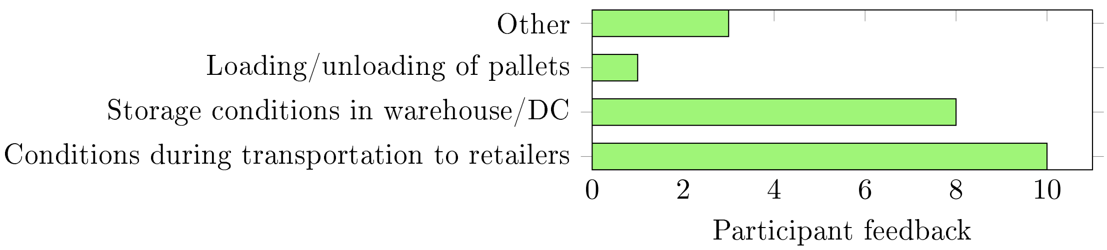


Figure 3.4: Critical quality control points

The purpose of questions four and five was to determine what environmental conditions influence fresh produce quality, and which of these environmental conditions were considered to be important conditions to monitor throughout the supply chain. Figure 3.5 shows the environmental conditions that the participants suggested were important to measure throughout the supply chain. Temperature and relative-humidity (RH) were considered extremely important environmental conditions to monitor, as stated by at least 13 participants. Ethylene was also considered to be a condition to monitor, since four participants said it was extremely important to monitor it, and seven participants said it was moderately important. Other environmental conditions such as the lighting, shock and vibration during transportation, as well as controlled atmosphere (CA) during transportation and storage were mentioned by the participants.

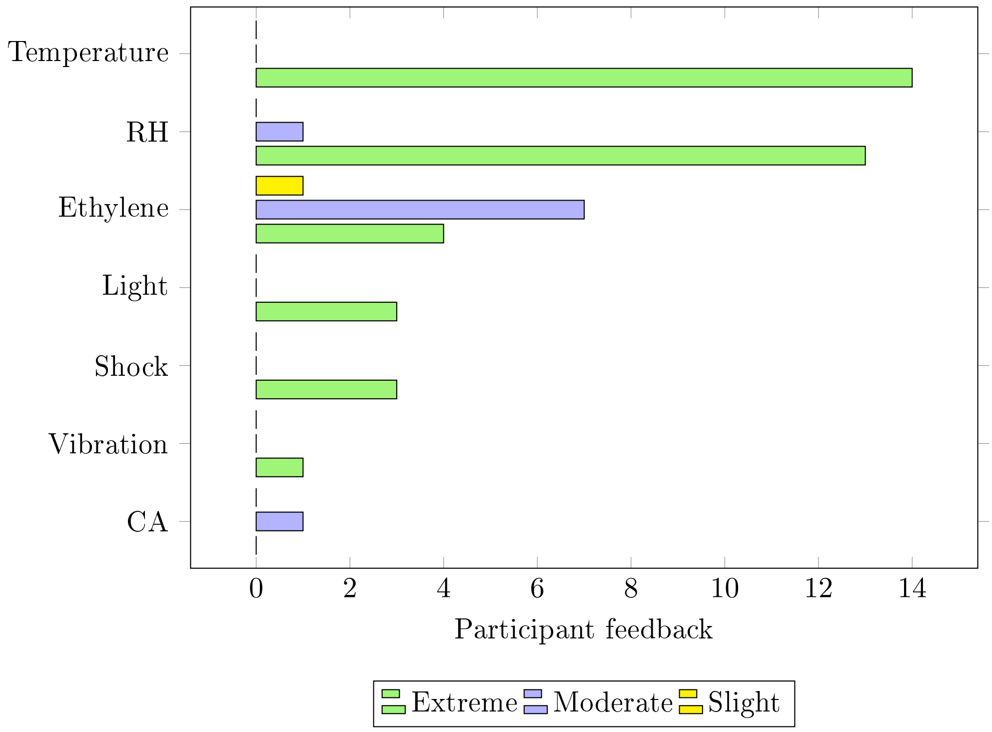


Figure 3.5: Level of importance of monitoring defined environmental conditions

The next question related to the level of influence predetermined logistic activities have on fresh produce quality. A list of logistic activities was provided to the participant and they had to select the level of influence they felt each activity had on fresh produce quality. From the feedback shown in Figure 3.6, it is noted that majority of the participants mentioned that transport scheduling and routing had an extreme influence on fresh produce quality. Activities such as transport mode selection, distribution network design, and storage mode and capacity were also highlighted as activities that had extreme influence on fresh produce quality. Participants also mentioned that activities such as loading capacity and order picking planning had moderate influence on fresh produce quality.

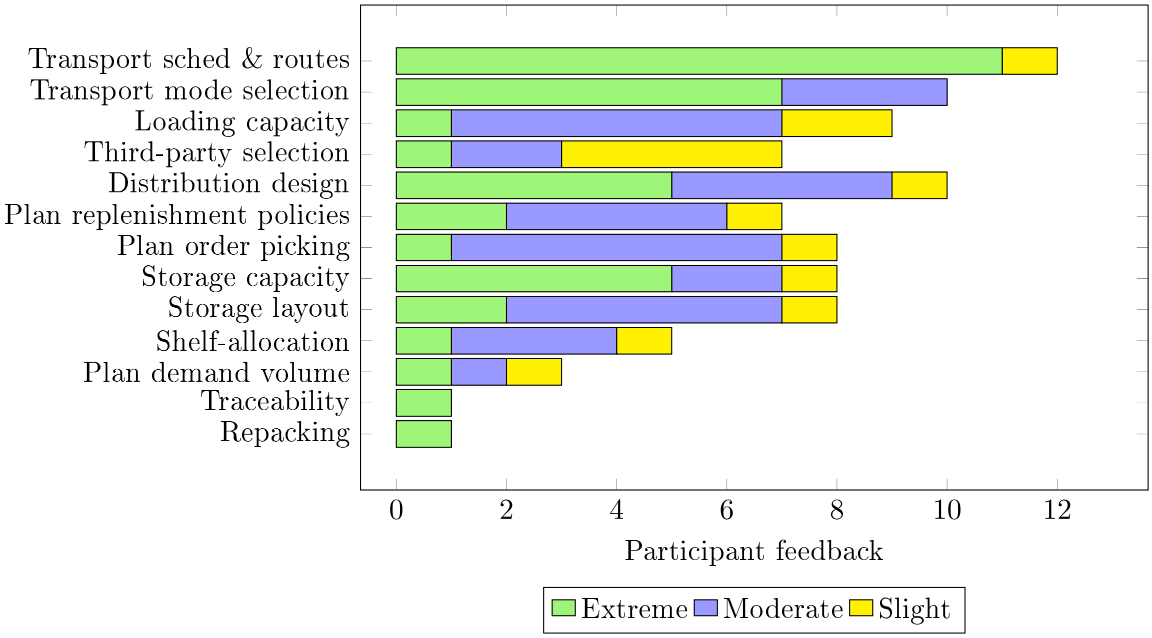


Figure 3.6: Different levels of influence specific logistic activities have on fresh produce quality

The last question focusing on Quality Controlled Logistics, was asked to receive feedback on how fresh produce quality information could add value to current logistic activities in the fresh produce industry. The participants shared their feedback and it was then clustered into groups with similar responses. As shown in Figure 3.7, supply chain management, transportation management, and monitoring environmental conditions were mentioned as the most common activities where fresh produce quality related information could create additional value. Four participants mentioned that it would create additional value to improve transparency and visibility through the supply chain, and three participants mentioned it would create additional value to inventory management and quality management.

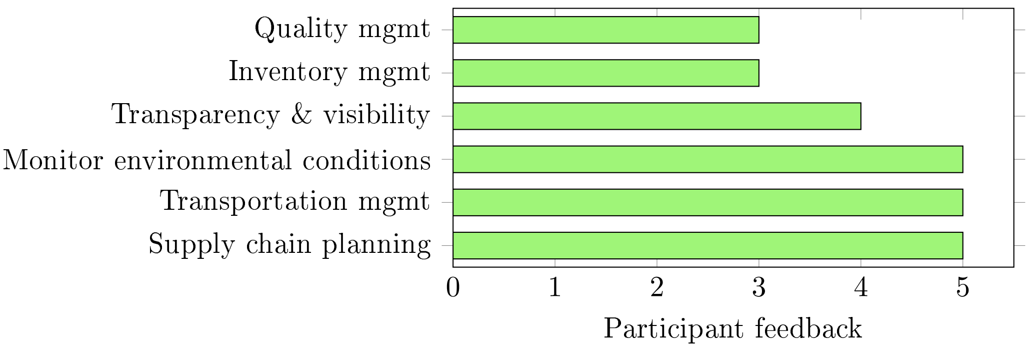


Figure 3.7: Logistic activities where fresh produce quality information can add value

3.3.2 Feedback regarding Internet of Things

The following set of questions was asked of the participants to identify their knowledge on the concept of IoT, and whether they believe that IoT-technologies could contribute to assisting logistic activities and decision-making in the fresh produce industry. The first question gave participants the opportunity to provide some benefits when implementing IoT-technologies in the supply chain. Their feedback was clustered into eight groups as shown in Figure 3.8. From the feedback, eight participants felt that IoT-technologies would assist with the monitoring of environmental conditions, and six participants said it would provide quick access to real-time data. It was mentioned five times that it would provide more visible product quality through the supply chain. Other benefits that were mentioned, include optimising supply chain, processes, cost reduction, supplier trust and increased supplier performance, and reducing human error.

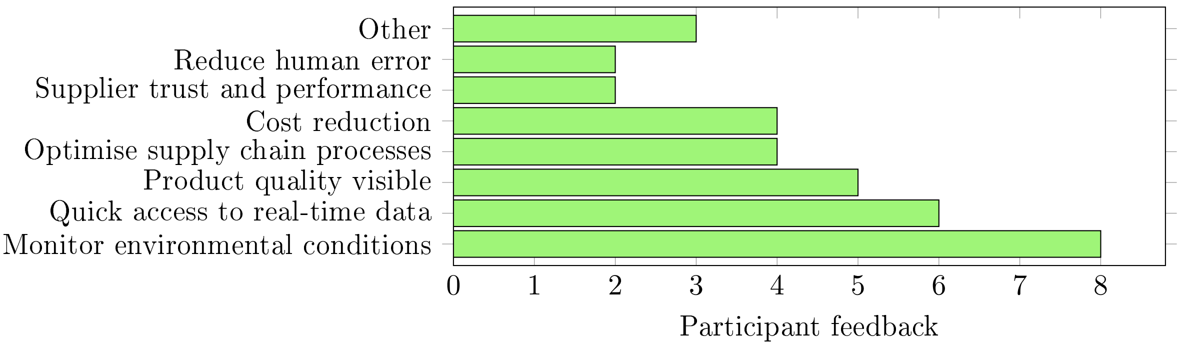


Figure 3.8: Benefits implementing IoT-technologies in the fresh produce industry

Next, the participants were asked to provide feedback on how IoT-technologies could add extra value to logistic-decisions within the fresh produce industry. Feedback was once again clustered into similar responses provided by the participants. Figure 3.9 shows the different value creation opportunities that were identified by the participants. Participants mentioned that IoT-technologies could add value to strategic supply chain planning by creating more flexible and adaptive planning, and using data to identify separate market requirements, and developing new business models. Another popular response was that IoT-technologies have the capability to make logistic activities more visible and transparent throughout the supply chain. An interesting response that was mentioned six times, was that participants believed that IoT-technologies would enhance stakeholder relationships and trust throughout the supply chain.

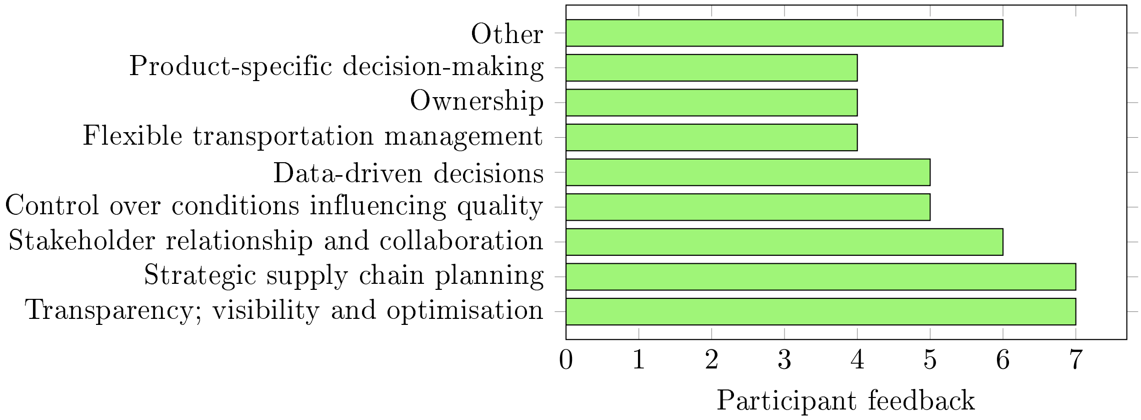


Figure 3.9: Value creation in the supply chain

Figure 3.10 shows the feedback participants provided to the question related to identify technical requirements for the implementation of IoT-technologies in the fresh produce industry. Popular feedback from the participants was the kind of network connectivity required, the type of application devices as well as the user interfaces required, and the type of sensing devices and data loggers to capture relevant data. Only two participants mentioned that data security was an important requirement for IoT implementations.

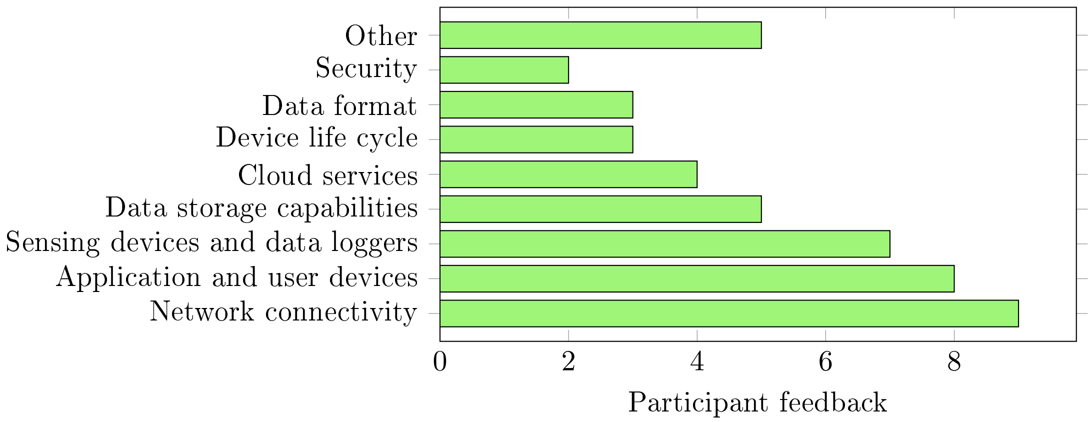


Figure 3.10: Technical IoT requirements

The aim of the last question was to determine what type of challenges the participants believes there were to implementing IoT-technologies in the fresh produce industry. From Figure 3.11, it is noted that acceptance and collaboration to implement IoT-technologies, as well as integrating these technologies with current systems, were the most common challenges mentioned by the participants. Cost of implementation was also mentioned by four participants, but other participants believed that the associated costs of IoT-technologies were not a significant challenge. Other challenges that were mentioned by the participants were the physical installation of the IoT-system, training the users, and receiving valuable information from the collected data.

Figure 3.11: Challenges implementing IoT-technologies

3.4 Discussion

By analysing the feedback from experts in the fresh produce industry, there seemed to be a positive attitude towards the implementation of IoT-technologies to assist several logistic activities in the fresh produce supply chain. The use of IoT-technologies in the fresh produce industry is not new, since solutions to monitor environmental conditions already exist. Although it is widely used during transportation management, it is believed that these technologies can create further benefit in the fresh produce industry, and will be discussed in the points below.

3.4.1 Temperature-management and transportation

From the feedback given by the participants, it is clear that temperature management, otherwise known as "cold-chain monitoring" during transportation, plays an important role within fresh produce supply chain logistics. Stakeholders in the fresh produce industry realise that inappropriate temperature-management is one of the key reasons why fresh produce is wasted throughout the supply chain. Therefore, transportation companies realise the value of reliable temperature monitoring within different transportation modes. Transport companies have started to invest in solutions such as: (i) refrigerated and deep-freeze trucks; (ii) trucks with isolation barriers at the doors; and (iii) temperature recording systems within the trucks, to monitor the temperature conditions while transporting fresh produce to their required destinations. The use of these solutions makes it easier to ensure that temperature stays within acceptable limits, and provides more accurate temperature reading, since in the past temperature logging was done manually.

3.4.2 Monitoring other influences on fresh produce quality

Previously discussed in the literature review (refer to Chapter 2) fresh produce quality depends on both intrinsic and extrinsic attributes. From the feedback, it is realised that companies invest in multiple solutions to monitor extrinsic attributes such as temperature, relative-humidity within transportation and storage infrastructure, and lighting, shock, and vibration during transportation.

Although many participants agreed that influences such as ethylene have an influence on fresh produce quality, there have not been many solutions implemented to monitor and track these intrinsic attributes throughout the supply chain. Monitoring intrinsic attributes can provide meaningful information on fresh produce quality, especially when these attributes can be incorporated into shelf-life or prediction models to assist logistic-decisions.

3.4.3 Importance of quality-related shelf-life models

Participants were asked what type of methods they use to estimate remaining shelf-life of fresh produce, and majority responded that best-before-dates are used. The problem with this method, is that it is a static method and ignores temperature exposure history as well as other conditions affecting shelf-life. To develop more accurate and dynamic shelf-life models, it is required to monitor attributes that influence the fresh produce quality such as temperature, relative-humidity, and ethylene release, depending on the fresh produce characteristics.

Developing accurate quality-related shelf-life models can be a game-changer in the fresh produce industry, as it has the capability to become a useful tool to assist decisions regarding several logistic activities in the fresh produce supply chain. Most warehouses and distribution centres use a "First-In-First-Out" inventory management approach. The problem with this approach is that it assumes that all fresh produce arriving the same day at warehouses or distribution centres has the same shelf-life, which is not true due to different conditions the produce has been exposed to. Knowing the predicted shelf-life based on quality, products can be distributed via a First-Expiry-First-Out (FEFO) approach. Another benefit using quality-related shelf-life models and the FEFO inventory management approach, is that fresh produce shipments can be distributed more "intelligently" by matching the remaining shelf-life to the required lead time until the shipment reaches the desired location. Not only can it reduce food waste during transportation, but it ensures that remaining shelf-life in a shipment is uniform, meaning the variation of quality is less.

3.4.4 Need for accurate visual inspection

Visual inspection is a fast and common method used to assist quality management, and to decide whether the fresh produce pallets should be accepted or rejected. The problem with visual inspection is that it only reflects visible deterioration and does not consider other influences that reduces quality. The challenge with perishable products is that they usually look fresh until just before they are about to get spoiled. This makes it difficult to distribute correct quality fresh produce to the various market segments, as good-quality fresh produce may be rejected, and bad-quality fresh produce accepted.

Fortunately, from the feedback provided, participants realise this challenge and agreed that there is a need to make intrinsic quality attributes more visible and transparent through the supply chain to improve and assist logistic activities such as quality management, better supply chain management, and monitoring environmental conditions to ensure optimal fresh produce quality for end consumers. The benefits of making fresh produce quality information more visible are numerous since it might: (i) improve quality consistency; (ii) reduced waste due to better logistic-decisions; and (iii) a higher delivery yield, since fresh produce will be accepted based on more accurate quality information.

3.4.5 Need for pallet-level monitoring

Many companies in the fresh produce industry realise the importance of monitoring environmental conditions, since it influences the quality of fresh produce to some extent, and multiple solutions can be implemented to assist companies. But only a few companies realise that pallet-to-pallet variations exist, hence they realise that environmental monitoring only provide limited fresh produce quality information. To address this problem, new solutions must be created to monitor and act upon these variations, and one method is implementing pallet-level monitoring. Pallets are an effective position to monitor, as they spend most of their life cycle with the fresh produce itself. Pallet-level monitoring is capable of capturing the actual condition of the fresh produce, providing more accurate data to develop shelf-life prediction models.

Another important benefit of implementing pallet-level monitoring is that it can act upon quality variation and reduce losses. For example, Jedermann *et al.* (2014) mention in a case study that the temperature within pallets during transit is not the same. The result is that some pallets may experience quality degradation faster than others. Knowing the quality of fresh produce inside pallets can change several logistic activities such as inventory management and distribution, and it can enhance shelf-life optimisation.

3.5 Conclusion

The aim of this chapter was to identify current knowledge on quality-controlled logistic within the fresh produce industry, and to identify whether there were opportunities to implement Internet of Things technologies in this industry. Questionnaires were developed to receive feedback from experts within the fresh produce industry, regarding the two concepts. After the analysis of expert feedback, key discussion points and recommendations were provided.

Chapter 4

Traditional logistic activities versus quality-controlled logistics

The aim of the previous chapter was to identify whether experts within the fresh produce industry are familiar with the concept of quality-controlled logistics and to receive their feedback and insight on the topic. The following chapter will list and describe key traditional logistic activities that are currently being implemented in most fresh produce supply chains, as well the impacts they have on fresh produce quality. Thereafter, several strategies are discussed to potentially implement quality-controlled logistic activities. Lastly, a discussion on dynamic shelf-life modelling will be provided, and how it can be used to assist quality-controlled logistics to potentially reduce fresh produce waste.

4.1 Key traditional logistic activities and the influence on quality

Fresh produce is wasted due to the natural decay of produce quality which cannot be prevented. Hence, the actors in the fresh produce supply chain are responsible for monitoring and controlling activities that influence the quality of fresh produce. There are specific logistic activities where critical decisions need to be made in order to control the quality of fresh produce to ensure that the produce has sufficient remaining shelf-life during consumption. Zestlabs (2016b) and McBeath (2013) identified and discussed how the following key logistic activities within each stage of the fresh produce supply chain have an influence on produce quality.

4.1.1 Harvesting

When to send the harvested load from the farm to the pre-cooling facility

Produce is placed in picking baskets once it have been harvested and these are loaded onto trucks. The trucks transport the baskets to the pre-cooling facility when the loading capacity has been reached. The problem with this activity is that the baskets that were loaded initially, spend a longer time in higher temperatures and it influences the quality of the produce. This results in quality variation between the produce even when the produce has been harvested on the same day (Zestlabs, 2016b).

Determining the sequence of pre-cooling

Produce that has been harvested earlier during the day can be sent directly to the pre-cooling facility, but as time moves on, the capacity of the pre-cooling facility struggles to match the rate of produce being harvested, and baskets are left outside the pre-cooling facility. The baskets left outside the facility will then require more time in the pre-cooling facility to reduce the pulp temperature to the required temperature (Zestlabs, 2017a). What might happen is that some baskets that are loaded for shipment never reach optimal pulp temperatures, or that baskets spend too much time in the pre-cooling facility to wait until the later baskets have reached optimal temperature. Another consideration is although baskets have been in the same pre-cooling environment, the temperature of each basket will still vary after pre-cooling (McBeath, 2013). Without tracking the temperature of each basket, it is difficult to identify which baskets require longer pre-cooling and which baskets are ready to be transported.

4.1.2 Processing and packaging

Which pallets to load together on shipments

After the produce has been washed, graded and packaged according to specific market requirements, the packaged produce is put onto pallets and placed in a cold storage facility until they need to be shipped. When pallets are picked to be shipped to various locations, they are usually selected based on a First-In-First-Out policy (Zestlabs, 2016b). For example, pallets that were placed first into cold storage will be selected for shipment first. When pallets are selected for shipment, the different variations in produce quality and remaining shelf-life are not considered. These variations influence the remaining freshness of the delivered produce and when they are not considered, it can lead to disappointment in delivered freshness, or produce is rejected by retailers because it does not meet the recommended requirements (Zestlabs, 2016b).

4.1.3 Distribution

Which pallets to pick for each retailer

Distribution centres receive fresh produce pallets from various farmers and usually each pallet has different produce quality and variations in remaining shelf-life. These pallets must then be transported to multiple retailers in various locations. Once again, pallets are selected based on a First-In-First-Out policy, and the different produce quality and remaining shelf-life variations are not considered. When these variations are not considered it can impact the delivered freshness of the fresh produce and increase the risk of pallets being rejected (Zestlabs, 2016b). When selecting which pallets to transport to the retailer, the location of the retailer, transit time, and retailer requirements should also be taken into account. The reason therefore, is that the conditions of transportation during transit further influence the remaining shelf-life and product quality (McBeath, 2017). For example, when a pallet is received by the farmer and the estimated remaining shelf-life is 5 to 7 days, the pallet should be transported to a retailer that is situated close to the distribution centre, whereas a pallet with an estimated remaining shelf-life of 10 to 12 days can be sent to a retailer that is further away.

Choosing third-party transport solutions

Monitoring the conditions inside the means of transportation is important since pallets spend a lot of time being shipped from one location to another location until they reach the retailer. In most cases, stakeholders are not responsible for the transport of the pallets and rather invest in third-party transport solutions to ship the pallets. The issue here is that the stakeholders do not have control over the transportation conditions (McBeath, 2013). For example, before trucks can be loaded with fresh produce pallets, the refrigerated container on the truck should be switched on to cool the inside of the container to the desired temperature. This is usually done as the truck is on its way to collect the shipment. Unfortunately, stakeholders can only monitor whether the temperature inside the container is correct once the truck has arrived at the loading or unloading zones (Zestlabs, 2017a). If the temperature is not correct, either the pallets cannot be loaded; or the produce quality and remaining shelf-life will decrease dramatically if they are loaded into the container. This will possibly result in pallets being rejected due to the lack of appropriate temperature control.

4.1.4 Retailer

Which pallets to accept and reject

Fresh produce pallets are transported from large distribution centres to multiple retail stores, but before the pallets are unloaded the shipment needs to be inspected to decide whether the shipment will be accepted or rejected (McBeath, 2013). In most cases a few pallets are randomly selected for inspection. Retailers usually rely on visual inspection and truck-level data loggers to determine the quality and remaining shelf-life. But the issue with visual inspection is that it is not a reliable method for estimating remaining shelf-life because fresh produce can look fresh on the day of inspection but by the following day it will have become spoilt (Zestlabs, 2016b). Hence, fresh produce pallets may be accepted although the remaining shelf-life actually does not meet the retailer's freshness requirements. Retailers also measure the temperature inside the trucks to determine whether the pallets were transported within the right conditions and then accept or reject the entire shipment based on the results of those measurements. This means that they do not consider that each pallet may have a unique temperature profile; hence pallets are rejected even though they could still be accepted, or pallets are accepted when they should be rejected.

Moving pallets from the back store to the shelves

When the stock levels on the shelf spaces are low, stock-clerks are notified to restock the shelves.

Fresh produce pallets are stored in a temperature-controlled storage at the back of the retail store. The stock-clerk picks the required number of produce packages from various pallets and places it on trays to transport the fresh products through the store to restock the shelves. The problem is that the stock-clerk does not realise that the amount of time they spend removing the fresh produce from the storage, transporting it through the store and restocking the shelves can reduce the quality of the fresh produce products. The reason is that once the produce is removed from the back store, it is exposed to warm temperatures in the store, and the more time it spends in those temperatures the more likely it is subjected to quality degradation.

Sales allocation and discounts

Fresh produce close to the use-by date is normally perceived as being of lower quality products by consumers and is less likely to be purchased. This often leads to excess produce on the shelves and then become wasted because the produce has reached its acceptable quality period (Buisman *et al.*, 2017). Retailers have adopted the strategy of giving discounts on fresh produce that reaches the use-by date to persuade consumers to purchase the less-favourable produce and to reduce food waste. The problem is that use-by dates are usually determined by the producers and the retailers have limited knowledge of whether the quality of the produce actually matches the use-by dates. Hence, retailers carry the risk of discounting produce that could have been sold at a higher price; or consumers might be dissatisfied because the produce quality does not match their expected value (Wang & Li, 2012).

4.2 Strategies to implement quality-controlled logistics

Now that the key traditional logistic activities were identified, it is necessary to discuss several strategies to assist the implementation of quality-controlled logistics activities. These strategies were identified and developed with assistance from reviewed literature and the feedback from the questionnaires in Chapter 3.

4.2.1 Harvesting and process and packaging

Monitoring time and temperature deviations

High temperature has a big impact on the shelf-life of produce because it increases the rate of quality degradation. Produce is normally harvested in warm temperatures and are only sent to the pre-cooling facility when the trucks are fully loaded, meaning the time produce spends waiting to be transported to the pre-cooling facility is not considered. For example, suppose it takes 30 minutes to fill one picking basket in temperature of 22°C and there are ten baskets to fill before they are loaded onto the truck. This means that the first basket will spend five hours waiting before it is transported to the pre-cooling facility. This will result in the first basket having less remaining shelf-life than the last basket.

Monitoring the time each picking basket spends in uncontrolled temperatures can assist farmers to decide when it is necessary to send the baskets to the pre-cooling facility to ensure that the quality is not affected by the warm temperatures (Zestlabs, 2016b). For example, the farmer can decide to make more frequent trips with smaller loads to ensure that the baskets do not spend too much time in warm temperatures. It may also help to determine the shelf-life variation between the different baskets that have been harvested on the same day. Shelf-life variation between the baskets may be used to notify workers to make real-time adjustments to the pre-cooling processes to ensure that the baskets will be pre-cooled within the correct time and temperature before they are transported to the processing and packaging facility (Zestlabs, 2016b). Additionally, the temperature of the baskets may be tracked wirelessly inside the pre-cooling facility and notifications can be sent to workers when the baskets have reached optimal temperatures, eliminating manual checks and ensuring that temperatures are monitored more accurately. This would not only improve produce quality at the pre-cooling facility but it may benefit profits and company branding downstream in the supply chain.

4.2.2 Distribution

First-Expiry-First-Out inventory management

Most distribution centres use a First-In-First-Out (FIFO) strategy to determine which pallets should be loaded for shipment. The FIFO strategy assumes that all pallets are exposed to the same environmental conditions, product quality and remaining shelf-life. Thus pallets that are received first are loaded for shipment first because it is assumed that first pallet has the least remaining shelf-life, as shown on the left-hand side of Figure 4.1. The concept of using shelf-life information to improve inventory management was introduced by Labuza *et al.* (1990). They suggested that pallets with the least remaining shelf-life should be loaded for shipment first. For example, as shown on the right-hand side of Figure 4.1, the pallet that arrived second at the distribution centre should be shipped first because the remaining shelf-life of the pallet is the least. The main benefit of implementing a First-Expiry-First-Out (FEFO) strategy is the ability to deliver more fresh produce with longer remaining shelf-lives that otherwise may have spoiled in the distribution centre or during transit (Zestlabs, 2016a).

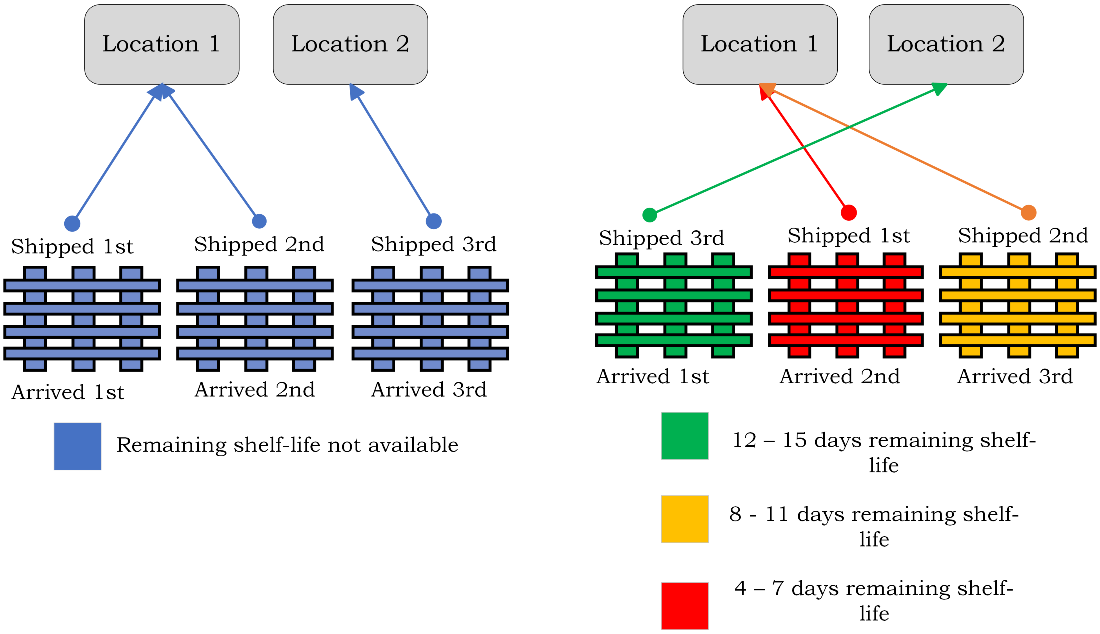


Figure 4.1: First-In-First-Out versus First-Expiry-First-Out inventory management

Intelligent distribution

Intelligent distribution builds on the FEFO strategy by adding intelligence about the locations to which different shipments should be distributed. To make distribution more intelligent, decisions should be based on matching remaining shelf-life of pallets with the transit time to the various locations as well as the consumption velocity and freshness requirements of the retailers (Zestlabs, 2016a). Ideally, pallets with lower remaining shelf-life are distributed to retailers who are located the closest to the distribution centre and pallets with longer remaining shelf-life are sent to retailers who are located further away from the distribution centre. Figure 4.2 illustrates a simple example of how a FEFO strategy is adapted to incorporate intelligent distribution. On the left-hand side of the figure, the pallets that arrived second and third are distributed to the first retailer because they have less remaining shelf-life than the pallet that arrived first. On the right-hand side of the figure, the transit times to the retailers are considered. Since the shipment requires five days of transit, the first and the third pallets are distributed to this retailer because they will have sufficient remaining shelf-life at the retailer after distribution. The second pallet is distributed to the second retailer because the shipment only requires two days of transit.

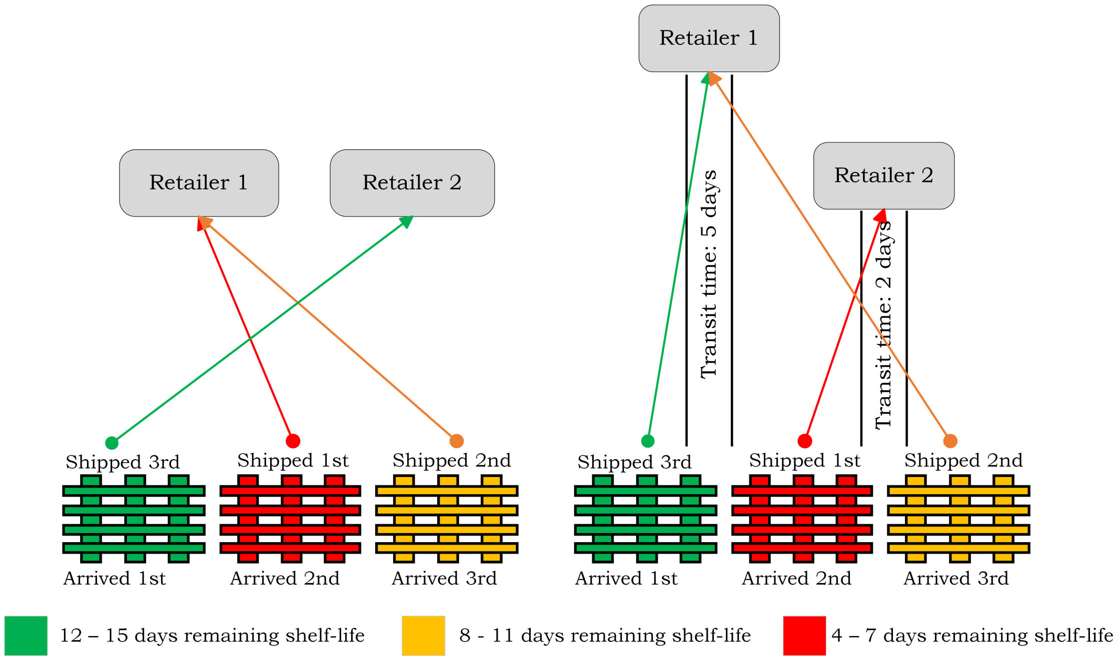


Figure 4.2: Intelligent distribution based on transit time

Additionally, the shipment dates of pallets can be calculated based on the date of expected delivery, freshness requirements, and the transit time to the retailers. The remaining shelf-life of pallets is then matched to an optimal retailer based on the above-mentioned attributes (McBeath, 2017). This concept is illustrated in Figure 4.3. Assume Retailer 1 requires pallets to remain fresh for at least two days from expected delivery, thus the pallets may have a short remaining shelf-life. The transit time to Retailer 1 is four days, this means that once the pallets are distributed to Retailer 1, they should have a remaining shelf-life of at least six days otherwise the pallets may not fulfil the freshness requirements of the retailer. The distributor should then be able to prepare the shipment date based on the minimum required remaining shelf-life. Now consider Retailer 2 and Retailer 4 where both have freshness requirements of three days from expected delivery. The transit time to Retailer 2 is seven days whereas the transit time to Retailer 4 is one day. Although the freshness requirements are the same for both retailers, it does not mean that pallets with similar remaining shelf-life can be distributed to both retailers, because in the case of Retailer 2, the pallets should have at least six days more remaining shelf-life to ensure that the freshness requirement is met.

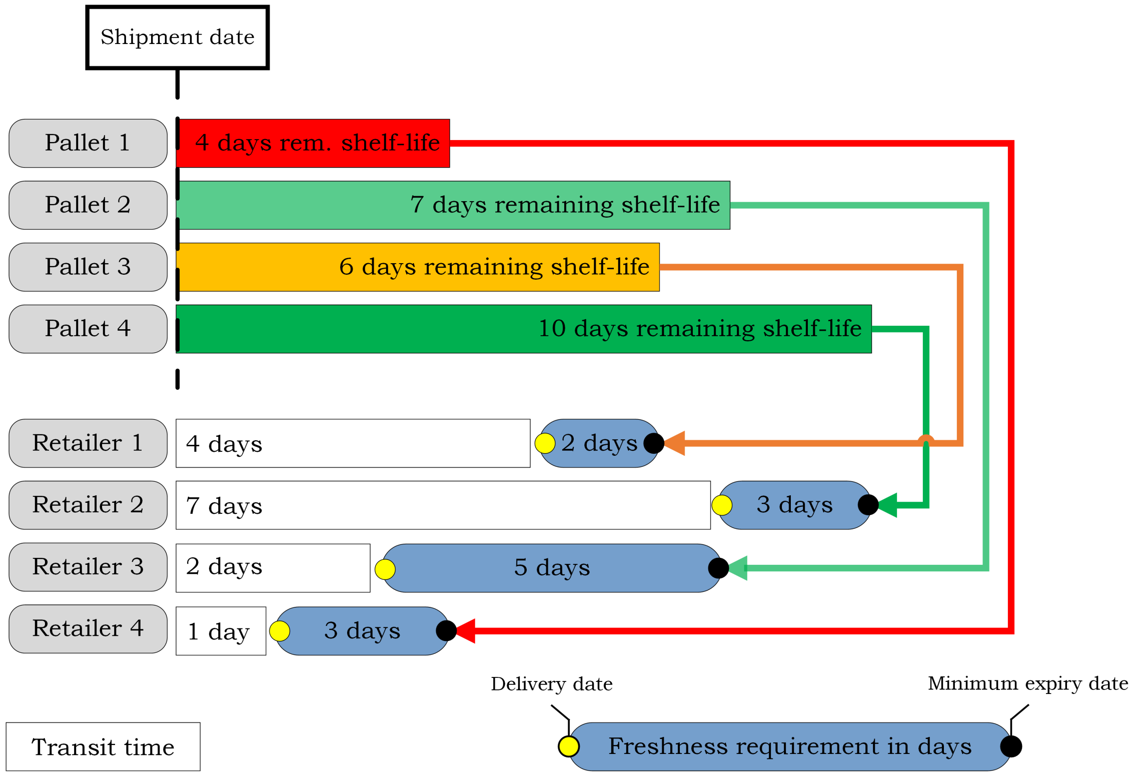


Figure 4.3: Intelligent distribution based on customer freshness requirements

Intelligent distribution can become even more advanced by considering additional attributes such as retailer importance, product type and variety, and specific contractual obligations of each retailer (Zestlabs, 2016a). These attributes can be implemented into an intelligent routing algorithm that runs on an autonomous system to provide decision support for the distributors. The benefit of such a system will be to gain insights on the remaining shelf-life of pallets being delivered, and to build confidence on the quality of delivered freshness of pallets instead of blindly sending pallets that might be spoiled to retailers who may reject them.

Quality assurance when using third-party transport solution

In most cases, parts of the transport processes need to be subcontracted to third-party transport solutions. Some third-party transporters do have temperature sensors and loggers installed inside their trucks to monitor environmental conditions. Hence, quality control can be based on the data of the conditions inside trucks (Zestlabs, 2017a). But third-party transport solutions are often reluctant to share real-time data or they only provide data on demand after a claim for product damage has been raised. This means that the stakeholders do not have control over the conditions that the produce is exposed to during transport, and it is difficult to estimate the remaining shelf-life without receiving any data during transport.

Thus, to receive more accurate real-life data on produce quality and determining the shelf-life lost during transport, it would be beneficial to monitor the quality on a pallet or packaging level (Zestlabs, 2016a). Stakeholders will be able to have real-time data available on the pallets without interacting with the third-party transport solution. Additionally, it provides stakeholders with insights on whether the third-party transport solutions adhere to the required quality regulations, or whether they should consider investing in other third-party solutions who are willing to comply with the required quality regulations.

4.2.3 Retailer

Accept number of pallets with remaining shelf-life

Once fresh produce pallets are distributed to the retailers, random pallets are selected to test the quality to determine whether to accept or reject the shipment. Usually they have limited knowledge on the actual remaining shelf-life because visual inspection and truck temperature conditions may not provide sufficient information to accept or reject the pallets. But when the shelf-life of each pallet is available at the point of delivery, they can accept or reject shipment based on pallet-specific information and reduce the risk of selling bad quality produce when it was assumed that the produce had sufficient remaining shelf-life (Zestlabs, 2017b). Furthermore, accepting pallets based on remaining shelf-life will improve the retailer's brand and customer loyalty because consumers will realise that the produce has less quality variation after purchase.

Dynamic pricing and discount models based on remaining shelf-life

Consumers base their perception of produce quality by means of use-by dates on packages. Consumers are less likely to purchase produce close to the use-by date because they assume the produce will be spoilt when it is past the date (Tsiros & Heilman, 2005). Instead of allowing consumers to measure produce quality based on use-by dates, they should be able to measure produce quality based on remaining shelf-life available. Retailers can use the remaining shelf-life of produce to develop dynamic pricing and discount models. Implementing shelf-life dependent pricing and discount models may increase the quantity of fresh products sold and reduce the amount of produce being thrown away because it passed the use-by date, even when the produce may still be of acceptable quality (Buisman *et al.*, 2017). Thus, instead of losing profit because of produce not being sold at all, retailers can still gain profit by selling produce at a discount based on the remaining shelf-life available. Furthermore, retailers may subjectively persuade consumers to buy fresh produce with lower remaining shelf-life and still show a profit even though the fresh produce is sold at a discounted price. Consumers have the opportunity to decide whether they want to buy fresh produce with a shorter remaining shelf-life at a discounted price, or whether they want to buy fresh produce with a longer remaining shelf-life for a higher price.

Table 4.1 summarises the traditional logistic activities as well as the quality-controlled logistic activities that were discussed.

Table 4.1: Traditional logistics versus quality-controlled logistics

Relevant stake-holder	**Traditional logistic activities**	**Quality-controlled logistic activities**
Harvesting	• When to send the harvested load from the farm to the pre-cooling facility. • Determining the sequence of pre-cooling.	• Monitoring time and temperature deviations.
Process and packaging	• Which pallets to load together on shipments.	• Creating loads with uniform shelf-life.
Distribution	• Which pallets to pick for each retailer. • Choosing third-party transport solutions.	• First-Expiry-First-Out stock rotation management. • Intelligent distribution. • Quality assurance when using third party transport solution.
Retailer	• Which pallets to accept and reject. • Moving pallets from back store to shelves. • Sales allocation and discounts.	• Accepting the number of pallets based on remaining shelf-life. • Condition monitoring to adjust replenishment strategies. • Dynamic pricing and discount models based on remaining shelf-life

4.3 Introducing dynamic shelf-life to assist quality-controlled logistics

To implement quality-controlled logistics, it is necessary to have relevant information on fresh produce quality available to assist decision-making. Fresh produce quality is greatly impacted by influences such as microbiological infestations; biochemical and physical changes; and mechanical changes happening through the supply chain (Pang *et al.*, 2015). These influences are evoked by various conditions the fresh produce is exposed to, and although it is difficult to prevent these influences, it is possible to monitor the conditions and to use the information to create shelf-life prediction models to determine available quality of the fresh food.

Dynamic shelf-life can be defined as the time span for which the fresh food products can be stored at a certain reference temperature until they are no longer suitable for human consumption or when the food quality does not meet the freshness requirements of consumers (Jedermann *et al.*, 2014). Shelf-life and "best-before" dates are often confused as being a similar concept. Best-before dates are fixed dates that have been determined by the producer and imply that the product is useful for a couple of days, if it has been stored under the correct conditions (Sjödahl & Lilja, 2014). Shelf-life is a dynamic value that depends on product and packaging characteristics; and the environmental conditions products were exposed to during storage and distribution (Hertog *et al.*, 2014).

4.3.1 Modelling dynamic shelf-life

Dynamic shelf-life models are models where the shelf-life of fresh produce is calculated as a function of environmental conditions in the supply chain, taking into account the freshness requirements of the consumers. The purpose of dynamic shelf-life models is to predict the quality of fresh produce by translating the impact of logistics on produce quality in terms of remaining shelf-life (Hertog *et al.*, 2014). Most research on shelf-life models agrees that factors such as relative humidity, gas concentrations and temperature have the most influence on product quality, hence these parameters can be used to predict the remaining shelf-life of fresh produce (Hertog *et al.*, 2014; Jedermann *et al.*, 2014; Sciortino *et al.*, 2016).

A simple and fairly accurate temperature-dependent shelf-life can be modelled by using of Arrhenius' law for reaction kinetics as explained by Hertog *et al.* (2014); InfraTab (2011)and Labuza (1984) where the change in quality of a product over time t can be expressed as shown in Equation 4.1:

$$\frac{dq}{dt} = kq^n \tag{4.1}$$

where:
q = Quality of the product
k = Reaction rate constant
n = Reaction order.

It is then possible to create a kinetic-mathematical model that describes the evolution of the rate constant k of chemical reactions depending on storage times at different temperatures T for a specific activation energy, according to Arrhenius' law:

$$log\frac{k_2}{k_1} = -\frac{E_a}{R}(\frac{1}{T_2} - \frac{1}{T_1}) \tag{4.2}$$

where:

E_a = Activation energy of a specific produce

R = Universal gas constant (≈ 8.31 J/mol K)

The deterioration rate can be considered as inversely proportional to the storage time of the product, then Equation 4.2 can be rewritten as:

$$Det_{Tt} = Det_0 e^{-(\frac{E_a}{RT_t})} \tag{4.3}$$

where:

Det_{Tt} = Deterioration rate at temperature T_t

Det_0 = Deterioration rate at optimal temperature

E_a = Activation energy

R = Universal gas constant (≈ 8.31 J/mol K)

T_t =Temperature at time t in Kelvin

Equation 4.3 allows to calculate the amount of deterioration loss when the product is exposed to different temperatures.

Another popular approach is to use any known reaction activity of a produce type to develop a shelf-life model. It is assumed that the speed of ageing increases proportionally to the increase of a reaction at higher temperatures. Thus, the temperature dependency can be modelled as an exponential function with the Q_{10} value as the key parameter. Q_{10} is the factor by which the reaction rate increases when the temperature rises by ten degrees (Jedermann *et al.*, 2014). The Q_{10} parameter can be defined by measuring the rate of reaction of a specific quality attribute at different temperatures as shown in Equation 4.4:

$$Q_{10} = (\frac{R_2}{R_1})^{(\frac{10}{T_2 - T_1})} \tag{4.4}$$

where:

Q_{10} = Temperature coefficient

R_1 = Rate of reaction at temperature 1

R_2 = Rate of reaction at temperature 2

T_1 = Temperature 1 in Celsius or Kelvin

T_2 = Temperature 2 in Celsius or Kelvin.

After Q_{10} is determined the *Accelerated Ageing Rate* can be calculated as shown in Equation 4.5:

$$A = Q_{10}^{\frac{(T_e - T_a)}{10}} \tag{4.5}$$

where:
A = Accelerated ageing rate
T_e = Elevated temperature
T_o = Optimal temperature.

Finally, the remaining shelf-life can be calculated by dividing the expected or required shelf-life by the accelerated ageing rate as shown in Equation 4.6:

$$SL_{est} = \frac{SL_{exp}}{A} \tag{4.6}$$

where:
SL_{est} = Estimated shelf-life
SL_{exp} = Expected shelf life.

These shelf-life models are only based on single quality attributes. To cover a wider range of environmental conditions multiple quality factors such as colour, firmness, or taste should be considered. Implementing multiple quality attributes will surely improve the accuracy of shelf-life modelling but it also increases the complexity of the model development. Hence, the selection of shelf-life models depend on the amount of data available in real time, the budget to carry out laboratory tests, and the technical capabilities of monitoring environmental data (Jedermann *et al.*, 2014). It is necessary to realise that it is nearly impossible to eliminate all shelf-life uncertainties, because produce types have different biological quality attributes to consider and not all produce will react the same way in specified environmental conditions. Nevertheless, the models can provide great insights for inventory management, prioritising pallets for shipment and potentially reduce food waste along the supply chain.

4.3.2 Impact of dynamic shelf-life on food waste

The use of dynamic shelf-life predictions to monitor and control quality will certainly raise awareness on how logistic activities affect the quality of fresh produce. Stakeholders will be able to accurately predict the quality of fresh produce and use the information to either continue with their current logistics activities, or change their strategies to minimise the amount of produce being wasted (Ostojic *et al.*, 2017), especially reducing the waste of good quality produce. Buisman *et al.* (2017) agreed that dynamic shelf-life predictions resulted in only low-quality products being wasted, whereas fixed expiry dates caused even high quality products to become waste. Furthermore, dynamic shelf-life predictions may provide additional benefits such as improved product safety, controlled distribution, better traceability and transparency, and increased consumer satisfaction.

4.4 Conclusion

The aim of this chapter was to list and discuss the key traditional logistic activities that are currently implemented in most fresh produce supply chains, as well as the impacts they have on fresh produce quality. Several strategies were developed and discussed to change logistic activities to become more quality controlled. Lastly, the concept of dynamic shelf-life modelling was discussed as well as how it could be used to implement quality-controlled logistics throughout the fresh produce supply chain to potentially reduce food waste.

Chapter 5

Development of a simulation model for investigating quality-controlled logistic activities

The previous chapter identified and discussed traditional logistic activities that take place within a fresh produce supply chain, as well as the influences they have on the quality of fresh produce at each stage of the supply chain. Thereafter, several quality-controlled logistic activities have been proposed and discussed to determine how they can improve the quality of fresh produce and possibly reduce waste that occurs due to logistic activities. The concept of dynamic shelf-life predictions was identified as a suitable application to implement quality-controlled logistic activities.

The following chapter will explore the impact of implementing selected quality-controlled logistic activities on fresh produce quality as well as the amount of waste being produced throughout the supply chain. This will be done by means of a simulation study based on a fresh produce supply chain. The chapter will provide a brief explanation on simulation modelling and why it is used in this research study. Thereafter an overview of the studied supply chain will be provided. The remainder of this chapter will focus on the model development and the design of experiments to measure the effect of quality-controlled logistic activities on quality and on the amount of waste produced in the selected retail chain.

5.1 Discrete-event simulation

Simulation modelling can be defined as the experimentation with a model based on a real-world system to study the behaviour of the model, given certain conditions (Bekker, 2016). It is a tool often used to study "what-if" scenarios for stochastic, complex processes. Schriber *et al.* (2014) define discrete-event simulation as models that change only at a discrete but random, set of simulated points, called event times. Ingalls (2001) mentions that discrete-event simulation is a powerful modelling tool due to its ability to mimic the dynamics of real systems.

Simulation modelling is often used as an analysis tool in research when experimentation with the actual system is not possible, and when the system is too complex to analyse analytically. Other benefits of simulation include (Bekker, 2016):

1. The ability to analyse systems before implementation, hence avoiding and minimising cost;
2. To assist tactical and strategic planning;
3. Apply changes to the system without disrupting the processes within the system; and
4. To evaluate alternatives.

Given the benefits of simulation modelling, one must consider the drawbacks as well. Some drawbacks include that the simulation analyst needs to have experience and training to use simulation software, and they should have a sound statistical background to interpret the simulation results. Simulation studies may be costly and time-consuming, depending on the complexity of the observed system (Bekker, 2016).

Discrete-event simulation modelling will be used in this research study because it will provide the researcher with the ability to analyse the impact of implementing quality-controlled logistics within the fresh produce supply chain. The simulation model will be used to evaluate various logistic alternatives without disrupting the actual supply chain. The software package, Tecnomatix Plant Simulation®, will be used to develop the simulation model, since a licence is already available and the researcher has training and experience with this software.

5.2 Case study

The case study will focus on strawberry production in South Africa. The reasons for this selection are that strawberries are among the fresh produce categories that are the most perishable and they tend to have a short postharvest life of approximately 14 days, even when handled under optimal conditions. The remaining shelf-life of strawberries is heavily influenced by the temperatures they are exposed to (do Nascimento Nunes *et al.*, 2014; Leithner *et al.*, 2017; Sciortino *et al.*, 2016). This means that high wastage of strawberries can occur throughout the supply chain if there is a lack of proper temperature management and if the logistic activities do not consider the short remaining shelf-life.

5.2.1 Supply chain overview

A strawberry supply chain from a South African retail chain was analysed in this case study. The reason this retail chain was analysed is because they focus on consumers who are highly value-conscious of food and grocery prices. It is believed that the retail chain may benefit from this case study since a key value of the retail chain is to ensure exceptional quality. The names of the retail chain and the supplier are not mentioned due to confidentiality reasons. Therefore, terms such as 'supplier', 'distribution centre', and 'retail store' will be used instead of mentioning the actual company names. The retail chain owns three large distributions centres and about 400 food retail stores across the country. To reduce the complexity of the study, the supply chain network will be limited to the Western Cape province.

The distribution centre is located in the Cape Town area and receives most of its strawberries from a local strawberry supplier in Stellenbosch. The strawberry supplier owns multiple strawberry farms with a total size of about 80 hectares. The supplier produces approximately 5 to 10 tons of strawberries every week during harvesting season. Strawberry deliveries to the distribution centre are done once a day from Monday to Sunday. The distribution centre supplies strawberries to 67 retail stores in the Western Cape province. The distribution centre supplies stock to the retail stores daily. An automatic replenishment software is used to determine the quantity of stock needed for each district in the Western Cape. Delivery routes to the retail stores are determined daily by route planners and deliveries are mostly done during the evening. Each stage of the supply chain will be discussed separately.

5.2.2 Supplier

Strawberries are picked each day at the strawberry fields to supply the distribution centre and other smaller clients. Based on the information provided by the supplier, it is assumed that the supplier has the capacity to fulfil the demand of the distribution centre. The supplier has 70 full-time employees who do the picking and strawberry picking starts at 06:00 until 17:00 with an hour break between 12:00 and 13:00. The strawberries are placed into punnets with a capacity of approximately 400 g strawberries per punnet. The punnets are placed into trays to carry the strawberries from the field to the loading tractor. It takes an experienced employee approximately four minutes to fill a tray. Each tray can carry eight punnets and the loading tractor has a capacity of approximately 324 trays until it is fully loaded. The trays are transported from the field to a pre-cooling facility, where they should be cooled to approximately seven-eights of the exposed temperatures during harvesting, and it takes up to two and a half hours to reach the desired temperatures. After the trays are pre-cooled, they are placed in a refrigerated storage room. The trays remain in the storage room until the required daily quantity of strawberries is available to be delivered to the distribution centre. It is the supplier's responsibility to transport the trays from the storage to the distribution centre.

5.2.3 Distribution centre

The distribution centre receives trays filled with strawberry punnets on a daily frequency. The distribution centre has an agreement with the supplier to receive deliveries during the afternoon to ensure that there is sufficient time available to inspect the strawberries before they are distributed to the various retailers. Once the delivery truck stops at the distribution centre, an initial temperature inspection is done. Before the trays are unloaded, the temperature is measured at three different points in the trucks. If the average temperature exceeds 10°C, the trays are rejected and sent back to the supplier. Thereafter, individual strawberry punnets are selected from random trays for further quality inspections. The trays are stored inside a refrigerated room until the desired quantities for each retail store are determined, or when they are thrown away due to spoilage or handling damage. During the late afternoon, the delivery trucks are loaded and transport the trays with other fresh food products to various retailers. The distribution centre transports and delivers the fresh products during the night to ensure that the products are available at the retailer in the morning.

5.2.4 Retail stores

There are 67 retail stores in the Western Cape province to whom the distribution centre delivers fresh food products. Figure 5.1 illustrates the distribution of the retailers in the Western Cape. The locations of the retailers were clustered into the five municipal districts of the Western Province. The most retail stores are in the City of Cape Town District as 51 of the retail stores are located there. The Cape Winelands District has the second most retail stores as eight stores are in this area. The Eden District has six retail stores available and the Overberg District as well as the West Coast District each have only one retail store.

The retail store does not place a replenishment order, since the replenishment fulfilment is automatically done by software owned by the distribution centre. The software uses each retail store's safety stock and forecasts the quantity of fresh food products that need to be delivered to the retail store in each district. Majority of the retail stores receive deliveries on a daily basis. The deliveries arrive at the store every evening or early morning, depending on the distance that needs to be travelled to each store. The fresh food products are unloaded and stored in a refrigerated back store until it is required to fill the display shelves.

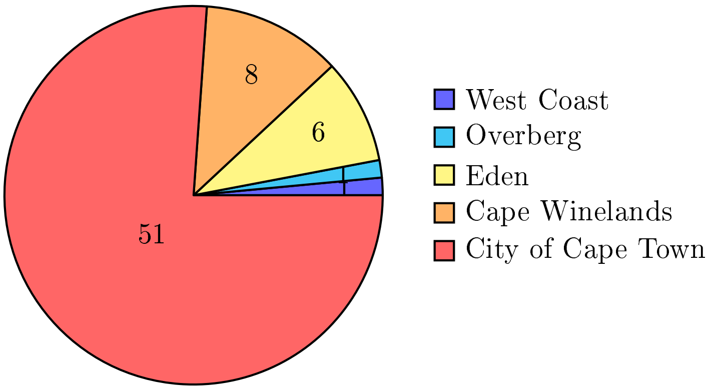


Figure 5.1: Distribution of retail stores in the Western Cape

The shelves are filled every morning before the retail store opens for business and thereafter it is the store manager's responsibility to ensure that there are enough products available on the shelves. During strawberry season, the retail stores reserve approximately 14 refrigerated shelf spaces for strawberries, which can occupy 750 strawberry punnets when they are fully stocked. The strawberries remain on the shelves until the consumers purchase them or when the sell-by date on each strawberry punnet has been reached.

5.2.5 Consumer demand

It is difficult to identify the purchasing strategy of consumers since it depends on various perceived psychological and economical beliefs. According to Grunert (2005) and Herbon *et al.* (2014) consumers tend to purchase fresh products based on the trade-off between price and quality. This suggests that consumers may decide to either pay more for high-quality products or pay less for lower-quality products.

Furthermore, consumers tend to measure quality of fresh produce based on the sell-by date on packaging labels (Lebersorger & Schneider, 2014; Teller *et al.*, 2018). Tsiros & Heilman (2005) concluded in their studies that products close to their sell-by date are perceived as low quality and are therefore less likely to be purchased. Wang & Li (2012) also mention that supermarket consumers prefer to buy newly replenished products instead of expiring products.

5.3 Supply chain model development

The following section will discuss the steps that were followed to develop an appropriate simulation model, given the case study described in the previous section.

5.3.1 Limitations and assumptions

The model development is limited due to the lack of receiving quantitative data, such as production quantities, order and delivery quantities, and replenishment quantities as well as sales volume at the retail store, from both the supplier and the retailer chain who were analysed during this study. This is in part due to confidentiality reasons. The supplier as well as the distribution centre only agreed to share data regarding the logistic activities occurring throughout the supply chain. Due to not having been able to receive any quantitative data from the analysed retail chain, some assumptions needed to be made based on literature and data gathered from similar case studies.

The simulation runtime is set to one month during strawberry harvesting season. Therefore, it is assumed that the fields will have enough strawberries to supply the high demand. It is assumed there are sufficient tractors available to transport the trays filled with strawberry punnets, from the fields to the pre-cooling facility. The pre-cooling facility, the storage thereafter, as well as the distribution centre are large enough to store all incoming trays in cold temperatures. All trucks in the study are assumed to be able to control the temperatures during transit. To define the routes and transit time to the retail stores, it is assumed that at least one full truck load is responsible for delivering a mix of products to retail stores in the same district. The quantity of trays that needs to be delivered to each retail store is dependent on the safety stock available at each retail store. Since the safety stock and replenishment quantities are not available, it will have to be assumed. It will also be assumed that all the retail stores have the same back store capacities and shelf space availability at the display. Lastly, loading and unloading times between each stage will be assumed to follow a uniform distribution to incorporate variability. The simulation and analysis of remaining shelf-life and waste ends after trays have been removed from the retail store's display shelves.

5.3.2 Concept model and description

Figure 5.2 provides an overview of the strawberry supply chain. The concept model and description to assist the model development for each stage in the supply chain are discussed individually.

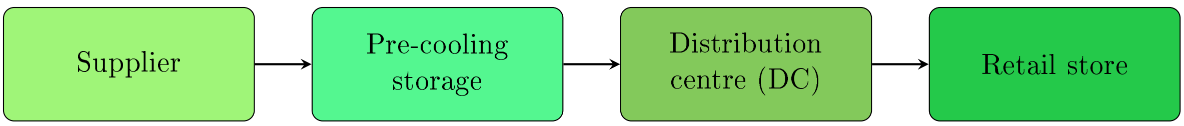


Figure 5.2: Overview of the strawberry supply chain

5.3.2.1 Entities and attributes

The main entity moving through the supply chain model will imitate the trays in which the strawberry punnets are placed during harvesting. The reason therefore is to reduce the number of entities moving through the simulation model because the number of entities influences the simulation run-time. During the harvest an initial shelf-life and temperature are assigned to each tray. A uniform distribution is used to determine the initial shelf-life of each tray to account for the shelf-life variation between the trays. The sell-by date for each tray is also determined during harvest.

5.3.2.2 Supplier

To simplify the harvesting stage, strawberry fields are grouped into three main farms. Harvesting occurs simultaneously at each farm following the same harvest rate. The harvest rate is determined by calculating the number of trays that need to be filled per day per farm, to produce 5 to 10 tons of strawberries per week.

Figure 5.3 shows the concept model and the flow of the entities at the supplier stage. The simulation starts by loading the trays with eight strawberry punnets. Once a tray is loaded, it is placed onto the tractor that will transport the trays from the farm to the pre-cooling facility. The tractor waits at the field until it is fully loaded. The tractor then moves from the farm to the pre-cooling facility where all trays are unloaded before they are placed in the pre-cooling facility. The tractor moves back to the farm to collect trays that are waiting to be loaded.

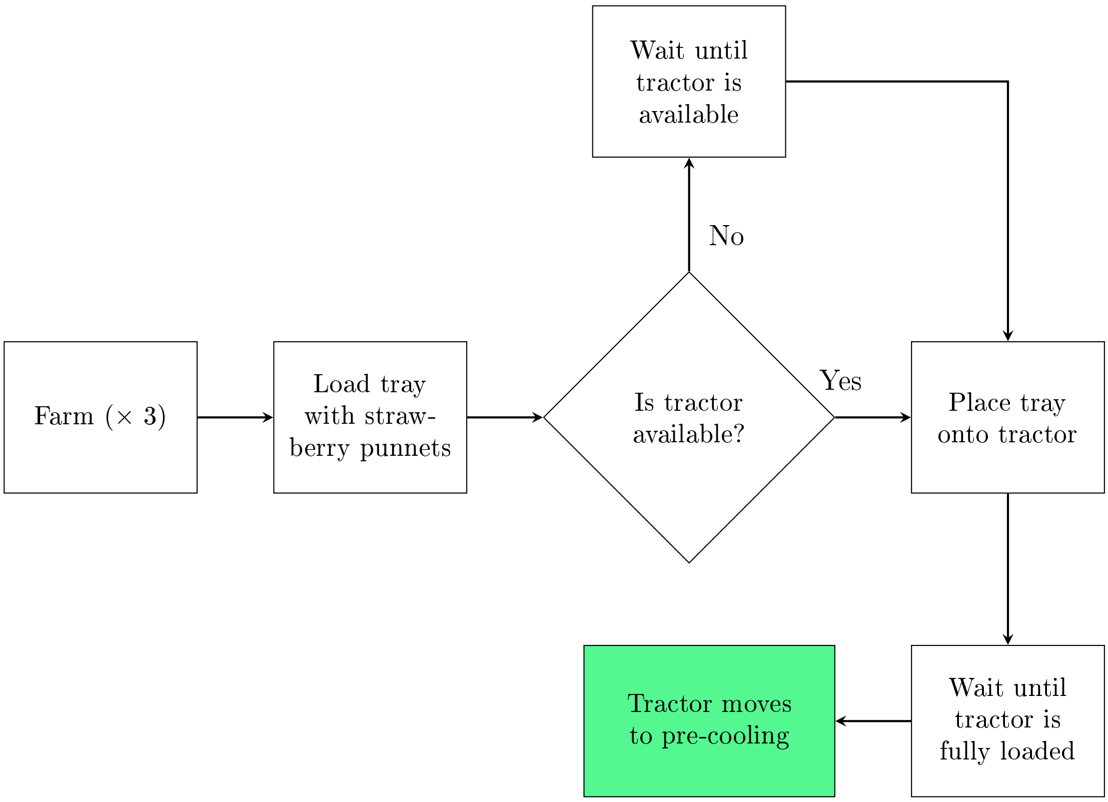


Figure 5.3: Concept model for the supplier stage

5.3.2.3 Pre-cooling facility

Figure 5.4 illustrates the concept model and flow of entities at the pre-cooling facility. At the pre-cooling facility the trays are pre-cooled for two-and-a-half hours and the temperature allocated to each tray is reduced to seven-eights of the initial temperature. Thereafter, the trays are moved to a refrigerated storage room. A method is created to model the delivery from the refrigerated storage to the distribution centre. Once a day in the afternoon, the method checks whether there are enough trays available to load a full truck for delivery. If there are enough trays available, the trays are moved out of the refrigerated storage to a loading area to load the trucks. Once the truck is loaded, it moves to the distribution centre.

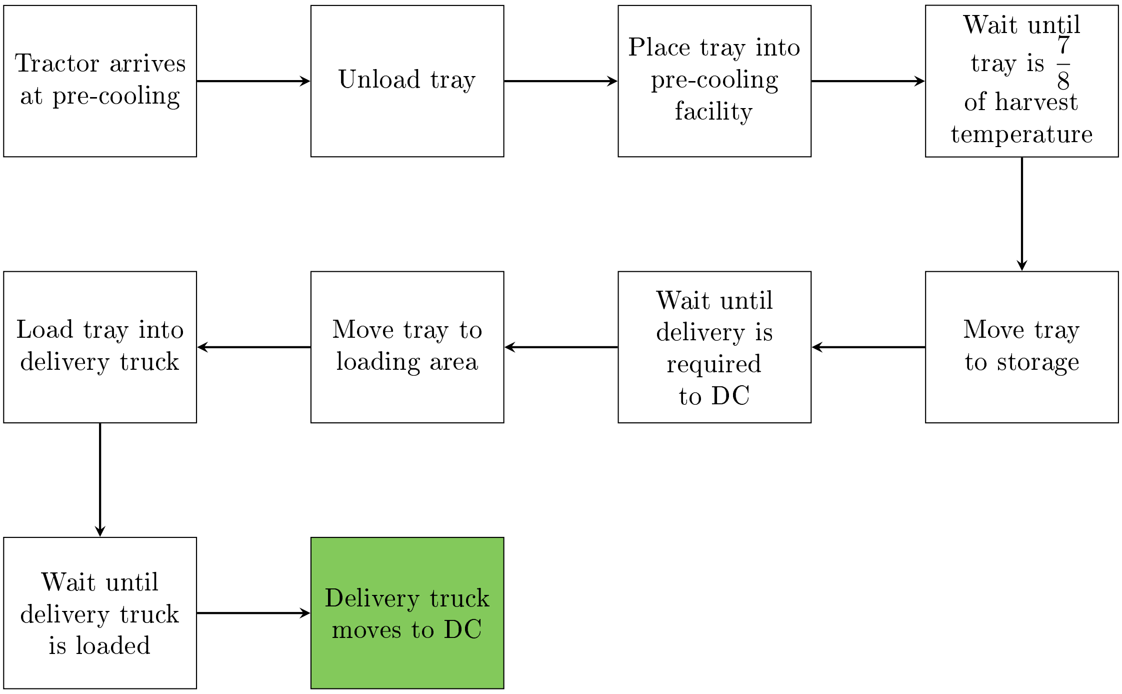


Figure 5.4: Concept model for the pre-cooling stage

5.3.2.4 Distribution centre

The concept model and the flow of entities at the distribution centre are shown in Figure 5.5. The full truck load of trays arrives at the distribution centre and moves back to the pre-cooling facility after the trays have been unloaded. During unloading, the temperatures of the trays are inspected. If the temperature of a tray exceeds 10°C then the tray is removed from the process. The reason for this is because strawberries lose shelf-life more than three times faster at 10°C and higher (do Nascimento Nunes *et al.*, 2014) which will result in waste whilst it is being stored in the distribution centre. Trays with temperatures less than 10°C, are assumed to have acceptable quality and are stored in the distribution centre where they wait until there are enough available that are selected to be delivered to a retail store. The model is primarily implemented to follow a First-In-First-Out stock-rotation strategy, meaning that trays which entered the distribution centre first will be selected to leave there first.

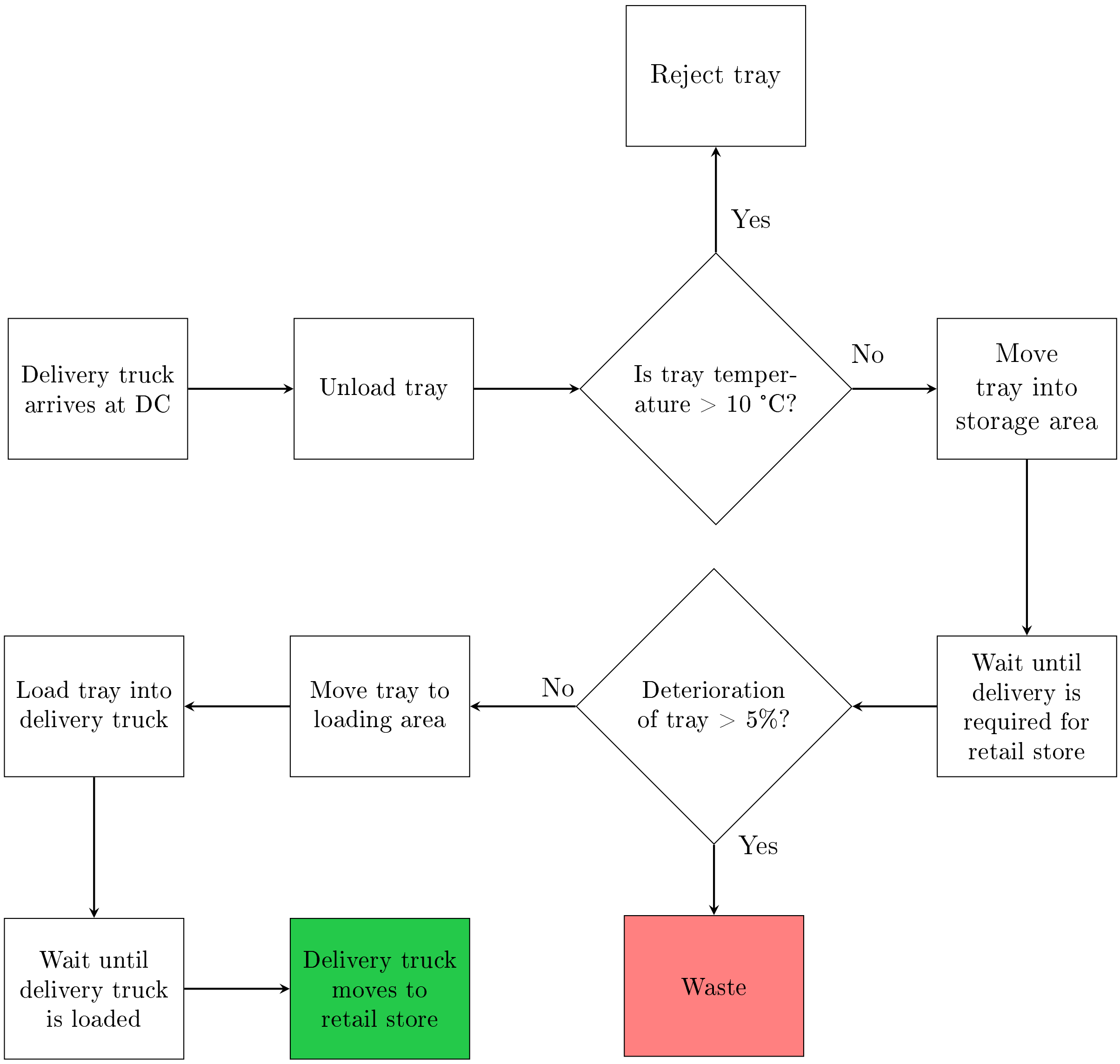


Figure 5.5: Concept model for the distribution centre stage

A method is created to model the ordering and delivery from the distribution centre to the retail stores. The retail stores are clustered into five districts. Every evening the quantity that is required for delivery to each retail store in every district is calculated. The total quantity for each district is calculated and the method checks if there are enough trays available in the distribution centre to deliver to each district. For each district there is a designated loading area. The required number of trays is moved from the distribution centre to each loading area. A limited number of trucks are available to transport the trays from the distribution centre to the retail stores. If a truck is available, it moves to the loading area, picks up the trays and moves to the retail stores in the designated district.

5.3.2.5 Retail store

To reduce modelling complexity, only one retail store per district with less than ten stores was modelled. Districts with more than ten stores were divided into suburbs and one store in each suburb was modelled. The stores which are located furthest from the distribution centre in each district or suburb were selected for modelling purposes.

Figure 5.6 illustrates the concept model and the flow of entities at the retail stores. Once the truck arrives at the retail store, the trays are unloaded into a refrigerated back store. The trays wait in the back store until the display shelves need to be replenished. A method is created to model replenishment. In the morning, the shelves are filled until the capacity is reached. Thereafter, the method checks the capacity of the shelves. If the shelves are less than 50% full, the method moves more trays to the shelves.

5.3.2.6 Consumer behaviour and demand

Consumers can purchase strawberries from 8 a.m. to 8 p.m. Thus they have 12 hours every day to shop. To model the amount of purchases per day a Poisson distribution with a rate $\lambda = 94$ trays (750 punnets) is used at each retail store. The reason why this λ was chosen is because the store manager mentioned that the expected number of purchases a day, during strawberry season, are usually equal to the amount of strawberry punnets available on the display shelves. Since the maximum available shelf space is 750 punnets it is assumed that approximately 750 purchases are expected per day.

A method is created to select the purchasing behaviour of consumers where consumers select strawberries based on the sell-by date. This is done by sorting the strawberries according to the sell-by date that was assigned to them during the harvest stage. The strawberries are sorted so that those with the most remaining time available are selected first every time a consumer comes to select strawberries to purchase.

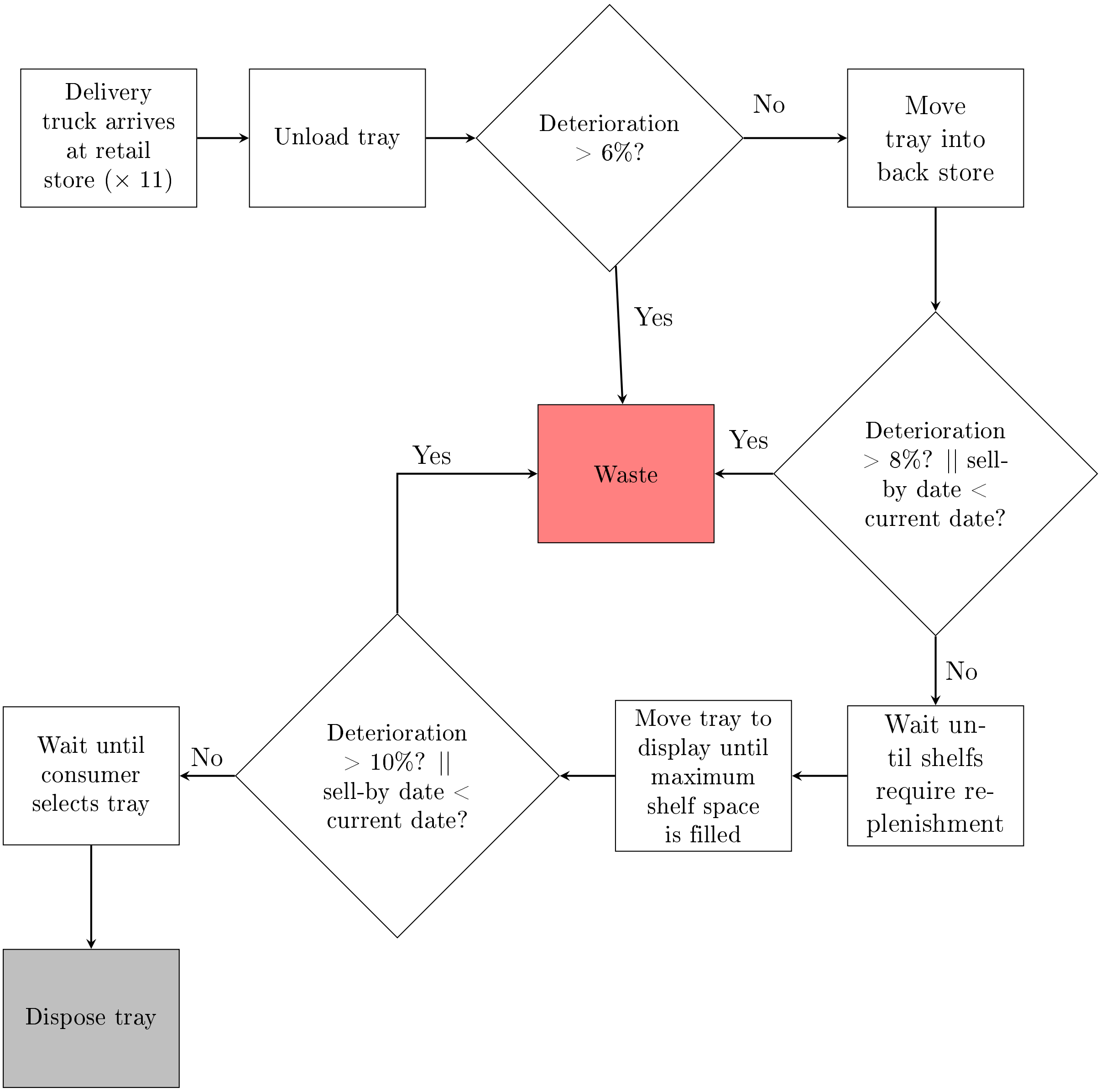


Figure 5.6: Concept model for the retail store stage

5.3.3 Waste along the supply chain

Trays are defined as waste when the amount of deterioration of each tray has reached a defined limit, or when the sell-by date has been reached before being purchased at the retail store. The quality limits were determined by using the values from Hertog *et al.* (1999) and Leithner *et al.* (2017) as reference, and are defined for each stage as follow:

1. **Distribution centre:** when the deterioration is more than 5% of initial deterioration;

2. **Unloading at the retail store:** when the deterioration is more than 6% of initial deterioration to ensure that the shelf-life is at least more than three days;

3. **Retail back store:** when the deterioration is more than 8% of the initial deterioration to ensure that the shelf-life of purchased strawberries is at least two days, or when the sell-by date has been reached before trays are placed on shelves;

4. **Display shelves:** when the deterioration is more than 10% of the initial deterioration, or when the sell-by date has been reached before purchase occurs.

The total amount of waste is calculated by adding the waste that occurred during each of these stages.

5.3.4 Remaining shelf-life calculations

For the purpose of this study, shelf-life will refer to the quality of strawberries since shelf-life modelling is a convenient method to estimate food quality as discussed in Section 4.3. There are several shelf-life models that can be used as a general reference to estimate the remaining shelf-life of produce. To determine which shelf-life model to use often depends on available data for the specific produce (Jedermann *et al.*, 2014; Sciortino *et al.*, 2016). Actual shelf-life modelling can become complex since it is affected by many attributes such as variety, location of the farm, season, weather conditions and preharvest practices.

A simple and fairly accurate temperature-dependent remaining shelf-life can be modelled with the use of Arrhenius' law for reaction kinetics as explained by Hertog *et al.* (2014); InfraTab (2011) and (Sciortino *et al.*, 2016). Since the shelf-life of strawberries is heavily influenced by storage temperatures, it would be convenient to use the zero-order reaction kinetics (Hertog *et al.*, 2014; Lebersorger & Schneider, 2014). The change in quality of a product over time t can be expressed as shown in Equation 5.1:

$$\frac{dq}{dt} = kq^n \tag{5.1}$$

where:
q = Quality of the product
k = Reaction rate constant
n = Reaction order.

It is then possible to create a kinetic-mathematical model that describes the evolution of the rate constant k of chemical reactions depending on storage times at different temperatures T for a specific activation energy, according to Arrhenius' law:

$$log\frac{k_2}{k_1} = -\frac{E_a}{R}(\frac{1}{T_2} - \frac{1}{T_1}) \tag{5.2}$$

where:
E_a = Activation energy of a specific produce
R = Universal gas constant.

The deterioration rate can be considered as inversely proportional to the storage time of the product, then Equation 5.2 can be rewritten as:

$$Det_{Tt} = Det_0 e^{-(\frac{E_a}{RT_t})} \tag{5.3}$$

where:
Det_{Tt} = Deterioration rate at temperature T_t
Det_0 = Deterioration rate at optimal temperature
E_a = Activation energy
R = Universal gas constant
T_t =Temperature at time t in Kelvin

Equation 5.3 calculates the amount of deterioration loss when the product is exposed to different temperatures. Hence, the remaining shelf-life can be calculated by subtracting the deterioration loss from the current shelf-life (Sciortino *et al.*, 2016):

$$SL_{rem} = SL_{rem-1} - Det_{Tt} \tag{5.4}$$

where:
SL_{rem} = Remaining shelf-life at time t
SL_{rem-1} = Remaining shelf-life at time $t-1$
Det_{Tt} = Deterioration rate at temperature T_t.

Table 5.1 lists the parameters that are required to calculate the remaining shelf-life of strawberries. The values were gathered from studies focusing on shelf-life models of strawberries.

Table 5.1: Parameters required for shelf-life calculations (from Hertog *et al.* (1999); Sciortino *et al.* (2016) and Leithner *et al.* (2017)).

Parameters	**Values**
Activation energy	70108 J/mol
Universal gas constant	8.314 J/mol K
Optimal storage temperature	2°C
Shelf-life at optimal temperature	14 days

To reproduce the shelf-life calculation in the simulation model, it is necessary to determine the initial shelf-life of the strawberries. Hertog *et al.* (1999) did a study to determine the initial quality of strawberries by identifying the initial spoilage due to infection of strawberries at harvest. The spoilage rates from his study are used to calculate the initial quality at harvest. A uniform distribution with a minimum of 0.08 and a maximum of 3.22 is used to determine the initial spoilage, and is then used to calculate the initial shelf-life of each tray of strawberries during harvesting as shown in Equation 5.5:

$$SL_0 = 14 \times (1 - \frac{SP}{100}) \tag{5.5}$$

where:
SL_0 = Initial shelf-life once harvested
14 = Maximum shelf-life at optimal conditions
SP = Initial spoilage at harvest.

With the initial shelf-life available, the shelf-life model described above can be used to determine the remaining shelf-life of the trays. Since the shelf-life model is temperature-dependent, the rate of deterioration will vary based on the temperatures to which the trays are exposed.

5.3.5 Temperature

Throughout the supply chain, strawberries are exposed to different temperatures. Although the optimal storage temperatures should be close to 2°C to receive optimal shelf-life, it is difficult to assure that the optimal temperature is kept throughout the supply chain. Table 5.2 shows the temperatures which strawberries were exposed to in similar studies.

Table 5.2: Temperatures along the supply chain from similar studies

Stages	**Temperatures in °C**	**References**
Harvest	23 23.9	Leithner *et al.* (2017) do Nascimento Nunes *et al.* (2014)
Pre-cool storage	4 0.6 - 10	Leithner *et al.* (2017) Alcéo (2016)
Transport to distribution centre	1.7 7 4 1.1 – 10	do Nascimento Nunes *et al.* (2014) Aiello *et al.* (2012) Leithner *et al.* (2017) Alcéo (2016)
Distribution centre	1.1 5 3 8.4 – 9.6	do Nascimento Nunes *et al.* (2014) Aiello *et al.* (2012) Leithner *et al.* (2017) Alcéo (2016)
Transport to retailer	0.6 - 10 7 4 7.5 – 7.9	do Nascimento Nunes *et al.* (2014) Aiello *et al.* (2012) Leithner *et al.* (2017) Alcéo (2016)
Retailer back store	7.7 1.1 6.7	Alcéo (2016) do Nascimento Nunes *et al.* (2014) Nunes *et al.* (2003)
Display	7.6 – 17.5 25 10 20	Alcéo (2016) Aiello *et al.* (2012) Leithner *et al.* (2017) Nunes *et al.* (2003)

Temperatures at the harvest stage were determined by gathering historical temperatures during strawberry harvesting season (WeatherUnderground, n.d). The minimum, maximum, and mode temperature for each hour were calculated (refer to Appendix B), and a triangular distribution was used to determine the hourly temperature during harvesting. Thus trays that were harvested during different times of the day, would have different temperatures assigned to them. During pre-cooling, the temperature of each tray is reduced to seven-eights of the temperature it was exposed to during the harvest stage. The temperature is kept until it is loaded onto the truck for delivery to the distribution centre. To model temperature throughout the rest of the supply chain, the temperatures from previous studies were used as reference. To incorporate temperature-variability for each tray, a normal distribution is used to determine temperatures which are assigned to each tray as it enters a stage. The mean and standard deviation for each normal distribution were calculated using the temperatures listed in Table 5.2. Table 5.3 shows the temperatures that will be used in this simulation model.

Table 5.3: Temperatures used in this research project

Stages	Temperatures in °C
Harvest and transport to pre-cooling	Triangular distribution for each hour
Pre-cool storage	Seven-eights of harvested temperature
Transport to distribution centre	Normal(4.76,3.76)
Distribution centre	Normal(5.42,3.57)
Transport to retailer	Normal(6.17,3.34)
Retailer back store	Normal(5.17,3.56)
Display	Normal(16.02,7.17)

5.4 Design of experiments

The goal of this simulation model is to analyse the impact of quality-controlled logistic activities on the quality of strawberries and on the amount of waste being produced throughout the supply chain.

5.4.1 Logistic activities to evaluate

Chapter 4 discussed the potential benefits of implementing several logistic strategies based on shelf-life information to improve the quality of fresh products throughout the supply chain. With the information from Chapter 4 as well as the information regarding the current logistics at the analysed retail chain, the following logistic activities were selected to evaluate in this case study:

1. When to send harvested strawberries from the farm to the pre-cooling facility;
2. Which trays to pick at the distribution centre for delivery to which retail store;
3. Which trays should be placed on the display shelves; and
4. Implementing pricing and discount models based on remaining shelf-life.

Table 5.4 summarises the retail chain's current logistics activities as described in Section 5.2. It is assumed that the shelf-life information is not known during these logistic activities and that the sell-by dates are fixed once they are determined by the supplier.

Table 5.4: Retail chain's current logistic activities

Stage	**Logistic activity**	**Current strategy**
Supplier	When to send harvested load from farm to pre-cooling	Wait until tractor is fully loaded
Distribution centre	Which trays to pick for each retail store	First-In-First-Out policy
Retail store	Which trays should be placed on the display	First-In-First-Out replenish-ment

Quality-controlled logistics activities are defined in this study as activities where decisions are based on available shelf-life information. Therefore, it is assumed that shelf-life information is captured and monitored to assist these decisions. Table 5.5 shows the different quality-controlled logistics activities that will be evaluated against the current logistic activities.

Table 5.5: Quality-controlled logistic activities to evaluate

Stage	**Logistic activity**	**QCL strategy**
Supplier	When to send harvested load from farm to pre-cooling	Send load to pre-cooling every 2 hours
Distribution centre	Which trays to pick for each retail store	Last-In-First-Out stock-rotation Least-Shelf-life-First-Out stock-rotation Least-Shelf-Life-First-Out with intelligent distribution
Retail store	Which trays should be placed on the display Pricing and discount	Last-In-First-Out stock-rotation Least-Shelf-Life-First-Out stock-rotation Dynamic pricing based on remaining shelf-life

Send load to pre-cooling every two hours

Once the strawberries are picked and placed into the trays, the trays are loaded onto the tractor. The tractor waits on the farm until its loading capacity has been reached. To fully load a tractor can take up to 5 hours, meaning that the trays are exposed to high temperatures for that period. This has a negative influence on the remaining shelf-life of the strawberries since they are greatly influenced by temperatures. For this reason the logistic activity will be adapted so that the tractor will transport the loaded trays to the pre-cooling facility every two hours. This suggests that the loaded trays will spend less time in high temperatures, possibly allowing an increase in remaining shelf-life when the trays are moved from the farm to the pre-cooling facility. The remaining shelf-life of the trays will be measured once the tractor leaves the farm, to evaluate the impact of this activity.

Last-In-First-Out and Least-Shelf-life-First-Out stock-rotation at the distribution centre
The First-In-First-Out stock-rotation distributes the trays that entered the distribution centre first to the retail stores where the Last-In-First-Out stock-rotation distributes the trays that entered the distribution centre last to the retail stores. Both stock-rotations do not consider the remaining shelf-life of the trays and assume all trays are exposed to the same environmental conditions and remaining shelf-life. The remaining trays are stored for longer periods which may result in those trays becoming wasted because they do not fulfil the acceptable quality limits.

The Least-Shelf-life-First-Out stock-rotation distributes trays with the least shelf-life first to the retail stores. This suggests that the trays which remain in storage are known to have longer remaining shelf-life, reducing the chance of becoming waste due to not fulfilling the quality limits. The remaining shelf-life of the trays as well as the amount of waste will be measured, to evaluate the impact of these stock-rotation strategies.

Least-Shelf-life-First-Out with intelligent distribution
The Least-Shelf-life-First-Out stock-rotation can be combined with the distribution of trays to the various retail stores. Instead of distributing the trays randomly to the retail stores (following the Least-Shelf-life-First-Out stock-rotation), the trays are sorted so that the remaining shelf-life takes into account the required travel distance to each retail store. This suggests that trays with less remaining shelf-life will be distributed to closer retail stores whereas trays with longer remaining shelf-life will be distributed to retail stores further away.

Last-In-First-Out and Least-Shelf-life-First-Out replenishment at the retail stores
Again, both First-In-First-Out and Last-In-First-Out replenishment do not consider the remaining shelf-life of the trays when they are moved from the back store to the display shelves. Thus, the remaining trays stored in the back store may become waste because they reached their sell-by date before being purchased by the consumer. Also, consumers tend to select the best quality products on display, with the result that lower quality products will turn into waste.

Following the Least-Shelf-life-First-Out replenishment strategy will suggest that the store manager moves trays with lower remaining shelf-life to the display shelves first. This may possibly lead to less waste at the shelves because consumers will be unknowingly influenced to purchase lower shelf-life products because the shelf-life variance between the products on display will be reduced. Trays stored in the back store will also have longer shelf-life meaning that the trays will have smaller probability to turn into waste. The remaining shelf-life of the trays after being purchased by the consumers as well as the amount of waste at the retail store will be measured, to evaluate the impact of these replenishment strategies.

Least-Shelf-life-First-Out replenishment with dynamic pricing based on remaining shelf-life

Lastly, the impact of Least-Shelf-life-First-Out replenishment strategy combined with dynamic pricing model will be evaluated. Considering that the shelf-life information of the trays is known, dynamic pricing models can be used to determine the selling price. To implement the pricing model, it is assumed that an exponential relationship exists between the remaining shelf-life and the price as shown in Equation 5.6 (Herbon *et al.*, 2014):

$$P_{disc} = P_0 \times e^{-Disc \times (SL_{avg} - SL_{rem})} \tag{5.6}$$

where:
P_{disc} = Price after discount
P_0 = Initial selling price before discount
$Disc$ = Discount percentage
SL_{avg} = Expected average shelf-life at the retail store upon arrival
SL_{rem} = Current shelf-life at time t.

An initial selling price is set, given that the expected average shelf-life of trays arriving at the retail store is eight days, as observed in previous experimental runs. It is decided that discounting will commence once the shelf-life of the trays reaches these three limits:

1. 5% discount when the shelf-life is reduced by half of the expected average shelf-life;
2. 10% discount when the shelf-life is further reduced by half of the expected average shelf-life; and
3. 15% discount when there is only one day of remaining shelf-life left.

Discounting occurs every time the display shelves need to be replenished. When the dynamic pricing strategy is implemented it is assumed that the consumers' behaviour tends to be more influenced by pricing rather than the quality of the strawberries. Without discount it is decided that 60% of the consumers will buy strawberries based on the price and 40% of the consumers will buy strawberries based on the shelf-life (Buisman *et al.*, 2017; Rossi *et al.*, 2012). As the average remaining shelf-life at the display decreases, the probability that the consumer will buy strawberries based on price will increase (Herbon *et al.*, 2014).

A method is created to observe the average shelf-life at the display before consumers purchase strawberries. A ratio is calculated between the current average shelf-life and expected average shelf-life as shown in Equation 5.7:

$$Ratio = \frac{SL_{rem}}{SL_{avg}} \tag{5.7}$$

This ratio is used to determine the probabilities of whether consumers will buy strawberries based on either a pricing behaviour or a quality behaviour:

1. If the ratio is >0.75 then 60% of the consumers will buy strawberries based on the price and 40% will buy based on quality;
2. If the ratio is <0.75 and >0.5 then 75% of the consumers will buy strawberries based on the price and 25% will buy based on quality; and
3. If the ratio is <0.5 then 80% of the consumers will buy strawberries based on the price and 20% will buy based on quality.

A large ratio will suggest that the current average remaining shelf-life is still high, meaning that it will be less likely that the strawberries may be on discount. A small ratio will suggest that the current average remaining shelf-life at the display shelves is low, meaning that it is more likely that the strawberries may be on discount.

5.4.2 Output measurements

In order to evaluate the impact of the defined logistic activities, the following output measurements have been identified to investigate the outcome of the experiments:

Waste

1. The amount of waste that occurred at the distribution centre; and
2. The total amount of waste that occurred across all retail stores.

Average remaining shelf-life

1. The average shelf-life of the trays before they leave the farms;
2. The average shelf-life of the trays before they leave the distribution centre;
3. The total average shelf-life of the purchased trays across all retail stores; and
4. The average shelf-life of wasted trays across all retail stores.

Monetary value

1. The total sales of strawberry purchases from all the retail stores; and
2. The total losses due to waste from all the retail stores.

The waste and average remaining shelf-life will be the key output measurements. The monetary value measurements will be used to additionally quantify the impact of waste within the supply chain.

5.4.3 Experiment set-up

The following subsection explains how the experiments were designed to evaluate the impact of quality-controlled logistics on the average shelf-life and on the amount of waste throughout the supply chain. A decision variable is assigned to each of the described logistic activities. This is done to specify the various logistic activities to simulate for each experimental run. Tables 5.6 to 5.8 show the decision variables assigned to each of the logistic activities.

Table 5.6: Decision variables for supplier logistic activities

Logistic activity	**Decision variable**
Wait until tractor is fully loaded	1
Send load to pre-cooling every 2 hours	2

Table 5.7: Decision variables for distribution centre logistic activities

Logistic activity	**Decision variable**
First-In-First-Out stock-rotation	1
Last-In-First-Out stock-rotation	2
Least-Shelf-life-First-Out stock-rotation	3
Least-Shelf-Life-First-Out with intelligent distribution	4

Table 5.8: Decision variables for retail store logistic activities

Logistic activity	**Decision variable**
First-In-First-Out replenishment	1
Last-In-First-Out replenishment	2
Least-Shelf-Life-First-Out replenishment	3
Dynamic pricing based on remaining shelf-life	4

For each experiment a different logistic activity is adapted to evaluate the impact of the various logistic activities combinations. A total of 32 experiments are defined and Table 5.9 shows all the logistics activities combinations that were evaluated in this simulation study. For example, Experiment one illustrates the current logistic activities that are implemented in the supply chain. This means that the tractor waits until it is fully loaded at the farm, the distribution centre follows a First-In-First-Out stock-rotation to send trays to the retail stores, and the retail store follows a First-In-First-Out replenishment strategy to move the trays to the display shelves.

Table 5.9: Experiment set-up

Experiment	Supplier	Distribution centre	Retail store
Exp 1	1	1	1
Exp 2	1	1	2
Exp 3	1	1	3
Exp 4	1	1	4
Exp 5	1	2	1
Exp 6	1	2	2
Exp 7	1	2	3
Exp 8	1	2	4
Exp 9	1	3	1
Exp 10	1	3	2
Exp 11	1	3	3
Exp 12	1	3	4
Exp 13	1	4	1
Exp 14	1	4	2
Exp 15	1	4	3
Exp 16	1	4	4
Exp 17	2	1	1
Exp 18	2	1	2
Exp 19	2	1	3
Exp 20	2	1	4
Exp 21	2	2	1
Exp 22	2	2	2
Exp 23	2	2	3

Continued on next page

Table 5.9 – *Continued from previous page*

Experiment	Supplier	Distribution centre	Retail store
Exp 24	2	2	4
Exp 25	2	3	1
Exp 26	2	3	2
Exp 27	2	3	3
Exp 28	2	3	4
Exp 29	2	4	1
Exp 30	2	4	2
Exp 31	2	4	3
Exp 32	2	4	4

For Experiments 1 to 4 the logistic activities are altered at the retail store whilst the logistic activities are kept constant at both the supplier and the distribution centre. For Experiments 5 to 8 the stock-rotation strategy at the distribution centre is altered from First-In-First-Out to Last-In-First-Out. The logistic activities at the retail store are then altered for each experiment run. For Experiments 9 to 12 the Least-Shelf-life-First-Out stock-rotation strategy at the distribution centre is implemented where deliveries are done randomly. Once again, the logistic activities at the retail store are altered for each experiment run. For Experiments 13 to 17 the Least-Shelf-life-First-Out stock-rotation combined with intelligent distribution is implemented and the different logistic activities are altered at the retail store. For Experiments 18 to 32 a similar procedure is followed for the distribution centre's and retail stores' logistic activities, where the only difference is that the logistic activity at the supplier is altered.

5.5 Conclusion

This chapter described the design and development of the simulation model to imitate a South African strawberry supply chain. A brief explanation of simulation modelling as an analysis tool was provided as well a description of the overview of the analysed supply chain. Thereafter the various steps that were followed to develop the simulation model were discussed, and lastly the design of experiments was described. The following chapter will focus on the analysis and discussion of the results that were obtained from the simulation study.

Chapter 6

Analysis and discussion of simulation results

The previous chapter explained the design and the development of a simulation model to evaluate the impact of quality-controlled logistics on the average remaining shelf-life of the strawberry trays as well as the waste that occurred throughout the supply chain. This chapter will analyse and discuss the results obtained from the simulation study.

6.1 Results and analysis

The simulation model was designed to imitate the strawberry supply chain for a one-month period per experiment. The number of replications for each experiment was determined following the method that is described in Appendix C. Each experiment ran for 33 replications, meaning that the experiment was executed 33 times. After each experiment the decision variables were adapted individually as described in Section 5.4. The total simulation runtime was 16 hours and 16 minutes. A detailed report of the simulation results is provided in Appendix C.

6.1.1 Results of baseline logistic activities

To evaluate the impact of the quality-controlled logistic activities, it is necessary to have a baseline to compare the various output measurements of the defined logistic activities. Therefore, Experiment 1 which illustrates the current logistic activities identified from the case study is selected as the baseline, as shown in Table 6.1.

Table 6.1: Experiment set-up of baseline logistic activities

Supplier	Distribution centre	Retail store
1	1	1

Table 6.2 shows the output measurement results of the baseline logistic activities. Following this set of logistic activities, it can be observed that zero waste occurred at the distribution centre. The

reason why the distribution centre did not experience any waste is most likely due to the responsive lead time the retail chain implemented. The distribution centre aims to distribute the strawberry trays to the retail stores within the same day that they receive the strawberry trays from the supplier. Thus, the time the strawberry trays spend in storage is normally less than 24 hours.

Table 6.2: Results of the baseline logistic activities

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	5,614 trays
Total average shelf-life at retail stores (at purchase)	8.338 days
Average remaining shelf-life of wasted trays at retail stores	6.468 days
Total sales	R3,075,516.86
Total loss due to waste	R2,065,282.19

Considering the short storage time that the strawberry trays experience, the First-In-First-Out stock-rotation strategy will result in very little or no waste at the distribution centre. The reason therefore is because the majority of the strawberry trays will be distributed to the retail stores within one day, and the remainder of the strawberry trays will most likely be distributed the following day.

A total of 5,614 trays of strawberries were wasted at the retail stores. This resulted in a loss of R2,065,282.19 due to waste. The large amount of waste is most likely influenced by the First-In-First-Out replenishment strategy because the shelf-life of the strawberry trays is not considered when they are moved from the back store to the display shelves. The result is that the shelf-life of the strawberry trays on display varies significantly and consumers are most likely to purchase the strawberries that they believe have the best shelf-life.

Additionally, consumers also tend to select the strawberry trays with the latest sell-by date available because they assume that the sell-by date is an accurate representation of remaining shelf-life of the strawberry trays. As a consequence, the strawberry trays with less time left are most likely to become waste because consumers will not purchase them.

The wasted strawberry trays have a remaining shelf-life of 6.468 days and this was measured to illustrate the misconception of sell-by dates. The problem with sell-by dates is that it is determined by the supplier and is a fixed date. Thus, the environmental influences on the strawberry trays throughout the supply chain are not considered. This results an inaccurate representation of the shelf-life of the strawberries. Consumers may decide not to purchase the strawberries due to the sell-by date but actually the strawberries may have acceptable remaining shelf-life available.

6.1.2 Overview of experiment results

The following section presents the results of the experiment runs and observes the impact of the various quality-controlled logistics on both the total waste across the supply chain, and the remaining shelf-life of the strawberry trays at the retail stores once they are selected to be purchased.

6.1.2.1 Total waste reduction

Figure 6.1 shows the total waste that occurred during each experiment. It is noted that some experiments have significant impact on the total waste that occurred throughout the supply chain. Furthermore it is noticed that the experiments which resulted in a large reduction in total waste, seem to provide similar results. Therefore it is necessary to determine whether there are statistical significant difference between the various experiments.

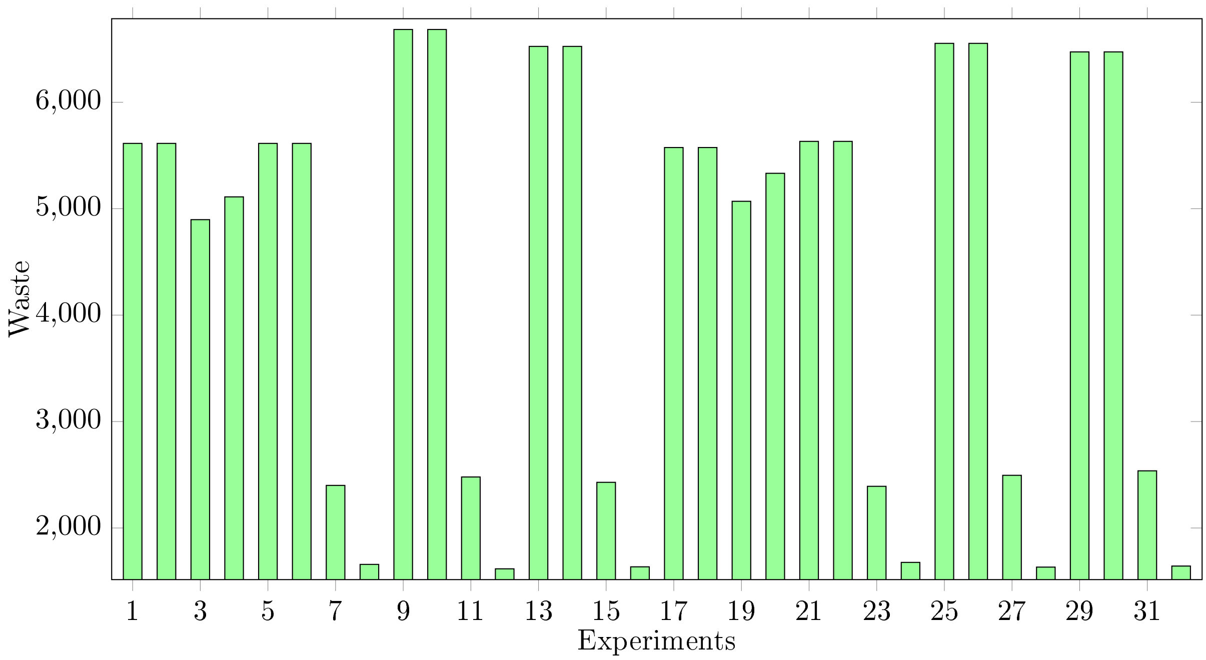


Figure 6.1: The total waste generated across the supply chain for each experiment

Measuring statistical significance using the t-test

The t-test is a statistical hypothesis test to determine the probability of the difference between two means (Rohatgi & Saleh, 2015). Tecnomatix Plant Simulation® uses the t-test to determine whether experiments are statistically significantly different. It provides a pair-wise comparison of the estimated means of each experiment. To test for significant difference, it is assumed that the means of each experiment are equal. Hence the hypothesis test is set up as:

$$H_0 : \mu_1 = \mu_2 = \mu_3 = \ldots = \mu_k$$
$$H_1 : \mu_1 \neq \mu_2 \neq \mu_3 \neq \ldots \neq \mu_k$$

The null hypothesis suggests that the means of the experiments are equal whereas the alternative hypothesis suggests the means of the experiments are not equal. To test the defined hypothesis, a p-value needs to calculated. The p-value is the probability that the result from the experiment occurred by chance (Rohatgi & Saleh, 2015). The p-value determines whether to reject the null hypothesis. If the p-value is less than the chosen significance level ($\alpha = 0.05$) then it can be presumed that the mean values are different with a probability of 95%. The hypothesis that is tested in this scenario is as follows:

Null Hypothesis 1 *There are no differences between the mean total waste given a set of logistic activities.*

Hypothesis 1 *There is significant difference between the mean total waste given a set of logistic activities.*

Table 6.3 compares the p-values of each pair of experiments that obtained a significant reduction in total waste. Experiment 1 is also added to the table to compare the reduction in total waste obtained from the various experiments, to the baseline logistic activities. It can be observed from the table that all of the listed experiments differ statistically significantly from Experiment 1 because the p-value per pairwise comparison is less than α. This means that implementing the set of logistic activities of any of these experiments would result a significant difference in the mean total waste.

The p-values of each pair of experiments that do not differ statistically significantly (p-values > α), are highlighted in the table. The green coloured cells in the table highlight the pair of experiments that are not statistically significantly different possibly due to the set of logistic activities being similar at both the distribution centre and the retail store, but differ at the supplier. For example, Experiment 8 illustrates the set of logistics where (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy, whereas Experiment 24 illustrates a similar set of logistics except that the tractor transports the strawberry trays every two hours to the pre-cooling facility. This suggests that the change in the logistic activity at the supplier does not have a significant contribution towards the reduction in the mean total waste for these experiments.

Table 6.3: The p-values of the experiments that obtained a significant reduction in total waste

	Ex7	**Ex8**	**Ex11**	**Ex12**	**Ex15**	**Ex16**	**Ex23**	**Ex24**	**Ex27**	**Ex28**	**Ex31**	**Ex32**
Ex1	0	0	0	0	0	0	0	0	0	0	0	0
Ex7		0	0	0	0.058	0	0.584	0	0	0	0	0
Ex8			0	0.001	0	0.033	0	0.111	0	0.04	0	0.172
Ex11				0	0.003	0	0	0	0.387	0	0.006	0
Ex12					0	0.035	0	0	0	0.133	0	0.014
Ex15						0	0.002	0	0	0	0	0
Ex16							0	0	0	0.777	0	0.384
Ex23								0	0	0	0	0
Ex24									0	0.001	0	0.003
Ex27										0	0.033	0
Ex28											0	0.35
Ex31												0

The red coloured cells highlight the pair of experiments that are not statistically significantly different possibly due to the logistic activity at the retail store that are the same for each pair of experiments that are compared. This suggests that the change in logistic activities at the distribution centre does not have a significant contribution towards the reduction in the mean total waste for these experiments. The cells that are not highlighted in the table illustrate the experiments that differ statistically significantly per pairwise comparison because the p-values are less than α.

The delta (δ) waste reduction was determined for each experiment listed in Table 6.3 to show how the total supply chain waste for that experiment compared to the waste that was obtained from the baseline logistic activities. Table 6.4 presents the experiments with their set of logistic activities at each stage. The experiments with the largest reduction in total food waste are highlighted in blue and the impact of these experiments are shown separately.

Table 6.4: The experiments that obtained the most waste reduction

Experiment	Supplier	Distribution centre	Retail store	Waste (in trays)	δ reduction
1 (baseline)	1	1	1	5614	-
7	1	2	3	2400	57 %
8	1	2	4	1658	70 %
11	1	3	3	2480	56 %
12	1	3	4	1617	71 %
15	1	4	3	2429	57 %
16	1	4	4	1636	71 %
23	2	2	3	2392	57 %
24	2	2	4	1677	70 %
27	2	3	3	2495	56 %
28	2	3	4	1633	71 %
31	2	4	3	2537	55 %
32	2	4	4	1643	71 %

Experiment 12

Experiment 12 illustrates the set of logistic activities where: (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Least-Shelf-life-First-Out stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy.

Table 6.5: Results of Experiment 12

Output measurements	Results
Waste at distribution centre	0 trays
Total waste at retail stores	1,617 trays
Total average shelf-life at retail stores (at purchase)	7.164 days
Average remaining shelf-life of wasted trays at retail store	2.206 days
Total sales	R3,048,909.73
Total loss due to waste	R594,669.10

From Table 6.5 it is observed that zero waste occurred at the distribution centre. The total amount of waste at the retail stores reduced to 1,617 trays and the total losses due to waste dropped to R594,669.10. The average remaining shelf-life of the strawberry trays at the retail stores was 7.164 days before being purchased and the average remaining shelf-life of the wasted strawberry trays was 2.206 days.

Experiment 16

Experiment 16 illustrates the set of logistic activities where: (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Least-Shelf-life-First-Out with intelligent distribution stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy.

Table 6.6: Results of Experiment 16

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	1,636 trays
Total average shelf-life at retail stores	7.167 days
Average remaining shelf-life of wasted trays at retail store	2.203 days
Total sales	R3,051,797.39
Total loss due to waste	R601,585.99

From Table 6.6 it is observed that zero waste occurred at the distribution centre and the amount of waste at the retail store reduced to 1,636 trays. The reduction in waste resulted that the total losses due to waste dropped to R601,585.99. The average shelf-life being wasted at the retail stores reduced to 2.203 days and the average remaining shelf-life of the strawberry trays at the retail stores was 7.167 days before being purchased.

Experiment 28

Experiment 28 illustrates the set of logistic activities where: (i) the tractor transports the strawberry trays every two hours to the pre-cooling facility; (ii) the distribution centre follows a Least-Shelf-life-First-Out stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy.

From Table 6.7 it is observed that zero waste occurred at the distribution centre, and the amount of waste at the retail store reduced to 1,633 trays. The reduction in waste resulted that the total losses due to waste dropped to R600,629.40. The average shelf-life being wasted at the retail stores reduced to 2.248 days and the average remaining shelf-life at the retail stores reduced to 7.263 days before being purchased.

Table 6.7: Results of Experiment 28

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	1,633 trays
Total average shelf-life at retail stores (at purchase)	7.263 days
Average remaining shelf-life of wasted trays at retail store	2.248 days
Total sales	R3,050,917.05
Total loss due to waste	R600,629.40

Experiment 32

Experiment 32 illustrates the set of logistic activities where: (i) the tractor transports the strawberry trays every two hours to the pre-cooling facility; (ii) the distribution centre follows a Least-Shelf-life-First-Out with intelligent distribution stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy.

Table 6.8: Results of Experiment 32

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	1,643 trays
Total average shelf-life at retail stores (at purchase)	7.260 days
Average remaining shelf-life of wasted trays at retail store	2.225 days
Total sales	R3,053,064.65
Total loss due to waste	R604,271.81

From Table 6.8 it is observed that zero waste occurred at the distribution centre. The total amount of waste at the retail stores reduced to 1,643 trays and the total losses due to waste dropped to R604,271.81. The average remaining shelf-life of the strawberry trays at the retail stores was 7.260 days before being purchased and the average remaining shelf-life of wasted strawberry trays was 2.225 days.

When comparing the output measurements of the four experiments that were described, it appears that all of them provided similar results. Therefore the p-values presented in Table 6.3, are used to identify which one of these four experiments would result the most significant reduction in total waste. Experiment 12 differs statistically significantly from Experiment 16 ($0.035 < \alpha$) and Experiment 32 ($0.014 < \alpha$) but not from Experiment 28 ($0.133 > \alpha$). Experiment 16 does not differ statistically significantly from Experiment 28 ($0.777 > \alpha$) and Experiment 32 ($0.384 > \alpha$), and Experiment 28 does not differ statistically significantly from Experiment 32 ($0.35 > \alpha$).

Since there is no significant difference between the pairwise comparison of the experiments (except for Experiments 12 and 16, and Experiments 12 and 32), we refer to the total loss due to waste in order to select the desired experiment. Experiments 16, 28 and 32's total losses fluctuate around R600,000 whereas Experiment 12's total loss is significantly less than the other experiments. Therefore it is suggested that the set of logistic activities illustrated by Experiment 12 would obtain the best results when the focus is to reduce the total waste throughout the supply chain.

6.1.2.2 Increase in remaining shelf-life at the retail stores

The remaining shelf-life of the strawberry trays at the retail stores is measured to identify whether the defined quality-controlled logistic activities can increase the overall remaining shelf-life of the strawberries being purchased by the consumers. Figure 6.2 shows the remaining shelf-life of the strawberry trays at the retail stores, and it can be observed that some experiments have significant impact on the remaining shelf-life. Again it is noticed that there are experiments that seem to provide similar results, therefore they are tested for statistical significance difference.

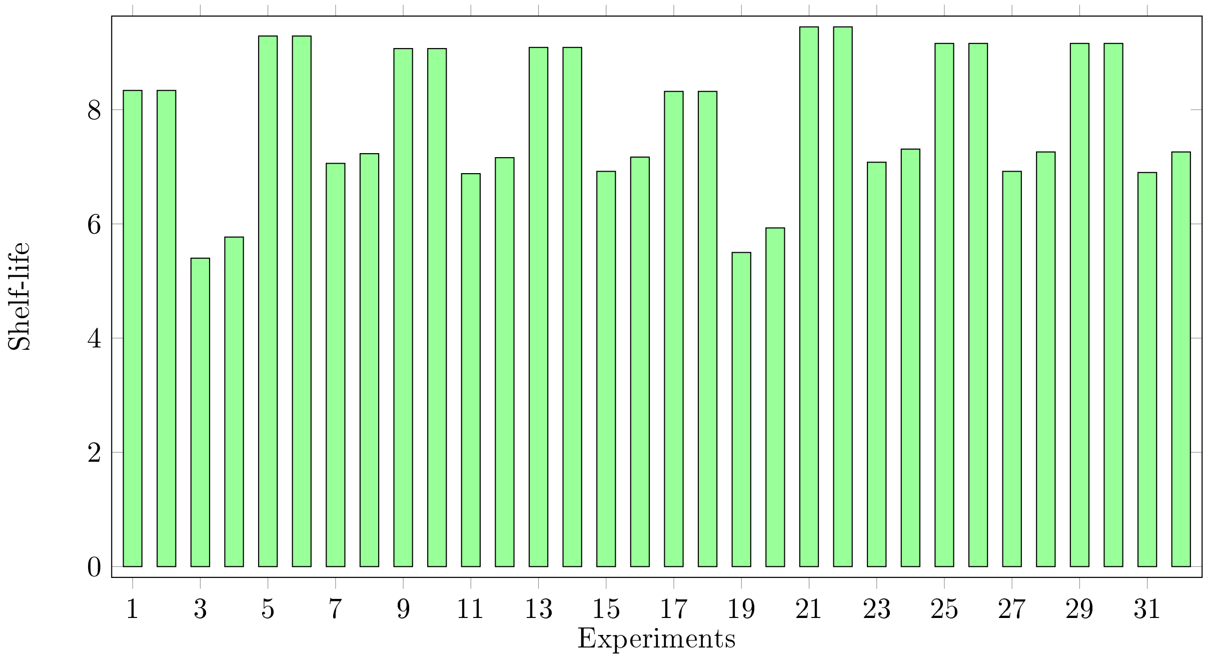


Figure 6.2: The remaining shelf-life of the strawberry trays once they are purchased by consumers

Measuring statistical significance using the t-test

The t-test and the p-values are used to determine whether the experiments are statistically significantly different from one another. To test for significant difference, it is assumed that the means of the remaining shelf-life at the retail stores of each experiment are equal. Hence the hypothesis test is set up as:

Null Hypothesis 2 *There are no differences between the mean remaining shelf-life given a set of logistic activities.*

Hypothesis 2 *There is significant difference between the mean remaining shelf-life given a set of logistic activities.*

The p-value determines whether to reject the null hypothesis. If the p-value is less than the chosen significance level ($\alpha = 0.05$) then it can be presumed that the mean values are different with a probability of 95%.

Table 6.9: The p-values of the experiments that obtained an increase in average remaining shelf-life

	Ex5	**Ex6**	**Ex9**	**Ex10**	**Ex13**	**Ex14**	**Ex21**	**Ex22**	**Ex25**	**Ex26**	**Ex29**	**Ex30**
Ex1	0	0	0	0	0	0	0	0	0	0	0	0
Ex5		0.999	0.001	0.001	0.002	0.002	0.016	0.016	0.02	0.02	0.021	0.021
Ex6			0.001	0.001	0.002	0.002	0.016	0.016	0.02	0.02	0.021	0.021
Ex9				1	0.169	0.169	0	0	0	0	0	0
Ex10					0.169	0.169	0	0	0	0	0	0
Ex13						1	0	0	0	0	0	0
Ex14							0	0	0	0	0	0
Ex21								0.999	0	0	0	0
Ex22									0	0	0	0
Ex25										1	0.91	0.91
Ex26											0.91	0.91
Ex29												1

Table 6.9 compares the p-values of each pair of experiments that obtained a significant increase in the average remaining shelf-life. From the table it is observed that all of the listed experiments differ statistically significantly from Experiment 1 because the p-value per pairwise comparison is less than α. This means that implementing the logistic activities of any of these experiments would result a significant difference in the mean remaining shelf-life at the retail stores.

The highlighted cells show the p-values of each pair of experiments that do not differ statistically significantly (p-values $> \alpha$). The green coloured cells highlight the pair of experiments that are not statistically significantly different possibly due to the logistic activities being similar at both the supplier and the distribution centre. This might suggest the change in the logistic activity at the retail store have no significant contribution towards the increase in the average remaining shelf-life for these pair of experiments. The red coloured cells highlight the pair of experiments that are not statistically significantly different possibly because the change in logistic activities at the distribution centre have no significant contribution towards the increase in the average remaining shelf-life.

The δ increase in the remaining shelf-life was determined for each experiment listed in Table 6.9 to compare how well they performed to the baseline logistic activities. Table 6.10 presents the experiments with their set of logistic activities at each stage. The four experiments that obtained the best increase in remaining shelf-life at the retail stores are highlighted in blue and the output measurements of these experiments are shown separately.

Table 6.10: The experiments that obtained the most increase in remaining shelf-life

Experiment	**Supplier**	**Distribution centre**	**Retail store**	**Shelf-life**	**δ increase**
1 (baseline)	1	1	1	8.260 days	-
5	1	2	1	9.290 days	11 %
6	1	2	2	9.290 days	11 %
9	1	3	1	9.074 days	9 %
10	1	3	2	9.074 days	9 %
13	1	4	1	9.088 days	9 %
14	1	4	2	9.088 days	9 %
21	2	2	1	9.449 days	13 %
22	2	2	2	9.450 days	13 %
25	2	3	1	9.161 days	10 %
26	2	3	2	9.161 days	10 %
29	2	4	1	9.162 days	10 %
30	2	4	2	9.162 days	10 %

Experiment 5

Experiment 5 illustrates the set of logistic activities where: (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores follow a First-In-First-Out replenishment strategy.

Table 6.11: Results of Experiment 5

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	5,614 trays
Total average shelf-life at retail stores (at purchase)	9.290 days
Average remaining shelf-life wasted at retail stores	8.137 days
Total sales	R3,075,516.86
Total loss due to waste	R2,065,282.13

From Table 6.11 it is observed that the average remaining shelf-life at the retail stores was 9.290 days and a total of R3,075,516.86 the strawberry trays were sold. Furthermore, it is observed that the total amount of waste at the retail stores are significantly high as 5,614 strawberry trays have been wasted. This resulted a total loss of R2,065,282.13 due to waste and the average remaining shelf-life that was wasted is 8.137 days.

Experiment 6

Experiment 6 illustrates the set of logistic activities where: (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores follow a Last-In-First-Out replenishment strategy.

From Table 6.12 it is observed that the average remaining shelf-life at the retail stores was 9.290 days and a total of R3,075,516.86 the strawberry trays were sold. Furthermore, it is observed that the total amount of waste at the retail stores are significantly high as 5,614 strawberry trays have been wasted. This resulted a total loss of R2,065,282.13 due to waste and the average remaining shelf-life that was wasted is 8.138 days.

Table 6.12: Results of Experiment 6

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	5,614 trays
Total average shelf-life at retail stores (at purchase)	9.290 days
Average remaining shelf-life wasted at retail stores	8.138 days
Total sales	R3,075,516.86
Total loss due to waste	R2,065,282.13

Experiment 21

Experiment 21 illustrates the set of logistic activities where: (i) the tractor transports the strawberry trays every two hours to the pre-cooling facility; (ii) the distribution centre follows a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores follow a First-In-First-Out replenishment strategy.

Table 6.13: Results of Experiment 21

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	5,633 trays
Total average shelf-life at retail stores (at purchase)	9.449 days
Average remaining shelf-life of wasted trays at retail store	8.354 days
Total sales	R3,030,299.50
Total loss due to waste	R2,072,272.61

From Table 6.13 it is observed that the average remaining shelf-life at the retail stores are 9.449 days and a total of R3,030,299.50 worth of the strawberry trays were sold. Furthermore, it is observed that the total amount of waste at the retail stores are significantly high as 5,633 strawberry trays have been wasted. This resulted a total loss of R2,072,272.61 due to waste and the average remaining shelf-life that was wasted is 8.354 days.

Experiment 22

Experiment 22 illustrates the set of logistic activities where: (i) the tractor transports the strawberry trays every two hours to the pre-cooling facility; (ii) the distribution centre follows a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores follow a Last-In-First-Out replenishment strategy.

Table 6.14: Results of Experiment 22

Output measurements	**Results**
Waste at distribution centre	0 trays
Total waste at retail stores	5,633 trays
Total average shelf-life at retail stores (at purchase)	9.450 days
Average remaining shelf-life of wasted trays at retail store	8.353 days
Total sales	R3,030,299.50
Total loss due to waste	R2,072,272.61

From Table 6.14 it is observed that the average remaining shelf-life at the retail stores are 9.450 days and a total of R3,030,299.50 worth of the strawberry trays were sold. Furthermore, it is observed that the total amount of waste at the retail stores are significantly high as 5,633 strawberry trays have been wasted. This resulted a total loss of R2,072,272.61 due to waste and the average remaining shelf-life that was wasted is 8.353 days.

When comparing the output measurements of these experiments it can clearly be noted that there are almost no difference between Experiments 5 and 6 as well as between Experiments 21 and 22. This is also confirmed with the per pairwise comparison of the p-values as shown in Table 6.9. Both Experiments 5 and 6 differ statistically significantly from Experiments 21 and 22. Since the goal is to increase the remaining shelf-life of the strawberries, it is suggested that the logistic activities of either Experiment 21 or Experiment 22 could be implemented.

6.2 Discussion of results

From the analysis of the results of the experiments, specific trends were noted when a specific logistic activity has been implemented. The following section will discuss the identified trends and impact thereof on (i) the total waste that occurred throughout the supply chain; and (ii) the remaining shelf-life of the strawberry trays at the retail stores.

6.2.1 The impact of the distribution centre stock-rotation strategies on waste

Figure 6.3 shows the impact of the different stock-rotation strategies at the distribution centre on the total waste. The blue bars represent the total waste that was produced in the supply chain and is the sum of the waste at the distribution centre (red bars) and the waste at the retail stores (green bars). From the figure it was noted that the distribution centre did not experience much waste as three of the four stock-rotation strategies resulted in zero waste. This might be due to the responsive lead time the retail chain implemented. The distribution centre aims to distribute the strawberry trays to the retail stores within the same day that they receive the strawberry trays from the supplier. Thus, the time the strawberry trays spend in storage is normally less than 24 hours.

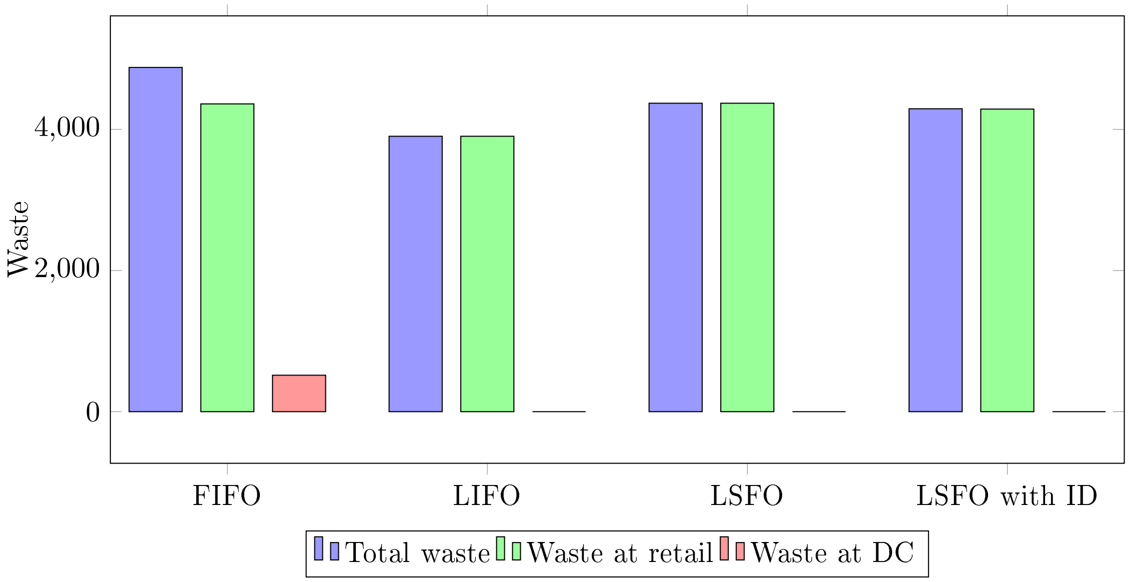


Figure 6.3: Waste across the supply chain due to stock-rotation policies

The First-In-First-Out stock-rotation strategy resulted in some waste at the distribution centre. The reason therefore is that this stock-rotation strategy is not guided by the remaining shelf-life of the strawberry trays, but rather by the date the strawberry trays entered the distribution centre and the strawberry trays are all treated the same way. Seeing that the strawberry trays are not placed in storage based on the remaining shelf-life, there may exist significant shelf-life variation from tray to tray. For instance, assume that some of the strawberry trays that arrived later at the distribution centre have very little remaining shelf-life available. Since a First-In-First-Out stock-rotation strategy was followed, the trays will become wasted before being selected to be delivered to the retail stores.

Furthermore it was observed that the Last-In-First-Out stock-rotation strategy produced the least waste, and all the waste occurred at the retail stores. This is possibly because the retail stores received the strawberry trays that were delivered last to the distribution centre from the supplier. Consequently, the remaining shelf-life of the strawberry trays should be higher (although variability will still exist) because they supposedly represent the strawberries that were harvested in the afternoon and may have experienced less waiting time in uncontrolled environments.

Both the Least-Shelf-life-First-Out with and without intelligent distribution stock-rotation strategies, produced less waste at the retail stores than the First-In-First-Out stock-rotation but produced more waste than the Last-In-First-Out stock-rotation. This might be due to prioritising the strawberry trays based on the remaining shelf-life. Thus, the strawberry trays with the lowest remaining shelf-life were batched together and delivered to the retail store who required delivery first. Whereas the strawberry trays with the most remaining shelf-life will be delivered to the retail store who require the last delivery. This stock-rotation strategy may have the result that the retail stores who are first in line for delivery, will receive strawberry trays with remaining shelf-life that may become unacceptable much faster during transport or storage, and may not even reach the display shelves to be purchased by the consumers.

6.2.2 The impact of the retail store's replenishment strategies on waste

Figure 6.4 shows the impact of the different replenishment strategies at the retail stores on the total waste. The blue bars represent the total waste that was produced in the supply chain and is the sum of the waste at the distribution centre (red bars) and the waste at the retail stores (green bars). From the figure it was noted that the distribution centre did not experience waste with the First-In-First-Out and Last-In-First-Out replenishment strategies, whereas the retail stores experienced a high amount of waste with both replenishment strategies. Furthermore, it was noted that the Least-Shelf-life-First-Out replenishment strategy, with and without dynamic pricing produced some waste at the distribution centre but the amount of waste at the retail store reduced significantly.

Both the First-In-First-Out and the Last-In-First-Out replenishment strategies contributes to the most waste at the retail stores. Again the reason therefore is that both these replenishment strategies are not guided by the remaining shelf-life of the strawberry trays, but rather by the date the strawberry trays entered the back stores of the retail stores and in addition, the strawberry trays are all treated as if the remaining shelf-life are the same for all strawberry trays. In consequence, the strawberry trays in the back store have a large variety in remaining shelf-life. If strawberry trays with lower remaining shelf-life are not moved to the display shelves fast enough, they become wasted before the consumer has the opportunity to purchase the strawberries.

In addition consumers tend to search for the best-looking strawberries and buy strawberries with the longest available sell-by date, even though it is not an accurate representation of the actual remaining shelf-life. If the strawberries have reached their sell-by date the retail stores are forced to remove them from the display shelves because consumers tend to assume that the strawberries have not any remaining shelf-life left. This results in the strawberry trays becoming wasted even though they may have had sufficient remaining shelf-life available and would have been acceptable for consumption.

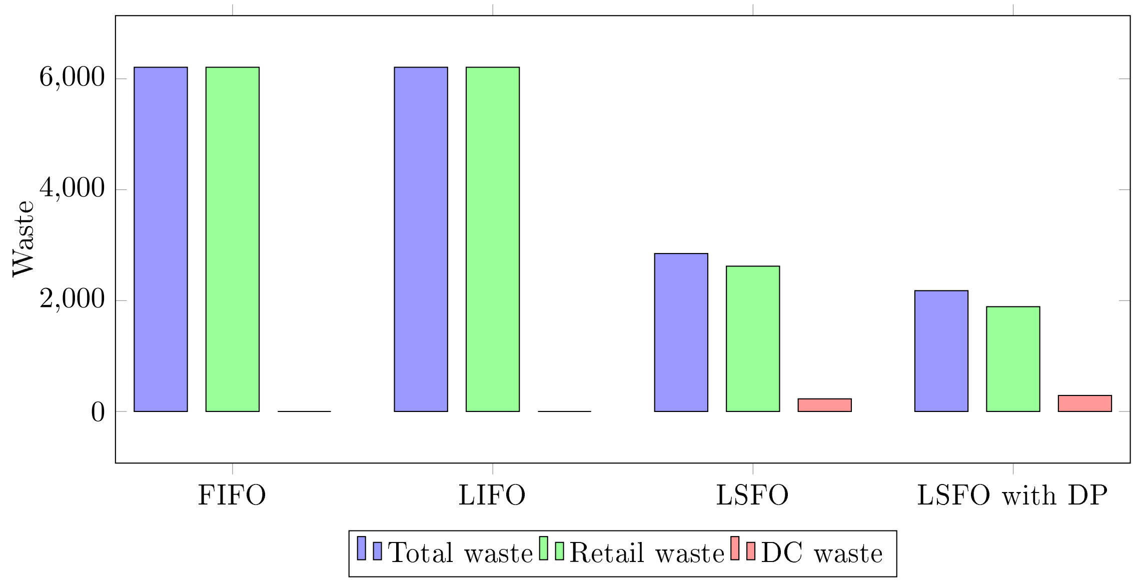


Figure 6.4: Waste across the supply chain due to replenishment strategies

A noteworthy observation was that the Least-Shelf-life-First-Out replenishment strategy with and without the dynamic pricing produced some waste at the distribution centre. This may be due to moving the lower shelf-life strawberry trays to the display shelves and keeping the higher remaining shelf-life strawberry trays in the back store. While doing so, the retail stores ensure that the lower remaining shelf-life strawberry trays are being purchased first and the remaining strawberry trays can be stored for longer times in the back store without turning into waste. Since less waste is produced in the back store, less strawberry trays might be required to order to account for losses. The consequence thereof is that the strawberry trays move slower out of the distribution centre, thus increasing the chances of becoming waste before they are delivered to the retail stores.

The Least-Shelf-life-First-Out replenishment strategy produced much less waste at the retail stores. This is most likely because the strawberry trays with lower remaining shelf-life are placed on display first and the strawberry trays with higher remaining shelf-life are kept in the back store until it is necessary to restock the display shelves. By doing so, this reduces the variability of the remaining shelf-life of the strawberries on display, meaning that it would be less likely for consumers to select strawberries with a much higher remaining shelf-life than the other strawberries also on display.

Combining Least-Shelf-life-First-Out replenishment with a dynamic pricing strategy reduced the waste at the retail store even further. The dynamic pricing strategy suggests that the strawberries on display receive a discount based on the remaining shelf-life. For example, strawberries with a remaining shelf-life of one day will cost less than the strawberries with a remaining shelf-life of five days. By implementing dynamic pricing based on shelf-life it is believed that consumers will be more willing to buy lower remaining shelf-life strawberries when they know that they will receive a discount. Thus the quantity of strawberries that are wasted on display becomes much less, because consumers will either buy strawberries with high remaining shelf-life when the price is kept constant, or buy low remaining shelf-life strawberries if they receive discount.

Table 6.15 shows the differences between the average revenue of total sales as well as the losses due to waste for each replenishment strategy that were implemented at the retail stores. When focusing on the average total sales, it is observed that the Least-Shelf-life-First-Out strategy resulted in an increase in sales of an average R57,197.62 more than the average sales of both First/Last-In-First-Out strategies.

Table 6.15: The losses and sales

Replenishment strategy	**Average total sales**	**Average total loss due to waste**
FIFO	R3,088,153.24	R2,289,457.46
LIFO	R3,088,153.24	R2,289,457.46
LSFO	R3,145,350.87	R964,440.96
LSFO with DP	R3,046,309.42	R695,264.41

Furthermore, the Least-Shelf-life-First-Out strategy with and without dynamic pricing resulted in a reduction of more than R1,300,000 due to less waste that occurred at the retail stores. This could be advantageous to the retail chain, since it creates the opportunity for the retail chain to invest in new strategies, such as emerging technologies, to capture accurate and dynamic shelf-life data throughout the entire supply chain, to ultimately assist the concept of quality-controlled logistics.

6.2.3 The impact of stock-rotation and replenishment strategies on remaining shelf-life at purchases

Figure 6.5 shows the impact of the different stock-rotation strategies at the distribution centre on the remaining shelf-life of the strawberry trays purchased at the retail stores. From the figure it was noted that the First-In-First-Out stock-rotation strategy resulted in the lowest remaining shelf-life of strawberries. This is possibly because the delivery trucks only transport the strawberry trays to the retail stores during the evening. The strawberry trays that entered the distribution centre first wait a longer time in storage to be selected for deliveries. Conversely, the Last-In-First-Out stock-rotation strategy allows the strawberry trays that entered the distribution centre last, to be selected for deliveries first, with the result that the selected strawberry trays did not wait in storage for a long time. Hence, when disregarding the waste that may have occurred due to shelf-life variability among the trays, the consumers were able to purchase high remaining shelf-life strawberries.

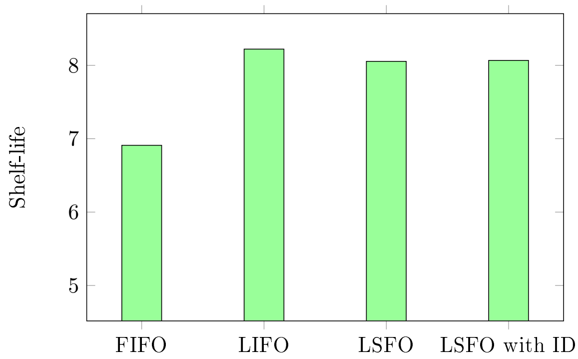


Figure 6.5: Impact of the distribution centre's stock-rotation strategies on remaining shelf-life at purchases

Furthermore, the Least-Shelf-life-First-Out stock-rotation strategy with and without intelligent distribution resulted in less remaining shelf-life than the Last-In-First-Out strategy. This is possibly because the lower remaining shelf-life strawberry trays are selected first for delivery to the retail stores, whilst the higher remaining shelf-life strawberry trays are kept in storage, potentially reducing unnecessary waste. Thus the strawberries available for purchase at the retail stores had less remaining shelf-life.

Figure 6.6 shows the impact of the different replenishment strategies on the remaining shelf-life of the strawberry trays purchased at the retail stores. From the figure it was observed that both the First/Last-In-First-Out replenishment strategies resulted that the remaining shelf-life of the strawberry trays were much higher than the Least-Shelf-life-First-Out replenishment strategies. This result was expected, especially since the purpose of the Least-Shelf-life-First-Out replenishment strategy was to move the strawberry trays with lower remaining shelf-life to the display. This was done to ensure that the strawberries do not become waste in the back store due to shelf-life variability, and to force consumers to unknowingly purchase the lower remaining shelf-life strawberries.

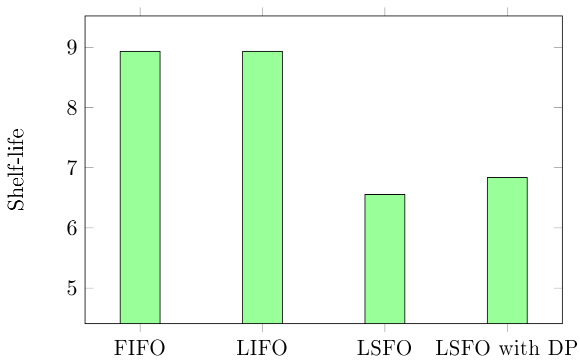


Figure 6.6: Impact of the retail store's replenishment strategies on remaining shelf-life at purchases

6.2.4 The impact of supplier logistic activities

Lastly, the impact of the supplier logistic activities is evaluated by observing: (i) the remaining shelf-life of the strawberry trays arriving at the pre-cooling facility; and (ii) the impact it has on the total waste as well as the remaining shelf-life at the retail stores.

The remaining shelf-life of strawberry trays arriving at the pre-cooling facility

Figure 6.7 illustrates the difference in remaining shelf-life of the strawberry trays that arrived at the pre-cooling facility from the three farms. For Experiments 1 to 16 the remaining shelf-life of the strawberry trays had similar results because the tractor waited at the farms until it was fully loaded before proceeding to the pre-cooling facility. For Experiments 17 to 32 the tractor transported a load of strawberry trays every two hours to the pre-cooling facility.

The change in this logistic activity resulted in two outcomes on the remaining shelf-life of the strawberry trays once they arrived at the pre-cooling facility. The results in Figure 6.7 show that the remaining shelf-life of the strawberry trays from Farm 1 increased by an average of 0.047 days (1.14 hours) and at Farm 2 it increased by an average of 0.037 days (0.89 hours). The reason for the slight increase in remaining shelf-life is possibly because the harvested strawberry trays spent less time waiting in warm uncontrolled temperatures.

However, at Farm 3 the remaining shelf-life decreased by an average of 0.032 days (0.77 hours). This in part may be due to being located the furthest from pre-cooling facility. The travelling time between the farms and pre-cooling facility, as well as the unloading time at the pre-cooling facility was not considered with this logistic activity. As a result, the harvested strawberry trays may more frequently experience longer times waiting on the farm, whilst waiting for the tractor to return.

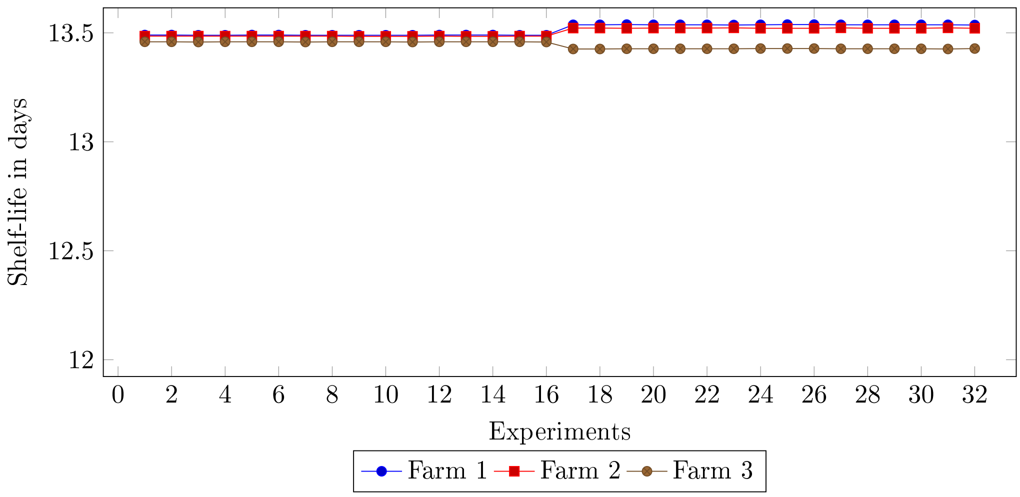


Figure 6.7: Remaining shelf-life of strawberry trays before transported to the pre-cooling facility

The benefit of adapting the logistic activity from waiting until the tractor is fully loaded to waiting every two hours to transport harvest strawberry trays to the pre-cooling facility, will most likely depend on the time needed for the tractor to travel to and from the pre-cooling facility. In addition to the two-hour waiting time, if it takes the tractor a long period of time to travel to and from the pre-cooling facility, the strawberry trays may experience additional waiting time on the farm. Therefore, if the distance between the farms and pre-cooling facility is large, the tractor should rather wait until it is fully loaded before travelling; otherwise, additional waiting time may be experienced by the strawberry trays.

Impact on total waste and remaining shelf-life at the retail stores

Figure 6.8 shows the impact of the two defined supplier logistic activities on the total waste within the supply chain. The blue bars represent the experiments where the "full tractor load" logistic activity were implemented whereas the green bars represent the experiments where the adapted activity (transporting strawberry trays every two hours from farm to pre-cooling facility) were implemented. From the figure it was observed that the adapted logistics activity had a positive impact on Experiments 4, 5, 6, and 15 but for the majority of the experiments the total amount of waste remained the same or increased slightly.

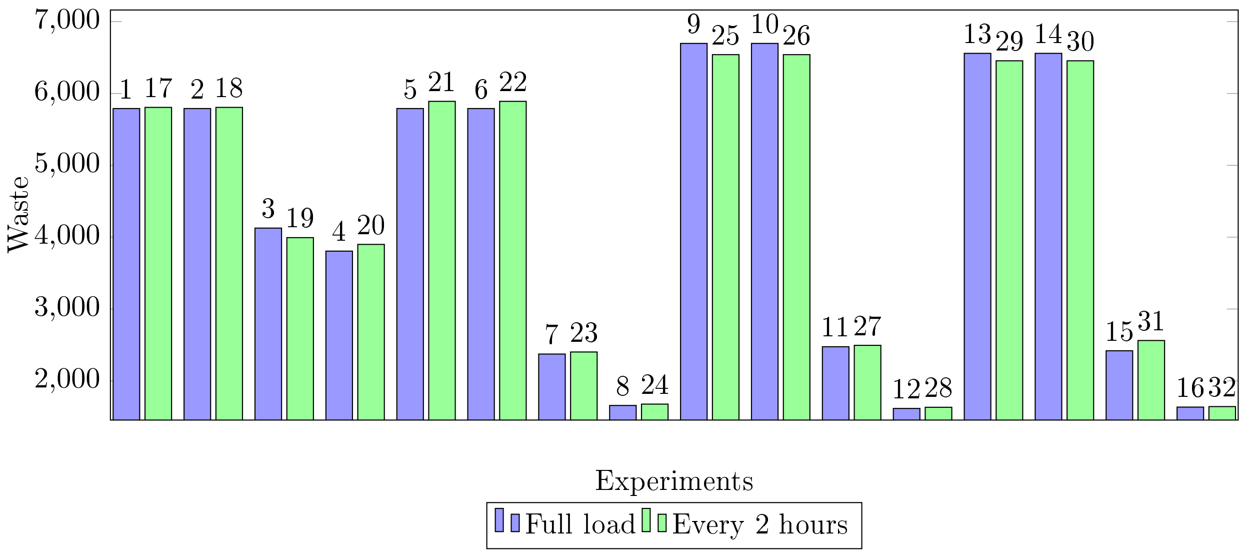


Figure 6.8: Impact on total supply chain waste

Figure 6.9 shows the impact of the two defined supplier logistic activities on the remaining shelf-life of strawberry trays at the retail stores before being purchased by the consumers. Again, the blue bars represent the experiments where the "full tractor load" logistic activity were implemented whereas the green bars represent the experiments where the adapted activity (transporting strawberry trays every two hours from farm to pre-cooling facility) were implemented. From the figure it was noted that the adapted logistic activity tends to have a positive influence on the remaining shelf-life of strawberry trays at the retail stores as the remaining shelf-life increased slightly in most of the experiments.

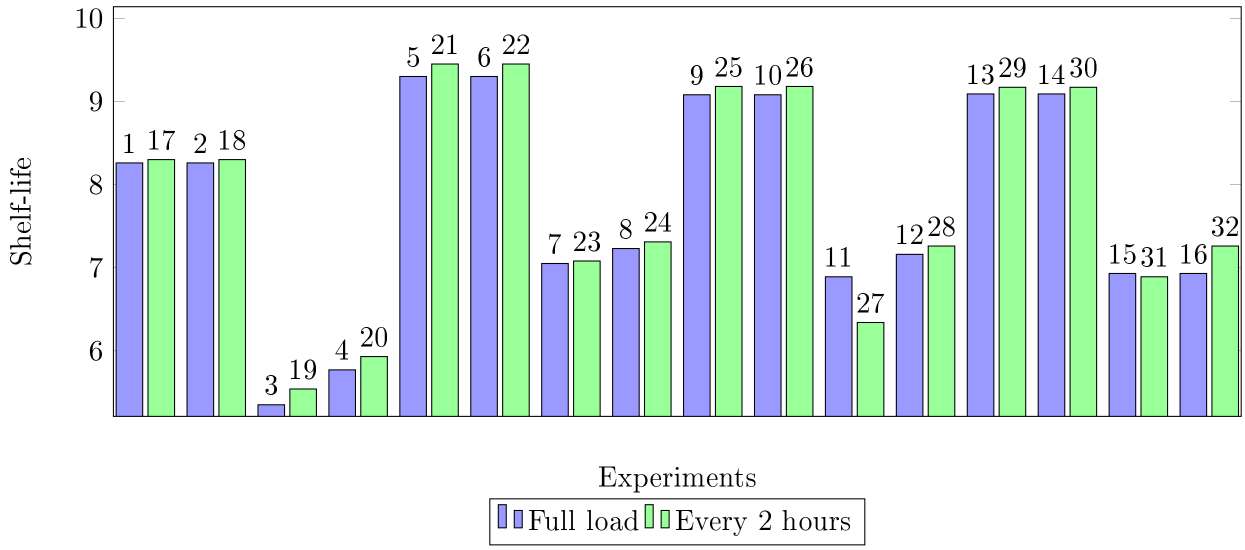


Figure 6.9: Impact on remaining shelf-life of strawberry trays at the retail stores

From the results of Figures 6.7, 6.8 and 6.9 it was observed that the adapted logistic activity has a slight impact on the reduction of waste throughout the supply chain as well as on the increase in remaining shelf-life of the strawberry trays. Yet, it should be considered that an increase in the frequency of travelling to and from the pre-cooling facility may perhaps increase any associated costs. It will most likely result in an increase in fuel consumption, and maintenance or repairing of the tractor might be required more often.

Additionally, one must ask oneself which supply chain actor will receive the most benefit from the adapted logistic activity. Since it was observed that there was no significant improvement in remaining shelf-life at the supplier stage, the supplier will probably be reluctant to change the logistic activity because it will possibly increase the costs to supply strawberry trays to the retail chain and they will not receive direct benefit from the adapted logistic activity. However, since the retail chain will receive the most benefit from this logistic activity (because they will save costs due to the reduction in total waste), it can be argued that the retail chain should be responsible for convincing the supplier that they could contribute towards the reduction of the total waste.

For example, consider Experiment 9 in Figure 6.8 where the total waste reduced from 6,683 strawberry trays to 6,553 strawberry trays which allowed the retail chain to save R51,653.74 due to less waste. The retail chain now has the opportunity to invest the savings into the supplier's logistic costs to assist them to adapt their logistic activities. Not only might this improve the remaining shelf-life of the strawberry trays as well as reduce waste along the supply chain, but it might enhance the supplier relationship and trust.

6.2.5 Trade-off between total waste reduction and increased remaining shelf-life

Figure 6.10 compares the remaining shelf-life of the purchased strawberries at the retail stores with the amount of waste that was produced across the supply chain, between each experiment. From the figure it is observed that the experiments which obtained the high remaining shelf-life were the experiments which resulted in high amounts of waste. On the other hand, the experiments that obtained the least total waste resulted in lower remaining shelf-life, yet they did not obtain the worst remaining shelf-life compared to other experiments. The baseline experiment (Exp 1) as well as the experiments that obtained the highest remaining shelf-life (Exp 21/22) and least waste (Exp 12) are highlighted in the figure.

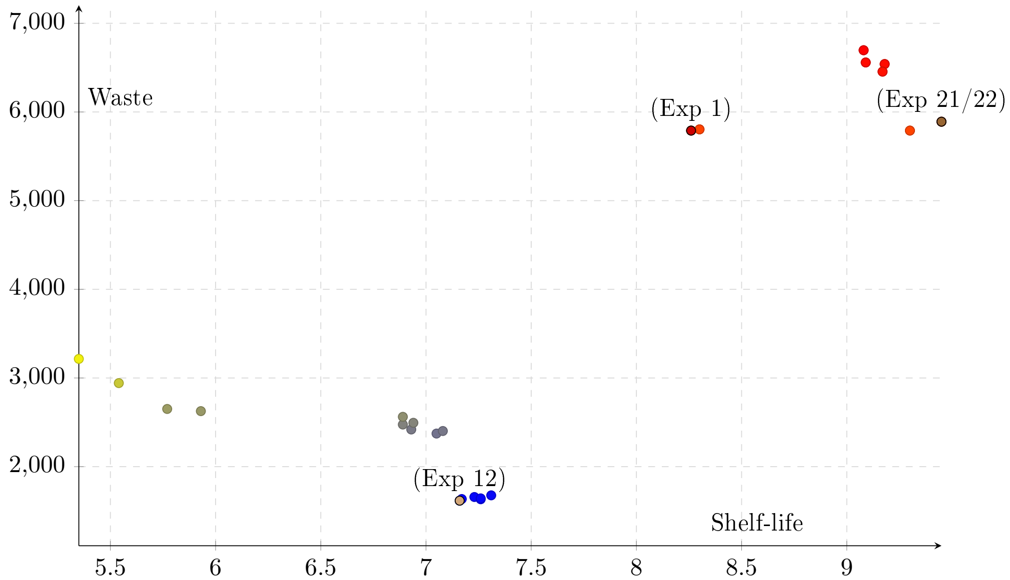


Figure 6.10: Comparing the remaining shelf-life of strawberries at purchase with the total waste that occurred for each experiment

Following the logistic activities of either Experiments 21 or 22 will ensure that the consumers will always be able to purchase high quality strawberries because the remaining shelf-life should be on average more than nine days at purchase. The reason for this is because both experiments follow a Last-In-First-Out stock-rotation strategy at the distribution centre and either follow a First-In-First-Out or a Last-In-First-Out replenishment strategy at the retail stores. Section 6.2.3 discussed the reasons why these logistic activities would result in high remaining shelf-life at purchases.

However, the retail chain will not experience a significant reduction in waste due to the impact of the selected logistic activities, as previously discussed. If the retail chain's aim is to reduce the amount of waste that occurred throughout the supply chain, they should consider sacrificing a high remaining shelf-life of strawberries and follow the logistic activities represented by Experiment 12. The reason for this is because Experiment 12 follows a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy at the retail stores which has a large contribution towards the reduction in waste across the supply chain, as discussed in Section 6.2.2.

The average total sales revenue and the average losses due to waste for the three experiments are analysed to determine which set of logistic activities to implement. From Table 6.16 it is observed that there is no increase in the average sales volumes when Experiments 12 and 21/22 are compared to the baseline experiment. Experiment 12 resulted in a reduction of 0.87% and the reason for this is due to the dynamic pricing and discounting strategy. It is acknowledged that the retail chain will be reluctant to accept the reduction in sales, thus Experiment 11 is also taken into account because it obtained an increase of 2% in the average total sales. The reason for this is because Experiment 11 followed the same set of logistic activities as Experiment 12 except that dynamic pricing and discounting strategy was not considered at the retail stores. However, the purpose of this strategy was to ensure that lower remaining shelf-life strawberries were purchased to reduce the amount of wastage that occurred, and not to optimise the number of purchases at the retail stores. Experiment 21/22 resulted in a reduction of 1.47% and the reason for this result is because more strawberries were wasted than in Experiment 1 thus fewer strawberries were available to be purchased.

Table 6.16: The sales revenue and losses for selected experiments

Experiments	**Average total sales**	**Increase in sales**	**Average total loss due to waste**	**Reduction in losses**
Exp 1 (baseline)	R3,075,516.86		R2,065,282.19	
Exp 11	R3,145,458.46	2%	R912,184.06	56%
Exp 12	R3,048 909.73	-0.87%	R594,669.10	71%
Exp 21/22	R3,030,299.50	-1.47%	R2,072,272.61	-0.34%

Although there was not a significant difference in the average total sales, the retail chain can benefit from the total reduction in losses due to waste. Comparing the average losses it is observed that Experiment 11 and Experiment 12 obtained a reduction in losses whereas Experiment 21/22 obtained an increase of 0.34%. It is suggested that the retail chain should implement the logistic activities represented by Experiment 12: (i) the tractor waits at the farm until it is fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre follows a Least-Shelf-life-First-Out stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy. The reason for this is because the savings that was obtained due to reduced losses from this experiment, is more significant than the increase in total sales that was obtained in Experiment 11. Additionally, one can argue that the logistic activities that resulted in a slightly lower remaining shelf-life at purchases would possibly increase the amount of food wasted during consumption. But comparing the remaining shelf-life of Experiment 12 with Experiments 21/22, shows that there is not a large reduction in the remaining shelf-life between these experiments. Therefore it should not have too much of an impact on food waste during the consumption stage.

Considering that the experiments were only tested for a one-month period, one could possibly anticipate significant savings in the future when the logistic activities are adapted to reduce the total waste across the supply chain. This creates the opportunity for the retail chain to invest in digital strategies to dynamically and accurately measure remaining shelf-life to assist the implementation of quality-controlled logistic activities. Furthermore, they can invest in the supplier to assist them improving their logistic activities, thereby also improving the supplier trust. Lastly, the retail chain may be rewarded with a trusted brand and increase in market satisfaction, since they will be known for their contribution to mitigating food waste.

6.3 Validation

The purpose of validation was to confirm that the right model was built for the particular objectives of this study. The results and discussion of the simulation study were validated by an expert working in the same retail chain that was selected as the case study. The expert analysed the results that were obtained from the simulation model and then had the opportunity to answer a set of questions to validate the results of this study. The key comments the expert provided are discussed in the following subsections.

6.3.1 Opinion regarding the various logistics activities that were evaluated and the feasibility of the results that were obtained regarding food waste and remaining shelf-life

The expert stated that the various logistic activities that were evaluated was valid and it made sense to develop various sets of logistic activities to experiment how the change in logistic activities at each stage in the supply chain would influence each other. He further acknowledged that it made sense that little waste occurred at the distribution centre and that most of the waste occurred at the retail stores. He confirmed that the only waste that should occur at the distribution centre would be due to the wrong handling of products. Furthermore, he agreed that the Least-Shelf-life-First-Out replenishment strategy would result in a large reduction in food waste at the retail stores because it would reduce the variability in remaining shelf-life at the display shelves and the products with low remaining shelf-life would always be selected by the consumers. The expert further agreed that dynamic pricing and discounting based on remaining shelf-life would be a good strategy to implement. The reason for this is because retail stores would certainly want to maximise the number of sales being made, rather than to risk the loss of sales because products became wasted before consumers could purchase them.

6.3.2 Other logistic activities and events that should have been considered in the simulation study

The expert explained that in some fresh produce supply chains, the produce is harvested when they are not fully ripe and is sent to a staging facility where various fresh produce commodities are stored. The staging facility receives multiple orders from clients requesting the desired quantity as well as the minimum required remaining shelf-life the ordered produce should have. The staging facility would then mechanically ripen the produce to ensure that the clients would receive produce with the required remaining shelf-life. The expert believes that significant waste occurs at the staging facility due to the ripening process. The reason for this is because it is difficult to ensure that all produce is ripened to the exact shelf-life requirements. He mentioned that the Least-Shelf-life-First-Out strategy would potentially have a big impact on the staging facility's inventory management because it would allow them to batch produce with the required minimum shelf-life together to ensure that the clients' shelf-life requirements would be addressed.

The reason why the staging facility was not implemented in this simulation study is because the case study only focused on the logistic activities for the strawberry production. To reduce modelling complexities, it was decided to only implement the pre-cooling facility where the strawberries are kept after harvesting until they are transported to the distribution centre. However, to incorporate the staging facility, future alterations to the simulation model can be done to evaluate the impact of the investigated logistic activities on the amount of waste that occurs at the staging facility.

The expert highlighted that the ordering strategy of the retail store would have a big impact on the amount of waste that would occur at the retail store and it would also influence the calculation to estimate the required remaining shelf-life the produce should have in store. The reason for this is because factors such as: (i) the rate of sales; (ii) number of units per tray; and (iii) required shelf-life of the stock need to be considered to determine the number of products to order for the retail stores. This would be to ensure that most products are sold with acceptable quality and to ensure that waste due to low-quality products would be kept to a minimum.

6.3.3 Opinion regarding the willingness to adapt current logistic activities to these quality-controlled logistic activities

The expert said that supply chain actors would be willing to adapt their logistic activities when they realise that it could reduce the amount of food being wasted and potentially increase the number of products being purchased in the retail stores. However, he mentioned that it would be a time-consuming and costly process to adapt logistic activities, and the actors must be willing to embrace the change.

6.4 Conclusion

This chapter provided the analysis and the discussion of the results that were obtained by simulating the experiments described in the previous chapter. The results obtained from the current logistic activities of the retail chain were analysed, after which selected experiments were identified to analyse their impact on waste reduction and increasing remaining shelf-life. Thereafter, trends were identified by evaluating the impact of various logistic activities at the supplier, distribution centre and the retail stores. The trade-off between waste reduction and increase in remaining shelf-life was discussed in order to identify which set of logistic activities would be most beneficial for the retail chain to implement. Lastly, the results of the simulation study were validated by an expert working in the fresh produce industry.

Chapter 7

An Internet of Things prototype to measure dynamic shelf-life

The previous chapters explored the concept of quality-controlled logistics activities and discussed several strategies that can be used to implement these activities within the fresh produce supply chain. Dynamic shelf-life predictions were identified as a suitable application to assist the implementation of quality-controlled logistics activities. Thereafter, the impact of selected quality-controlled logistic activities on (i) fresh produce quality, and (ii) waste reduction, was evaluated by simulating the strawberry supply chain of a South African retail chain.

This chapter will focus on how emerging technology such as Internet of Things (IoT) creates opportunities to collect real-time food quality data, which may be used to develop a dynamic shelf-life prediction application. The purpose of this application would be to assist quality-controlled logistic activities from a technical perspective. First, the chapter will introduce current IoT-technologies that are being tested to support dynamic shelf-life predictions. Thereafter a proposed IoT-application is described and the development of the application prototype is discussed. The chapter concludes with some challenges that need to be addressed before considering the implementation of IoT-technologies within the supply chain.

7.1 Introducing IoT-technologies to support dynamic shelf-life predictions

Due to it being perishable, fresh produce is given expiry dates to guarantee that the quality is still acceptable for consumption. Producers are obligated to provide a shelf-life expiry date, but it is difficult to accurately predict the shelf-life when they do not know the conditions the fresh produce will be exposed to (Sjödahl & Lilja, 2014). Temperature has a great impact on the shelf-life of fresh produce, and if the produce is stored and transported at the required temperatures, it could be consumed even after the printed expiry date and thus also reduce unnecessary food waste. To be able to communicate the dynamic remaining shelf-life of fresh produce, the produce flow as well as the effect of the environment on the remaining shelf-life should be measured and logged throughout the supply chain.

Internet of Things (IoT) is an emerging technology that offers promising solutions such as tracking, monitoring and data accessibility to make real-time decisions (Zhou *et al.*, 2015). Combining these technologies with packaging is not new, as Yam *et al.* (2005) developed a conceptual model to illustrate how sensing technologies can be used to monitor and control the quality of fresh produce. Yam & Lee (2012) further discussed that the following components should be investigated when one wants to design an intelligent packaging system:

Environmental conditions

An intelligent packaging system should have the ability to measure and monitor external and internal environmental conditions around the food product. External conditions refer to the conditions outside packaging such temperature and humidity. Internal conditions focus more on the kinetic changes inside the packaging (Barska & Wyrwa, 2017; Heising *et al.*, 2014). Both conditions influence the quality attributes of the food.

Smart packaging devices

Smart package devices are defined by Kuswandi *et al.* (2011) as "devices that have the ability to track the product, sense the environment inside or outside the package and inform the manufacturer, retailer and consumer regarding the condition of the product". These devices are attached onto either the primary or secondary packaging to facilitate communication throughout the supply chain. Three main technologies are currently available to communicate data and information: (i) indicators; (ii) sensors; and (iii) data carriers (Heising *et al.*, 2014; Kerry *et al.*, 2006).

Indicators

Indicators are devices that convey information about the presence or absence of a target substance or the degree of reactions between two or more substances. Information is displayed by visual changes e.g. different colour intensities or diffusion of a dye along the indicator geometry (Han, 2005; Kerry *et al.*, 2006). A distinct feature of indicators is that the type of information involved can be qualitative or semi-qualitative. Within the food industry, the most common indicators are time-temperature indicators, freshness indicators and leakage indicators (Dobrucka & Cierpiszewski, 2014; Robertson, 2016).

Time-temperature indicators (TTI)

Temperature is one of the most important environmental conditions to monitor, as it has a great influence on food quality (Yam & Lee, 2012). TTIs are indicators that continually monitor the current temperature of a product and react to thermal changes in the environment. They are self-adhesive labels that provide visual indications of the temperature history throughout the supply chain. TTIs have the ability to show and warn role players whether the food products have been heated or cooled below their critical temperature point (Ghaani *et al.*, 2016). In most cases TTIs are placed on the outside of the packaging and do not come in contact with the product. This means that the temperature of the packaging surface is measured rather than the product itself (Barska & Wyrwa, 2017; Dobrucka & Cierpiszewski, 2014).

Freshness indicators

Freshness indicators have the ability to monitor and show the changes of the quality of food products during storage and transportation. They can provide direct information with regards to quality by monitoring microbial growth and chemical changes in the food product (Dobrucka & Cierpiszewski, 2014; Ghaani *et al.*, 2016). These chemical changes release chemical compounds.

Leakage indicators

Leakage indicators are colour indicators that measure the oxygen and carbon dioxide inside the package and are in direct contact with food. The colour changes as a result of chemical or enzymatic reactions occur inside the package (Dobrucka & Cierpiszewski, 2014).

Sensors

According to Lee *et al.* (2015), a sensor is defined as "an analytical device that detects or quantifies problem or visual signals to measure chemical or physical properties". It has the ability to give a continuous output signal. The most common sensors used in the food industry are gas sensors, biosensors and fluorescence-based oxygen sensors.

Data carriers

Data carriers, also known as automatic identification and traceability devices, are mainly used to store and transmit data (Yam *et al.*, 2005). Data carriers make information flow within the supply chain more efficient and provide the means of effective communication between the product and customers. Moreover, data carriers are more often placed on tertiary packaging. Barcodes and RFID tags are commonly known data carriers in the food industry (Robertson, 2016).

Barcodes

Barcodes are the least expensive and most popular form of data carriers. General barcode data carriers consist of linear symbology with patterns of bars and spaces to represent the data (Yam *et al.*, 2005). The first barcode consisted of 12 digits and only limited information such as manufacturing identification number and item number could be stored. To address the demand for increased data storage, new barcode symbologies such as the Reduced Spaced Symbology (RSS) were introduced. These barcodes are suitable to use on loose items such as apples, pears and oranges, and have the ability to store more information such as packed date, batch number and packaged weight (Yam *et al.*, 2005). The data stored on barcodes is accessed via scanners and sent to wireless Local Area Networks to convert it into usable information.

Radio Frequency Identification (RFID)

RFID tags are an advanced form of data carriers which use radio waves for product identification and traceability through wireless communication in a fixed frequency band (Lee *et al.*, 2015). The three main components of RFID systems are the (i) tag; (ii) reader; and (iii) software. The tag is an integrated circuit that contains an unique tracking identifier called an electronic product code (EPC), and stores the required data. The reader captures the data with transmitted signals; and provides network connectivity between the tag data and the system software, and lastly the software controls the whole system (Lee *et al.*, 2015; Todorovic *et al.*, 2014).

RFID systems can be classified into three types namely (i) passive tags; (ii) active tags; and (iii) semi-active tags. Passive tags have no battery and are powered by energy; or an electric field supplied by the reader, such as an antenna (Todorovic *et al.*, 2014). Active tags are self-powered or equipped with batteries on the tags to increase the range of collecting data and tag-to-tag related communication, and semi-active tags have batteries that are used to back up the memory and data (Lee *et al.*, 2015).

RFID technologies are useful in the food supply chain, as they have the ability to store information such as temperature, relative humidity, and nutritional data, and to provide real-time updates of the stored information to various actors in the supply chain. Lee *et al.* (2015) further explain how RFID tags can be applied to perishable food that requires strict controlled conditions during storage and distribution.

7.2 A proposed Internet of Things application

The following section begins with a description of a proposed IoT-application that could possibly be used to assist the implementation of dynamic shelf-life predictions. Thereafter, the development of a prototype of the proposed application will be discussed.

7.2.1 Purpose of the proposed application

The purpose of this IoT-application is twofold. Firstly, the application should predict the remaining shelf-life left to transport, store, and display fresh produce. Secondly, the application should be able to communicate the remaining shelf-life of the fresh produce to all relevant stakeholders in the supply chain. Hence, all actors in the supply chain should be allowed to use the application. This application should assist the supply chain actors to implement quality-controlled logistics which should ultimately contribute to the reduction of food waste.

7.2.2 Requirements for the proposed application

The requirements for the proposed application were identified from the feedback obtained by experts in the fresh produce industry, as discussed in Chapter 3. The requirements were then discussed with the analysed retail chain from Chapter 5 to observe whether they agree with the defined requirements. The feedback and insights were transformed into the following key requirements for the proposed IoT-application.

7.2.2.1 Tray-level monitoring

Monitoring the environmental conditions such as the temperature inside the trucks during transport or within the storage facility, is popular within the fresh produce industry. It allows the actors in the supply chain to control the environment to ensure optimal conditions for the fresh produce. Yet, experts realise that monitoring the environment does not provide accurate information about the actual remaining shelf-life of the fresh produce. Theoretically, monitoring fresh produce on product-level would provide the most accurate data on the remaining shelf-life but the costs, including the life cycle of the sensors, and the amount of sensors required have to be considered.

It is suggested to monitor the conditions which the fresh produce is exposed to, on tray-level. For example, consider the strawberry supply chain that was analysed in Chapter 5. At harvest the strawberry punnets are placed in trays and move through the supply chain via the trays. Since the trays spend majority of their life cycle with the strawberries, it is feasible to capture the conditions on tray-level. This provides more accurate data that can be used to develop dynamic shelf-life predictions. Furthermore, the trays as well as the sensors could be reused by sending them back to the suppliers after the trays have reached the retail stores.

7.2.2.2 Conditions to monitor

The following conditions were selected to monitor, as experts mentioned that these conditions should be monitored to provide meaningful information on fresh produce quality. The data of these conditions can also be used to develop dynamic shelf-life predictions.

- **Temperature sensor**
  Most fresh produce is sensitive to high temperatures, because increased temperatures influence the internal composition of the fresh produce and increase the rate of quality degradation. Fresh produce has to be stored at optimal temperatures to prolong the shelf-life and to ensure that quality is maintained during storage and distribution. Therefore, measuring temperature provides the ability to monitor whether the produce is exposed to optimal temperatures and the temperature data can be used to calculate remaining shelf-life.

- **Relative-humidity sensor**
  Relative-humidity is defined by Rao (2015), as the percentage of saturated water vapour at a given temperature. As the temperature of air increases, the water-holding capacity also increases. As the relative-humidity of the air decreases, the vapour pressure decreases. This results that the capacity of the air for removing water from the moist produce, increases. Hence, it is important to maintain a high vapour pressure to prevent drying-out to take place (Rao, 2015). Relative-humidity is an important condition to measure because it has an effect on the quality of fresh produce. When the produce loses excess moisture content, the firmness decreases and its appearance will be unacceptable to consumers.

- **Ethylene sensor**
  Ethylene is an invisible, colourless, and odourless gas that is produced by much fresh produce. It is a naturally occurring gas, associated with plants under stress and maturation (Janssen *et al.*, 2014). This means that once fresh produce starts to ripen, it releases ethylene and when they are exposed to ethylene, they start to ripen more quickly (Janssen *et al.*, 2014; Jedermann, 2014). Monitoring ethylene is important, especially during transportation and storage, and the reason is twofold. Firstly, the amount of ethylene concentration indicates the maturity of the fresh produce, and secondly, it can be used to determine remaining shelf-life (Janssen *et al.*, 2014).

7.2.2.3 Network connectivity

Network connectivity was mentioned as the most important technical requirement to consider in order to implement IoT-technologies within the fresh produce industry. Selecting the type of network connectivity often depends on the use of proposed application. Techspirited (2018) mentioned that the following requirements should guide the selection of connectivity:

1. Functioning: How access is provided to the Internet;
2. Signal: The strength of the signal to send and receive data;

3. Speed: The speed of data being transferred, measured in megabits per second;
4. Cost: The cost of implementing connectivity;
5. Security: The complexity of encryption required to ensure the security of data;
6. Mobility: Connection availability during movement;
7. Power consumption: The amount of power consumed during connectivity; and
8. Bandwidth: The amount of data that can be transmitted in a fixed amount of time.

Wi-Fi and 3G modules are both popular wireless connectivity technologies to use in IoT-applications. Both technologies are compared to the requirements listed above, and shown in Table 7.1.

Table 7.1: Comparison between Wi-Fi and 3G connectivity

Criteria	**Wi-Fi**	**3G**
Functioning	Access provided by a router located in range.	Access provided by a telecommunication service provider.
Signal	Strong signal only in range of router.	Strong signal as long as network is in range.
Speed	Maximum speed can be up to 600 mbps.	Depends on device and whether the device is stationary or in motion. Maximum speed on a fixed wireless LAN can be more than 2.05 mbps.
Cost	Depends on hotspot availability.	Depends on the plan chosen by the service provider.
Security	More vulnerable to attacks when network is not secure. Restrictions to access can be added.	More secure since it is directly linked to service provider. They have their own security measurements.
Mobility	Limited mobility due to the range restriction to routers.	Better mobility because it can be used wherever the service provider has coverage.
Power consumption	Uses four to five times less power per byte than 3G.	Consumes more power than Wi-Fi which makes it difficult to send large chunks of data.
Bandwidth	Has a larger bandwidth than 3G, making it more stable.	Has a smaller bandwidth, making 3G speed more volatile.

7.2.3 Proposed architecture

A proposed architecture for the IoT-application was developed using the requirements that were identified from the questionnaire feedback as well as insights from the analysed retail chain. The IWF Internet of Things reference architecture that was discussed in Chapter 2, was used as a guideline to develop the proposed architecture, as shown in Figure 7.1.

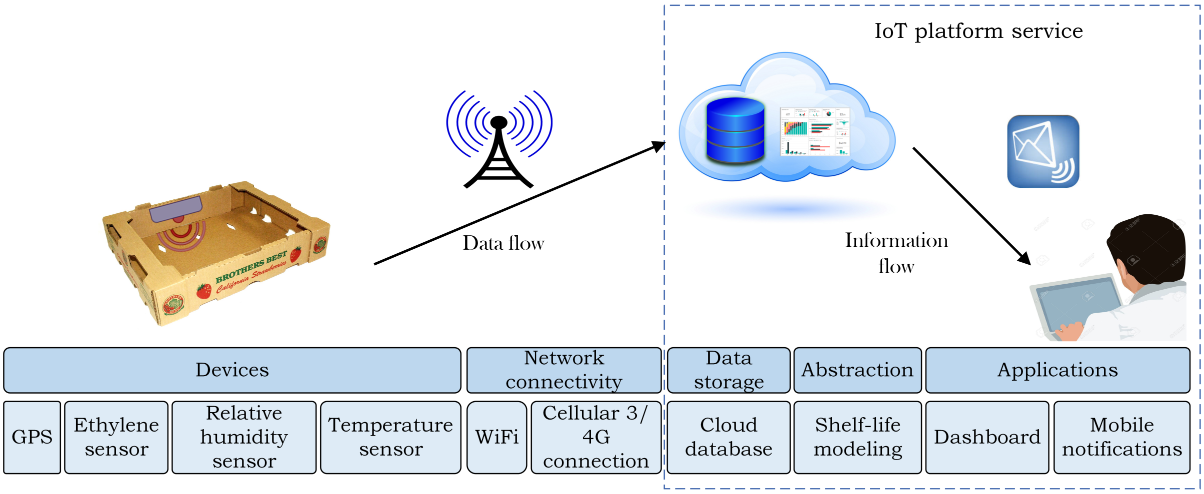


Figure 7.1: The proposed architecture

An embedded system is placed in the trays that transport the fresh produce throughout the supply chain. The embedded system consists of sensors that measure the conditions that are required to predict the remaining shelf-life of the fresh produce. A GPS module is added to the embedded system to track the location of the trays. The measured data are sent via a predetermined network connectivity to an IoT platform service. The data are stored onto a database and the database updates each time a new measurement is received. The data are then used to calculate the remaining shelf-life for each tray. The measured conditions, the GPS location as well as the remaining shelf-life should be presented on a digital display on the trays as well as on a dashboard on the IoT platform. Authorised users are able to log onto the platform, via mobile devices, to view the dashboard. The platform will send notifications to the users when predetermined condition thresholds have been exceeded. The users could then act upon the notifications they receive.

7.2.4 Application prototype

To illustrate the working of the proposed architecture, a simple prototype was developed. The development of the prototype is described in this subsection.

7.2.4.1 Devices

Figure 7.2 shows the embedded system that should be placed inside the trays. The embedded system consists of various devices that collect data on the conditions the trays are exposed to. A description of each device shown in the figure follows.

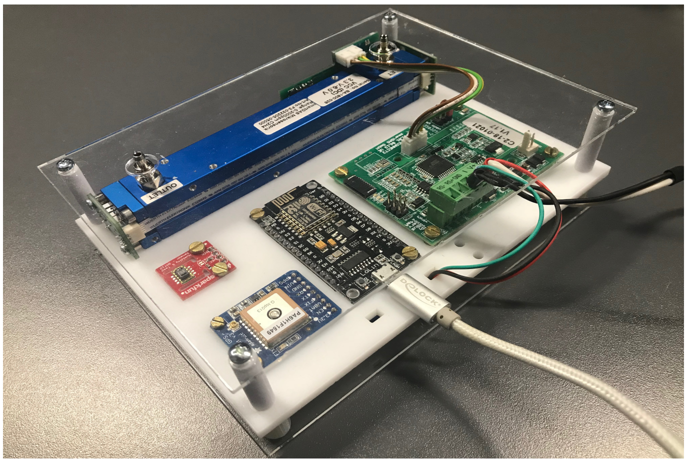


Figure 7.2: The embedded system that consists of various sensor devices

NodeMCU ESP8266 Lua Board microcontroller

Microcontrollers are small, affordable controllers that can be used to program specific tasks and to execute the tasks when they are required. The purpose of the microcontroller is to register data from the sensors and to send the data to a cloud platform every fixed period. The NodeMCU ESP8266 Lua Board was selected for the microcontroller. The NodeMCU is a fast leading edge low cost technology with a built-in WiFi module and PCB antenna. Many Internet development tools and built-in APIs can be used with the NodeMCU to program the required tasks that need to be executed. The only drawback with this microcontroller is that it requires an external power supply (MicroRobotics, n.d.).

SparkFun humidity and temperature sensor (SHT15)

The SHT15 is an easy-to-use and highly accurate temperature and humidity sensor. It is fully calibrated meaning no adjustments are required to read and send measurements. The sensor has long-term stability at low cost. There are four pins on the sensor that need to be connected to the microcontroller to communicate the temperature and humidity measurements (SparkFun, 2015).

FlowEVO gas sensor

The FlowEVO is non-dispersive infrared (NDIR) gas sensor that can be used to measure the amount of ethylene concentration in trays. The sensor can be easily integrated into systems where long-term stability and reliable performance are required. There are three pins on the sensor that need to be connected to the microcontroller to communicate the ethylene measurements. A few drawbacks of this sensor are that it is robust, it is expensive, and has a high power consumption (SmartGas, n.d.). However, companies are investing in research and emerging technology to improve the accessibility of ethylene sensors, since ethylene measurements can improve the accuracy of remaining shelf-life prediction of fresh produce.

Adafruit Ultimate GPS module

The GPS module provides the ability to track the movement and location of the trays. Monitoring the movement of trays can provide insights to estimate the stage in the supply chain where conditions are not adequate for the shelf-life of fresh produce. The Adafruit Ultimate is a high quality GPS module that can track up to 22 satellites, has an excellent receiver, a built-in antenna and low power usage. The module has its own microcontroller with some empty memory, and only requires an additional controller to send the 'start' command. The time, date, longitude and latitude are logged every 15 seconds and the data can be stored for 16 hours if there is no power available (Adafruit, 2017).

7.2.4.2 Network connectivity

Network connectivity refers to the means of transferring data between the devices and the IoT platform services. Wireless connectivity provides the ability to gain access to the Internet without physical connection. Selecting the required wireless connectivity often depends on the connectivity requirements for the application. Ideally, a 3G network would be the better connectivity to use because it has mobility, a strong signal and does not depend on additional routers to connect to the Internet. The amount of required data to send per device is minimal, therefore it is not necessary to have a large bandwidth and a fast transfer of data. However, due to cost constraint to use 3G connectivity, a Wi-Fi network via a hotspot will be used as connectivity.

7.2.4.3 Internet of Things platform service

An Internet of Things (IoT) platform is an application that connects devices to the cloud. It usually consists of a set of components that has the ability to manage, control and monitor devices, as well as deploy independent connectivity between remote data collection and data management. An IoT platform acts as a mediator between devices and the application used by end users. There are multiple IoT platform services available and they can be differentiated by their ease-of-use, scalability, integration, data security and deployment.

For the purpose of this architecture Losant Enterprise IoT platform® was selected because it is an easy-to-use open source enterprise IoT platform designed to build complex real-time connected solutions. Losant allows users to quickly set up devices, easily collect and visualise data and take action through highly customisable workflows (Losant, 2018). The following components available on Losant, were used to assist the development of the IoT-application.

Connection from microcontroller to Losant

The data gathered by the microcontroller are transferred to the Losant platform using a MQTT protocol. MQTT is a lightweight communication protocol that transfers messages from the device to the platform once it is connected to a network. Losant uses the protocol together with JSON-formatted payloads to manage and process the collected data for further data abstraction and analysis.

Data storage

Cloud storage refers to an online space where data can be stored and accessed at any time, anywhere. Losant provides the ability to store device data on a centralised cloud storage which can be accessed by any authorised stakeholders. Sensor data such as temperature, relative-humidity and ethylene as well as the GPS location can be stored in a data table to track the conditions and the location of the trays, thus historic data as well as real-time data is available. The benefit of using cloud storage on Losant, is that it automatically scales as the demand for connected devices increases.

Abstraction and applications

The goal of abstraction and applications is to transform data into meaningful information that can be used to meet specific business goals and requirements. Losant has an IoT workflow engine that provides the ability to (i) process and filter real-time data; and (ii) create instant alerts and notifications to react to conditions. The IoT workflow engine is used to transform the JSON payloads received from the devices into workable data and then to transform the data into valuable information. Workflows were created on the Losant platform to define the logic behind the calculation of remaining shelf-life, and to define the logic if predetermined conditions have been triggered. Figure 7.3 shows the workflows that were created in Losant.

Once the device is connected to Losant it starts to send JSON payloads to the platform. The JSON payloads consist of temperature, relative-humidity, and ethylene measurements as well as the GPS location. The measurements and location are stored in a table. The values in the table are retrieved to calculate the remaining shelf-life as explained in Chapter 5, and are stored in the same table. Each time a new JSON payload is received from the device, the remaining shelf-life of the tray is recalculated.

Various conditions that need to be fulfilled can be added to the workflows. For example, suppose notifications need to be generated when any one of the measurements has reached a predetermined limit, or when the remaining shelf-life of the tray is reducing faster than expected. If one of these conditions is triggered, an alert can be generated which notifies the required stakeholders about the issue so that they can address it rapidly.

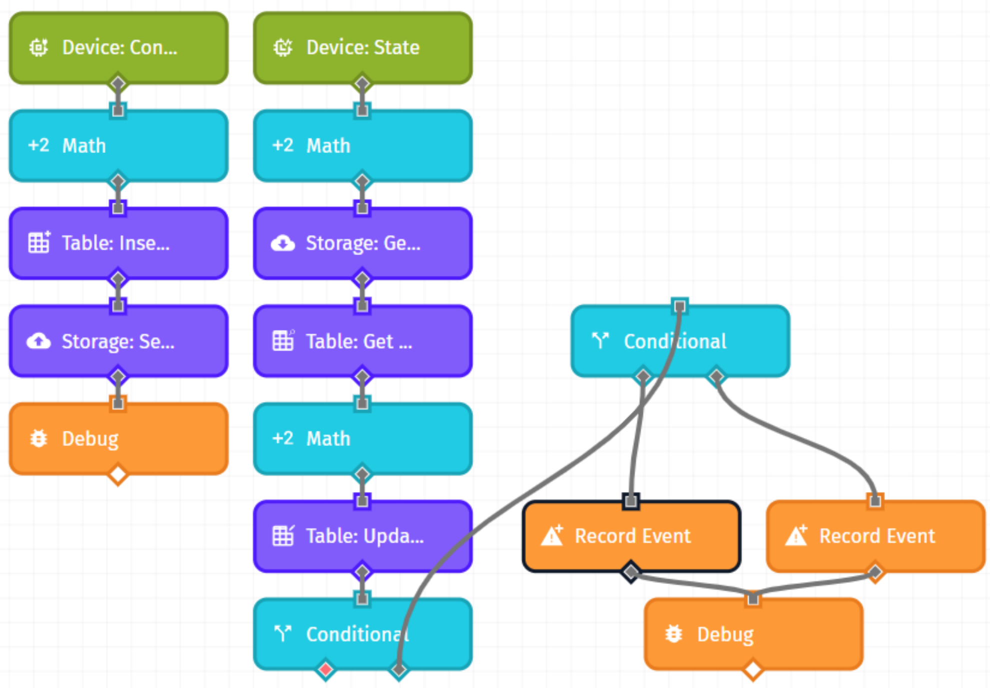


Figure 7.3: The workflows developed in Losant

Act and collaborate

Act and collaborate refers to allowing users to collaborate with the connected devices. This means that the data retrieved from the devices must be accessible to users so that it can assist them with making various decisions. Losant has features to publish dashboards and to customise webpages so that relevant information can be displayed to the users. The dashboards can be viewed via any mobile device that has internet connectivity and when the user has logged onto the Losant IoT platform. Additionally, there is an option to email reports about the information displayed on the dashboards.

Figure 7.4 illustrates an example dashboard that was created on Losant. The dashboard visually presents the GPS location of the tray as well as the conditions such as temperature, relative-humidity and ethylene to which the tray is exposed to. The table that stores the calculated remaining shelf-life are also be displayed on the dashboard. Additionally, indicators can be displayed on the dashboard to inform the user when defined conditions have been exceeded.

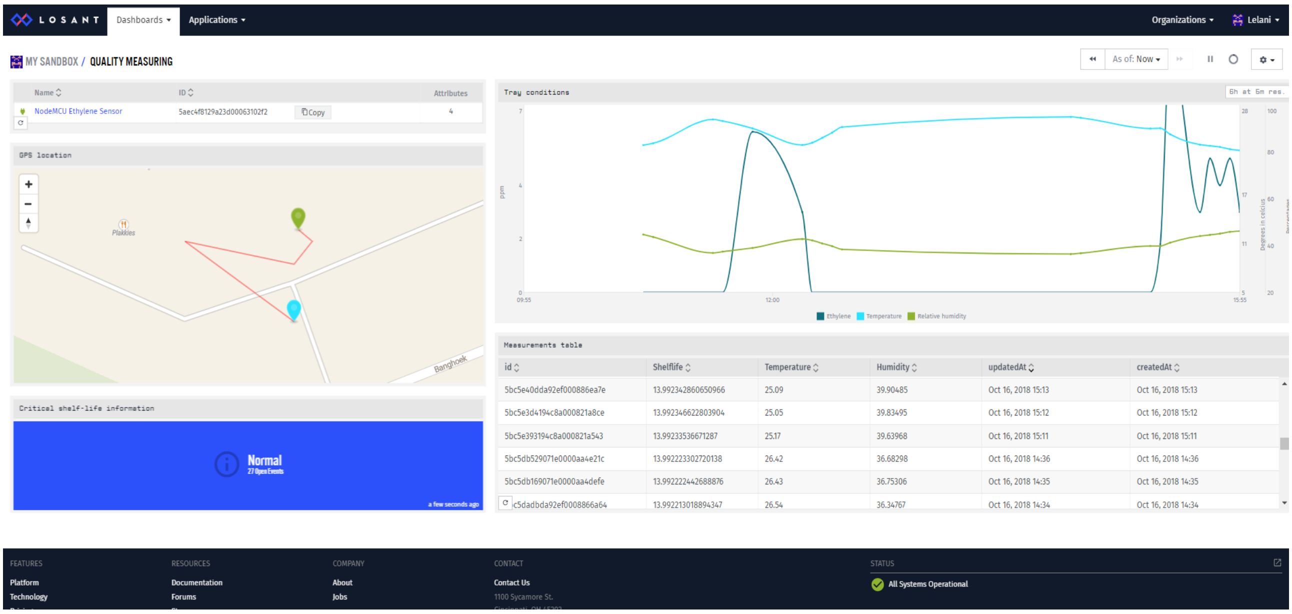


Figure 7.4: Example of the dashboard developed in Losant

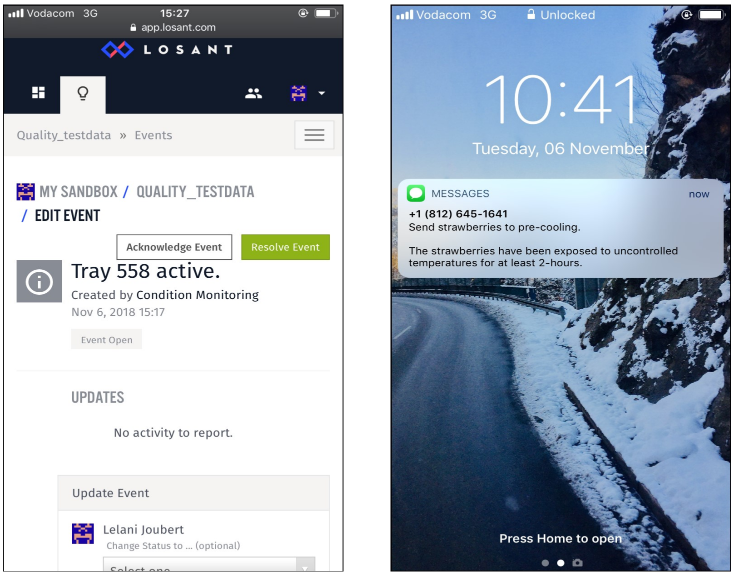
7.2.5 Prototype limitations

The developed application is a high-level prototype to illustrate how IoT-technologies could be used to measure dynamic shelf-life. The prototype has only one device connected to it which measures the conditions as well as the GPS location of one tray only. The reason for this is that ethylene sensors are expensive, and the prototype development is not the main focus of the research project. Further development, field experiments and detailed analysis are required to fully explore the implementation of IoT-technologies within the fresh produce supply chain.

7.3 Example to illustrate the IoT-prototype within the strawberry supply chain

The following example will illustrate how this IoT-application prototype could be used to assist the concept of quality-controlled logistics within the fresh produce supply chain. Suppose the strawberry supply chain that was analysed in Chapter 5, have implemented the following logistic activities: (i) the tractor transports the strawberry trays every two-hours to the pre-cooling facility; (ii) the distribution follows a Least-Shelf-life-First-Out stock-rotation strategy; and (iii) the retail stores follow a Least-Shelf-life-First-Out replenishment strategy.

It is assumed that each tray is equipped with the embedded system that was discussed in Section 7.2.4. Once the tray is filled with strawberries the employee places the tray onto the tractor and then activates the embedded system. The system starts to measure the environmental conditions that are used to dynamically predict the remaining shelf-life of the strawberries inside the tray. As soon as the system is activated a notification is sent to the IoT-platform as shown in Figure 7.5a.



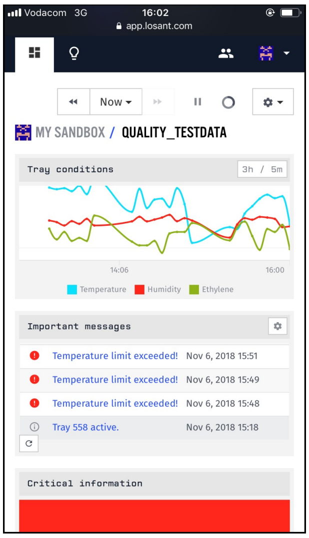
(a) Notification of the activited tray

(b) Text notification

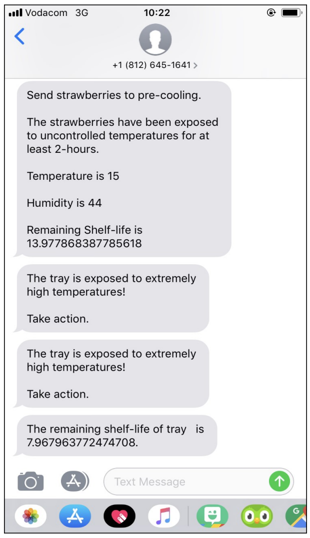
Figure 7.5: Example 1

The time of activation is recorded in a data table on the IoT-platform and this results that the IoT-application can determine the amount of time that the tray spends in uncontrolled temperatures. As soon as the tray spend more than two hours on the tractor, a text notification is sent to the responsible person as shown in Figure 7.5b, and an event is logged on the IoT-platform. The responsible person needs to acknowledge and act upon the notification to stop receiving multiple texts.

Authorised users have the accessibility to view and monitor the various conditions the tray is exposed to during transportation and storage, throughout the supply chain. A dashboard can be accessed via any mobile application that is connected to the Internet. Figure 7.6a shows an example of a dashboard that is viewed on a mobile phone. Users can track important events that occurred within the supply chain, and decide whether they want to act upon the events if it is required from them. Additionally, the application can send text notifications (as shown in Figure 7.6b) to the responsible people when critical events have occurred. For example, if the remaining shelf-life of the tray have dropped rapidly during storage at the distribution centre, the responsible person should be notified. This is to ensure that the tray is batched into the shipment with the least remaining shelf-life and that it should be delivered to the retail store first.



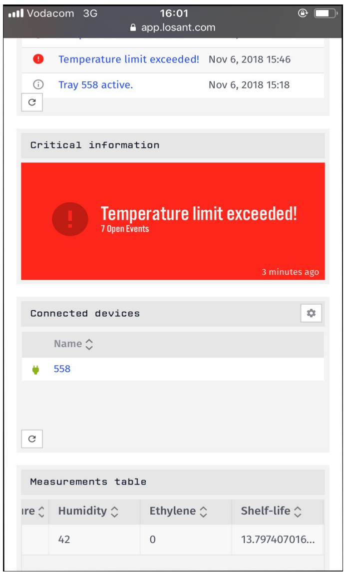
(a) Dashboard on mobile phone



(b) Multiple text notifications

Figure 7.6: Example 2

Figures 7.7a and 7.7b illustrate an example where the temperature has exceeded some predetermined limit. While the strawberry trays are transported to the various retail stores, the conditions inside the truck must be correct to ensure that the strawberries will not experience significant reduction in the remaining shelf-life. However, there may be occasions where the conditions inside the truck have changed and the truck driver might not have noticed it. The IoT-application can then notify the necessary people when conditions are not adequate, allowing them to rapidly respond to the issue without losing too much remaining shelf-life.



(a) An event on the IoT-platform

(b) Text notification for exceeding tempereture limits

Figure 7.7: Example 3

7.4 Challenges to implement IoT-applications in the fresh produce supply chain

There is no doubt the implementation of IoT-applications will provide numerous benefits to the fresh produce industry, as it certainly creates the possibility to measure and predict the remaining shelf-life of fresh produce dynamically. The benefit of implementing dynamic shelf-life in logistics activities is greatly discussed in previous chapters, as it has the potential to reduce food waste across the supply chain and also reduce the monetary losses associated with food waste. Experts within the fresh produce industry had a positive attitude towards IoT-technologies. Feedback from the experts suggested that IoT-applications would benefit information visibility across the chain, as it could improve quality inspections and easily identify stages that critically influence the remaining shelf-life. However, the implementation of IoT-applications is not a simple task and the following challenges need to be addressed before the implementation of such applications.

7.4.1 Responsibility and ownership

It is important that all actors within the supply chain should participate in the concept of dynamic shelf-life prediction because each actor has a set of logistic activities that affects the remaining shelf-life of fresh produce. However, a big challenge is to identify which actor should be responsible and lead the implementation of the IoT-application. The actors have different responsibilities and receive different benefits from the application and this will be discussed for each actor separately.

7.4.1.1 Supplier

The supplier would have to be responsible for installing the sensors inside the trays, and ensuring that all the sensors are activated and working correctly (Jedermann *et al.*, 2017). However, installing the sensors requires technical skills and equipment and most farms do not have the required technical infrastructure available to assist the installation. Additionally, the workers would require training to use the sensors correctly as they would most likely not have sufficient technical knowledge to do this(Sjödahl & Lilja, 2014). Furthermore, it was observed in Chapter 6 that there was no significant improvement in the remaining shelf-life at the farms when dynamic shelf-life was considered in the logistic activities. Hence, the supplier would not receive much benefit from the IoT-application. The only benefit from this application might be that the supplier could receive a better reputation given that the retail stores and consumers will receive fresh produce with a higher remaining shelf-life.

7.4.1.2 Distribution center

The distribution centre would not have any responsibility towards the sensors as they do not need to install or retrieve them (Jedermann *et al.*, 2017). The challenge for the distribution centre is that they need to receive the sensor data and the dynamic remaining shelf-life from the trays, and apply it within their own warehouse and storage management systems. This calls for the distribution centre to redesign and optimise their current systems to autonomously receive the sensor data (Zestlabs, 2016a). Although it might be a time-consuming project, the distribution centre will certainly benefit from the IoT-application as it would assist logistic activities to incorporate dynamic shelf-life and potentially reduce food waste.

7.4.1.3 Retail stores

The retail stores would have to be responsible to retrieve the sensors before the fresh produce leaves the store and send it back to the supplier. Additionally, they would also need to adapt their ordering and replenishment systems to autonomously receive the sensor data from the trays (Jedermann *et al.*, 2017). The retail stores would have to redesign their current systems to integrate dynamic remaining shelf-life within their logistic activities. The retail stores will possibly receive the most benefit from this IoT-application, as it was observed in Chapter 6 that waste was significantly reduced by implementing dynamic shelf-life within their logistic activities, hence reducing the monetary losses due to waste.

Determining the responsibilities and ownership of the IoT-application throughout the supply chain is a difficult task because the actors would not receive equal benefits compared to the responsibility they have to ensure implementation. For example, the supplier is required to install the sensors in the trays but the only benefit they might receive is a better reputation, whereas the retail stores might experience significant waste reduction and reduce monetary losses due to waste. To overcome these challenges there needs to be a change in the mindset of the actors as they should leave the idea of receiving individual benefits, and change their focus to improve and benefit the supply chain as a whole (Sjödahl & Lilja, 2014). Porter & Kramer (2011) mentioned that actors who aim to improve the supply chain as a whole are most likely to increase their competitive advantage through shared value, both socially and economically.

7.4.2 Implementation and installation costs

A challenge to address before implementing the IoT-application, is to consider the high initial costs of investing in the sensor devices. Companies and academic institutions have invested in a lot of research to make sensors accessible and less costly (Janssen *et al.*, 2014). However, the number of sensors that would be required would make the implementation of the IoT-application an expensive project. Furthermore, the actors would have to invest in new software systems that would autonomously receive measurements from the sensors and communicate the remaining shelf-life of the trays dynamically, to assist various logistic activities.

Another challenge that arises, is that the actor who must invest the most in the application is generally not the one who receives the most benefits (Jedermann *et al.*, 2017). For example, it would be unfair to expect that the supplier should carry the expenses for the installation and implementation of the sensors. The reason is that the supplier will probably not receive any monetary benefit when implementing dynamic shelf-life predictions within their logistic activities. Jedermann *et al.* (2017) further mention that new business models should be developed to share the cost of installing and retrieving sensors throughout the supply chain. Sjödahl & Lilja (2014) proposed that the retail stores should contribute towards investing in the installation and also manage the implementation, since they will potentially receive the most benefit from the IoT-application.

7.4.3 Network connectivity challenges

Access to network connectivity is becoming a necessity, especially when industries are focused to implement emerging technologies such as IoT within their operations. Developed countries have already provided free Wi-Fi access to the public and data contracts are economically affordable (Jedermann *et al.*, 2017). However, ensuring continuous network connectivity in South Africa remains a challenge for the implementation of IoT-applications. This is in part due to data contracts being costly as van Zyl (2016) stated that data prices were on average 134% more expensive than the cheapest prices in the BRICS-member countries.

Furthermore, ECN (2018) mentions that the network infrastructure remains a challenge in South Africa as there are areas where network connectivity is limited. Hence, the availability of high quality and faster network connectivity at the farms needs to be addressed before the implementation of IoT-applications can be considered, particularly because shelf-life measurements start at the farms. Additionally, the actors in the supply chain would need to develop strategies to ensure network connectivity within the transportation modes, to receive sensor data from the trays during transportation.

However, the state of network connectivity in South Africa is still evolving, as approximately half of the country's network providers are providing good accessible networking services with decent speeds. The network providers are also investing in research to improve mobile networking technologies that would increase network capacity and support faster speeds (OpenSignal, 2017). As Internet-based applications continue to evolve, continuous network connectivity would definitely become more accessible in South Africa allowing all actors to have reliable network connectivity to implement the IoT-application.

7.5 Conclusion

This chapter explored how IoT-technologies could be used to develop dynamic shelf-life prediction applications to assist quality-controlled logistics. Thereafter a proposed IoT-application was described and the development of an application prototype was discussed. The chapter concluded with some challenges that need to be addressed before considering the implementation of IoT-technologies within the fresh produce supply chain.

Chapter 8

Final conclusions and recommendations

This chapter presents a summary of the work that have been done in the research study and demonstrates how the research objectives and sub-questions were satisfied. The chapter then concludes with a discussion of recommendations for further research.

8.1 Research summary

The purpose of this research study was twofold. Firstly the study investigated the impact of quality-controlled logistics on food waste in the fresh produce supply chain. Thereafter the study explored how quality-controlled logistics could be implemented with the use of Internet of Things technologies. Chapter 2 provided relevant literature that was reviewed to gain knowledge on topics such as food waste, fresh produce supply chains, food quality, and Internet of Things. Chapter 3 identified the current knowledge on quality-controlled logistics from experts working in the fresh produce industry, and also discussed whether the experts believed that Internet of Things technologies could provide opportunities to assist logistic activities. Thereafter Chapter 4 discussed the key traditional logistic activities that were currently implemented in most fresh produce supply chains, as well as the impact they had on produce quality. Several strategies were discussed to identify potential means to implement quality-controlled logistic activities.

Chapter 5 focused on the development of a simulation model to investigate the impact of selected quality-controlled logistic activities on food waste as well on food quality whereafter Chapter 6 analysed the results that were obtained from the simulation model. Several trends that have been identified from the results were highlighted and discussed. Lastly, Chapter 7 discussed how emerging technologies such as Internet of Things could be used to dynamically predict the shelf-life of produce. An Internet of Things application prototype was proposed and developed to illustrate how these technologies could assist quality-controlled logistics throughout the supply chain and to highlight practical challenges that need to be addressed before implementing these technologies. Table 8.1 presents the chapters in which each objective that was developed at the beginning of the study, have been fulfilled.

Table 8.1: Summary of the chapters that fulfilled each objective

Objectives	Chapters
Obj 1: Awareness of the problem should be highlighted by defining the nature and contribution of this research study. Fresh produce supply chains will be investigated to identify the reasons for food waste, which stage in the supply chain contributes the most to food waste, and to determine the impact of food waste.	Ch.1 and Ch.2
Obj 2: It will be necessary to understand the concept of quality-controlled logistics, to identify the critical quality control points in the supply chain and to determine quality measurements that need to be measured throughout the fresh produce supply chain, that could assist logistic activities.	Ch.2, Ch.3 and Ch.4
Obj 3: Research on digitisation will be necessary to identify whether opportunities exist to implement emerging technologies within the fresh produce supply chain, and to identify how they can assist with quality measuring and monitoring to implement quality-controlled logistics.	Ch.2 and Ch.3
Obj 4: A fresh produce supply chain will be selected as a case study for the development of a simulation model to evaluate and quantify the impact of quality-controlled logistics on food waste and to identify whether these logistics can increase food quality for end consumers.	Ch.5 and Ch.6
Obj 5: Information and requirements will be gathered to develop an Internet of Things application prototype, to illustrate how emerging technologies could be used assist the implementation of quality-controlled logistics.	Ch.2, Ch.3 and Ch.7

8.2 Key findings

The key findings of this research study are summarised in line with the sub-questions that were defined at the beginning of the study.

What are the main components, characteristics, and challenges within fresh produce supply chains?

It was identified that fresh produce supply chains usually consist of four stages namely: (i) harvesting; (ii) processing and packaging; (iii) distribution; and (iv) retailing. Although they normally consist of four stages, it did not necessarily mean that there were only four actors involved and therefore, fresh produce supply chains were classified as complex. The number of actors involved depended on the size and strategy of the supply chain, and these actors might even partake in different supply chain processes. Fresh produce supply chains were also defined as complex due to the supply design and performance measurements being highly dependent on product integrity. The reason for this was because fresh produce is perishable by nature, meaning that they deteriorate rapidly once they have been harvested. Perishability influences the value and the quality of the products, therefore food quality had to be considered as a key performance measurement for fresh produce supply chains.

A major challenge that fresh produce supply chains faced, was that food quality is becoming increasingly important to measure and monitor throughout the fresh food supply chain. This was in part due to consumers' expectations of food quality which are becoming a key influence during their purchase decision. On top of that, it was realised that it is difficult to measure food quality because (i) each actor in the supply chain had their own perception of quality; and (ii) there were various product and environmental factors involved that influenced food quality.

What are the various logistic activities to consider within fresh produce supply chains? There were various logistic activities identified where critical decisions had to be made in order to control the quality of fresh produce to ensure that the produce would have sufficient remaining shelf-life during consumption. Table 8.2 shows the key logistic activities, that was defined by industry experts as well as literature, that should be considered within the fresh produce supply chain.

Table 8.2: Various logistic activities to consider within fresh produce supply chains

From industry experts	**From literature**
Temperature management	Determining the sequence of pre-cooling
Transport modes & route scheduling	When to send the harvested load from farm to the pre-cooling facility Choosing third party transport solutions
Stock levels & inventory management	Which pallets to load together on shipments Which pallets to pick for each retailer Which pallets to accept and reject
Replenishment strategies	Moving pallets from the back store to the shelves Sales allocation and discounts

To what extent is food wasted in the fresh produce supply chain, and in which stage (e.g. harvesting, processing, packaging or distribution) does the most wastage occur? A strawberry supply chain simulation model was developed to quantify the extent of food being wasted and to identify in which stage the most wastage occurred. From the simulation results, it was estimated that most food waste occurred at the retail store and little waste occurred at the distribution centre. The reason why the distribution centre did not experience significant waste was most likely due to the responsive lead time the retail chain implemented as their goal was to distribute the strawberries within the same day that they received them from the supplier.

Approximately 40% of the strawberry trays that were received at all the retail stores, turned into waste. The reason for this was twofold. The retail stores followed a First-In-First-Out replenishment strategy to move strawberries from the back store to the display shelves. The problem with this strategy was that it was not guided by the remaining shelf-life of the strawberries but rather by the date the strawberry trays entered the back stores of the retail stores. In consequence, the strawberries in the back store had a large variety in remaining shelf-life. The strawberries with lower remaining shelf-life became wasted before the consumer could purchase the strawberries, if they were not moved fast enough to the display shelves.

In addition, consumers tend to search for the best-looking strawberries and buy strawberries with the longest available sell-by date, even though it was not an accurate representation of the actual remaining shelf-life. If the strawberries reached their sell-by date the retail stores were forced to remove them from the display shelves because the consumers assumed that the strawberries did not have any remaining shelf-life left. This resulted in strawberries becoming wasted even though they may have had sufficient remaining shelf-life available.

How can quality-controlled logistic activities be implemented in the fresh produce supply chains?

Several strategies have been defined to assist the implementation of quality-controlled logistic activities within fresh produce supply chains. Table 8.3 summarises and briefly describes each of the defined strategies. To implement these quality-controlled logistics activities, it was realised that relevant information regarding fresh produce quality should be available. Dynamic shelf-life modelling was identified as a tool to implement these activities. The reason for this was because the purpose of dynamic shelf-life models is to predict the quality of fresh produce by translating the impact of logistics activities on produce quality in terms of remaining shelf-life. It was also established that dynamic shelf-life predictions could raise awareness on how logistic activities affect the quality of fresh produce and additionally provide insights for inventory management, prioritising pallets for shipment and potentially reduce food waste along the supply chain.

Table 8.3: Strategies to implement quality-controlled logistic activities

Strategy	**Description**
Monitoring time & temperature deviations	Monitoring the time spent in uncontrolled temperature and notifying stakeholders about the effect on produce quality.
Create loads with uniform shelf-life	Batching pallets with similar remaining shelf-life together to reduce shelf-life variability within shipment.
First-Expiry-First-Out stock-rotation management	Pallets with the least remaining shelf-life should be loaded for shipment first.
Intelligent distribution	Matching remaining shelf-life of pallets with the transit time to the various locations.
Accepting the number of pallets based on remaining shelf-life	When shelf-life is available at the point of delivery, pallets can be accepted or rejected based on pallet-specific information.
Dynamic pricing and discount models	Discounts on produce can be determined based on the remaining shelf-life available.

Will quality-controlled logistic activities contribute to the reduction of food waste and improve fresh produce quality, and if so how?

A strawberry supply chain was selected as a case study to develop a simulation model to evaluate and quantify the impact of quality-controlled logistic activities on food waste and to identify whether these activities could increase food quality for end consumers. Various sets of logistic activities were defined and evaluated to determine the impact of quality-controlled logistics on food waste and remaining shelf-life.

The main conclusion that was developed from the analysis and discussion of the simulation results, was that the retail chain would have to make a trade-off between maximising the remaining shelf-life of strawberries at the retail stores; or minimising the total waste that occurred throughout the supply chain. The reason for this is because it was observed that the set of logistic activities which obtained high remaining shelf-life also resulted in high amounts of food waste. On the other hand, the set of logistic activities that obtained the least total waste resulted in lower remaining shelf-life; however, they did not obtain the worst remaining shelf-life compared to other logistic activities.

The set of logistic activities that obtained the highest remaining shelf-life at the retail stores were: (i) the tractor transported the strawberry trays every two hours to the pre-cooling facility; (ii) the distribution centre followed a Last-In-First-Out stock-rotation strategy; and (iii) the retail stores followed a First/Last-In-First-Out replenishment strategy. This set of logistic activities resulted in a 13% increase in remaining shelf-life. The reason for this was because the Last-In-First-Out stock-rotation strategy allowed the strawberry trays that entered the distribution centre last, to be selected for deliveries first with the result that the selected strawberry trays did not wait in storage for a long time. Disregarding the waste that may have occurred due to shelf-life variability among the trays, the consumers were able to purchase high remaining shelf-life strawberries.

The set of logistic activities that obtained the most reduction in total waste were: (i) the tractor waited at the farm until it was fully loaded before progressing to the pre-cooling facility; (ii) the distribution centre followed a Least-Shelf-life-First-Out stock-rotation strategy; and (iii) the retail stores followed a Least-Shelf-life-First-Out with dynamic pricing replenishment strategy. This set of logistic activities obtained a 71% reduction in the total waste. The reason for this result was mainly due to the Least-Shelf-life-First-Out with dynamic pricing replenishment strategy that was implemented at the retail stores. The strawberry trays with lower remaining shelf-life were placed on display first and this allowed the strawberry trays with higher remaining shelf-life to be kept in the back store until it was necessary to restock the display shelves. By doing so, it reduced the variability of the remaining shelf-life of the strawberries on display, meaning that consumers were less likely able to select strawberries with a much higher remaining shelf-life than the other strawberries also on display. By implementing dynamic pricing based on shelf-life it was assumed that consumers would be more willing to buy lower remaining shelf-life strawberries when they knew that they would receive a discount. Thus the number of strawberries that were wasted on display was much less because consumers either bought strawberries with high remaining shelf-life when the price was kept constant, or bought low remaining shelf-life strawberries if they received discount.

What is the Internet of Things and can it contribute to improved logistics activities?
Internet of Things (IoT) was defined in this study as a system in which various types of sensors are embedded into any network to collect data, and to communicate and share information. It was identified that IoT-technologies could create capabilities to monitor and control environmental conditions that influence food quality and to collect data that could be used to determine accurate shelf-life of fresh produce. Feedback from experts working in the fresh produce industry stated that IoT-technologies would contribute to a more flexible and adaptive supply chain planning, and the data being collected by devices would allow supply chains to identify new market requirements and improved business models to become more competitive. Experts also mentioned that IoT-technologies might enhance stakeholder relationships and trust throughout the supply chain.

What are the benefits and challenges to implementing Internet of Things technologies within the fresh produce supply chain?
Some of the major benefits of implementing IoT-technologies in the fresh produce supply chain in-

cluded that it: (i) would assist the monitoring of environmental conditions; (ii) would provide quick access to real-time data; (iii) would allow produce quality to become more visible throughout the supply chain so that it could assist improved logistic activities; and (iv) provide the means to identify elements that contribute to food waste and allowing stakeholders to take action to mitigate the elements to reduce food waste.

However, it was also established that the implementation of IoT-technologies is not a simple task and that there were various challenges that needed to be addressed. Feedback from industry experts stated that a big challenge would be to identify who would take responsibility and ownership to guide the implementation of IoT within the supply chain. The reason for this is because it was identified that stakeholders might not receive equal benefit from the implementation. Another challenge that was identified was that the supply chain actor who must invest the most in the IoT-application would probably not be the one who would receive the most benefit. The implementation of IoT-technologies requires high initial investments, therefore the actors in the supply chain would have to collaborate to share the cost of installing and implementing these technologies.

How can Internet of Things technologies be implemented within the fresh produce supply chain to assist quality-controlled logistics?
IoT-technologies created the opportunity to collect real-time food quality data, which could be used to develop a dynamic shelf-life prediction application. To be able to communicate the dynamic remaining shelf-life of fresh produce, the produce flow, as well as the effect of the environment on the remaining shelf-life should be measured and logged throughout the supply chain. A prototype IoT-application was developed to illustrate some of the technical requirements and the challenges that need to be addressed to implement dynamic shelf-life prediction throughout the supply chain.

8.3 Answering the primary research question

From the key findings that were summarised in line with the above-mentioned sub-questions, the primary research question is answered as follow:

How can Internet of Things technologies assist quality-controlled logistic activities within the fresh produce supply chain, thereby reducing food waste?
Internet of Things (IoT) technologies create the opportunity to collect real-time fresh food quality data that can be used to dynamically predict the remaining shelf-life of fresh food. Supply chain actors are then able to make more intelligent logistic-decisions by using the data that is obtained from an IoT-application and to convert their current logistic activities into quality-controlled logistic

activities. This can be done by using the available remaining shelf-life information to implement the Least-Shelf-life-First-Out stock-rotation and replenishment strategies in the supply chain. A simulation study confirmed that these strategies will result in a significant reduction in food waste at the retail stores.

8.4 Research limitations and suggestions for future research

A number of limitations within this research study have been identified; however, these limitations provide the opportunity for future research. Future research to further investigate the impact of quality-controlled logistic on food waste and food quality with the assistance of Internet of Things could focus on the following suggestions:

1. Only fifteen participants were willing to partake in the interviewer questionnaire during the FRUIT LOGISTICA exhibition. Language constraints was the main reason for this limited number of participants because for most attendees, English was either their second or third language. The feedback that was obtained from the participants is currently a limited view but future research can focus on receiving feedback from larger samples of experts working in the fresh produce industry.

2. The impact of the selected quality-controlled logistic activities was evaluated on the supply chain design of a South African retail chain who aims to provide high quality products for their consumers and thus they already had several quality-controlled logistic strategies in place to ensure that high quality is always achieved. A suggestion is that future research should expand on evaluating the impact of quality-controlled logistics activities on other retail chains' supply chain design to compare the impact these activities would have on their strategies and also to identify how the different retail chains would respond towards the implementation of these activities.

3. This research study only investigated the impact of quality-controlled logistics activities on one commodity group. It was established that the implementation of these activities could reduce food waste significantly and this further contributed that retail stores saved a substantial amount of money due to less waste that occurred. Hence it is suggested that future research should explore how the retail chains would benefit from quality-controlled logistics activities when more than one commodity group is investigated.

4. This research study did not consider the impact that dynamic pricing and discounting would have on the retail stores' profit. The purpose of dynamic pricing and discounting in this study was to determine the impact it had on food waste at the retail stores. Future research could focus

on optimising dynamic pricing strategies and to identify trade-offs between creating increased profits and reducing waste throughout the supply chain.

5. It was determined that the cost of installing Internet of Things technologies is a key challenge that need to be addressed before it could be implemented in the supply chain. However, it was identified that the retail chains would save a substantial amount of money due to less waste that occurred when these technologies could assist actors to make improved logistic decisions. Therefore it is suggested that future research should investigate financial strategies to find possible solutions to assist the installation and implementation of these technologies. Furthermore it is suggested that a cost-benefit analysis should be conducted to identify whether the savings due to reduced waste would actually provide the financial means to assist the installation of Internet of Things technologies.

6. This research study developed a concept to illustrate that the implementation of an Internet of Things application to predict dynamic shelf-life of fresh produce is feasible. A high-level prototype was developed to practically illustrate the concept. However, there are still various technical challenges that need to be addressed before this concept could be implemented. Future research could focus on a detailed technical development of an Internet of Things application to dynamically predict remaining shelf-life of fresh produce. Thereafter field experiments within a real-life supply chain could be conducted to test the application and investigate whether it would assist quality-controlled logistic activities.

8.5 Theoretical and practical contribution

This research study theoretically contributed towards research by determining the value that could be received by implementing Internet of Things technologies to assist quality-controlled logistics, thereby reducing food waste. The reason for this is because it was identified that various research contributed towards the development of frameworks and architectures to illustrate how Internet of Things technologies could be implemented in the food industry. Yet, limited research were available to define the value that the food industry could be received by combining Internet of Things with quality-controlled logistic planning. Part of this research study was also published in the proceedings of the South African Institute for Industrial Engineering (SAIIE) and was presented at the annual conference held in October 2018.

This research study practically contributed towards the field of fresh produce supply chain management by illustrating how quality-controlled logistic could be implemented in a South African strawberry supply chain to reduce food waste. The expert within the fresh produce industry acknowledged that this research not only contributed towards fresh produce supply chains but also towards food supply chains in general. The expert stated that the idea of implementing Internet of Things in food supply chains is still novel. This study provides information to assist the industry to gain a better understanding of Internet of Things technologies, and how they can be used to assist food logistics to mitigate food waste.

References

Adafruit (2017). Adafruit Ultimate GPS Breakout: 66 channel w/10 hz updates. [online] Available at https://www.adafruit.com/product/746 [Accessed 5 April 2018]. 135

Aiello, G., Scalia, G.L. & Micale, R. (2012). Simulation analysis of cold chain performance based on time–temperature data. *Production Planning & Control*, **23**, 468–476. 90

Akkerman, R., Farahani, P. & Grunow, M. (2010). Quality, safety and sustainability in food distribution: A review of quantitative operations management approaches and challenges. *Operations Research Spectrum*, **32**, 863–904. 20

Alcéo, R.G.A. (2016). Temperatures and shelf-life duration in the strawberry supply chain. Http://hdl.handle.net/10400.5/13359. 90

Aramyan, L.H., Ondersteijn, C.J.M., Van Kooten, O. & Lansink, A.O. (2006). Performance indicators in agri-food production chains. In *Quantifying the agri-food supply chain*, 49–66, Springer. 2, 23, 24, 25

Aramyan, L.H., Oude Lansink, A.G.J.M., Van der Vorst, J.G.A.J. & Van Kooten, O. (2007). Performance measurement in agri-food supply chains: A case study. *Supply Chain Management: An International Journal*, **12**, 304–315. 24

Arora, R.K. (2007). *Foodservice and Catering Management*. APH Publishing Corporation, New Dehli. 22

Aung, M.M. & Chang, Y.S. (2014). Temperature management for the quality assurance of a perishable food supply chain. *Food Control*, **40**, 198–207. 22, 27, 33

Barska, A. & Wyrwa, J. (2017). Innovations in the Food Packaging Market Intelligent Packaging a Review. *Czech Journal of Food Sciences*, **35**, 1–6. 46, 127, 128

Bekker, J. (2016). *Discrete-event Simulation*. Department of Industrial Engineering, Stellenbosch University. 9, 76, 77, 179

Bigaj, Z. & Koliński, A. (2017). The analysis of the cold chain efficiency with the use of mobile technology. *LogForum*, **13**. 28

Blanco, A., Masini, G., Petracci, N. & Bandoni, J. (2005). Operations management of a packaging plant in the fruit industry. *Journal of Food Engineering*, **70**, 299 – 307. 20

Blaxter, L. (2010). *How to research*. McGraw-Hill Education (UK). 6

Bogataj, M., Bogataj, L. & Vodopivec, R. (2005). Stability of perishable goods in cold logistic chains. *International Journal of Production Economics*, **93**, 345–356. 28

Bourlakis, M.A. & Weightman, P.W.H. (2008). *Food Supply Chain Management*. John Wiley & Sons. 19, 21, 27

Bowersox, D., Closs, D. & Cooper, M. (2007). *Supply Chain Logistics Management*. McGraw-Hill higher education, McGraw-Hill. 28

Brettel, M., Friederichsen, N., Keller, M. & Rosenberg, M. (2014). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *International Journal of Mechanical, Industrial Science and Engineering*, **8**, 37–44. 36

Broekmeulen, R.A. & van Donselaar, K.H. (2009). A heuristic to manage perishable inventory with batch ordering, positive lead-times, and time-varying demand. *Computers & Operations Research*, **36**, 3013–3018. 30

Buisman, M., Haijema, R. & Bloemhof-Ruwaard, J. (2017). Discounting and dynamic shelf life to reduce fresh food waste at retailers. *International Journal of Production Economics*. 65, 70, 74, 94

Burmeister, C., Luettgens, D. & Piller, F.T. (2015). Business Model Innovation for Industrie 4.0: Why the 'Industrial Internet' Mandates a New Perspective on Innovation. 35

Chen, H.K., Hsueh, C.F. & Chang, M.S. (2009). Production scheduling and vehicle routing with time windows for perishable food products. *Computers & Operations Research*, **36**, 2311 – 2319. 2, 22

Chen, I.J. & Paulraj, A. (2004). Understanding supply chain management: Critical research and a theoretical framework. *International Journal of Production Research*, **42**, 131–163. 35

Chopra, S. & Meindl, P. (2014). *Supply Chain Management: Global Edition*. Pearson International Edition, Pearson Education Limited. 23, 29

Chopra, S., Laux, C., Schmidt, E. & Rajan, P. (2017). Perception of Performance Indicators in an Agri-Food Supply Chain: A Case Study of India's Public Distribution System. *International Journal on Food System Dynamics*, **8**, 130–145. 23, 24, 28

Coelho, L.C. & Laporte, G. (2014). Optimal joint replenishment, delivery and inventory management policies for perishable products. *Computers & Operations Research*, **47**, 42–52. 29

Coles, R. & Kirwan, M.J. (2011). *Food and beverage packaging technology*. John Wiley & Sons. 25, 46

CSIR (2013). Quantifying the cost of food waste in South Africa. [online] Available at: https://www.csir.co.za/quantifying-cost-food-waste-south-africa [Accessed 16 March 2017]. 16

CSIRO (2015). Refrigerating foods. [online] Available at: https://www.csiro.au/en/Research/Health/Food-safety/Refrigerating-foods [Accessed 16 March 2017]. 22

Da Xu, L., He, W. & Li, S. (2014). Internet of things in industries: A survey. *IEEE Transactions on industrial informatics*, **10**, 2233–2243. 43

Dani, S. (2015). *Food Supply Chain Management and Logistics: From Farm to Fork*. Kogan Page. 20, 21, 22, 23, 27, 43, 44

Dinter, B. (2013). Success factors for information logistics strategy—An empirical investigation. *Decision Support Systems*, **54**, 1207–1218. 35

do Nascimento Nunes, M.C., Nicometo, M., Emond, J.P., Melis, R.B. & Uysal, I. (2014). Improvement in fresh fruit and vegetable logistics quality: Berry logistics field studies. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **372**. 77, 83, 90

Dobrucka, R. & Cierpiszewski, R. (2014). Active and intelligent packaging food–research and development–a review. *Polish Journal of Food and Nutrition Sciences*, **64**, 7–15. 46, 47, 127, 128

Duan, Q. & Liao, T.W. (2013). A new age-based replenishment policy for supply chain inventory optimization of highly perishable products. *International Journal of Production Economics*, **145**, 658–671. 29, 30

ECN (2018). The State of Connectivity in South Africa. [online] Available at: http://www.ecn.co.za/connectivity-sa/ [Accessed 16 October 2018]. 144

Entrup, M.L. (2006). *Advanced Planning in Fresh Food Industries: Integrating Shelf Life into Production Planning*. Contributions to Management Science, Physica-Verlag HD. 20

Erol, S., Schumacher, A. & Sihn, W. (2016). Strategic guidance towards industry 4.0:A three-stage process model. In *International Conference on Competitive Manufacturing*. 35

FAO (2013). Food wastage footprint. 1

Fellow, P.J. (2015). *Food Processing Technology: Principles and Practices*. Woodhead Publishing Series in Food Science, Technology and Nutrition, 4th edn. 33

Ghaani, M., Cozzolino, C.A., Castelli, G. & Farris, S. (2016). An overview of the intelligent packaging technologies in the food sector. *Trends in Food Science & Technology*, **51**, 1–11. 22, 26, 46, 128

GreenMatch (2017). Tackling Food Waste with the Internet of Things. [online] Available at: https://www.greenmatch.co.uk/blog/2017/09/tackling-food-waste-with-internet-of-things [Accessed 21 May 2018]. 48

Grunert, K.G. (2005). Consumer behaviour with regard to food innovations: Quality perception and decision-making. *Innovation in Agri-Food Systems, Wageningen Academic Publishers, Wageningen*, 57–82. 26, 33, 80

Gunasekaran, A. & Kobu, B. (2007). Performance measures and metrics in logistics and supply chain management: A review of recent literature (1995–2004) for research and applications. *International Journal of Production Research*, **45**, 2819–2840. 23

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R. & Meybeck, A. (2011). Global food losses and food waste. *Food and Agriculture Organization of the United Nations*. 1, 12, 13, 14, 15, 16, 18

Haberl, H., Erb, K.H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C. & Steinberger, J.K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35**, 4753–4769. 18

Han, J.H. (2005). *Innovations in food packaging*. Academic Press. 127

Hartmann, M. & Halecker, B. (2015). Management of Innovation in the Industrial Internet of Things. In *ISPIM Conference Proceedings*, 1, The International Society for Professional Innovation Management (ISPIM). 35, 37

Heising, J.K., Dekker, M., Bartels, P.V. & Van Boekel, M.A.J.S. (2014). Monitoring the quality of perishable foods: Opportunities for intelligent packaging. *Critical Reviews in Food Science and Nutrition*, **54**, 645–654. 22, 25, 26, 28, 33, 45, 47, 127

Heising, J.K., Claassen, G.D.H. & Dekker, M. (2017). Options for reducing food waste by 'Quality Controlled Logistics' using intelligent packaging along the supply chain. *Food Additives & Contaminants: Part A*. 2, 34

Herbon, A., Levner, E. & Cheng, T. (2014). Perishable inventory management with dynamic pricing using time–temperature indicators linked to automatic detecting devices. *International Journal of Production Economics*, **147**, 605 – 613, interdisciplinary Research in Operations Management. 80, 94

Hermann, M., Pentek, T. & Otto, B. (2016). Design principles for Industrie 4.0 scenarios. In *System Sciences (HICSS), 2016 49th Hawaii International Conference on*, 3928–3937, IEEE. 35

Hertog, M., Boerrigter, H., van den Boogaard, G., Tijskens, L. & van Schaik, A. (1999). Predicting keeping quality of strawberries (cv. 'Elsanta') packed under modified atmospheres: an integrated model approach. *Postharvest Biology and Technology*, **15**, 1 – 12. 86, 89

Hertog, M., Uysal, I., Mc Carthy, U., Verlinden, B. & Nicolaï, B. (2014). Shelf life modelling for first-expired-first-out warehouse management. **372**, 20130306. 72, 87

Hevner, A.R., March, S.T., Park, J. & Ram, S. (2004). Design science in information systems research. *MIS Quarterly*, **28**, 75–105. 9

Hodges, R.J., Buzby, J.C. & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. *The Journal of Agricultural Science*, **149**, 37–45. 12, 13

i SCOOP (2016). Digitization, digitalization and digital transformation: the difference. [online] Available at: https://www.i-scoop.eu/digitization-digitalization-digital-transformation-disruption/ [Accessed 29 May 2017]. 35

InfraTab (2011). Perishable Condition Monitoring (White Paper). [online] Available at: https://infratab.com/assets/img/resources_pdf/2011MarchFreshtimePerishableMonitoring.pdf?v=e5f38a6923 [Retrieved 19 December 2017]. 72, 87

Ingalls, R.G. (2001). Introduction to simulation. In *Proceedings of the 33nd conference on Winter simulation*, 7–16, IEEE Computer Society. 76

IoT World Forum (2017). About. [online] Available at: https://www.iotwf.com/iotwf2017/about [Accessed 18 January 2018]. 39

Janssen, S., Schmitt, K., Blanke, M., Bauersfeld, M., Wöllenstein, J. & Lang, W. (2014). Ethylene detection in fruit supply chains. *Philosophical Transactions of the Royal Society A*, **372**. 131, 143

Jedermann, R. (2014). Result of project: Intelligent container. 131

Jedermann, R., Nicometo, M., Uysal, I. & Lang, W. (2014). Reducing food losses by intelligent food logistics. 2, 61, 72, 73, 74, 87

JEDERMANN, R., PRAEGER, U. & LANG, W. (2017). Challenges and opportunities in remote monitoring of perishable products. *Food Packaging and Shelf Life*, **14**, 18 – 25, Quality and Safety of Fresh Horticultural Commodities. 142, 143

JOBLING, J. (2000). Temperature management is essential for maintaining produce quality. *Good Fruit and Vegetables Magazine*, **10**, 30–31. 27

JONGEN, W.M.F. & MEULENBERG, M. (2005). *Innovation in Agri-food Systems*. EBL-Schweitzer, Wageningen Academic Publishers. 27

JONKMAN, J., BLOEMHOF, J.M., VAN DER VORST, J.G.A.J. & VAN DER PADT, A. (2017). Selecting food process designs from a supply chain perspective. *Journal of Food Engineering*, **195**, 52–60. 2, 19

KERRY, J.P., O'GRADY, M.N. & HOGAN, S.A. (2006). Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat science*, **74**, 113–130. 127

KIREZIEVA, K., JACXSENS, L., UYTTENDAELE, M., VAN BOEKEL, M.A.J.S. & LUNING, P.A. (2013a). Assessment of food safety management systems in the global fresh produce chain. *Food Research International*, **52**, 230–242. 30

KIREZIEVA, K., NANYUNJA, J., JACXSENS, L., VAN DER VORST, J.G.A.J., UYTTENDAELE, M. & LUNING, P.A. (2013b). Context factors affecting design and operation of food safety management systems in the fresh produce chain. *Trends in Food Science & Technology*, **32**, 108–127. 21

KOCH, V., KUGE, S., GEISSBAUER, R. & SCHRAUF, S. (2014). Industry 4.0: Opportunities and challenges of the industrial internet. *PwC and Strategy&*. 36

KUSWANDI, B., WICAKSONO, Y., ABDULLAH, A., HENG, L.Y., AHMAD, M. *et al.* (2011). Smart packaging: Sensors for monitoring of food quality and safety. *Sensing and Instrumentation for Food Quality and Safety*, **5**, 137–146. 46, 127

LA LONDE, B.J. & MASTERS, J.M. (1994). Emerging logistics strategies: Blueprints for the next century. *International Journal of Physical Distribution & Logistics Management*, **24**, 35–47. 35

LABUZA, T.P. (1984). Application of chemical kinetics to deterioration of foods. *Journal of Chemical Education*, **61**, 348. 72

LABUZA, T.P., TAOUKIS, P.S. *et al.* (1990). The relationship between processing and shelf life. 66

LAZZARINI, S., CHADDAD, F. & COOK, M. (2001). Integrating supply chain and network analyses: The study of netchains. *Journal on Chain and Network Science*, **1**, 7–22. 19

LEBERSORGER, S. & SCHNEIDER, F. (2014). Food loss rates at the food retail, influencing factors and reasons as a basis for waste prevention measures. *Waste Management*, **34**, 1911 – 1919. 80, 87

LEE, S.Y., LEE, S.J., CHOI, D.S. & HUR, S.J. (2015). Current topics in active and intelligent food packaging for preservation of fresh foods. *Journal of the Science of Food and Agriculture*, **95**, 2799–2810. 128, 129

LEITHNER, M., GRONALT, M. & FIKAR, C. (2017). Simulating Economic Impact of Food Losses in Strawberry Supply Chains. 77, 86, 89, 90

LOSANT (2018). Iot Platform:Overview. [online] Available at: https://www.losant.com/iot-platform [Accessed 24 May 2018]. 135

LUNDQVIST, J., DE FRAITURE, C., MOLDEN, D. *et al.* (2008). *Saving water: from field to fork: Curbing losses and wastage in the food chain*. Stockholm International Water Institute Stockholm, Sweden. 18

LUNING, P.A. & MARCELIS, W.J. (2007). A conceptual model of food quality management functions based on a techno-managerial approach. *Trends in Food Science & Technology*, **18**, 159–166. 2, 24, 25, 26, 27, 30

LUNING, P.A., MARCELIS, W.J., JONGEN, W.M.F. *et al.* (2002). *Food quality management: A techno-managerial approach.*. Wageningen Pers. 23, 24

MACHEKA, L., SPELT, E., VAN DER VORST, J.G.A.J. & LUNING, P.A. (2017). Exploration of logistics and quality control activities in view of context characteristics and postharvest losses in fresh produce chains: A case study for tomatoes. *Food Control*, **77**, 221–234. 30

MARIJA, B., LUDVIK, B. & ROBERT, V. (2005). Stability of perishable goods in cold logistic chains. *International Journal of Production Economics*, **93**, 345–356. 22

MCBEATH, B. (2013). Winning the Freshness Wars: Creating Shopper Loyalty and Improving Profitability in Retail Grocery. 62, 63, 64

MCBEATH, B. (2015). The IoT Impact: Finding Your Company's Role in the New Smart Connected World. 42, 43

MCBEATH, B. (2017). Measuring Produce Freshness: The Key tot Preventing Waste. 63, 68

MICROROBOTICS (n.d.). NodeMCU ESP8266 Lua Board. [online] Available at: https://www.robotics.org.za/NODEMCU [Accessed 5 April 2018]. 134

MOHEBI, E. & MARQUEZ, L. (2015). Intelligent packaging in meat industry: An overview of existing solutions. *Journal of Food Science and Technology*, **52**, 3947–3964. 47

MOUTON, J. (2001). How to succeed in your masters and doctoral studies. *Van Schaik*. 7, 8

NAHMIAS, S. (1982). Perishable inventory theory:A review. *Operations Research*, **30**, 680–708. 29

NEUBERT, G., OUZROUT, Y. & BOURAS, A. (2004). Collaboration and integration through information technologies in supply chains. *International Journal of Technology Management*, **28**, 259–273. 35

NUNES, M., EMOND, J. & BRECHT, J. (2003). Quality of strawberries as affected by temperature abuse during ground, in-flight and retail handling operations. In *International Conference on Quality in Chains. An Integrated View on Fruit and Vegetable Quality 604*, 239–246. 90

OELOFSE, S.H.H. (2013). Food waste in South Africa/ Africa: Opportunities and challenges, [PowerPoint Presentation]. 17

OELOFSE, S.H.H. & NAHMAN, A. (2013). Estimating the magnitude of food waste generated in South Africa. *Waste Management & Research*, **31**, 80–86. 1, 16

OPENSIGNAL (2017). State of Mobile Networks: South Africa. [online] Available at: `https://opensignal.com/reports-data/national/data-2017-08-southafrica/report.pdf` [Accessed 16 October 2018]. 144

OSTOJIC, G., STANKOVSKI, S., TEGELTIJA, S., ŁDUKIĆ, N. & TEJIĆ, B. (2017). Implementation of IoT for food wastage minimisation. In *XVII International Scientific Conference on Industrial Systems*, 116–121. 74

PADFIELD, R., PAPARGYROPOULOU, E. & PREECE, C. (2012). A preliycnary assessment of greenhouse gas emission trends in the production and consumption of food in Malaysia. *International Journal of Technology*, **3**, 56–66, cited By 2. 18

PANG, Z., CHEN, Q., HAN, W. & ZHENG, L. (2015). Value-centric design of the internet-of-things solution for food supply chain: Value creation, sensor portfolio and information fusion. *Information Systems Frontiers*, **17**, 289–319. 71

PAPARGYROPOULOU, E., LOZANO, R., STEINBERGER, J.K., WRIGHT, N. & BIN UJANG, Z. (2014). The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, **76**, 106–115. 18

PARFITT, J., BARTHEL, M. & MACNAUGHTON, S. (2010). Food waste within food supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**, 3065–3081. 1, 12

Pflaum, A., Bodendorf, F., Prockl, G. & Chen, H. (2017). Introduction to The Digital Supply Chain of the Future: Technologies, Applications and Business Models Minitrack. In *Proceedings of the 50th Hawaii International Conference on System Sciences*. 35

Pfohl, H.C., Yahsi, B. & Kurnaz, T. (2017). *Concept and Diffusion-Factors of Industry 4.0 in the Supply Chain*, 381–390. Springer International Publishing, Cham. 36

Porter, M.E. & Heppelmann, J.E. (2015). How Smart, Connected Products are Transforming Companies. 41, 42

Porter, M.E. & Kramer, M. (2011). Creating Shared Value. *Harvard Business Review*. 143

Qin, Y., Wang, J. & Wei, C. (2014). Joint pricing and inventory control for fresh produce and foods with quality and physical quantity deteriorating simultaneously. *International Journal of Production Economics*, **152**, 42–48. 29

Quested, T.E., Parry, A.D., Easteal, S. & Swannell, R. (2011). Food and drink waste from households in the uk. *Nutrition Bulletin*, **36**, 460–467. 1

Rao, C.G. (2015). *Engineering for Storage of Fruits and Vegetables: Cold Storage, Controlled Atmosphere Storage, Modified Atmosphere Storage*. Elsevier Science. 131

Restuccia, D., Spizzirri, U.G., Parisi, O.I., Cirillo, G., Curcio, M., Iemma, F., Puoci, F., Vinci, G. & Picci, N. (2010). New eu regulation aspects and global market of active and intelligent packaging for food industry applications. *Food Control*, **21**, 1425–1435. 47

Robertson, G.L. (2016). *Food Packaging: Principles and Practice*. CRC Press, third edition edn. 127, 128

Rohatgi, V. & Saleh, A. (2015). *An Introduction to Probability and Statistics*. Wiley Series in Probability and Statistics, Wiley. 101, 102

Romsdal, A. (2014). Differentiated production planning and control in food supply chains. *Norges teknisk-naturvitenskapelige universitet, Fakultet for ingeniørvitenskap og teknologi, Institutt for produksjons-og kvalitetsteknikk*. 29

Rossi, R., Rijpkema, W.A. & van der Vorst, J.G., eds. (2012). *The impact of dual sourcing on food supply chain networks: The case of Egyptian strawberries*. 94

Rüssmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group*, 14. 36

SAUNDERS, M., LEWIS, P. & THORNHILL, A. (2009). *Research Methods for Business Students*. Always learning, Prentice Hall. 6, 7, 8, 51, 52

SCHRIBER, T.J., BRUNNER, D.T. & SMITH, J.S. (2014). Inside discrete-event simulation software: How it works and why it matters. In *Proceedings of the 2014 Winter Simulation Conference*, 132–146, IEEE Press. 76

SCIORTINO, R., MICALE, R., ENEA, M. & SCALIA, G.L. (2016). A webgis-based system for real time shelf life prediction. *Computers and Electronics in Agriculture*, **127**, 451 – 459. 1, 2, 72, 77, 87, 88, 89

SCRAUF, S. & BERTTMAN, P. (2016). How digitization make the supply chain more efficient, agile, and customer-focused. *PwC and Strategy&*. 35

SCRAUF, S., GEISSBAUER, R. & VEDSO, J. (2016). Industry 4.0: Building the digital enterprise. *PwC and Strategy&*. 35

SEGARS, A.H. & GROVER, V. (1995). The Industry-Level Impact of Information Technology: An Empirical Analysis of Three Industries. *Decision Sciences*, **26**, 337–368. 35

SHACKLETT, M. (2018). Four Ways IoT Is Decreasing Commercial Food Waste. [online] Available at: `https://www.techrepublic.com/article/4-ways-iot-is-decreasing-commercial-food-waste/` [Accessed 21 May 2018]. 4, 48, 49

SHUKLA, M. & JHARKHARIA, S. (2013). Agri-fresh produce supply chain management: A state-of-the-art literature review. *International Journal of Operations & Production Management*, **33**, 114–158. 4

SJÖDAHL, C. & LILJA, C. (2014). Reduced Food Waste by the Use of Dynamic Shelf Life. ISSN1651--0100. 72, 126, 142, 143

SMARTGAS (n.d.). NDIR Ethylene Sensor for Fruit and Vegetable Storage. [online] Available at: `https://www.smartgas.eu/fileadmin/03_anwendungen/fruchtlager/smartGAS-Fruit-storage-brochure.pdf` [Accessed 5 April 2018]. 134

SPARKFUN (2015). SparkFun Humidity and Temperature Sensor Breakout - SHT15. [online] Available at: `https://www.sparkfun.com/products/retired/13683` [Accessed 5 April 2018]. 134

STALLINGS, W. (2015). *Foundations of Modern Networking: SDN, NFV, QoE, IoT, and Cloud*. Pearson Education. 38, 40

STROECKEN, R. (2017). Food waste in the Fresh Produce Supply Chain. 12, 13

SUNDMAEKER, H., GUILLEMIN, P., FRIESS, P. & WOELFFLÉ, S. (2010). Vision and challenges for realising the Internet of Things. *Cluster of European Research Projects on the Internet of Things, European Commision*. 37, 42

SUNDMAEKER, H., VERDOUW, C., WOLFERT, S. & FREIRE, L.P. (2016). Internet of food and farm 2020. *Digitising the Industry-Internet of Things Connecting Physical, Digital and Virtual Worlds. River Publishers, Gistrup/Delft*, 129–151. 4, 43, 45

TAYLOR, D.H. & FEARNE, A. (2009). Demand management in fresh food value chains: A framework for analysis and improvement. *Supply Chain Management: An International Journal*, **14**, 379–392. 28

TECHSPIRITED (2018). 3G vs. Wi-Fi. [online] Available at: `https://techspirited.com/3g-vs-wifi` [Accessed 24 May 2018]. 131

TELLER, C., HOLWEG, C., REINER, G. & KOTZAB, H. (2018). Retail store operations and food waste. *Journal of Cleaner Production*, **185**, 981 – 997. 80

TODOROVIC, V., NEAG, M. & LAZAREVIC, M. (2014). On the usage of RFID tags for tracking and monitoring of shipped perishable goods. *Procedia Engineering*, **69**, 1345–1349. 129

TRIENEKENS, J.H., WOGNUM, P.M., BEULENS, A.J.M. & VAN DER VORST, J.G.A.J. (2012). Transparency in complex dynamic food supply chains. *Advanced Engineering Informatics*, **26**, 55–65. 1, 4, 19, 20, 21, 28, 33

TSIROS, M. & HEILMAN, C.M. (2005). The Effect of Expiration Dates and Perceived Risk on Purchasing Behavior in Grocery Store Perishable Categories. *Journal of Marketing*, **69**, 114–129. 70, 80

TSOLAKIS, N.K., KERAMYDAS, C.A., TOKA, A.K., AIDONIS, D.A. & IAKOVOU, E.T. (2014). Agrifood supply chain management: A comprehensive hierarchical decision-making framework and a critical taxonomy. *Biosystems Engineering*, **120**, 47–64. 19, 21

UCHEREK, M. (2011). Opakowania inteligentne i ich pos-trzeganie przez konsumentów. 12–17. 47

VAN BOEKEL, M.A.J.S. (2005). Technological innovation in food industry: Product design. *Innovation in Agri-food Systems:Product Quality and Consumer Acceptance. Wageningen Academic Publishers, Wageningen*, 147–172. 7, 23, 25, 26

VAN BOEKEL, M.A.J.S. (2008). *Kinetic Modeling of Reactions in Foods*. Food Science and Technology, CRC Press. 22

Van der Vorst, J.G.A.J., Beulaens, A.J.M. & Van Beek, P. (2005). Innovations in Logistics and ICT in Food Supply Chain Networks. *Innovations in Agri-Food Systems*, 245–292. 2, 19, 20, 25

Van der Vorst, J.G.A.J., van Kooten, O., Marcelis, W.J., Luning, P.A. & Beulens, A.J.M. (2007). Quality controlled logistics in food supply chain networks: Integrated decision-making on quality and logistics to meet advanced customer demands. 2, 3, 30, 31

Van der Vorst, J.G.A.J., Tromp, S.O. & Van der Zee, D.J. (2009). Simulation modelling for food supply chain redesign: Integrated decision making on product quality, sustainability and logistics. *International Journal of Production Research*, **47**, 6611–6631. 19, 21

Van der Vorst, J.G.A.J., van Kooten, O. & Luning, P.A. (2011). Towards a diagnostic instrument to identify improvement opportunities for quality controlled logistics in agrifood supply chain networks. *International Journal on Food System Dynamics*, **2**, 94–105. 1, 32, 33, 34

van Zyl, G. (2016). Data prices: How SA compares to the rest of the world. 143

Vanderroost, M., Ragaert, P., Devlieghere, F. & De Meulenaer, B. (2014). Intelligent food packaging: The next generation. *Trends in Food Science & Technology*, **39**, 47–62. 26, 28, 34, 46, 47

Vasseur, T. (2016). Can the Internet-of-Things Help Reduce Food Wastage. [online] Available at: https://www.itproportal.com/2016/01/15/can-the-internet-of-things-help-reduce-food-wastage/ [Accessed 21 May 2018]. 4, 49

Verdouw, C., Beulens, A.J., Trienekens, J. & Verwaart, T. (2010). Mastering demand and supply uncertainty with combined product and process configuration. *International Journal of Computer Integrated Manufacturing*, **23**, 515–528. 43

Verdouw, C.N., Sundmaeker, H., Meyer, F., Wolfert, J. & Verhoosel, J. (2013). Smart agri-food logistics: Requirements for the future internet. In *Dynamics in logistics*, 247–257, Springer. 43, 44

Verdouw, C.N., Wolfert, J., Beulens, A. & Rialland, A. (2016). Virtualization of food supply chains with the Internet of Things. *Journal of Food Engineering*, **176**, 128–136. 46

Voigt, K. (2012). China Looks to Lead the Internet of Things. [online] Available at: http://www.cnn.com/2012/11/28/business/china-internet-of-things/ [Accessed 23 June 2017]. 43

Wang, X. & Li, D. (2012). A dynamic product quality evaluation based pricing model for perishable food supply chains. *Omega*, **40**, 906–917. 28, 65, 80

WeatherUnderground (n.d). Cape Town, South Africa History. [online] Available at: https://www.wunderground.com/history/daily/FACT/date/2010-1-10req_city=Stellenbosch&req_state=WP&req_statename=South%20Africa&reqdb.zip=00000.magic=46&reqdb.wmo=68999 [Accessed 12 June 2018]. 90

WWF (2017). Food Loss and Waste: Facts and Futures. 1, 17

Yam, K.L. & Lee, D.S. (2012). *Emerging Food Packaging Technologies: Principles and Practice*. Woodhead Publishing Series in Food Science, Technology and Nutrition, Elsevier Science. 33, 46, 47, 48, 127, 128

Yam, K.L., Takhistov, P.T. & Miltz, J. (2005). Intelligent Packaging: Concepts and Applications. *Journal of Food Science*, **70**. 127, 128, 129

Zestlabs (2016a). Pallet-level Monitoring (White Paper). [online] Available at: https://www.zestlabs.com/wp-content/uploads/2016/03/Pallet-Monitoring-for-the-Fresh-Food-Supply-Chain.pdf [Retrieved 3 February 2018]. 48, 66, 67, 69, 70, 142

Zestlabs (2016b). Why Quality Consistency Matters (White Paper). [online] Available at: https://www.zestlabs.com/wp-content/uploads/2016/03/Why-Food-Supply-Chain-Quality-Matters-1.pdf [Retrieved 3 February 2018]. 62, 63, 64, 66

Zestlabs (2017a). Comparing Pallet- and Trailer-level Temperature Monitoring (White Paper). [online] Available at: https://www.zestlabs.com/wp-content/uploads/2018/03/WP-04-0318-Pallet-vs-Trailer.pdf [Retrieved 3 February 2018]. 63, 64, 69

Zestlabs (2017b). Improving Quality and Profitablility for Retail Stores (White Paper). [online] Available at: https://www.zestlabs.com/wp-content/uploads/2017/12/WP-01-1117.Improving.Quality.and_.Profitability.for_.Retail.Grocers.pdf [Retrieved 3 February 2018]. 70

Zhang, J., Liu, L., Mu, W., Moga, L.M. & Zhang, X. (2009). Development of temperature-managed traceability system for frozen and chilled food during storage and transportation. *Journal of Food, Agriculture & Environment*, **7**, 28–31. 22

Zhou, L., Chong, A.Y.L. & Ngai, E.W.T. (2015). Supply chain management in the era of the Internet of Things. *International Journal of Production Economics*, **159**, 1 – 3. 4, 37, 127

Appendix A

Questionnaire

This appendix provides the design of the interviewer questionnaire that was used in Chapter 3 to receive expert insight regarding quality-controlled logistics and the Internet of Things.

INDUSTRIAL ENGINEERING Stellenbosch University

ESB BUSINESS SCHOOL REUTLINGEN UNIVERSITY

Master's research in collaboration with ESB Business School and Stellenbosch University.

FRUIT LOGISTICA 2018 – QUESTIONNAIRE

Aim of the questionnaire:

The aim of this questionnaire is to receive experts' opinions from the food (perishable fruit) industry to assist research on how 'Internet-of-Things' (IoT)-technologies can improve Quality-Controlled Logistics[1] decision-making within the fruit supply, to potentially reduce food waste.

From this questionnaire the researcher would like to gain the following information:

- essential logistics decision regarding fruit quality; and requirements/inputs necessary for these decisions;
- establishing ways to use IoT-technologies to enhance Quality Controlled Logistics; and
- essential requirements or considerations to implement IoT in the fruit supply chain.

Ziel des Fragebogens:

Ziel dieses Fragebogens ist es, Expertenmeinungen aus der Lebensmittelindustrie (verderbliche Früchte) einzuholen, um die Forschung zu unterstützen, wie Internet-of-Things (IoT)-Technologien die qualitätskontrollierte Logistik-Entscheidung innerhalb der Fruchtzufuhr verbessern können, um Lebensmittelabfälle zu reduzieren.

Aus diesem Fragebogen möchten die Forscher folgende Informationen gewinnen:

- *Die wichtigsten logistischen Entscheidungen in Bezug auf die Qualität der Früchte und die für diese Entscheidungen notwendigen Anforderungen und Inputs;*
- *die Etablierung von Möglichkeiten zur Nutzung von IoT-Technologien zur Verbesserung der qualitätskontrollierten Logistik; und*
- *Grundlegende Anforderungen oder Überlegungen zur Einführung von IoT in der Fruchtlieferkette.*

[1] Quality Controlled Logistics – using product quality information to assist logistic decisions throughout the supply chain, to ensure high quality fruit accepted by consumers.

Master's research in collaboration with ESB Business School and Stellenbosch University.

COMPANY INFORMATION

Company name / Unternehmen (not compulsory):

____

Company size/ Unternehmensgröße (e.g. small, medium, large):

____

Company role in the fruit industry (e.g. packaging, transportation, produce storage, etc.):

Rolle des Unternehmens in der Obst-, Früchteindustrie (z.B. Verpackung, Transport, Lagerung von Produkten, etc.):

____

Participant's role in the company and years of experience in the fruit industry:

Die Rolle des Teilnehmers im Unternehmen und die jahrelange Erfahrung in der Obst-, Früchteindustrie:

____

QUESTIONS

Based on the company's role in the fruit supply chain/ *Basierend auf der Rolle des Unternehmens in der Fruchtzulieferkette*

1. What are general logistic decisions to consider with regards to the company's role in the fruit supply chain?
   Welche allgemeinen logistischen Entscheidungen sind im Hinblick auf die Rolle des Unternehmens in der Fruchtzulieferkette zu berücksichtigen?

Temperature management/ *Temperaturverfolgung*	☐
Stock levels and inventory management/ *Lagerbestände und Bestandsführung*	☐
Order picking / *Kommissionierentscheidungen*	☐
Replenishment policies/ *Nachfüll-, Wiederbeschaffungsentscheidungen*	☐
Transportation modes and route scheduling/ *Wahl Verkehrsträger und Routenplanung*	☐
Layout design/ *Layoutgestaltung*	☐
Storage practices/ *Lagerungspraktiken*	☐
Shelf space allocation/ *Regalbelegung*	☐

Other:

____

Fruit quality related questions/ *Fragen zur Fruchtqualität:*

2. Which stage in the fruit supply chain has the most influence on product quality after harvesting?
   Welche Stufe in der Fruchtzulieferkette hat den größten Einfluss auf die Produktqualität nach der Ernte?

Transport to packing facilities after harvesting/ *Transport zu den Verpackungsanlagen nach der Ernte*	☐
Storage at packaging facilities/ *Lagerung bei der Verpackung*	☐
Transport to retailer distribution centers (DC)/ *Transport zu den Distributionszentren (DZ)*	☐
Storage at wholesalers and DC/ *Lagerung bei Großhändlern und DC*	☐

Other:

____

3. Where are critical quality control points in the fruit supply chain that influences fruit quality?
Wo sind kritische Qualitätskontrollpunkte in der Fruchtzulieferkette, die die Fruchtqualität beeinflussen?

Loading/unloading of pallets/ *Be- und Entladung von Paletten*	
Storage conditions in warehouse/DC/ *Lagerbedingungen im Lager/DC*	
Conditions during transportation to retailers/ *Bedingungen während des Transports zu den Einzelhändlern*	

Other:

____

4. How important is it to have information about environmental influences (such as temperature, humidity, or ethylene) available to assist logistic decision-making?
Wie wichtig ist es, Informationen über Umwelteinflüsse (wie Temperatur, Luftfeuchtigkeit oder Ethylen) zur Verfügung zu haben, um logistische Entscheidungen zu unterstützen?

Environmental influences	Extremely important/ *Extrem wichtig*	Moderately important/ *mittelmäßig wichtig*	Slightly important/ *Weniger wichtig*	Not important/ *nicht wichtig*
Temperature/ *Temperatur*				
Relative-humidity/ *Luftfeuchtigkeit*				
Ethylene/ *Ethylen*				
Other influences/ *Anderer einflüsse:*				

5. From the company's view, what are major environmental influencers that should be measured to monitor fruit quality?
   Was sind aus Sicht des Unternehmens die wichtigsten Umwelteinflüsse, die gemessen werden sollten, um die Qualität der Früchte zu überwachen?

6. What type of methods are implemented to estimate remaining shelf-life of fruit throughout the supply chain?
   Welche Methoden werden eingesetzt, um die verbleibende Haltbarkeit von Früchten in der gesamten Lieferkette abzuschätzen?

   Quality related prediction models/ *Qualitätsbezogene Vorhersagemodelle* ☐

   Best-before-dates/ *Mindesthaltbarkeitsdaten* ☐

   Other:

   ____

7. How will information on fruit quality influence or add value to current logistic decisions within the company?
   Wie werden Informationen über die Qualität von Früchten die aktuellen logistischen Entscheidungen im Unternehmen beeinflussen oder wertschöpfend beeinflussen?

8. Below is a list of different logistic-decisions to consider in the fruit supply chain. How does these logistic-decisions influence fruit quality; and is it practically possible to adapt these decisions to ensure optimal/improved quality?
   Nachfolgend finden Sie eine Liste verschiedener logistischer Entscheidungen, die in der Fruchtzulieferkette zu berücksichtigen sind. Wie beeinflussen diese logistischen Entscheidungen die Qualität der Früchte, und ist es praktisch möglich, diese Entscheidungen anzupassen, um eine optimale/verbesserte Qualität zu gewährleisten?

Logistic decisions	Extreme influence	Moderately influence	Slight influence	No influence	Flexible to change or adapt to quality preferences (Y/N)
Transport scheduling and routing/ *Transportterminierung und Routenplanung*					
Transportation mode selection/ *Auswahl des Verkehrsträgers*					
Loading capacity/ *Ladekapazität*					
Thrid Party Selection/ *Drittanbieter-auswahl*					
Distribution network design/ *Planung des Vertriebsnetzes*					
Planning order picking/ *Planung der Kommissionierung*					
Planning replenishment policies/ *Planung der Nachschub-strategien*					
Storage mode and capacity/ *Lagerart und Kapazität*					
Storage layout *Lagerlayout*					
Shelf-allocation/ *Regal-Zuordnung*					
Demand volume/ *Bedarfsmengen*					

Other:

Internet-of-Things related questions/ *Fragen zum Thema Internet-of-Things*:

9. What are potential benefits for implementing IoT-technologies in the fruit supply chain (e.g. improving quality monitoring, sharing of information, etc.)?
Welche potenziellen Vorteile ergeben sich für die Implementierung von IoT-Technologien in der Fruchtzulieferkette (z.B. Verbesserung der Qualitäts-überwachung, Informationsaustausch, usw.)?

10. What are key (technical or non-technical) requirements to consider for developing an IoT-system to monitor environmental conditions?
Was sind die wichtigsten (technischen oder nicht-technischen) Anforderungen, die bei der Entwicklung eines IoT-Systems zur Überwachung der Umweltbedingungen zu beachten sind?

11. What value creation opportunities will IoT-technologies provide for companies within the fruit supply chain?
Welche Chancen für die Wertschöpfung bieten IoT-Technologien für Unternehmen innerhalb der Fruchtzulieferkette?

12. How can IoT-technologies contribute to identify customer preference and acceptability of fruit quality?
    Wie könnten IoT-Technologien dazu beitragen, Kundenpräferenzen und Akzeptanz der Fruchtqualität zu erkennen?

13. What are the main challenges related to the implementation and use of IoT technologies in the fruit supply chain?
    Welches sind die wichtigsten Herausforderungen im Zusammenhang mit der Einführung und Nutzung von IoT-Technologien in der Fruchtzulieferkette?

END. THANK YOU - *VIELEN DANK*

Appendix B

Harvest temperatures

This appendix provides the historic temperatures of Stellenbosch as well as the minimum, maximum and mode values that were used in Chapter 5 to determine the harvesting temperatures.

Table B.1: Historic average hourly temperatures in °C

Hours	Sep			Oct			Nov		
	2015	**2016**	**2017**	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
12:00 am	19.4	18.7	19.4	21.1	18.8	18.4	18.4	19.2	19.3
1:00 am	18.8	18.3	19.3	20.8	18.6	18.1	18.1	19.1	19.2
2:00 am	17.8	17.9	18.5	20.6	18.3	17.6	17.6	18.7	18.9
3:00 am	17.7	17.5	18.6	20.3	18.0	16.7	16.7	18.3	18.6
4:00 am	18.0	17.3	18.4	19.8	17.7	16.3	16.3	18.1	18.5
5:00 am	17.6	17.0	17.8	19.5	17.4	16.4	16.4	17.9	18.2
6:00 am	17.5	16.9	18.1	19.8	17.3	16.1	16.1	17.9	18.0
7:00 am	18.6	18.5	18.7	20.5	18.3	16.1	16.1	18.3	17.9
8:00 am	21.0	20.4	20.5	22.3	20.0	18.2	18.2	20.0	19.9
9:00 am	22.7	21.9	22.2	24.4	21.7	20.1	20.1	21.9	21.9
10:00 am	24.0	23.1	23.7	25.9	23.2	21.8	21.8	23.4	23.6
11:00 am	24.2	24.1	24.6	27.3	24.2	23.7	23.7	24.5	25.0
12:00 pm	25.2	24.8	25.9	28.2	25.2	24.4	24.4	25.7	25.9
1:00 pm	25.8	25.1	26.0	28.0	25.3	24.1	24.1	26.2	26.4
2:00 pm	25.9	25.2	26.3	28.1	24.8	25.4	25.4	26.2	26.3
3:00 pm	25.6	24.9	25.7	27.7	24.5	25.0	25.0	26.2	25.5
4:00 pm	24.5	24.3	25.0	27.1	23.7	24.4	24.4	24.5	25.0
5:00 pm	24.5	23.4	24.3	26.4	23.0	23.9	23.9	24.8	24.3
6:00 pm	23.4	22.4	23.2	25.1	21.9	22.9	22.9	23.7	23.4
7:00 pm	22.2	21.3	22.2	24.0	21.1	21.6	21.6	22.5	22.1
8:00 pm	21.2	20.0	20.9	22.7	20.0	20.2	20.2	21.1	20.8
9:00 pm	20.7	19.4	20.1	21.8	19.3	19.8	19.8	20.5	20.3
10:00 pm	20.2	19.0	19.9	21.7	19.2	18.7	18.7	19.4	20.0
11:00 pm	19.9	18.8	19.4	21.1	18.9	18.9	18.9	19.3	19.5

Table B.2: The minimum, maximum and mode temperatures in °C for each hour

Hours	**Min**	**Max**	**Mode**
12:00 am	18.0	21.1	19
1:00 am	16.6	20.8	18
2:00 am	17.4	20.6	18
3:00 am	16.7	20.3	18
4:00 am	16.3	19.8	18
5:00 am	16.4	19.5	17
6:00 am	16.1	19.8	17
7:00 am	16.1	20.5	18
8:00 am	18.2	22.3	20
9:00 am	20.1	24.4	22
10:00 am	21.8	25.9	24
11:00 am	23.7	27.3	24
12:00 pm	24.4	28.2	24
1:00 pm	24.1	28.0	25
2:00 pm	24.6	28.1	26
3:00 pm	24.3	27.7	24
4:00 pm	23.7	27.1	25
5:00 pm	22.8	26.4	24
6:00 pm	21.9	25.1	23
7:00 pm	20.7	24.0	21
8:00 pm	19.6	22.7	20
9:00 pm	19.0	21.8	20
10:00 pm	18.7	21.7	19
11:00 pm	18.5	21.1	19

Appendix C

Additional information for the simulation study

This appendix provides the method that was used to determine the required number observations for each experiment as well as the Tecnomatix Plant Simulation® evaluation report of the key output measurements.

C.1 Determining the required number of observations

According to Bekker (2016), the simulation of stochastic systems is statistical sampling with the aid of a computer. Therefore a sufficient number of observations are must be made to draw a conclusion with a certain level of confidence on the output measurements being studied. The number observations required for this study was determined following the method explained by Bekker (2016).

1. Do a trial run of 10 replications ($n = 10$), therefore 10 observations of the mean of the output measurements are made.

2. Estimate the mean of the observations and the standard deviation of the mean:

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{n} \bar{X}_i}{n} \tag{C.1}$$

$$S_{\bar{X}} = \sqrt{\frac{\sum_{i=1}^{n}(\bar{X}_i - \bar{\bar{X}})^2}{n-1}} \tag{C.2}$$

where:

$\bar{X}_i$ = The observations, i=1,...,10
$\bar{\bar{X}}$ = The mean of the observations
$S_{\bar{X}}$ = The standard deviation of mean.

3. Now determine the confidence interval half-width:

$$h = t_{n-1;1-\alpha} \frac{S_{\bar{X}}}{\sqrt{n}} \tag{C.3}$$

   where the value t is the upper critical point on the cumulative Student t-distribution.

4. If the calculated h is judged "too wide" by the simulation anlayst, they then select a smaller h called h^*, and the actual number of replications required to realise this narrower half-width is given by:

$$n^* = n(\frac{h}{h^*})^2 \tag{C.4}$$

   where:

   h^* = The desired confidence interval half-width. This means the simulation analyst has to choose a target value for h^*, but it should at least be equal to or smaller than h. The reason for this is because a larger value results in more replication and better accuracy of estimation, but more simulation time.

   n^* = The required number of replications.

   n = The number of initial replications made (usually 10)

   h = The confidence interval half-width that results from the n replications calculated from Equation C.3.

5. The simulation is run for n^* replications, and the calculations above are repeated to obtain a "final" point and interval estimator. The analysis is done per output measurement, and maximum n^* that is determined for each output measurement is used.

The required number of replications was determined by calculating the n^* for the total amount of food waste, and the n^* for the average remaining shelf-life of the strawberries output measurements. The calculations for both output measurements are shown in Table C.1 and Table C.2. Since the n^* for the total amount of food waste is higher than the n^* for the average remaining shelf-life, the simulation model will run for 33 replications per experiment.

Table C.1: The calculations to determine the required number of replications for the total waste output measurement

Experiments	$\bar{X}$	$\bar{\bar{X}}$	$\bar{X}_i - \bar{\bar{X}}$	$(\bar{X}_i - \bar{\bar{X}})^2$	$\sum_{i=1}^{n}(\bar{X}_i - \bar{\bar{X}})^2$	$S_{\bar{X}}$
Exp 01	5790	**4220.941**	1569.059	2461947.322	130619135.3	**3809.62**
Exp 02	5790		1569.059	2461947.322		
Exp 03	3215.3		-1005.641	1011313.067	**h**	2725.241
Exp 04	2650.8		-1570.141	2465341.582	**h***	1500.000
Exp 05	5790		1569.059	2461947.322	**n***	33.009
Exp 06	5790		1569.059	2461947.322	**alpha**	0.050
Exp 07	2373.4		-1847.541	3413406.361	**t-value**	2.262
Exp 08	1657.8		-2563.141	6569689.864		
Exp 09	6696.3		2475.359	6127404.035		
Exp 10	6696.3		2475.359	6127404.035		
Exp 11	2475.2		-1745.741	3047610.330		
Exp 12	1616.3		-2604.641	6784152.785		
Exp 13	6558.3		2337.359	5463248.848		
Exp 14	6558.3		2337.359	5463248.848		
Exp 15	2419.3		-1801.641	3245908.942		
Exp 16	1635.1		-2585.841	6686571.738		
Exp 17	5803.8		1582.859	2505443.801		
Exp 18	5803.8		1582.859	2505443.801		
Exp 19	2942.5		-1278.441	1634410.432		
Exp 20	2626.3		-1594.641	2542878.723		
Exp 21	5890.3		1669.359	2786760.723		
Exp 22	5890.3		1669.359	2786760.723		
Exp 23	2402.1		-1818.841	3308181.219		
Exp 24	1676.6		-2544.341	6473669.216		
Exp 25	6540.4		2319.459	5379891.792		
Exp 26	6540.4		2319.459	5379891.792		
Exp 27	2494.6		-1726.341	2980251.954		
Exp 28	1632.5		-2588.441	6700024.869		
Exp 29	6454.9		2233.959	4990574.489		
Exp 30	6454.9		2233.959	4990574.489		
Exp 31	2561.9		-1659.041	2752415.795		
Exp 32	1642.4		-2578.541	6648871.755		

Table C.2: The calculations to determine the required number of replications for the average remaining shelf-life output measurement

Experiments	$\bar{X}$	$\bar{\bar{X}}$	$\bar{X}_i - \bar{\bar{X}}$	$(\bar{X}_i - \bar{\bar{X}})^2$	$\sum_{i=1}^{n}(\bar{X}_i - \bar{\bar{X}})^2$	$S_{\bar{X}}$
Exp 01	8.260	**7.856**	0.404	0.163	49.761	**2.351**
Exp 02	8.260		0.404	0.163		
Exp 03	5.350		-2.506	6.281	**h**	1.682
Exp 04	5.770		-2.086	4.350	**h***	1.000
Exp 05	9.298		1.442	2.079	**n***	28.294
Exp 06	9.298		1.442	2.080	**alpha**	0.050
Exp 07	7.055		-0.801	0.642	**t-value**	2.262
Exp 08	7.234		-0.622	0.387		
Exp 09	9.080		1.224	1.499		
Exp 10	9.080		1.224	1.499		
Exp 11	6.893		-0.963	0.928		
Exp 12	7.164		-0.692	0.479		
Exp 13	9.087		1.231	1.516		
Exp 14	9.087		1.231	1.516		
Exp 15	6.931		-0.925	0.855		
Exp 16	7.168		-0.688	0.473		
Exp 17	8.296		0.440	0.194		
Exp 18	8.296		0.440	0.194		
Exp 19	5.537		-2.319	5.378		
Exp 20	5.928		-1.928	3.718		
Exp 21	9.445		1.589	2.526		
Exp 22	9.446		1.590	2.527		
Exp 23	7.078		-0.778	0.605		
Exp 24	7.311		-0.545	0.297		
Exp 25	9.179		1.323	1.749		
Exp 26	9.179		1.323	1.749		
Exp 27	6.935		-0.921	0.847		
Exp 28	7.263		-0.593	0.351		
Exp 29	9.165		1.309	1.714		
Exp 30	9.165		1.309	1.714		
Exp 31	6.891		-0.965	0.930		
Exp 32	7.260		-0.596	0.355		

The simulation model ran for 33 replications per experiment. This above-mentioned process was repeated for $n = 33$ and the new h for the total waste was 1 497.5 and the new h for the average remaining shelf-life was 0.937.

C.2 Simulation study evaluation report

An illustration of the simulation model that was developed in Tecnomatix Plant Simulation®, as well as the input and key output values from the simulation study are provided in this section.

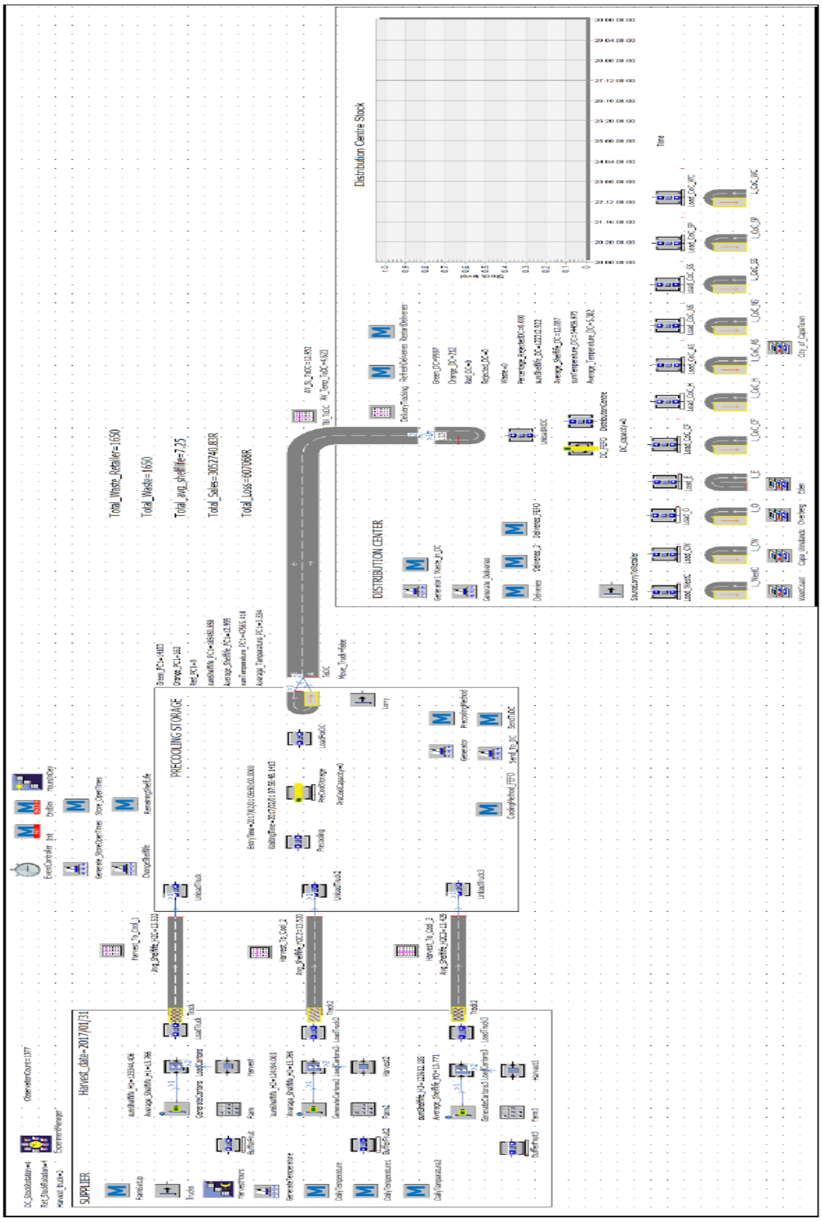


Figure C.1: The model that was developed in Tecnomatix Plant Simulation®

	root.DC_StockRotation	root.Ret_StockRotation	root.Harvest_truck	root.Avg_Shelflife_H2C	root.Avg_Shelflife_H2C2	root.Avg_Shelflife_H2C3	root.Total_Waste_Retailer	root.Total_Waste	root.Total_avg_shelflife	root.Total_Sales	root.Total_Loss
Exp 01	1	1	1	13.4897198553345	13.4844065609789	13.4592343408753	5613.4	5613.4	8.33753466095904	3075516.864	2065282.128
Exp 02	1	2	1	13.4897198553345	13.4844065609789	13.4592343408753	5613.4	5613.4	8.33763423317869	3075516.864	2065282.128
Exp 03	1	3	1	13.4892700411563	13.4843354994941	13.4585364663551	3052.2	3976	5.39516524397635	3146083.92	1122965.424
Exp 04	1	4	1	13.4888723369005	13.4850404310376	13.4586645689425	2650.8	3805.9	5.77020464681579	3034154.9515245	975282.336
Exp 05	2	1	1	13.4897198553345	13.4844065609789	13.4592343408753	5613.4	5613.4	9.29036159557512	3075516.864	2065282.128
Exp 06	2	2	1	13.4897198553345	13.4844065609789	13.4592343408753	5613.4	5613.4	9.29046117316209	3075516.864	2065282.128
Exp 07	2	3	1	13.4890711661973	13.4845971658341	13.4588318832782	2400	2400	7.06025921808241	3145311.288	883008
Exp 08	2	4	1	13.4888428984378	13.4851865729122	13.4589422991523	1657.8	1657.8	7.23414207958048	3050626.79206369	609937.776
Exp 09	3	1	1	13.4896698252988	13.4845194193311	13.4604468984988	6683.7	6683.7	9.07384143655943	3112124.904	2459066.904
Exp 10	3	2	1	13.4896698252988	13.4845194193311	13.4604468984988	6683.7	6683.7	9.07384143655943	3112124.904	2459066.904
Exp 11	3	3	1	13.4893840084434	13.4846721841568	13.4583027649812	2479.3	2479.3	6.88439646845962	3145458.456	912184.056
Exp 12	3	4	1	13.4903490200445	13.4846761166846	13.4592431773434	1616.3	1616.3	7.16384297662025	3048909.72503685	594669.096
Exp 13	4	1	1	13.4904874130054	13.4854061139718	13.4587519842224	6524.7	6524.7	9.0883663535446	3118158.792	2400567.624
Exp 14	4	2	1	13.4904874130054	13.4854061139718	13.4587519842224	6524.7	6524.7	9.0883663535446	3118158.792	2400567.624
Exp 15	4	3	1	13.4896638261685	13.4852320013043	13.4594129919119	2428.9	2428.9	6.91895423833581	3146083.92	893640.888
Exp 16	4	4	1	13.4887865887581	13.4851191146498	13.4584226278256	1635.1	1635.1	7.16813211477659	3051797.39117323	601585.992
Exp 17	1	1	2	13.536999616842	13.521903655479	13.4265532337641	5569.5	5571.8	8.32114216067535	3012712.92	2049130.44
Exp 18	1	2	2	13.536999616842	13.521903655479	13.4265532337641	5569.5	5571.8	8.32121685632745	3012712.92	2049130.44
Exp 19	1	3	2	13.537147261884	13.5219548183962	13.4272592007142	3048.8	4080.9	5.50063783584901	3143729.232	1121714.496
Exp 20	1	4	2	13.536500597023	13.5222799770834	13.4269579974571	2626.3	3899.5	5.92771475642645	3023702.76817635	966268.296
Exp 21	2	1	2	13.5372750577145	13.522535391271	13.4267698243381	5632.4	5632.4	9.44942785208918	3030299.496	2072272.608
Exp 22	2	2	2	13.5372750577145	13.522535391271	13.4267698243381	5632.4	5632.4	9.44950236077184	3030299.496	2072272.608
Exp 23	2	3	2	13.5369917098406	13.5212251542578	13.4271607660052	2391.5	2391.5	7.07882426140431	3146451.84	879880.68
Exp 24	2	4	2	13.5366587578561	13.5213654216262	13.4275939406509	1676.6	1676.6	7.31101716988348	3055571.28325734	616854.672
Exp 25	3	1	2	13.5371311158638	13.5212448674427	13.4264596460036	6553.3	6553.3	9.1613319560141	3110947.56	2411090.136
Exp 26	3	2	2	13.5371311158638	13.5212448674427	13.4264596460036	6553.3	6553.3	9.1613319560141	3110947.56	2411090.136
Exp 27	3	3	2	13.5363354298991	13.5221406601982	13.4273442622681	2494.8	2494.8	6.91929477856267	3145458.456	917886.816
Exp 28	3	4	2	13.5372067828117	13.5214872419555	13.4274788585915	1632.5	1632.5	7.26310404087154	3050917.05049626	600629.4
Exp 29	4	1	2	13.5374564972899	13.5212743129604	13.4264727754437	6473.2	6473.2	9.16209509450182	3118085.208	2381619.744
Exp 30	4	2	2	13.5374564972899	13.5212743129604	13.4264727754437	6473.2	6473.2	9.16209509450182	3118085.208	2381619.744
Exp 31	4	3	2	13.5367853025522	13.5219156798125	13.4263393283585	2537	2537	6.90595065958189	3146083.92	933413.04
Exp 32	4	4	2	13.536129541336	13.5214990406503	13.4278263387608	1642.4	1642.4	7.26029941230038	3053064.65339297	604271.808

Figure C.2: Overview of all executed experiments

Input values	set by	Original Value	Technical Notation
root.DC_StockRotation	Tab		root.DC_StockRotation
root.Ret_StockRotation	Tab		root.Ret_StockRotation
root.Harvest_truck	Tab		root.Harvest_truck

Figure C.3: The input values are set by decision variables

Target value	evaluated by	Technical Notation
root.Avg_Shelflife_H2C	Tab	root.Avg_Shelflife_H2C
root.Avg_Shelflife_H2C2	Tab	root.Avg_Shelflife_H2C2
root.Avg_Shelflife_H2C3	Tab	root.Avg_Shelflife_H2C3
root.Total_Waste_Retailer	Tab	root.Total_Waste_Retailer
root.Total_Waste	Tab	root.Total_Waste
root.Total_avg_shelflife	Tab	root.Total_avg_shelflife
root.Total_Sales	Tab	root.Total_Sales
root.Total_Loss	Tab	root.Total_Loss
root.Average_Shelflife_DC	Tab	root.Average_Shelflife_DC
root.Waste	Tab	root.Waste
root.Rejected_DC	Tab	root.Rejected_DC
root.WestCoast.Waste	Tab	root.WestCoast.Waste
root.WestCoast.Average_Shelflife	Tab	root.WestCoast.Average_Shelflife
root.WestCoast.Tot_Sales	Tab	root.WestCoast.Tot_Sales
root.WestCoast.Cost_of_Waste	Tab	root.WestCoast.Cost_of_Waste
root.WestCoast.Wasted_SL	Tab	root.WestCoast.Wasted_SL
root.Cape_Winelands.Waste	Tab	root.Cape_Winelands.Waste
root.Cape_Winelands.Average_Shelflife	Tab	root.Cape_Winelands.Average_Shelflife
root.Cape_Winelands.Tot_Sales	Tab	root.Cape_Winelands.Tot_Sales
root.Cape_Winelands.Cost_of_Waste	Tab	root.Cape_Winelands.Cost_of_Waste
root.Cape_Winelands.Wasted_SL	Tab	root.Cape_Winelands.Wasted_SL
root.Overberg.Waste	Tab	root.Overberg.Waste
root.Overberg.Average_Shelflife	Tab	root.Overberg.Average_Shelflife
root.Overberg.Tot_Sales	Tab	root.Overberg.Tot_Sales
root.Overberg.Cost_of_Waste	Tab	root.Overberg.Cost_of_Waste
root.Overberg.Wasted_SL	Tab	root.Overberg.Wasted_SL
root.Eden.Waste	Tab	root.Eden.Waste
root.Eden.Average_Shelflife	Tab	root.Eden.Average_Shelflife
root.Eden.Tot_Sales	Tab	root.Eden.Tot_Sales
root.Eden.Cost_of_Waste	Tab	root.Eden.Cost_of_Waste
root.Eden.Wasted_SL	Tab	root.Eden.Wasted_SL
root.City_of_CapeTown.Waste_CF	Tab	root.City_of_CapeTown.Waste_CF
root.City_of_CapeTown.Average_Shelflife_CF	Tab	root.City_of_CapeTown.Average_Shelflife_CF
root.City_of_CapeTown.Total_Sales_CF	Tab	root.City_of_CapeTown.Total_Sales_CF
root.City_of_CapeTown.Cost_of_Waste_CF	Tab	root.City_of_CapeTown.Cost_of_Waste_CF
root.City_of_CapeTown.Wasted_SL_CF	Tab	root.City_of_CapeTown.Wasted_SL_CF
root.City_of_CapeTown.Waste_H	Tab	root.City_of_CapeTown.Waste_H
root.City_of_CapeTown.Average_Shelflife_H	Tab	root.City_of_CapeTown.Average_Shelflife_H
root.City_of_CapeTown.Total_Sales_H	Tab	root.City_of_CapeTown.Total_Sales_H
root.City_of_CapeTown.Cost_of_Waste_H	Tab	root.City_of_CapeTown.Cost_of_Waste_H
root.City_of_CapeTown.Wasted_SL_H	Tab	root.City_of_CapeTown.Wasted_SL_H
root.City_of_CapeTown.Waste_AS	Tab	root.City_of_CapeTown.Waste_AS
root.City_of_CapeTown.Average_Shelflife_AS	Tab	root.City_of_CapeTown.Average_Shelflife_AS
root.City_of_CapeTown.Total_Sales_AS	Tab	root.City_of_CapeTown.Total_Sales_AS
root.City_of_CapeTown.Cost_of_Waste_AS	Tab	root.City_of_CapeTown.Cost_of_Waste_AS
root.City_of_CapeTown.Wasted_SL_AS	Tab	root.City_of_CapeTown.Wasted_SL_AS
root.City_of_CapeTown.Waste_NS	Tab	root.City_of_CapeTown.Waste_NS
root.City_of_CapeTown.Average_Shelflife_NS	Tab	root.City_of_CapeTown.Average_Shelflife_NS
root.City_of_CapeTown.Total_Sales_NS	Tab	root.City_of_CapeTown.Total_Sales_NS
root.City_of_CapeTown.Cost_of_Waste_NS	Tab	root.City_of_CapeTown.Cost_of_Waste_NS
root.City_of_CapeTown.Wasted_SL_NS	Tab	root.City_of_CapeTown.Wasted_SL_NS
root.City_of_CapeTown.Waste_SS	Tab	root.City_of_CapeTown.Waste_SS
root.City_of_CapeTown.Average_Shelflife_SS	Tab	root.City_of_CapeTown.Average_Shelflife_SS
root.City_of_CapeTown.Total_Sales_SS	Tab	root.City_of_CapeTown.Total_Sales_SS
root.City_of_CapeTown.Cost_of_Waste_SS	Tab	root.City_of_CapeTown.Cost_of_Waste_SS
root.City_of_CapeTown.Wasted_SL_SS	Tab	root.City_of_CapeTown.Wasted_SL_SS
root.City_of_CapeTown.Waste_SP	Tab	root.City_of_CapeTown.Waste_SP
root.City_of_CapeTown.Average_Shelflife_SP	Tab	root.City_of_CapeTown.Average_Shelflife_SP
root.City_of_CapeTown.Total_Sales_SP	Tab	root.City_of_CapeTown.Total_Sales_SP
root.City_of_CapeTown.Cost_of_Waste_SP	Tab	root.City_of_CapeTown.Cost_of_Waste_SP
root.City_of_CapeTown.Wasted_SL_SP	Tab	root.City_of_CapeTown.Wasted_SL_SP
root.City_of_CapeTown.Waste_WC	Tab	root.City_of_CapeTown.Waste_WC
root.City_of_CapeTown.Average_Shelflife_WC	Tab	root.City_of_CapeTown.Average_Shelflife_WC
root.City_of_CapeTown.Total_Sales_WC	Tab	root.City_of_CapeTown.Total_Sales_WC
root.City_of_CapeTown.Cost_of_Waste_WC	Tab	root.City_of_CapeTown.Cost_of_Waste_WC
root.City_of_CapeTown.Wasted_SL_WC	Tab	root.City_of_CapeTown.Wasted_SL_WC

Figure C.4: The output values that were evaluated

Evaluations of the output value 'root.TotalWaste'.

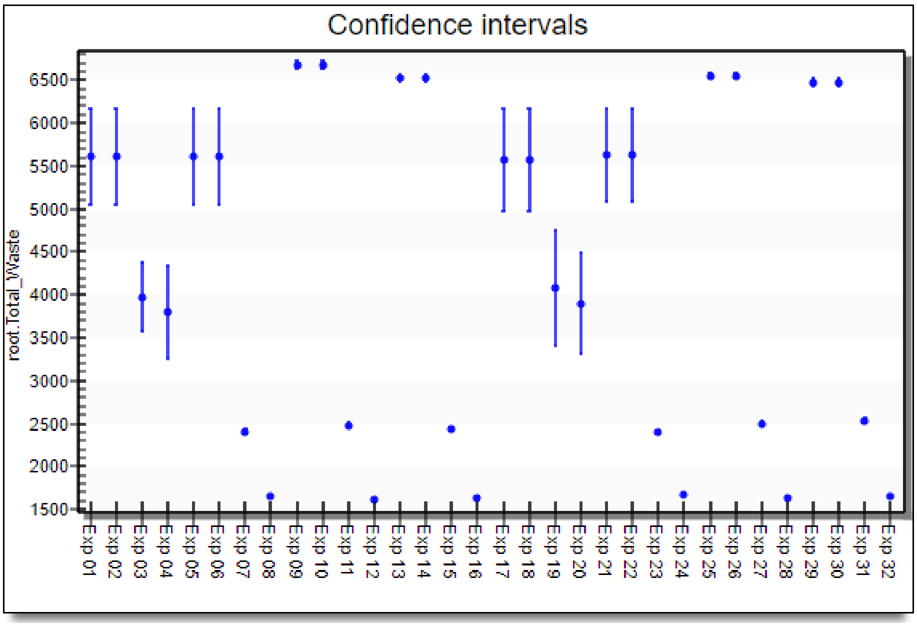


Figure C.5: The confidence intervals of the total waste output value per experiment

Experiment	root.Total_Waste	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 01	5613.4	790.414406076545	4186	6741	5047.52621827659	6179.27378172341
Exp 02	5613.4	790.414406076545	4186	6741	5047.52621827659	6179.27378172341
Exp 03	3976	560.076582065147	2977	4525	3575.02976070348	4376.97023929652
Exp 04	3805.9	756.423668764184	2381	4639	3264.36087983974	4347.43912016026
Exp 05	5613.4	790.414406076545	4186	6741	5047.52621827659	6179.27378172341
Exp 06	5613.4	790.414406076545	4186	6741	5047.52621827659	6179.27378172341
Exp 07	2400	40.3264456928976	2350	2470	2371.12947568735	2428.87052431265
Exp 08	1657.8	26.6116098306349	1629	1723	1638.74820618546	1676.85179381454
Exp 09	6683.7	58.7538178428752	6601	6798	6641.63694442075	6725.76305557925
Exp 10	6683.7	58.7538178428752	6601	6798	6641.63694442075	6725.76305557925
Exp 11	2479.3	39.6794097178338	2419	2549	2450.8927019283	2507.7072980717
Exp 12	1616.3	21.3856130247559	1569	1644	1600.98960380307	1631.61039619693
Exp 13	6524.7	53.1957600649858	6442	6590	6486.61607125553	6562.78392874447
Exp 14	6524.7	53.1957600649858	6442	6590	6486.61607125553	6562.78392874447
Exp 15	2428.9	16.6896508185494	2409	2466	2416.95153884882	2440.84846115118
Exp 16	1635.1	14.379383389663	1615	1655	1624.80550638373	1645.39449361627
Exp 17	5571.8	829.063970189673	4162	6822	4978.25620766125	6165.34379233875
Exp 18	5571.8	829.063970189673	4162	6822	4978.25620766125	6165.34379233875
Exp 19	4080.9	944.220954602847	1862	5121	3404.91297565437	4756.88702434563
Exp 20	3899.5	827.915085554605	1860	4743	3306.77871758542	4492.22128241458
Exp 21	5632.4	758.875952386894	4162	6436	5089.10524001742	6175.69475998257
Exp 22	5632.4	758.875952386894	4162	6436	5089.10524001742	6175.69475998257
Exp 23	2391.5	26.2181023128847	2352	2429	2372.72992623699	2410.27007376301
Exp 24	1676.6	23.4577634625832	1646	1715	1659.80610907481	1693.39389092519
Exp 25	6553.3	39.9556698798175	6504	6623	6524.69492164823	6581.90507835177
Exp 26	6553.3	39.9556698798175	6504	6623	6524.69492164823	6581.90507835177
Exp 27	2494.8	38.4586357878956	2431	2538	2467.26667886376	2522.33332113625
Exp 28	1632.5	24.5458754172672	1582	1661	1614.92710755105	1650.07289244895
Exp 29	6473.2	64.0673256990244	6372	6553	6427.33289585881	6519.06710414119
Exp 30	6473.2	64.0673256990244	6372	6553	6427.33289585881	6519.06710414119
Exp 31	2537	43.1637708166364	2471	2610	2506.09817680741	2567.90182319259
Exp 32	1642.4	21.4175421351505	1606	1672	1627.06674510223	1657.73325489777

Figure C.6: The minimum and maximum values for the output value 'root.TotalWaste'

	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06	Exp 07	Exp 08	Exp 09	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	Exp 19	Exp 20	Exp 21	Exp 22	Exp 23	Exp 24	Exp 25	Exp 26	Exp 27	Exp 28	Exp 29	Exp 30	Exp 31	Exp 32
Exp 01	1	0	0	1	1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.91	0.91	0.001	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 02		0	0	1	1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.91	0.91	0.001	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 03			0.575	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.767	0.812	0	0	0	0	0	0	0	0	0	0	0	0
Exp 04				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.482	0.795	0	0	0	0	0	0	0	0	0	0	0	0
Exp 05					1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.91	0.91	0.001	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 06						0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.91	0.91	0.001	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 07							0	0	0	0	0	0	0	0.058	0	0	0	0	0	0	0	0.584	0	0	0	0	0	0	0	0	0
Exp 08								0	0	0	0.001	0	0	0	0.033	0	0	0	0	0	0	0	0.111	0	0	0	0.04	0	0	0	0.172
Exp 09									1	0	0	0	0	0	0	0.002	0.002	0	0	0.002	0.002	0	0	0	0	0	0	0	0	0	0
Exp 10										0	0	0	0	0	0	0.002	0.002	0	0	0.002	0.002	0	0	0	0	0	0	0	0	0	0
Exp 11											0	0	0	0.003	0	0	0	0	0	0	0	0	0	0	0	0.387	0	0	0	0.006	0
Exp 12												0	0	0	0.035	0	0	0	0	0	0	0	0	0	0	0	0.133	0	0	0	0.014
Exp 13													1	0	0	0.005	0.005	0	0	0.005	0.005	0	0	0.192	0.192	0	0	0.067	0.067	0	0
Exp 14														0	0	0.005	0.005	0	0	0.005	0.005	0	0	0.192	0.192	0	0	0.067	0.067	0	0
Exp 15															0	0	0	0	0	0	0	0.002	0	0	0	0	0	0	0	0	0
Exp 16																0	0	0	0	0	0	0	0	0	0	0	0.777	0	0	0	0.384
Exp 17																	1	0.001	0	0.867	0.867	0	0	0.005	0.005	0	0	0.007	0.007	0	0
Exp 18																		0.001	0	0.867	0.867	0	0	0.005	0.005	0	0	0.007	0.007	0	0
Exp 19																			0.653	0.001	0.001	0	0	0	0	0	0	0	0	0.001	0
Exp 20																				0	0	0	0	0	0	0	0	0	0	0.001	0
Exp 21																					1	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 22																						0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 23																							0	0	0	0	0	0	0	0	0
Exp 24																								0	0	0	0.001	0	0	0	0.003
Exp 25																									1	0	0	0.004	0.004	0	0
Exp 26																										0	0	0.004	0.004	0	0
Exp 27																											0	0	0	0.033	0
Exp 28																												0	0	0	0.35
Exp 29																													1	0	0
Exp 30																														0	0
Exp 31																															0

Figure C.7: Table of the p-values of the T-test of the output value 'root.TotalWaste'

Evaluations of the output value 'root.TotalShelf-avg-shelflife'.

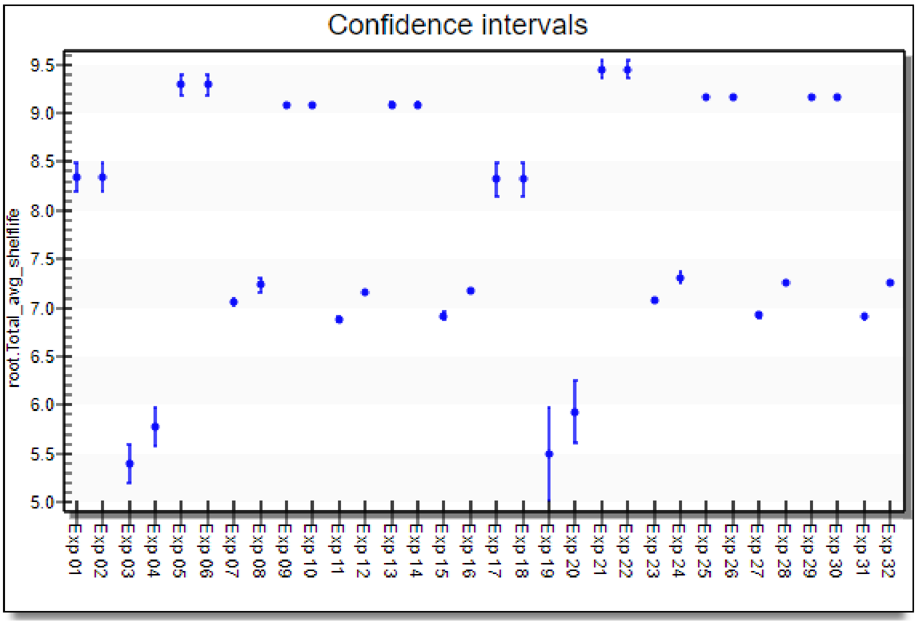


Figure C.8: The confidence intervals of the total average shelf-life output value per experiment

Experiment	root.Total_avg_shelflife	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 01	8.33753466095904	0.202432548845753	8.0274508673253	8.62719271572771	8.19260907372454	8.48246024819354
Exp 02	8.33763423317869	0.202559541094026	8.0274508673253	8.62719271572771	8.19261772960558	8.48265073675179
Exp 03	5.39516524397635	0.271067918959001	5.10526075958087	5.8871604565292	5.2011021965091	5.58922829144359
Exp 04	5.77020464681579	0.275236380576412	5.53662766676342	6.43164047545184	5.57315731272462	5.96725198090696
Exp 05	9.29036159557512	0.144941787331797	9.09701691922825	9.51288972626649	9.18659481615327	9.39412837499697
Exp 06	9.29046117316209	0.144801453884519	9.09701691922825	9.51288972626649	9.1867948613151	9.39412748500908
Exp 07	7.06025921808241	0.046136520232369	6.99428565823888	7.13941864440141	7.02722914299934	7.09328929316548
Exp 08	7.23414207958048	0.0958969454111212	7.1667053802538	7.49905503694299	7.16548750200911	7.30279665715186
Exp 09	9.07384143655943	0.0144114079507395	9.05494605253555	9.10469238091102	9.06352401590724	9.08415885721162
Exp 10	9.07384143655943	0.0144114079507395	9.05494605253555	9.10469238091102	9.06352401590724	9.08415885721162
Exp 11	6.88439646845962	0.0433076606553326	6.81420386400255	6.94121016068435	6.85339163159908	6.91540130532017
Exp 12	7.16384297662025	0.0204497452413497	7.12280967134061	7.18896655242593	7.14920258724217	7.17848336599833
Exp 13	9.0883663535446	0.0280753651376232	9.04007762224646	9.12205051677254	9.06826662747489	9.10846607961431
Exp 14	9.0883663535446	0.0280753651376232	9.04007762224646	9.12205051677254	9.06826662747489	9.10846607961431
Exp 15	6.91895423833581	0.0598908036636938	6.82844662440288	6.99958019484207	6.87607719143601	6.96183128523562
Exp 16	7.16813211477659	0.015143897478417	7.1508701118247	7.18967979054997	7.15729028994361	7.17897393960957
Exp 17	8.32114216067535	0.240779608929326	7.95731694103155	8.65648601040312	8.1487631316252	8.49352118972549
Exp 18	8.32121685632745	0.240803356015652	7.95731694103155	8.65648601040312	8.14882082625425	8.49361288640065
Exp 19	5.50063783584901	0.663850952418909	5.09705338460979	7.28877349849023	5.02537340992508	5.97590226177294
Exp 20	5.92771475642645	0.447170515587135	5.61205475769311	7.17560255258723	5.60757627111398	6.24785324173892
Exp 21	9.44942785208918	0.121585594697949	9.20795079484996	9.58187693699877	9.36238224696625	9.53647345721212
Exp 22	9.44950236077184	0.121654886309311	9.20795079484996	9.58187693699877	9.36240714837218	9.53659757317149
Exp 23	7.07882426140431	0.0286280224643847	7.03025260762233	7.11886094764067	7.05832887669137	7.09931964611724
Exp 24	7.31101716988348	0.0873543835351769	7.25802733746659	7.55123250740608	7.24847838645399	7.37355595331297
Exp 25	9.161331956014	0.0157307313898438	9.1308208355266	9.17888553186952	9.15007000482443	9.17259390720377
Exp 26	9.161331956014	0.0157307313898438	9.1308208355266	9.17888553186952	9.15007000482443	9.17259390720377
Exp 27	6.91929477856267	0.0308759720947419	6.84892423776946	6.97391189847062	6.89719004089681	6.94139951622853
Exp 28	7.26310404087154	0.012121015796588	7.2419847743736	7.28197836369469	7.25442635863998	7.27178172310311
Exp 29	9.16209509450182	0.013958230882499	9.13898954355279	9.18701787419416	9.1521021125484	9.17208807645524
Exp 30	9.16209509450182	0.013958230882499	9.13898954355279	9.18701787419416	9.1521021125484	9.17208807645524
Exp 31	6.90595065958189	0.0351674479474447	6.86074465211654	6.96586072674567	6.88077356689406	6.93112775226971
Exp 32	7.26029941230038	0.00921260592977395	7.24704051943287	7.27262315838863	7.25370391996506	7.26689490463571

Figure C.9: The minimum and maximum values for the output value 'root.TotalShelf-avg-shelflife'

	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06	Exp 07	Exp 08	Exp 09	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	Exp 19	Exp 20	Exp 21	Exp 22	Exp 23	Exp 24	Exp 25	Exp 26	Exp 27	Exp 28	Exp 29	Exp 30	Exp 31	Exp 32
Exp 01	0.999	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.871	0.872	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 02		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.87	0.871	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 03			0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.65	0.006	0	0	0	0	0	0	0	0	0	0	0	0
Exp 04				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.258	0.358	0	0	0	0	0	0	0	0	0	0	0	0
Exp 05					0.999	0	0	0.001	0.001	0	0	0.002	0.002	0	0	0	0	0	0	0.016	0.016	0	0	0.02	0.02	0	0	0.021	0.021	0	0
Exp 06						0	0	0.001	0.001	0	0	0.002	0.002	0	0	0	0	0	0	0.016	0.016	0	0	0.02	0.02	0	0	0.021	0.021	0	0
Exp 07							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.297	0	0	0	0	0	0	0	0	0
Exp 08								0	0	0	0.047	0	0	0	0.059	0	0	0	0	0	0	0.001	0.077	0	0	0	0.367	0	0	0	0.412
Exp 09									1	0	0	0.169	0.169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 10										0	0	0.169	0.169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 11											0	0	0	0.158	0	0	0	0	0	0	0	0	0	0	0	0.054	0	0	0	0.238	0
Exp 12												0	0	0	0.601	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 13													1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 14														0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 15															0	0	0	0	0	0	0	0	0	0	0	0.987	0	0	0	0.563	0
Exp 16																0	0	0	0	0	0	0	0.001	0	0	0	0	0	0	0	0
Exp 17																	0.999	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 18																		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exp 19																			0.111	0	0	0	0	0	0	0	0	0	0	0	0
Exp 20																				0	0	0	0	0	0	0	0	0	0	0	0
Exp 21																					0.999	0	0	0	0	0	0	0	0	0	0
Exp 22																						0	0	0	0	0	0	0	0	0	0
Exp 23																							0	0	0	0	0	0	0	0	0
Exp 24																								0	0	0	0.119	0	0	0	0.1
Exp 25																									1	0	0	0.91	0.91	0	0
Exp 26																										0	0	0.91	0.91	0	0
Exp 27																											0	0	0	0.379	0
Exp 28																												0	0	0	0.568
Exp 29																													1	0	0
Exp 30																														0	0
Exp 31																															0

Figure C.10: Table of the p-values of the T-test of the output value 'root.TotalShelf-avg-shelflife'

Evaluations of the output value 'root.TotalSales'.

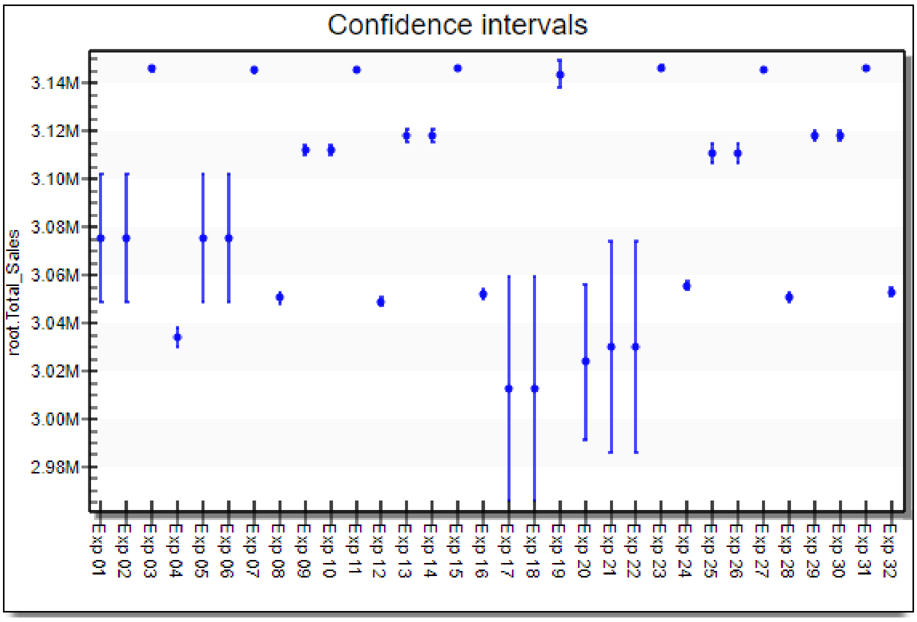


Figure C.11: The confidence intervals of the total sales output value per experiment

Experiment	root.Total_Sales	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 01	3075516.864	37237.6725571559	3000019.68	3128055.84	3048857.65532351	3102176.07267649
Exp 02	3075516.864	37237.6725571559	3000019.68	3128055.84	3048857.65532351	3102176.07267649
Exp 03	3146083.92	1409.02632543324	3143876.4	3148291.44	3145075.16933808	3147092.67066192
Exp 04	3034154.9515245	5504.18720331142	3024184.97552678	3041976.8489719	3030214.39173193	3038095.51131707
Exp 05	3075516.864	37237.6725571559	3000019.68	3128055.84	3048857.65532351	3102176.07267649
Exp 06	3075516.864	37237.6725571559	3000019.68	3128055.84	3048857.65532351	3102176.07267649
Exp 07	3145311.288	1455.75281450679	3142772.64	3146819.76	3144269.08489228	3146353.49110772
Exp 08	3050626.79206369	3166.26197907547	3046728.97228244	3055425.43128599	3048360.00058538	3052893.58354199
Exp 09	3112124.904	2753.53429862069	3106348.56	3115914.48	3110153.5926794	3114096.2153206
Exp 10	3112124.904	2753.53429862069	3106348.56	3115914.48	3110153.5926794	3114096.2153206
Exp 11	3145458.456	1055.70176025108	3144244.32	3146819.76	3144702.65759494	3146214.25440505
Exp 12	3048909.72503685	2126.99430069954	3045010.33616941	3051774.33520657	3047386.96646946	3050432.48360424
Exp 13	3118158.792	4080.24588634748	3111131.52	3124008.72	3115237.66081575	3121079.92318425
Exp 14	3118158.792	4080.24588634748	3111131.52	3124008.72	3115237.66081575	3121079.92318425
Exp 15	3146083.92	1026.07985546529	3144612.24	3147923.52	3145349.32852027	3146818.51147973
Exp 16	3051797.39117323	2794.18350632414	3047467.66900289	3054788.94300699	3049796.97825641	3053797.80409005
Exp 17	3012712.92	64960.8347530857	2923492.32	3127320	2966206.13451755	3059219.70548245
Exp 18	3012712.92	64960.8347530857	2923492.32	3127320	2966206.13451755	3059219.70548245
Exp 19	3143729.232	7752.9434636591	3121801.2	3147923.52	3138178.74177166	3149279.72222834
Exp 20	3023702.76817635	45275.1173236869	2895491.58493694	3045162.43016044	2991289.38899074	3056116.14736195
Exp 21	3030299.496	61535.968903005	2937473.28	3127320	2986244.64177738	3074354.35022262
Exp 22	3030299.496	61535.968903005	2937473.28	3127320	2986244.64177738	3074354.35022262
Exp 23	3146451.84	1262.65608152352	3143508.48	3147923.52	3145547.87877868	3147355.80122132
Exp 24	3055571.28325734	2407.65058409011	3051751.6565125	3060139.00007022	3053847.59713698	3057294.9693777
Exp 25	3110947.56	5388.48954820468	3102669.36	3118489.92	3107089.83051661	3114805.28948339
Exp 26	3110947.56	5388.48954820468	3102669.36	3118489.92	3107089.83051661	3114805.28948339
Exp 27	3145458.456	1251.28865588529	3143140.56	3146819.76	3144562.63295036	3146354.27904964
Exp 28	3050917.05049626	2815.45779007754	3046861.38647504	3055940.07358392	3048901.40688614	3052932.69410638
Exp 29	3118085.208	2991.25974368102	3111131.52	3121433.28	3115943.7041885	3120226.7118115
Exp 30	3118085.208	2991.25974368102	3111131.52	3121433.28	3115943.7041885	3120226.7118115
Exp 31	3146083.92	1040.63490736025	3144980.16	3147555.6	3145338.90826199	3146828.93173801
Exp 32	3053064.65339297	2231.26525049254	3050230.06453012	3057463.67655328	3051467.24512761	3054662.06165832

Figure C.12: The minimum and maximum values for the output value 'root.TotalSales'

	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06	Exp 07	Exp 08	Exp 09	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	Exp 19	Exp 20	Exp 21	Exp 22	Exp 23	Exp 24	Exp 25	Exp 26	Exp 27	Exp 28	Exp 29	Exp 30	Exp 31	Exp 32
Exp 01	1	0	0.007	1	1	0	0.064	0.013	0.013	0	0.05	0.006	0.006	0	0.075	0.019	0.019	0	0.012	0.066	0.066	0	0.125	0.015	0.015	0	0.067	0.006	0.006	0	0.089
Exp 02		0	0.007	1	1	0	0.064	0.013	0.013	0	0.05	0.006	0.006	0	0.075	0.019	0.019	0	0.012	0.066	0.066	0	0.125	0.015	0.015	0	0.067	0.006	0.006	0	0.089
Exp 03			0	0	0	0.243	0	0	0	0.277	0	0	0	1	0	0	0	0.368	0	0	0	0.546	0	0	0	0.308	0	0	0	1	0
Exp 04				0.007	0.007	0	0	0	0	0	0	0	0	0	0	0.325	0.325	0	0.487	0.848	0.848	0	0	0	0	0	0	0	0	0	0
Exp 05					1	0	0.064	0.013	0.013	0	0.05	0.006	0.006	0	0.075	0.019	0.019	0	0.012	0.066	0.066	0	0.125	0.015	0.015	0	0.067	0.006	0.006	0	0.089
Exp 06						0	0.064	0.013	0.013	0	0.05	0.006	0.006	0	0.075	0.019	0.019	0	0.012	0.066	0.066	0	0.125	0.015	0.015	0	0.067	0.006	0.006	0	0.089
Exp 07							0	0	0	0.799	0	0	0	0.189	0	0	0	0.541	0	0	0	0.078	0	0	0	0.811	0	0	0	0.191	0
Exp 08								0	0	0	0.174	0	0	0	0.392	0.098	0.098	0	0.093	0.324	0.324	0	0.001	0	0	0	0.831	0	0	0	0.064
Exp 09									1	0	0	0.001	0.001	0	0	0.001	0.001	0	0	0.002	0.002	0	0	0.549	0.549	0	0	0	0	0	0
Exp 10										0	0	0.001	0.001	0	0	0.001	0.001	0	0	0.002	0.002	0	0	0.549	0.549	0	0	0	0	0	0
Exp 11											0	0	0	0.196	0	0	0	0.502	0	0	0	0.073	0	0	0	1	0	0	0	0.199	0
Exp 12												0	0	0	0.019	0.112	0.112	0	0.112	0.364	0.364	0	0	0	0	0	0.09	0	0	0	0
Exp 13													1	0	0	0.001	0.001	0	0	0.001	0.001	0	0	0.004	0.004	0	0	0.964	0.964	0	0
Exp 14														0	0	0.001	0.001	0	0	0.001	0.001	0	0	0.004	0.004	0	0	0.964	0.964	0	0
Exp 15															0	0	0	0.365	0	0	0	0.484	0	0	0	0.238	0	0	0	1	0
Exp 16																0.09	0.09	0	0.082	0.298	0.298	0	0.005	0	0	0	0.492	0	0	0	0.278
Exp 17																	1	0	0.667	0.542	0.542	0	0.067	0.001	0.001	0	0.096	0.001	0.001	0	0.081
Exp 18																		0	0.667	0.542	0.542	0	0.067	0.001	0.001	0	0.096	0.001	0.001	0	0.081
Exp 19																			0	0	0	0.3	0	0	0	0.503	0	0	0	0.365	0
Exp 20																				0.788	0.788	0	0.053	0	0	0	0.09	0	0	0	0.071
Exp 21																					1	0	0.227	0.002	0.002	0	0.317	0.001	0.001	0	0.272
Exp 22																						0	0.227	0.002	0.002	0	0.317	0.001	0.001	0	0.272
Exp 23																							0	0	0	0.094	0	0	0	0.486	0
Exp 24																								0	0	0	0.001	0	0	0	0.027
Exp 25																									1	0	0	0.003	0.003	0	0
Exp 26																										0	0	0.003	0.003	0	0
Exp 27																											0	0	0	0.24	0
Exp 28																												0	0	0	0.076
Exp 29																													1	0	0
Exp 30																														0	0
Exp 31																															0

Figure C.13: Table of the p-values of the T-test of the output value ‘root.TotalSales’

Evaluations of the output value 'root.TotalLosses'.

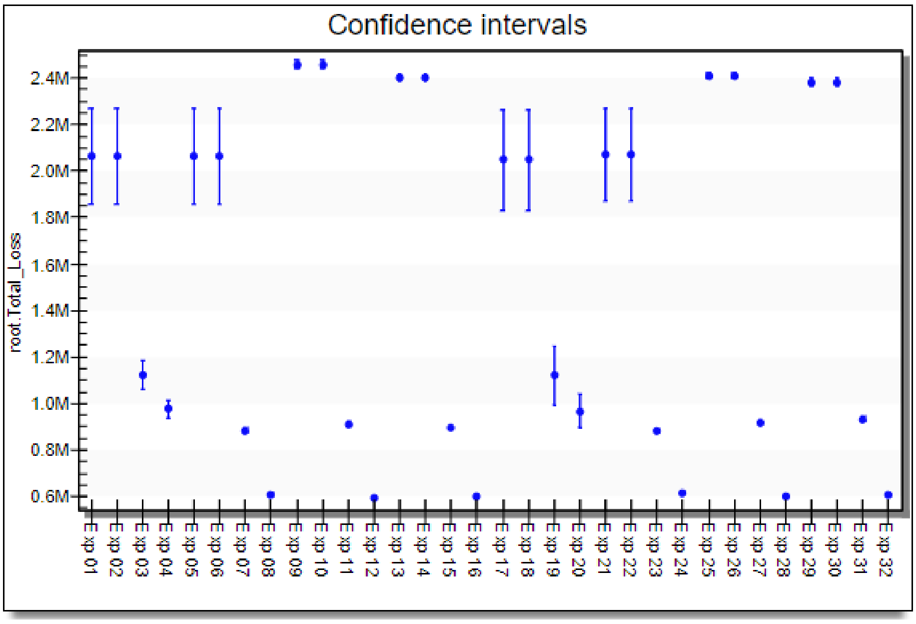


Figure C.14: The confidence intervals of the total losses output value per experiment

Experiment	root.Total_Loss	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 01	2065282.128	290809.268283683	1540113.12	2480148.72	1857085.84622832	2273478.40977168
Exp 02	2065282.128	290809.268283683	1540113.12	2480148.72	1857085.84622832	2273478.40977168
Exp 03	1122965.424	90817.8472478937	947761.92	1251663.84	1057947.07631421	1187983.77168579
Exp 04	975282.336	49361.5868765626	876017.52	1027232.64	939943.369980441	1010621.30201956
Exp 05	2065282.128	290809.268283683	1540113.12	2480148.72	1857085.84622832	2273478.40977168
Exp 06	2065282.128	290809.268283683	1540113.12	2480148.72	1857085.84622832	2273478.40977168
Exp 07	883008	14836.9058993339	864612	908762.4	872385.956694887	893630.043305113
Exp 08	609937.776	9790.94348888054	599341.68	633926.16	602928.240019761	616947.311980239
Exp 09	2459066.904	21616.7046607021	2428639.92	2501120.16	2443591.06459132	2474542.74340868
Exp 10	2459066.904	21616.7046607021	2428639.92	2501120.16	2443591.06459132	2474542.74340868
Exp 11	912184.056	14598.8484233881	889998.48	937828.08	901732.442893458	922635.669106542
Exp 12	594669.096	7868.19474406925	577266.48	604860.48	589036.095031225	600302.096968775
Exp 13	2400567.624	19571.7840431119	2370140.64	2424592.8	2386555.78493633	2414579.46306367
Exp 14	2400567.624	19571.7840431119	2370140.64	2424592.8	2386555.78493633	2414579.46306367
Exp 15	893640.888	6140.45632917026	886319.28	907290.72	889244.810173252	898036.965826748
Exp 16	601585.992	5290.46273673714	594190.8	608907.6	597798.441908695	605373.542091305
Exp 17	2049130.44	304750.369018018	1531283.04	2508478.56	1830953.44009708	2267307.43990292
Exp 18	2049130.44	304750.369018018	1531283.04	2508478.56	1830953.44009708	2267307.43990292
Exp 19	1121714.496	177048.48322335	667406.88	1256078.88	994961.878664368	1248467.11333563
Exp 20	966268.296	102674.9594822	684331.2	1030911.84	892761.200021206	1039775.39197879
Exp 21	2072272.608	279205.640402183	1531283.04	2367933.12	1872383.59990721	2272161.61609279
Exp 22	2072272.608	279205.640402183	1531283.04	2367933.12	1872383.59990721	2272161.61609279
Exp 23	879880.68	9646.16420295672	865347.84	893677.68	872974.794461113	886786.565538887
Exp 24	616854.672	8630.580333152	605596.32	630982.8	610675.863650807	623033.480349193
Exp 25	2411090.136	14700.4900622796	2392951.68	2436734.16	2400565.75557275	2421614.51642725
Exp 26	2411090.136	14700.4900622796	2392951.68	2436734.16	2400565.75557275	2421614.51642725
Exp 27	917886.816	14149.7012790845	894413.52	933780.96	907756.756487551	928016.875512449
Exp 28	600629.4	9030.91848351675	582049.44	611115.12	594163.981410187	607094.818589813
Exp 29	2381619.744	23571.6504712044	2344386.24	2410979.76	2364744.31904436	2398495.16895564
Exp 30	2381619.744	23571.6504712044	2344386.24	2410979.76	2364744.31904436	2398495.16895564
Exp 31	933413.04	15880.8145588514	909130.32	960271.2	922043.641210987	944782.438789013
Exp 32	604271.808	7879.94210236822	590879.52	615162.24	598630.396858011	609913.219141989

Figure C.15: The minimum and maximum values for the output value 'root.TotalLosses'

	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06	Exp 07	Exp 08	Exp 09	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	Exp 19	Exp 20	Exp 21	Exp 22	Exp 23	Exp 24	Exp 25	Exp 26	Exp 27	Exp 28	Exp 29	Exp 30	Exp 31	Exp 32
Exp 01	1	0	0	1	1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.905	0.905	0	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 02		0	0	1	1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.905	0.905	0	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 03			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.984	0.002	0	0	0	0	0	0	0	0	0	0	0	0
Exp 04				0	0	0	0	0	0	0.003	0	0	0	0.001	0	0	0	0.03	0.806	0	0	0	0	0	0	0.005	0	0	0	0.027	0
Exp 05					1	0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.905	0.905	0	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 06						0	0	0.002	0.002	0	0	0.005	0.005	0	0	0.905	0.905	0	0	0.957	0.957	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 07							0	0	0	0	0	0	0	0.058	0	0	0	0.002	0.031	0	0	0.584	0	0	0	0	0	0	0	0	0
Exp 08								0	0	0	0.001	0	0	0	0.033	0	0	0	0	0	0	0	0.111	0	0	0	0.04	0	0	0	0.172
Exp 09									1	0	0	0	0	0	0	0.002	0.002	0	0	0.002	0.002	0	0	0	0	0	0	0	0	0	0
Exp 10										0	0	0	0	0	0	0.002	0.002	0	0	0.002	0.002	0	0	0	0	0	0	0	0	0	0
Exp 11											0	0	0	0.003	0	0	0	0.005	0.132	0	0	0	0	0	0	0.387	0	0	0	0.006	0
Exp 12												0	0	0	0.035	0	0	0	0	0	0	0	0	0	0	0	0.133	0	0	0	0.014
Exp 13													1	0	0	0.005	0.005	0	0	0.005	0.005	0	0	0.192	0.192	0	0	0.067	0.067	0	0
Exp 14														0	0	0.005	0.005	0	0	0.005	0.005	0	0	0.192	0.192	0	0	0.067	0.067	0	0
Exp 15															0	0	0	0.003	0.052	0	0	0.002	0	0	0	0	0	0	0	0	0
Exp 16																0	0	0	0	0	0	0	0	0	0	0	0.777	0	0	0	0.384
Exp 17																	1	0	0	0.861	0.861	0	0	0.005	0.005	0	0	0.007	0.007	0	0
Exp 18																		0	0	0.861	0.861	0	0	0.005	0.005	0	0	0.007	0.007	0	0
Exp 19																			0.03	0	0	0.002	0	0	0	0.005	0	0	0	0.008	0
Exp 20																				0	0	0.026	0	0	0	0.173	0	0	0	0.342	0
Exp 21																					1	0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 22																						0	0	0.004	0.004	0	0	0.007	0.007	0	0
Exp 23																							0	0	0	0	0	0	0	0	0
Exp 24																								0	0	0	0.001	0	0	0	0.003
Exp 25																									1	0	0	0.004	0.004	0	0
Exp 26																										0	0	0.004	0.004	0	0
Exp 27																											0	0	0	0.033	0
Exp 28																												0	0	0	0.35
Exp 29																													1	0	0
Exp 30																														0	0
Exp 31																															0

Figure C.16: Table of the p-values of the T-test of the output value ‘root.TotalLosses’