IMPLEMENTATION OF A SMART STORAGE SYSTEM FOR FRUIT QUALITY PRESERVATION

by

Raed Okba AlZuabi

A Thesis Presented to the Faculty of the
American University of Sharjah
College of Engineering
In Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Engineering Systems Management

Sharjah, United Arab Emirates

February 2021

Declaration of Authorship

I declare that this thesis is my own work and, to the best of my knowledge and belief, it does not contain material published or written by a third party, except where permission has been obtained and/or appropriately cited through full and accurate referencing.

Signed…………………………………………………………….

Date…………15/02/2021……………………………………………

Approval Signatures

We, the undersigned, approve the Master's Thesis of Raed Okba AlZuabi

Thesis Title: Implementation of a Smart Storage System for Fruit Quality Preservation

Date of Defense: 01-February-2021

Name, Title and Affiliation	Signature
Dr. Noha Mohamed Hassan Hussein Associate Professor, Department of Industrial Engineering Thesis Advisor	
Dr. Zied Bahroun Associate Professor, Department of Industrial Engineering Thesis Co-Advisor	
Dr. Mahmoud Awad Associate Professor, Department of Industrial Engineering Thesis Committee Member	
Dr. Mohammad Jaradat Professor, Department of Mechanical Engineering Thesis Committee Member	
Dr. Moncer Hariga Head Department of Industrial Engineering	
Dr. Lotfi Romdhane Associate Dean for Graduate Affairs and Research College of Engineering	
Dr. Sameer Al Asheh Interim Dean College of Engineering	
Dr. Mohamed El-Tarhuni Vice Provost for Graduate Studies Office of Graduate Studies	

Acknowledgment

All praise is due to Allah Almighty, who is the source of all knowledge in this world and whose countless bounties have enabled me to work and complete this thesis successfully.

I would like to thank my advisors Dr. Noha Hussein and Dr. Zied Bahroun for providing knowledge, guidance, support, and motivation throughout my research stages. I'm deeply beholden for their great assistance, worthy discussion, and suggestions.

I would like to also thank Mr. Wasim Almasri and Mr. Ronald Almirez of the Mechanical Engineering department and Professor Yassir Makkawi of the Chemical Engineering department for their great help and advice on various issues throughout the project. And special thanks to my colleagues Arwa Abougharib and Alaa Youssef for supporting and encouraging me throughout this project, I appreciate their dignified advice and motivation. Finally, I would like to extend my sincere appreciation to the American University of Sharjah for fully funding my master's studies throughout the duration of the graduate teaching assistantship scholarship.

Dedication

To my beloved mother, my idol and father, and my dear siblings, all this is due to your endless encouragement, love, and support. I thank you all.

Abstract

Food packaging has evolved throughout the decades from being a simple container to hold food, to being an active agent in the role of preserving the product's shelf life. However, according to the Food and Agriculture Organization, almost 1.3 billion tons of food is wasted annually due to either overbuying, overproduction, or even spoilage if left untouched. In addition, due to the increasing population growth and the continuing reduction of the world's arable lands, the need for advanced packaging systems has never been more crucial. Therefore, this research implements a cost-effective and sustainable smart fruit storage system in which active and intelligent packaging techniques are combined in order to enhance the quality of the fruits. To this end, a literature review on the negative issues affecting the quality of fruits as well as the different types of smart packaging techniques is conducted. Based on the findings from the literature, a smart fruit packaging system was designed and manufactured using thin aluminum sheets due to its conductivity and cost-effectiveness. An experimental analysis is then executed using bananas and avocadoes inside and outside the packaging system while regulating the air composition and relative humidity within the compartment using Argon and Carbon gas, as well as Potassium Chloride powder. The data collected was used to study and analyze the differences in air quality measurements using Minitab through response surface regression analysis and factorial plots, as well as the color quality of the fruits (RGB Values) through correlation. The results of both analyses indicate a reduction in fruit respiration and an increase in shelf life between the fruits inside and outside the compartment. The fruits placed inside the packaging system had their shelf life extended by at least 2 times the normal duration respectively. Finally, an economic analysis is conducted to estimate the public price of the packaging system if sold to families of 4 – 5 members, while also estimating the benefits in terms of savings over the course of 4 years. The economic analysis generated a positive Internal Rate of Return (IRR) equal to roughly 22%.

Keywords: ***Shelf life; Quality preservation; Smart packaging; Fruit quality; Regression analysis; Economic analysis.***

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

In this chapter, a brief introduction on the issues affecting the quality and shelf life of fruits will be provided, while also describing the expected outcomes of smart packaging implementation. Then, the main aim and objectives of this research proposal will be stated, in addition to the key findings and main contributions of the thesis proposal being described in detail, followed by the general organization at the end of the chapter.

1.1. Overview

Food wastage is one of the many issues being battled nowadays by countries, food supply chain industries, and even households. According to the Food and Agriculture Organization of the United Nations, it is estimated that almost one-third of the food produced globally for human consumption is either being lost or wasted [1]. Besides, households play a major role in contributing to these losses especially when 50% of their waste is fresh fruits and vegetables [2]. Moreover, with the continued reduction of the worlds' arable lands due to erosion or pollution, as well as the increased population growth over the past few decades, these losses will only get worse.

According to the ReFED, US household members waste around 76 billion pounds of food per year due to improper storage, lack of visibility in refrigerators, and misjudged food needs, and in which fresh fruits and vegetables account for the largest losses (19% for fruits & 22% for vegetables) [3]. In addition, according to the U.S. Environmental Protection Agency, 40–50% of food waste comes from everyday consumers while 50-60% from businesses, in which food has become the largest single source of waste in the U.S.; filling landfills more than plastic and paper [4]. There are many issues causing fruit wastage in consumer households (refrigerated or not), and these issues affect not only the quality and freshness of the fruits but also their shelf life, especially in terms of improper storage. These issues vary from adding different fruits with different spoilage rates, temperature ranges, and even air composition together, causing the quality and shelf life of the fruits to deteriorate. Terms such as smart packaging, active packaging, and even intelligent packaging have emerged over the past few decades, and have been used many times in literature [5]. Smart packaging is introduced as the combination of both active and intelligent packaging, where it can sustain a product’s quality and prolong its shelf life (active), while also monitoring the conditions of the product (intelligent). Active packaging concepts that can be used to preserve the quality of fruits can vary from using oxygen, Carbon, and ethylene scavengers and emitters, to moisture regulators as well as antioxidant releasers, while intelligent packaging concepts such as using time-temperature indicators and ethylene sensors; can be used to help monitor the quality deterioration [6].

By implementing a smart packaging storage system for fruits in consumer households as well as different sectors of the supply chain (cooling warehouses, refrigeration trucks), the outcomes would result in not only preserving the quality and freshness of the fruits but also prolonging their shelf life. These results can be accomplished by using gas flushing of different air compositions of Carbon, Oxygen, and Argon depending on the fruit being stored, while also using a type of humidity control sachet to control the moisture with the packaged environment. Also, the air composition will be monitored using different sensors, as well as air quality sensors to monitor the quality of the air surrounding the fruits.

1.2. Thesis Objectives

Driven by the developing interest in the many benefits of active and intelligent packaging in the areas of fruit wastage in consumer households as well as different sectors of the fruit supply chain. This research aims to create and implement a cost-effective and sustainable smart storage system for fruits, in order to preserve not only their quality but also to prolong their shelf life. Besides, statistical analysis in terms of regression and correlation will be performed in order to test the variability between the independent and dependent variables within the system, while also performing an economic analysis in the form of household members; by implementing and calculating the costs and benefits, as well as the rate of return.

1.3. Research Contribution

- Create and implement a cost-effective and sustainable fruit storage system by combining different active and intelligent packaging techniques for maximum quality and efficiency.

- Active packaging techniques will help enhance the quality and shelf life of different fruits by implementing different gas flushing techniques depending on the type of fruit, as well as humidity control sachets for moisture control.
- Intelligent packaging techniques will aid in monitoring the quality of the fruits by using different sensors varying from Carbon and Oxygen sensors within the compartments, while also using an air quality sensor for fruit spoilage indication.

1.4. Thesis Organization

The rest of the thesis report is organized as follows: Chapter 2 provides a background and a literature review on the negative issues affecting the quality of fruits, followed by the different types of smart packaging techniques that can be used for fruit quality preservation. The methodology and structure of the smart fruit storage system in terms of design, manufacturing, and testing is explained in detail in Chapter 3. In addition, Chapter 4 contains the statistical analysis performed to analyze the difference in air quality measurements both inside and outside the packaging system using Minitab. Moreover, an economic analysis is conducted in Chapter 5 to estimate the price of the packaging system as well as the benefits in terms of savings. Lastly, Chapter 6 helps summarize and conclude the main findings and results acquired from the previous chapters.

Chapter 2. Background and Literature Review

In this chapter, we present multiple different issues that are negatively affecting the quality and shelf life of fruits, followed by the current best solutions used to preserve the quality of the fruits. Also, the definition and fundamentals of smart packaging are discussed in detail, followed by the basics of both active and intelligent packaging, as well as the different methods used to monitor and preserve the quality of fruits for each of the packaging techniques.

2.1. Adverse Issues Affecting Fruit Quality

It is extremely necessary to properly store fresh fruits within consumer households as well as throughout the supply chain, in order to maintain and preserve their quality, prevent spoilage, and ensure the best value for the money being spent. However, there are many factors that negatively affect the quality and shelf life of fruits, such as different storage requirements (Temperature & Humidity), different air compositions, and even the type of containers they are placed in, as well as their location.

2.1.1. Temperature and humidity. In order to maintain and preserve the quality and shelf life of fruits, each fruit needs to be handled and stored at a specific temperature requirement. Temperature management during storage is one of the most important factors in reducing fruit quality deterioration, due to the fact that increasing the temperature for certain fruits above a certain limit can result in higher respiration rates as well as shorter storage periods [7]. In addition, by lowering the temperature for certain fruits within their temperature requirement ranges, effects such as ethylene production can be suppressed, while also slowing down microbial development [8]. Also, humidity control within a package plays a major role in preserving the quality of fruits since most fruits require a specific humidity range to maintain their highest quality. Therefore, applying humidity absorption films and sachets would only keep reducing the humidity within the package affecting texture and color, however, by applying different compounds such as KCl and sorbitol in sachets within the package, it is possible to control the humidity within specific ranges [9]. As a result of these effects, the storage life and quality of fruits are prolonged and preserved. Table 1 helps show the different storage conditions for some fruits in terms of temperature range, relative humidity, and even ideal storage time if the conditions were optimum.

Table 1 Optimum Storage Conditions for multiple Fruits [8].

Fruits	Temp. Range (°C)	R. Humidity (%)	Storage Time
Apple	-1 -- 4.5	90 - 95	4 - 32 weeks
Apricot	-0.5 -- 0	85 - 95	1- 3 weeks
Avocado	4.5 -- 13	90 - 95	2 - 4 weeks
Banana	13.5 -- 15	85 -95	4 - 21 days
Cherry	-1 -- 0	90 - 95	3 - 7 days
Grapes	-1 -- 0	85 -95	12 - 24 weeks
Guava	7 -- 10	90	2 - 3 weeks
Lemon	0 -- 5	85 - 90	2 - 3 weeks
Mango	10 -- 13	85 - 90	2 - 3 weeks
Orange	0 -- 9	85 - 90	3 - 16 weeks
Passionfruit	7	90 - 95	2 - 5 weeks
Peach	-0.5 -- 0	85 - 95	2 - 6 weeks
Pineapple	5 -- 7	85 - 90	2 - 4 weeks
Raspberry	-0.5 -- 0	90 - 100	2 - 3 days
Strawberry	-0.5 -- 0	85 - 90	5 - 14 days
Tangerine	0 -- 3.5	85 - 90	2 - 4 weeks

2.1.2. Air composition. Another important factor that plays a major role in the preservation of quality of fruits in storage; is the gas composition surrounding its atmosphere. Multiple fruits require different gas composition ratios of Oxygen and Carbon in order to maintain maximum quality, however, the normal air composition consists of (20.95% Oxygen, 78.09% N_2, 0.93% argon, and 0.038% Carbon), which is not suitable for preserving the quality and shelf life of most fruits. Furthermore, by lowering Oxygen levels and increasing the Carbon composition surrounding the fruits, the respiration rate, as well as the metabolic rate of the fruits, reduces, which in effect extends their shelf life [10]. Table 2 helps show the recommended atmospheric gas composition ratios of Oxygen and Carbon, as well as the recommended temperature ranges needed to prolong the shelf life of multiple different fruits.

Table 2 Recommended Atmospheric Conditions of Multiple fruits [11].

Fruits	Temp. Range (°C)	Oxygen (%)	Carbon (%)
Apple	0 -- 5	2 - 3	1 - 5
Apricot	0 -- 5	10 - 12	8 - 11
Avocado	5 -- 13	2 - 5	2 - 5
Banana	12 -- 15	2 - 5	2 - 5
Kiwi	0 -- 5	2	5
Mango	10 -- 15	5	5
Pineapple	10 -- 15	5	10
Strawberry	0 -- 5	10	15 - 20

2.1.3. Fruit placement. A major factor that plays a huge role in preserving the quality of fruits and prolonging their shelf life; is the placement of different fruits together. Ethylene is an odorless gas released by fruits as time progresses, causing respiration in the fruit to accelerate, and resulting in the softening and ripening of multiple different kinds of fruits [12]. However, some fruits are extremely high ethylene producers, while others are very sensitive to gas. By adding multiple different kinds of fruits together, some fruits can accelerate the ripening of others, resulting in the deterioration and degradation of their quality. Figure 1 below helps show the list of high ethylene producing fruits in contrast to fruits that are sensitive to high ethylene productions, which as a result end up speeding their respiration rates.

Even though many factors negatively affect the quality and shelf life of fruits, many current practices are being implemented in households and supply chains that help negate these negative effects and aid in preserving the maximum quality for fruits.

Figure 1: High Producing Ethylene Fruits VS Ethylene Sensitive Fruits [13]

2.2. Fruit Quality Current Best Practices

The consumption and request for fresh-cut fruits have increased exponentially over the past few decades, mainly due to the demand for low-calorie products, and the customers' desire for healthier choices, however, as a result of poor product manipulation and storage conditions, the risk of fruit spoilage and quality degradation increases. One of the many current best practices used nowadays in the supply chain and households to preserve fruit quality is the use of refrigeration and low temperatures during storage. By reducing the temperatures surrounding the fruits, the respiration rates drop exceedingly, which as a result reduces the deterioration rate of quality for fruits. However, temperatures that are too low can be as much damaging as temperatures that are too high. By reducing the temperature low enough to reach the fruits' freezing point, effects such as loss of rigidity, softening, and the ability to soak water ensues, which as a result shortens the life of the fruit [14].

Another method used nowadays to prolong the shelf life of fruits is by scrubbing or peeling the fruit before storage. These preparation steps are implemented in order to remove any microbial organisms or bacteria covering the fruit before they are being stored, however, by removing the natural protection surrounding the fruit, it allows them to become more susceptible to desiccation and wilting, as well as internal issues such as microbes [15]. Furthermore, another common practice used in households to separate different fruits from each other, to reduce spoilage rates caused by high ethylene production fruits, is by using plastic bags. However, plastics are synthetically manufactured by combining different types of chemicals, such as bisphenol A and phthalates, which can easily leach into fruits [16]. Studies show that these chemicals can cause tissue and hormonal changes, which can negatively affect the shelf life of fruits. In addition, plastics bags have a high chance of tearing while being shifted around in the refrigerator, which can expose fruits to the air, and create the conditions needed for the spread and growth of bacteria [13]. Furthermore, at different stages of the cold supply chain such as cooling warehouses and refrigeration trucks, most fruits are refrigerated in the open air while being placed in either crates or box containers. This affects the deterioration rate of the fruits negatively since fruits need to be within a controlled atmosphere of specified composition; depending on the type of fruit, thus, increasing ethylene and Carbon production by the fruits [15].

2.3. Packaging Techniques

The consumption and request for fresh-cut fruits and vegetables from all around the globe have never been higher, and this in effect causes massive pressure on companies to prioritize on maintaining the maximum quality for their fruits from farm to table. Hence, paving the way to the creation of multiple different packaging techniques being implemented in order to prolong the shelf life of fruits, and this may vary from traditional to smart techniques.

2.3.1. Traditional packaging techniques. Traditional packaging techniques used in households and retailers vary such as plastic films as they are used to limit the oxygen intake of fruits to reduce their respiration, while also using water-absorbing plates to reduce moisture and hence, the fruit's spoilage rate. However, plastic films have multiple disadvantages such as the amount of oxygen they can cut off from the fruits as well as their negative impact on the environment. Additionally, the use of water-absorbing plates can also have harmful effects on the fruit if used for too long since they can negatively impact not only the flavor of the fruit but also its texture [16]. All in all, these current best practices are not sufficient in maintaining the quality and shelf life of fruits in households and along the supply chain, however, by applying and implementing new smart packaging technologies, it is possible to achieve and maintain the maximum quality for fruits within storage for longer periods.

2.3.2. Active packaging techniques. Due to the continuous changes in consumer demand as well as market trends and tastes over the past few decades, a new advanced food packaging concept was created in order to act as a response, and that is Active packaging. The techniques involved in active packaging can vary from substances that can absorb oxygen, ethylene, Carbon dioxide, and moisture to substances that can release antioxidants, antimicrobials, and even flavors.

In the past few years, multiple food packaging concepts were introduced in order to counter multiple issues being faced nowadays, such as the increases in consumer demand for well-preserved foods, new online trends such as (online shopping), and even globalization of markets; which resulted in longer storage times as well as farther distribution distances. Not only that but also due to the different variety of products being distributed, different temperature requirements had to be taken into consideration as well as different air compositions. Therefore, active packaging was introduced to not only prolong the shelf life of different products but also to improve the safety and sensory properties of the packaging itself, while maintaining the quality of the product.

2.3.2.1 Oxygen – Scavenging Technology. In many cases, fruit deterioration is caused by oxidization due to the presence of Oxygen. One of the many solutions used for removing oxygen from packages containing Oxygen sensitive food is the implementation of Modified Atmosphere Packaging (MAP) or vacuum packaging for short, however, this technology is not able to completely remove all of the oxygen. Besides, the oxygen permeating through the plastic films cannot be removed by (MAP). Therefore, by using an Oxygen – scavenger within the package itself, residual oxygen is absorbed, resulting in lower quality changes within the food [17]. In general, existing Oxygen-scavenging technologies utilize many concepts and methods, however, iron powder oxidation is the most widely used method nowadays [18]. However, there is a high potential hazard in implementing these sachets; which can be caused by any accidental consumption.

Another method used to minimize the quality changes in the product while being packaged, is the incorporation of oxygen scavengers within the packaging itself, hence the plastic films or sachets. However, what is important to note is that the speed and capacity of oxygen scavenger sachets are much higher compared to the oxygen scavenger films as well as much cheaper [19]. Oxygen-scavengers have multiple benefits and influences on fruit properties, starting with the prevention of the growth of molds and aerobic bacteria. In addition, Oxygen-scavengers can also eliminate any need for chemical usage; since they can be used to control insect infestation within the packaged product itself, and this can be done through MAP and even gas flushing where the gas composition within the package is controlled depending on the type of fruit. This can be achieved by flushing nitrogen or argon gas to exclude the oxygen within the package, hence reducing the oxygen composition in the packages' atmosphere.

2.3.2.2 Ethylene (C2H4) Scavengers. Ethylene acts as a plant hormone that can accelerate the respiration in fruits and vegetables, thus leading to maturing and causing ripening of many kinds of fruit. Furthermore, multiple post-harvest disorders, as well as the yellowing of vegetables, are caused by ethylene accumulation, and therefore, it is detrimental to the shelf life and quality of fruits and vegetables.

Many suppliers nowadays offer ethylene scavengers in either sachets or integrated into plastic films. The most commonly used method is the usage of potassium permanganate, which oxidizes ethylene to acetate and ethanol. In this process, the remaining ethylene left within the package can be indicated by the change of color from purple to brown [20]. However, potassium permanganate is toxic if it comes in contact with food, thus they are only supplied in sachets. Moreover, ethylene scavengers are not yet very successful as a result of their insufficient adsorbing capacity, and hence enormous amounts of fruits and vegetables are lost yearly [21].

2.3.2.3 Carbon Scavengers and Emitters. Carbon is sometimes formed in food due to deterioration and respiration reactions, which if not removed from the package can cause food deterioration and/or package destruction. Carbon-absorbers might, therefore, be useful. A good example is coffee when roasted, can contain up to 15 atm. The Oxygen and Carbon-scavenging sachet FreshLock1 or Ageless1 as seen in Figure 2 are used in coffee to delay oxidative flavor changes and absorb the occluded Carbon, which if not removed would cause the package to burst [22].

Figure 2: Ageless 1 Oxygen Scavenger Sachet [19]

In some cases, however, poultry, fish, and even cheese can benefit from packaging with high Carbon levels. It is advantageous because the high levels of Carbon can hinder the surfacing of microbial growth, and therefore, levels between 10% - 80% are desirable [17]. Also, multiple fruits require a certain percentage range of Carbon depending on the type of fruit, which can help maintain their maximum quality if kept within range as seen in Table 2.

2.3.2.4 Moisture regulators. Many products nowadays are vulnerable to moisture damage, and therefore need to be packaged using strong humidity barrier films. However, moisture can seep into the package during distribution, be trapped during packaging, or even when a refrigerator door opens, which can result in the product absorbing the humidity and creating spoilage. A huge issue being faced today is in the regulation of moisture within the packaged product itself. If the film or sachet is of low quality, high levels of water will be absorbed by the product resulting in softening, examples include crackers, crisps, and even instant coffee. And if the film or sachet absorbs too much moisture, dryness within the packaged product will occur and cause oxidation [23]. Therefore, to prevent these issues from occurring, a moisture-controlling sachet is needed.

The applications of these moisture regulators are used in almost all food industries, varying from cheese, meats, chips, spices, and even fruits. By applying these regulators through a film or a sachet, the results can lead to a reduction in the growth of molds, bacteria, and even yeast [24]. In addition, the use of different powder compounds such as potassium chloride, xylitol, and even sorbitol within sachets can help regulate and control the humidity within a package, hence prolonging the shelf life of the fruit [25].

2.3.3. Intelligent packaging techniques.

Traditional packaging in supply chains for decades included multiple functions such as protection, containment, ease-of-transport, and convenience, however, with the rise of customer demands for products with higher quality and shelf life, additional changes had to be made. Now by monitoring the changes and conditions in the packages as they are being transported from one place to another, certain parameters such as product quality and shelf life can be estimated and optimized, and hence, the idea of intelligent packaging was created.

The main purpose of intelligent packaging is to monitor the condition of the product, or even the environment surrounding the product. Intelligent packaging is also capable of many functions such as sensing, detecting, recording, and even communicating information about the condition or quality of the product during any stage of the supply chain [1]. In addition, the package would not only provide information and data on the product itself, but also the history of the product throughout the supply chain, such as any microbial growth, leaks in gases, or even changes in temperatures within the package. The intelligent part of the concept can be obtained by applying either indicators, sensors, or even biosensors. Indicators can help detect any changes that might occur within the package such as any temperature changes or any leaks, by using visual changes in color through either time-temperature indicators, freshness indicators, or even integrity indicators [5]. Biosensors, however, are devices mainly used to sense, detect, and communicate any information regarding any sudden changes in terms of biological reactions occurring within the package [26]. This section will provide details on multiple intelligent packaging concepts used nowadays, as well as their commercial applications.

2.3.3.1 Time-temperature indicators.

Temperature is one of the biggest environmental factors affecting the quality and shelf life of perishable products, and thus any changes or variations in it can negatively affect not only the quality but also the safety of the product. Therefore, by applying TTIs within each package, time and temperature are monitored throughout the entire supply chain, especially in frozen and chilled products such as fruits and vegetables [27]. In addition, TTIs can also aid in discovering any disruptions occurring within a cold supply chain, as well as continuously monitoring any changes in storage conditions while the packages are being held in warehouses.

One example of TTIs being implemented nowadays is the “3M Monitor Mark” (3M Company), which contains a fatty acid ester mixed with a blue dye at a certain melting point.

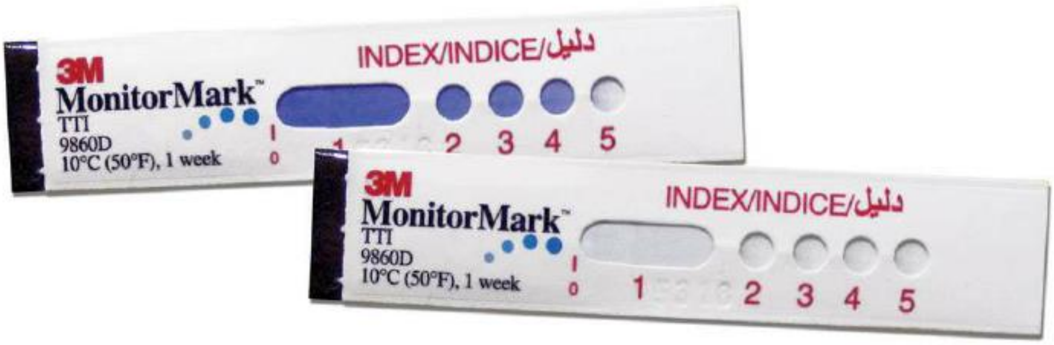

Figure 3: 3M Monitor Mark (TTI) [26]

Whenever there is a change in temperature exceeding the melting point, the ester melts and diffuses through the indicator causing a blue color to show. The response life of the TTIs and the range of temperatures used for the melting point; are both determined by the concentration and type of the ester; therefore, it can be used for multiple products with different temperature ranges [28].

2.3.3.2 Freshness indicators. Freshness indicators are basically a concept based on monitoring any changes in terms of microbial growth or metabolism occurring on the food itself by reacting to it, and thus can help provide accurate data on the quality and freshness of the product [29]. Chemical changes occurring in specific foods such as poultry or fruits while they are being in storage, in general, are good indicators of freshness and quality. These chemical changes vary based on the type of metabolite as well as concentration, and can include Carbon, glucose, ethylene, sulfuric compounds, and even microbial growth, and thus can be used as freshness indicators [30].

There are two ways in which product freshness can be monitored, one is by using freshness indicators which work based on changes in metabolites through color changes such as pH or ethylene, which both are produced by fruits, poultry, and fish as their quality starts to deteriorate. An example of a freshness indicator would be “UPM Raftalac Indicators” (Raftalac Ltd.), which is used for poultry and meat products, and uses a Nano-layer of silver which is opaque brown at the beginning of the packaging, however, when it comes in contact with hydrogen sulfide after a while, the layer is then changed to transparent [29]. As for the other method used for monitoring product freshness, that would be biosensors. Biosensors are much more specific in their monitoring of food freshness since they can target specific metabolites, as well as to detect any form of degradation in a product. An example of a biosensor would be Toxin Guard (Toxin Alert Inc.), which is based on the idea of incorporating antibodies into plastic films as a diagnostic system [5].

2.3.3.3 Integrity indicators. There are multiple types of integrity indicators being implemented nowadays in most packaged foods, and most of them consist of time indicators and gas indicators. Time indicators are the simplest type of integrity indicators in which they only provide information on how long a package has been opened. In addition, the mechanism works by a label that is activated only when the package is opened and experiences a color change with time while a timer is running [31].

As for gas indicators, they are the most commonly used integrity indicators in packaged products including poultry, fish, as well as fruits, and vegetables. These indicators are used as leak detectors for packages throughout the entire supply chain, and the most common one used is the oxygen indicator in (MAP) packaging applications [5]. The main reason is that the atmosphere in a meat or fish MAP package consists of a residual concentration of oxygen of less than 1%, thus making it easy for oxygen indicators such as (colorimetric redox eye) to detect any leaks of air coming in or out of the package, by changing its color, which is also applied to fruits as they need to be within a specific oxygen range depending on the type of fruit, and this can be seen in Figure 4. Also, these indicators can be used to detect changes in Carbon compositions within a package, allowing the customer the ability to manipulate the chemical compositions depending on the type of fruit, as well as monitor them. In conclusion, by applying several active packaging techniques such as gas flushing and compound sachets, with the addition of intelligent packaging techniques such as Oxygen, Carbon, and humidity sensors, it is more than possible to create and implement a sustainable and cost-effective fruit storage system to not only preserve and maintain the quality of multiple fruits but also to extend their shelf life.

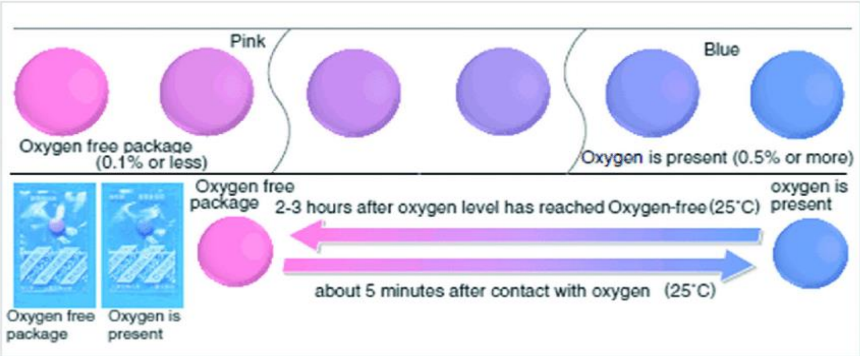

Figure 4: Colorimetric Redox Eye Oxygen Indicator [29]

2.3.4. Smart packaging techniques. Traditional packaging's main purpose is to help protect products from deteriorative effects that might negatively affect their quality, however, due to the increasing customers' expectations as well as product complexity in the past few decades, a new type of packaging technology was introduced. Smart packaging provides a total packaging solution that on the one hand monitors changes in a product or its environment (intelligent), and on the other hand acts upon these changes (active) [26]. The exact functionalities of specific smart packaging solutions vary and depend on the actual product being packaged, such as different types of food, beverages, pharmaceuticals, and even health and household products. Therefore, any system or package that actively helps in maintaining the quality of fruits while also monitoring them, is a smart package.

Chapter 3. Methodology

In this chapter, the methodology for the complete Smart Fruit Storage System will be explained in detail through steps underlining the process from start to finish as illustrated in Figure 5.

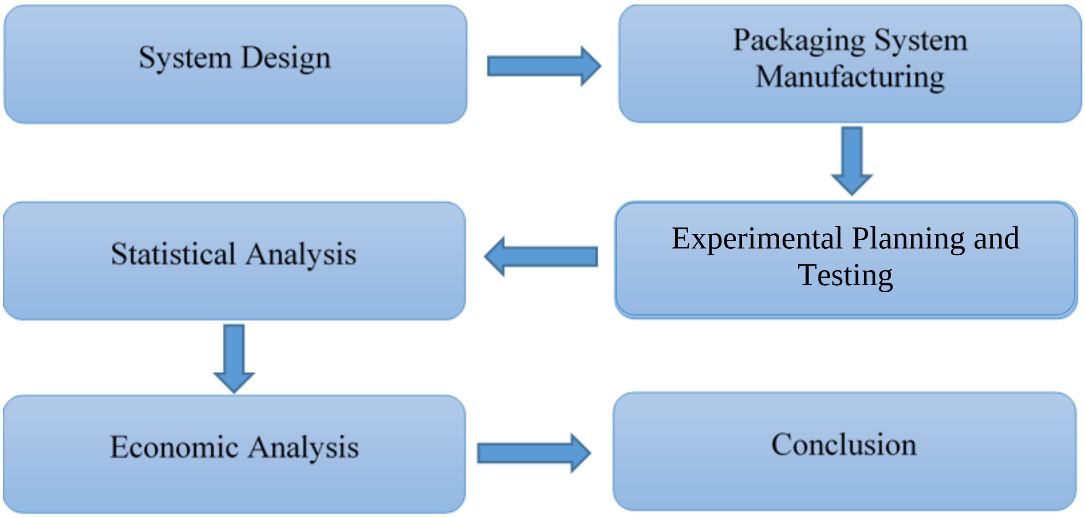

Figure 5: Methodology Flow Chart

As seen in Figure 5, the process will start with the system design, followed by the manufacturing of the compartment. The proposed system will then be tested for two different types of fruits (Bananas & Avocadoes) inside the compartment and outside, in order to determine the effects of the air composition and relative humidity regulation on the quality and shelf life of the fruit. This will be followed by analyzing the results from the experimental planning and testing stage to check the technical feasibility of the system in terms of elongating the life of the fruit. Subsequently, an economic analysis will be conducted to estimate the public price of the packaging system while also estimating the benefits in terms of savings over 4 years, followed by a conclusion of the main findings and results of the final system.

3.1. System Design

In this chapter, the need for product will be discussed in detail in terms of its main objectives and their importance, followed by a market survey explaining the main findings from the literature review and their relevance. Moreover, the system requirements for the packaging compartment will be specified and explained individually, followed by a detailed depiction of the packaging designs in the form of multiple alternatives and sketches, as well as the process and constraints.

3.1.1. Need for product. The FSS is a cheap & sustainable smart packaging system created to preserve the quality of fruits, while also prolonging their shelf life throughout consumer households. This is performed by implementing and combining multiple active and intelligent packaging techniques into one system, in which the active techniques include both gas flushing of Argon and Carbon, as well as KCl powder for regulating the humidity, while the intelligent techniques include the monitoring of not only the Oxygen, Carbon, and RH, but also the air quality. The air quality here is an indicator of the deterioration state of the fruit, where the sensor serves to detect and measure the concentration of gas in the environment, therefore, as the fruit deteriorates with time and produces natural gas, the percentage values of the air quality sensor increase as well [32]. By helping to regulate the air composition and humidity within the compartment, it is possible to extend and prolong the shelf life of the fruit, in order to counter the worldwide problem of food wastage and greenhouse gas emissions in landfills.

3.1.2. Market survey. Based on the literature review that was conducted on smart packaging techniques and consumer behaviors towards fruits, we discovered that each fruit differs from the other in terms of having an optimum air composition range in the form of Oxygen and Carbon. Additionally, each fruit also has an optimum relative humidity range which also differs from one fruit to another as seen in Tables 2.1.1 and 2.1.2. Using these findings, regulating the air composition and humidity within the compartment is plausible and can be executed depending on the type of fruit to within its optimum range, which will be monitored and controlled via sensors. Furthermore, according to the ReFED, US household members waste around 76 billion pounds of food per year, where fresh fruits and vegetables account for the largest losses (19% for fruits & 22% for vegetables) [3], which can help in determining the amount of savings in terms of the economic analysis that will be performed later in the report.

3.1.3. System requirements. Multiple requirements need to be taken into consideration before actually creating and manufacturing the packaging compartment. Table 3 will exhibit each requirement with a brief description needed to help satisfy the storage system's constraints in order to achieve the aim of this project. Each requirement will be discussed in more detail following the descriptions explained in Table 3.

Table 3 Each requirement with its description.

Requirements	**Req. Description**
Dimensions	The storage system needs to be within constrained dimensions to fit comfortably inside a refrigerator. Therefore, the storage compartment must not exceed the dimensions of the refrigerator cubicle.
Weight	The weight of the storage system must be light so it can be easily lifted in and out of the refrigerator within households, and also not add too much stress onto the shelf it will be placed on
Power	The power source used needs to have enough voltage to power not only the sensors within the compartment but also the valves and valve relays.
Durability	The storage system needs to be durable in order to withstand any minor damage or hard-wear, as well as have a long life span,
Corrosiveness	For the system not to gradually lose quality with time and also maintain maximum conditions for the fruits being placed inside, corrosion needs to be taken into consideration,
Traceability	Since the storage system will be applied within households; traceability will not be considered.
Visibility	In order to keep an eye on the conditions of the fruit while also monitoring its quality and color, one side of the compartment needs to be transparent or see-through.
Budget	The storage system must be cost-effective for household members to purchase it and use it in the long term.

Now in terms of the 3 main requirements that are needed to achieve our aim and objectives; the dimensions. weight and budget have to be specified in detail. The packaging compartment needs to fit with ease into a refrigerator cubicle, therefore, taking into consideration the average dimensions of a refrigerator cubicle, the length, width, and height of the compartment have to be constrained to the length being less than 45cm, the width less than 60cm, and the height being less than 20cm. The weight of the compartment must also not add too much stress onto the shelf it is placed on, hence, by taking into account the density of the material at which the compartment is made, the weight of the gas cylinders, and other factors, the maximum weight should not exceed 15kg. As for the budget, the total system must be cost-efficient and cheap for the consumer to buy and use for a long time, therefore, by taking into account the costs of the manufacturing, materials, and parts, the total system should not exceed 300$ or 1000 AED. Dimensions, weight, and budget are mapped in detail as illustrated in Table 4.

Table 4: Requirement Specification Mapping

Requirements	**Specifications**
Dimensions	Max Length = 45cm > (Fruit Compartment L = Gas Cylinder Compartment L = Power Compartment L)
	Max Width = 60cm > (Fruit Comp. W + Gas Cylinder Comp. W + Power Comp. W)
	Max Height = 20cm > (Fruit Compartment H = Gas Cylinder Compartment H = Power Compartment H)
Weight	Max Weight 15kg > (Density of Aluminum for Fruit Comp.) + (Gas Cylinder Sizes [litres]) + (Weight*# of fruits) + (Battery size + valves + servo-motor)
Budget	Max Budget [100-300] > (Prices of Valves & Relays) + (Price of Carbon & Argon Cylinders) + (Price of Battery + Controller) + (Gas and Humidity Sensors) + (KCL Powder)

As for other requirements that play a major role in prolonging the life of the packaging compartment, durability and corrosiveness are key players. The material that needs to be used to make the compartment needs to be conductive and able to withstand hard-wear, in addition, the material also needs to be corrosion resistant to help reduce any changes not only in the physical appearance but also in the chemical properties. Therefore, aluminum is the material used to make the packaging compartment since not only is it naturally corrosion-resistant, but it is also durable and approximately 1/3 the weight of steel, hence, it can be made thicker and stronger while still reducing the weight of the compartment. Moreover, to help solve the visibility issue in order to monitor the conditions of the fruit, plexiglass will be used not only for its transparency but also for its durability and protection against erosion. As for the power requirement, two power sources will be needed to power the sensors and controller board, as well as the valves and valve relays. The controller board which will power the sensors will be either powered by the laptop in which the program is run or possibly by a power charger since both the control board and sensors do not require a high voltage. As for the valves, since they require a higher voltage, will be driven by either a large battery or a power adaptor connected to a plug or wall.

3.1.4. Packaging design and process. Before the start of rough sketches for different storage compartments designs, multiple requirements in terms of dimensions, weight, and price have to be constrained, in addition to deciding on the type of controller.

3.1.4.1 Constraints. Firstly, the entire storage compartment must have the ability to be used with all types of fruits, hence, the dimensions of the compartment should be able to fit with ease into a refrigerator for any types of fruits that need to be refrigerated if experimented with, and that can be seen in Table 5.

Hence, the maximum dimensions for the entire storage system must not exceed 45cm in length, 60cm in width, and a height of 20cm. Also, the volume in liters for the gas cylinders needed was calculated by using the maximum height and diameter for each cylinder, and therefore, must not exceed 4 liters. In addition, taking into consideration the maximum weight the refrigerator shelf used in the experiment can handle, the whole storage system including the fruits must not exceed 15kg.

One of the aims of this project is to create a cost-effective system, therefore, the cost of the controller will be taken into consideration, and which will vary between either a PLC controller or an Arduino. Arduino microcontrollers are much cheaper than a PLC controller; while also having a common IDE that is easy to use, as well as an open-access software system allowing it to merge with prevailing programming language libraries in contrast to PLCs [33].

Table 5: Maximum Compartment Dimensions

	Compartment Dimensions				
Main Fruit Compartment	Length	Width	Height	Diameter	Litres
	45cm	30cm	20cm	-	-
Cylinder Compartment	Length	Width	Height	Diameter	Litres
	45cm	20cm	20cm	-	-
Power Compartment	Length	Width	Height	Diameter	Litres
	45cm	10cm	20cm	-	-
Gas Cylinders	Length	Width	Height	Diameter	Litres
	-	-	20cm	20cm	2-4 litres

Additionally, even though PLCs are more robust and can withstand extreme environmental conditions, Arduino is easier to use due to its simple programming language, and can directly load programs into the device without the need to burn the program [34]. Therefore, based on the points stated above, the type of controller that will be used to control all the components within the storage system will be an Arduino micro-controller instead of a PLC.

Moreover, an important requirement to be taken into consideration for the experiment is the power specifications for each of the components playing a part in the monitoring and regulating of the air composition and humidity surrounding the fruits. The main power source that will be used to perform these experiments and power the valves will be a power adapter that can convert the 220V in the wall of the manufacturing lab into 12V DC, therefore, the power requirements for each of the components must not exceed 12V, as shown in Table 6.

Table 6: Component Power Requirements

Compartment Power Outputs	
Oxygen Sensor	Voltage 0 - 5V
Carbon Sensor	Voltage 0 - 5V
Humidity Sensor	Voltage 0 - 5V
Air Quality Sensor	Voltage 0 - 5V
Valves	Voltage DC 12V
Valve Relay	Voltage 5V
Arduino UNO R3	Voltage 0 - 5V

Also, the sensor voltages are all analog and should not exceed 5V in order to be powered by the Arduino board connected to a 9V DC battery. Additionally, the electric solenoid valves connected to each gas cylinder used in the experiment as well as the exit valve must not exceed 12 volts. The valve relays which will act as middlemen between the solenoid valves and the main controller board must not also exceed 5 volts.

3.1.4.2 Design process. A rough sketch depicting the design process is illustrated in Figure 6, after which a detailed explanation will be given on the process from start to finish. In terms of regulating the Oxygen and Carbon, the staging process starts when the fruits are added into the fruit storage compartment, once the compartment is closed and sealed tight, the program code is run and the Arduino board will activate the valves connected between the compartment and gas cylinders to open.

Firstly, the oxygen sensor will monitor and check the oxygen value inside the compartment, if it is above the optimum range for that specific fruit as stated in Table 2.1.2, it sends a signal to the valve relay connected to both Argon and exit valves via the Arduino board, and opens both simultaneously.

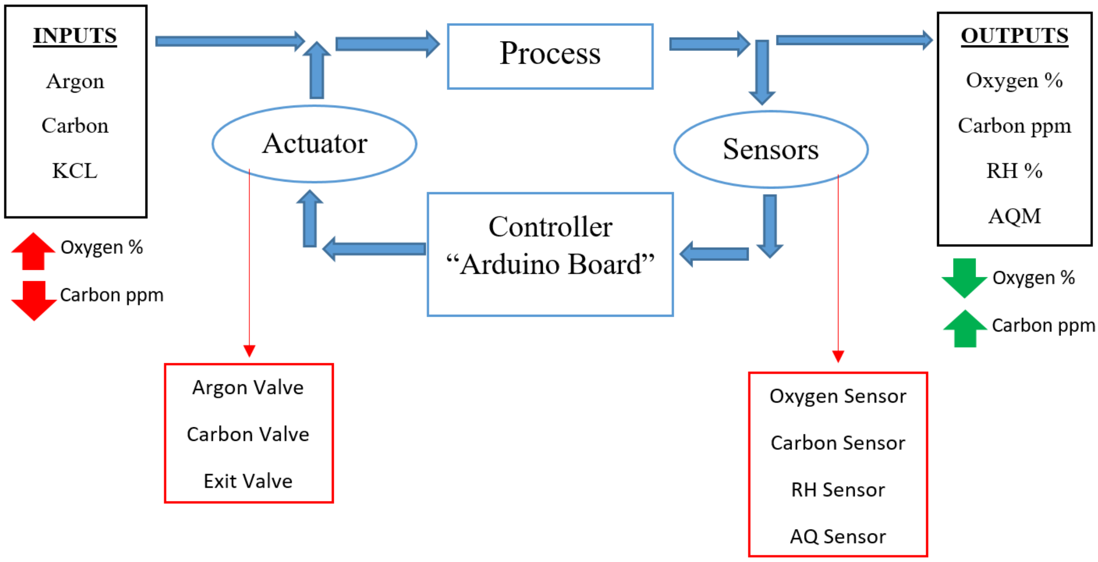

Figure 6: Rough sketch for the Design Process

Once the oxygen values drop to that range, the oxygen sensor sends a signal to the valve relay to close both valves via the Arduino board and hands the mantle to the Carbon sensor. Moreover, if the Carbon values are below that range, the sensor also sends a signal to the valve relay to open the Carbon valve to help flush Carbon gas inside, and once the values rise to that specific range, the valve is closed and the atmosphere within the compartment reaches EMA (Equilibrium Modified Atmosphere) with equilibrated Carbon and oxygen levels, and which varies depending on the type of fruit, hence, the process stage would be complete. Also, an air quality sensor will be collecting data from inside the compartment throughout the experiments and saving them in the form of (AQM) or air quality measurements.

As for regulating the relative humidity or moisture within the system, this helps play a major role in preserving and extending the quality of fruits, as well as prolonging their shelf life, however, fruits, in general, need to be kept within a specific humidity range in order to maintain its maximum quality, and this can differ depending on the type of fruit. Therefore, regulating the humidity within the compartment is the key to maintaining fruit quality. For this project, KCl powder is used in both experiments to help regulate humidity within a specific range depending on the type of fruit as seen in Table 2.1.1. This experiment will be done in the form of trial and error, once with an amount of 25g while the other being 50g. The amount that helps regulate the humidity within the compartment to that preferred range for that specific fruit, will be used in the conducting experiments stage to help extend and prolong the shelf life of the fruits.

3.1.4.3 Packaging design. The preliminary design is based on a stage process in which the system helps achieve and maintain EMA (Equilibrium Modified Atmosphere) throughout the entire progression, and in which the EMA differs based on the type of fruit. Also, the main purpose of this system is to help reduce oxygen and increase Carbon levels within the compartment, since the normal air composition consists of very high oxygen and very low Carbon stats, as well as to help regulate the humidity to an optimum range depending on the type of fruit. In addition, reducing the Oxygen and increasing the Carbon is considered the first stage of the process, moreover, as the experiment goes on over the course of weeks, Carbon levels will increase beyond the optimal levels while Oxygen levels drop, mainly because fruits taking in Oxygen and produce Carbon with time. Therefore, getting the Carbon and Oxygen levels back to their optimal ranges is considered the second stage. Based on the requirements and constraints mentioned in the previous sections, multiple alternatives were created in order to achieve EMA throughout the experiment in both stages, however, many were discarded due to violating either the technical or the economical requirements at which they will be discussed in detail.

3.1.4.3.1 Alternative #1. The first alternative that was proposed for the system is the addition of an oxygen tank. If the experiments are done over the course of weeks, the Carbon levels within the compartment will rise above the optimal range while Oxygen levels drop due to fruits taking in Oxygen and producing Carbon with time, therefore, the exit solenoid valve on the side of the compartment will open, allowing the Carbon levels to reduce until they are back to normal range. This will be monitored by a Carbon sensor, which in turn contacts the Arduino board to close off the valve. The only issue left is the low oxygen levels within the compartment, which is solved by adding an oxygen tank in addition to the Carbon & Argon cylinders. The oxygen tank will flush automatically the moment the exit valve closes, and the oxygen will be risen to a specific level and then shut off by an oxygen sensor, which will be regulating and monitoring the oxygen variations within the compartment the entire process as shown in Figure 7.

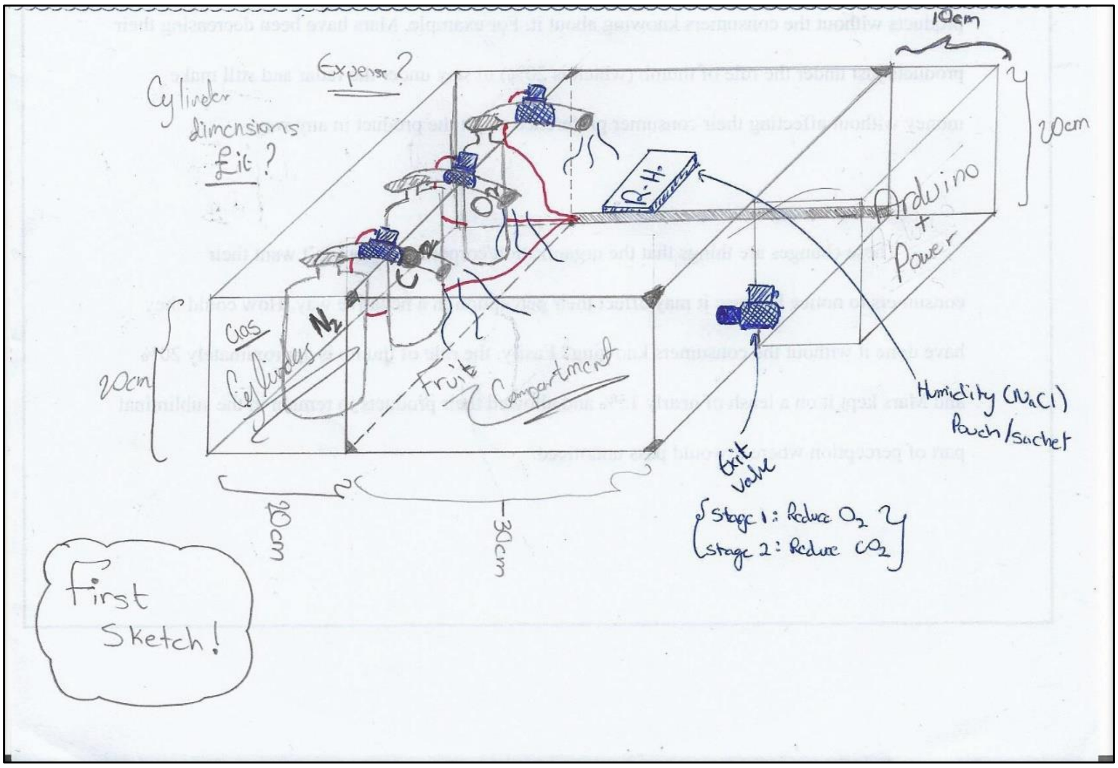

Figure 7: FSS Alternative #1 Sketch

In terms of meeting the multiple requirements and qualifications, this alternative does not satisfy the budget, weight, and dimension requirements. In terms of the budget, adding an oxygen tank would be exceeding the budget constraint added at the beginning of this project by 100 – 200 dirhams. In addition, the length of the compartment allows for two cylinders each a maximum of 4 liters with a maximum diameter of 20 cm, however, by adding an extra cylinder, the cylinder diameter will have to be reduced to between 10 – 15 cm as well as a maximum literage of 2 liters, which are not available. Additionally, adding an extra gas cylinder will exceed the weight constraint of 15kg, therefore, this alternative can not be applied as the main process for the system.

3.1.4.3.2 Alternative #2. The second alternative proposed was to remove the oxygen tank as the source of oxygen into the compartment, and to add an air vent at the back of the compartment, which opens and closes using a small servo-motor. Once the Carbon levels are dropped and the exit valve is closed in the second stage, the Arduino board will send a signal to a relay which will be connected to the servo-motor, allowing it to open the air vents. Moreover, the amount of oxygen entering the compartment will be monitored via an oxygen sensor, and once the oxygen levels are within the EMA range, the sensor will send a signal to the Arduino board to shut off the servo-motor, hence closing the air vents as illustrated in Figure 8.

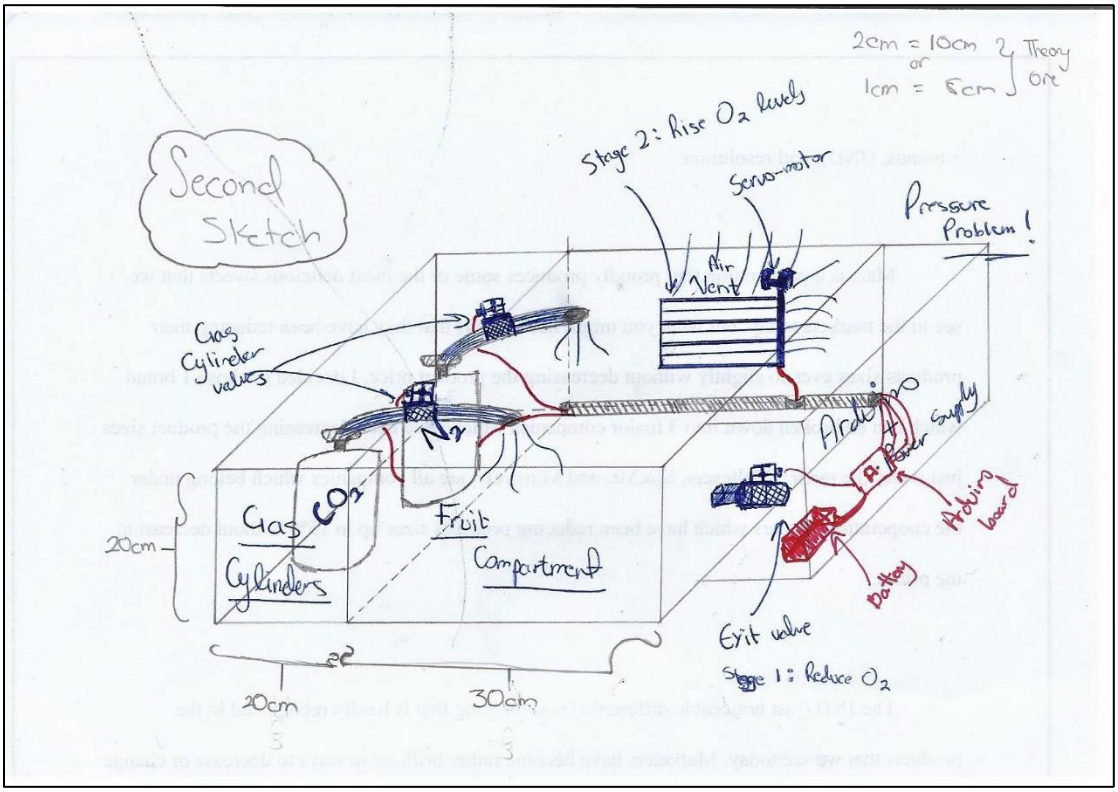

Figure 8: FSS Alternative #2 Sketch

In terms of satisfying the requirements, this alternative falls within the budget constraint added at the beginning of the project, and the addition of a small servo-motor and air vents only add 60 - 120 dirhams. Moreover, adding a servo-motor to the back of the compartment as well as air vents will not affect the final measurements, however, this alternative is not applicable functional wise as a result of the Argon and Carbon flushing the first stage of the experiment. Due to the gas flushing, the pressure within the compartment is increased, and therefore, will not allow the oxygen to pass through the air vents in the second stage. The pressure within the compartment has to be lower than the outside atmosphere to allow the air to pass into the compartment through the air vents, which is proven by Bernoulli's Principle of High Pressure to Low Pressure, and therefore, this alternative is not applicable to be used as the main process for the system.

3.1.4.3.3 Alternative #3. The third alternative proposed to counter the pressure problem; is to connect a vacuum pump to the compartment in order to reduce the pressure within the compartment as seen in Figure 9. Right after the exit valve to reduce the Carbon is closed off, a signal will be sent to the vacuum pump to help reduce the pressure within the storage compartment, which will be monitored through a pressure sensor. Afterward, once the pressure is dropped, the pressure sensor will signal the Arduino board to shut off the vacuum pump while to also open the air vents through the servo-motor. Once the oxygen levels within the compartment rise to the range specified, the oxygen sensor will signal the Arduino board to close off the vents.

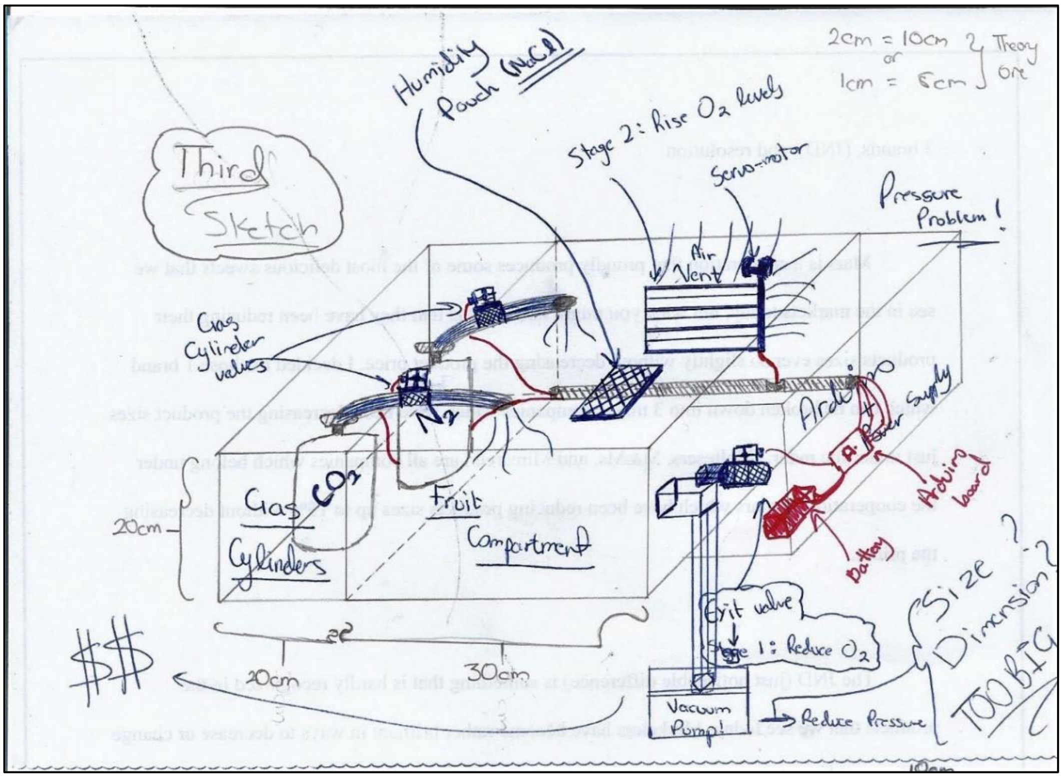

Figure 9: FSS Alternative #3 Sketch

Therefore, the vacuum pump helps satisfy the pressure requirement, however, it does not satisfy the others. In terms of price, vacuum pumps are extremely expensive and cannot fit within the budget, while in terms of dimensions, they are extremely big and require a large amount of power to activate, plus they are extremely heavy and will exceed the weight constraint. All in all, this alternative even though it satisfies the pressure problem, it creates others concerning price, power, size, and dimensions.

3.1.4.3.4 Final alternative. The final alternative that was decided on that not only solves the pressure problem but also removes the second stage as a whole. Additionally, the experiment will be performed over the course of only a week while using check valves to reduce the pressure within the compartment. The system sketch which can be seen in Figure 10 will experiment on fruits that deteriorate quickly, and for a week instead of 3-4 weeks. Check valves will be used to reduce the pressure caused by the Argon and Carbon flushing in the first stage in order not to cause any damage to the compartment or the fruit itself. Additionally, check valves are extremely cheap and lightweight compared to vacuum pumps and will not hinder the dimension constraints of the compartment. Moreover, instead of using stainless steel as the outer layer for the compartment like in the 3 alternatives, aluminum will be used instead due to its low cost and lighter weight. Based on the requirement descriptions and dimensions mentioned in the previous section, a rough sketch of the storage system was made and can be seen in Figure 9, followed by a rough model made on AutoCAD Inventor as illustrated in Figure 11.

Afterward, multiple sensors were acquired for the process of measuring and controlling the gas composition and humidity within the storage box. An Arduino DHT11 sensor with a DIY cable kit was attained in order to measure the relative humidity and temperature within the storage system. Also, an analog Carbon sensor along with an I2C analog oxygen sensor (both produced by DFRobot Gravity) was purchased to regulate the air composition within the container. All 3 sensors are compatible and programmed using an Arduino Uno board, furthermore, all 3 sensors were screwed to a rectangular plexiglass board and glued to the interior side of the storage container, while the wires were run through a small hole to the outside and sealed using an adhesive sealer in order to prevent any gas leakage that might disrupt the data measurements taken by the sensors, which can be demonstrated in Figures 15 and 16 as well.

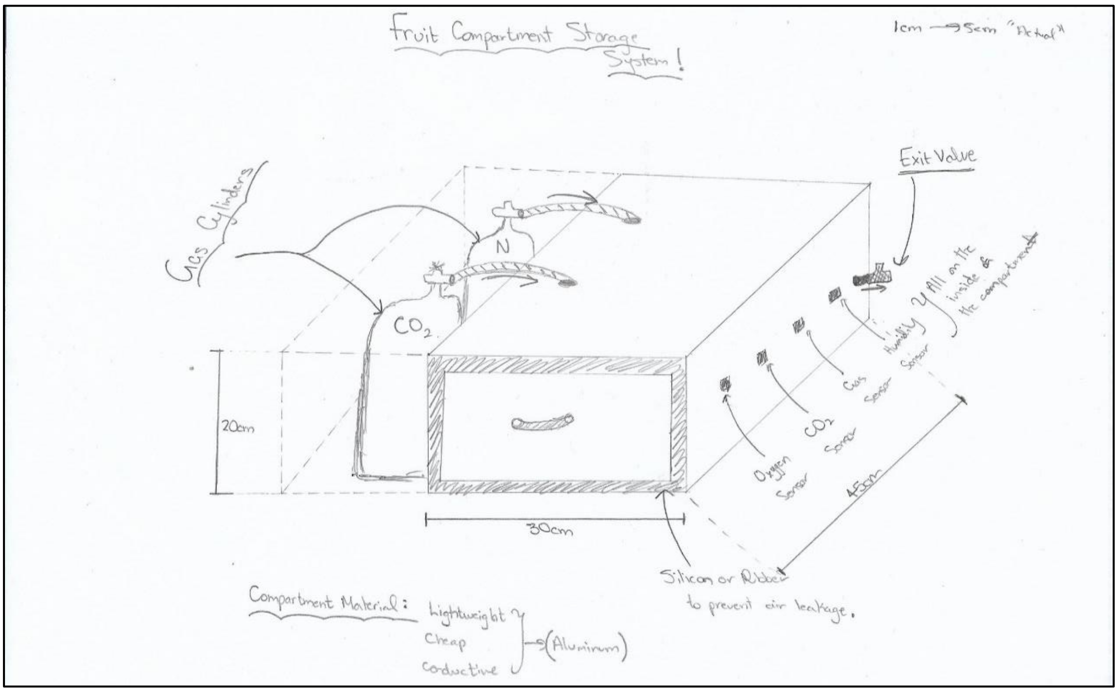

Figure 10: Final FSS Rough sketch

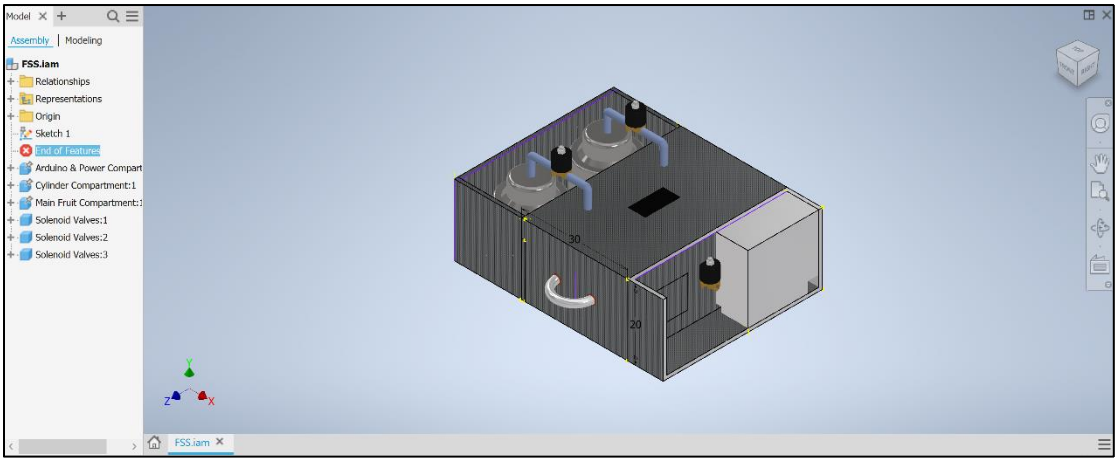

Figure 11: FSS Model on AutoCAD Inventor

3.2. Packaging System Manufacturing

The storage box was created using thin aluminum sheets due to its durable, conductive, and non-corrosive properties with the dimensions described in the technical requirement section in the previous chapter as seen in Figures 12 and 13. The sheets were welded shut all around the box in order to prevent any gas leakage except at the front where a sheet of plexiglass was used to allow for clear visibility of the fruit. Additionally, the plexiglass was separated from the front of the box using an adhesive sealer to prevent any gas leakage and with the use of screws to help tighten the space between the glass and the storage box. Additionally, 3 x 6 mm fittings were used to connect the gas hoses to the compartment as they were drilled and tightened to prevent any gas leakage.

Figure 12: Fruit Storage Box (Front View)

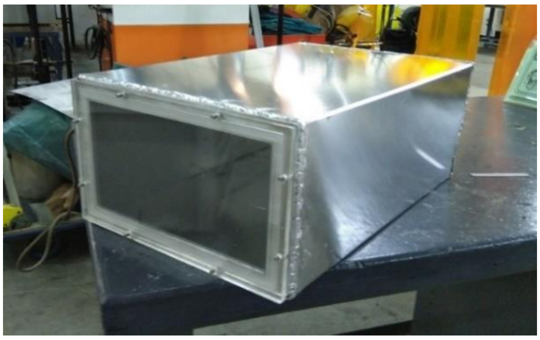

Figure 13: Fruit Storage Box

3.2.1. System setup. The setup for the system started with the acquiring of 3 normally closed solenoid valves that are powered with 12V DC, in which case one valve will be connected via a 6mm tube fitting to the right side of the box to allow oxygen to exit, while the other 2 valves are connected to the left side as well using 6mm tube fittings, where one is for the Carbon intake while the other valve is for the Argon as illustrated in Figure 14.

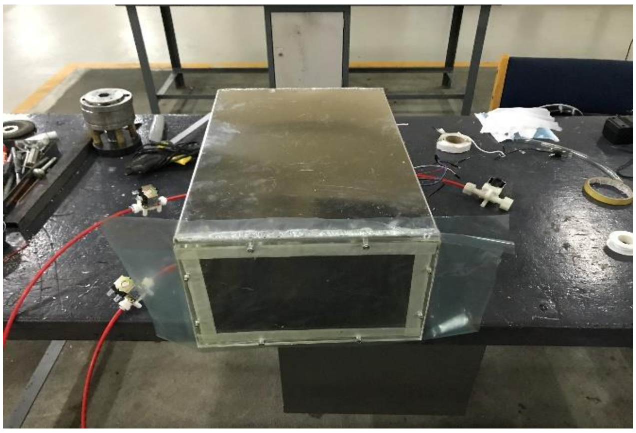

Figure 14: Gas Valve Connections

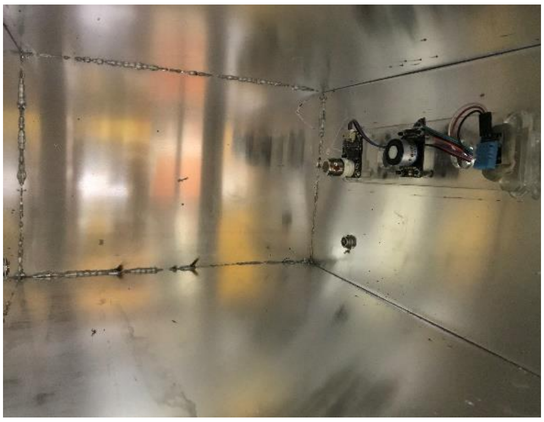

Figure 15: Interior Sensor Setup

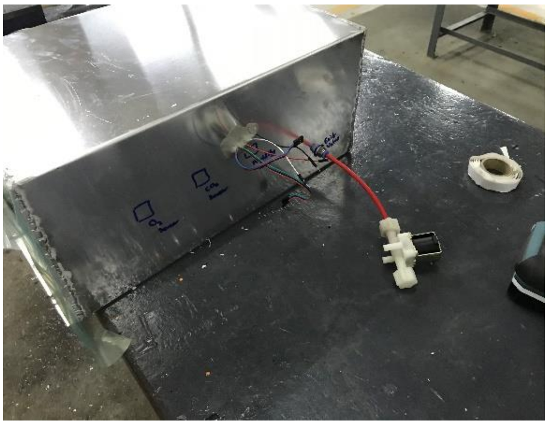

Figure 16: Outer Sensor Connections

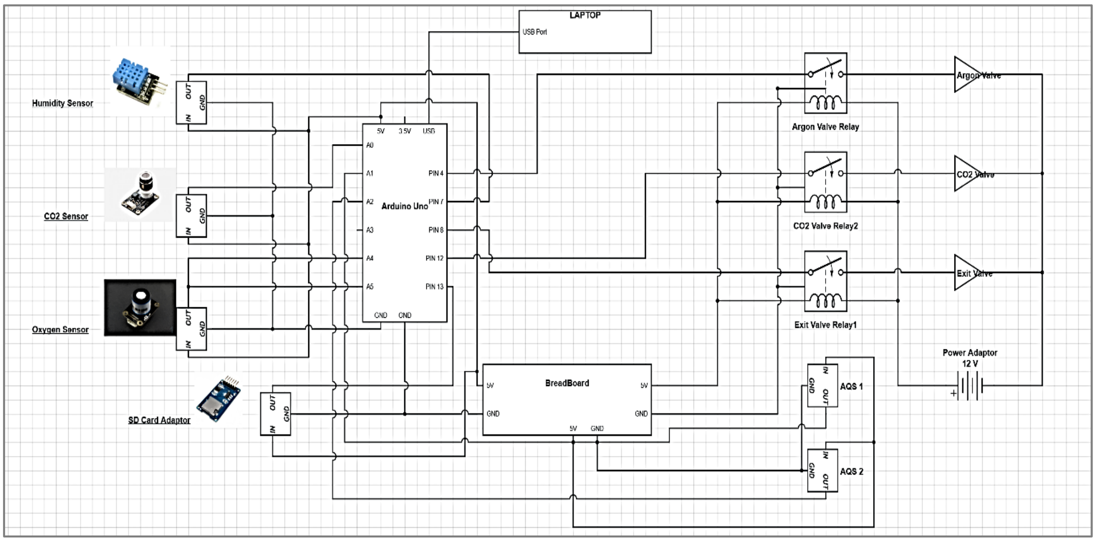

Figure 17: Storage System Network

As for the setup network between all the valves, sensors, and the Arduino board, which are all powered by the 9V DC battery, the diagram in Figure 17 helps display the connections in detail including the types of power source, which Arduino board pins are occupied, as well as the connections for the SD card adaptor.

From the left side of the network as seen in Figure 17, all 3 sensors, as well as SD Adaptor, are connected to the 5V pin and GND provided by the Arduino board, furthermore, while each of the gas sensors is connected to analog pins on the Arduino board (A0, A4 and A5), the humidity sensor and SD adaptor are occupying digital pins (Pin 7 and 13). A breadboard is used to act as a middleman between the Arduino board, valve relays, and air quality sensors (AQS) in terms of supplying 5V and GND, while the digital pins (Pin 4, 8 and 12) are being occupied by each of the relays as well as analog pins (A1 and A2) by each of the air quality sensors. The valve relays, in general, are used as an on/off switch for each of the solenoid valves since the Arduino does not have enough voltage to open and close each of the valves, and as each valve is connected to a relay on one side, a power adaptor is connected to the other to help stimulate the coils within the valve to open whenever the relay permits. The physical connections themselves can be seen in Figure 18.

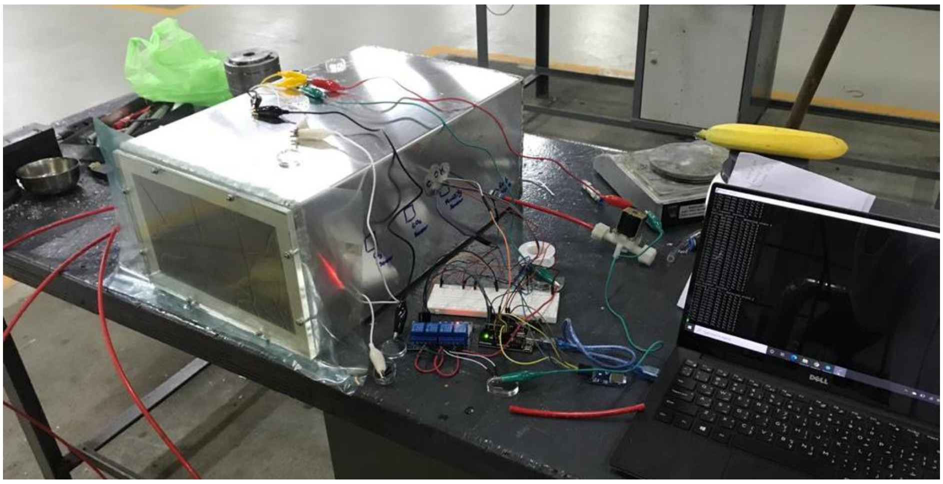

Figure 18: Physical Connections

3.2.2. System programming. Firstly, when programing and coding the system network using Arduino, the libraries and data codes for the humidity, SD card adaptor, and air quality sensors were already provided by the Arduino website, while the Carbon and Oxygen libraries, as well as data code, were provided by the manufacturers (DFRobot Gravity). Furthermore, the pins being occupied on the Arduino board from both analog and digital sides were defined in the code, where the digital pins (4, 8 and 12) are occupied by the valve relays for each valve and are defined as outputs, while the analog pins (A0, A1, A2, A4 and A5) and digital pin (7) were occupied by the sensors and defined as inputs.

Multiple states were defined at the beginning of the code connected to different actions occurring within the storage box. State 0 or (Base) as defined in the code occurs when the air composition within the box is at equilibrium, hence, when the Carbon and oxygen values are within the optimum range defined in the code depending on the type of fruit. State 1 or (Exhaust_Oxygen) is defined when the oxygen percentage within the box is above a certain range, hence, both argon and exit valves will open in order to reduce and exhaust the oxygen inside the box until it reaches the optimum array. State 2 or (Raise_Carbon) is defined when the Carbon percentage is below a certain value, therefore, the Carbon valve will open and help replenish the gas within the box until it hits the optimum range defined.

Afterward, the next step in the main Arduino code was to copy the data for reading the gas composition, natural gas, and humidity measurements from the Arduino and the sensors' manufacturers' website, while also printing the data code for saving and storing data using the SD card adaptor. Subsequently, multiple constraints were added in order to help create the requirements needed to open and close the valves depending on the gas measurements taken by the oxygen and Carbon sensors. The full sample code used for the experiments is included in the appendix for reference.

3.3. Experimental Planning and Testing

In this section of the methodology, the experimental design using factorials within Minitab is performed to determine the technical feasibility of the system, as well as to analyze the effects of the design parameters on the deterioration of the fruits through the air quality measurements, while correlating the effects as well; in terms of the fruit color and quality (RGB values). In addition, the system and connections set up for the fruit packaging compartment will be described, as well as how the packaging system was programmed using an Arduino controller board, and how the volumetric flow rate for each of the gases was calculated.

3.3.1. Experimental design. In terms of the experimental design, the first step was to determine and specify the design and response variables based on the results from the literature review. Therefore, Minitab was used, where the DOE (Design of Experiments) will be conducted in the form of a 2-level factorial, at which the design will be a half-fraction consisting of 8 runs as shown in Table 7.

The main reason a half fraction design was considered, is because the runs take weeks to perform and finish; especially in terms of experimenting with each of the variables, therefore, the number of runs was minimized to 8.

Table 7: Two-level factorial (8 runs)

	C1	C2	C3	C4	C5	C6	C7	C8-T
	StdOrder	RunOrder	CenterPt	Blocks	V-Argon	V-CO2	KCL	Fruit
1	8	1	1	1	470	592	50	Avocado
2	3	2	1	1	0	592	0	Avocado
3	5	3	1	1	0	0	50	Avocado
4	7	4	1	1	0	592	50	Banana
5	2	5	1	1	470	0	0	Avocado
6	1	6	1	1	0	0	0	Banana
7	4	7	1	1	470	592	0	Banana
8	6	8	1	1	470	0	50	Banana

The 4 factors taken into consideration which are also the design variables consist of the volume of Argon used, the volume of Carbon used, the amount of KCl powder, and the type of fruit, while the response variables entailed are the air quality measurements of the fruit while inside and outside the system. The main reason the type of fruit is taken into consideration as a design factor is that only two fruits are used (bananas and avocadoes), and in order to see the effects of the air quality measurements inside and outside the system, the type of fruit plays a major role. Initial experiments will be performed then to see the effects of each of the variables on the air quality measurements, and whether the measurements can act as a measure of the deterioration of the fruits or not. For that purpose, the air quality measurements are then correlated to the color of the fruits as it deteriorates using RGB values, this analysis will be conducted using the banana and avocado experiments, where 3 random points are taken on each of the fruits inside and outside the system. Afterward, each of the 3 colors (Red, Green and Blue) will be graphed against the air quality measurements taken roughly at that moment, in order to crisscross the correlation between them in the form of scatter plot graphs, as well as values such as the R-squared.

3.4. Conducting Experiments

In the following sections, the initial measurements are conducted in order to measure and calculate the gas flow rate, as well as the optimum amount of KCl powder, which will be explained in detail, followed by the initial trials performed on both fruits (Bananas & Avocadoes) while measuring their deterioration through color analysis (RGB values). In addition, the actual DOE runs will also be explained based on the planned DOE in the experimental design section, in terms of the design and response variables.

3.4.1. Initial measurements. Based on the planned DOE runs, the amount of Argon and Carbon pumped into the packaging compartment needs to be regulated, and hence, the flow rate for each of the gas cylinders needs to be measured, Additionally, to perform the runs, the amount of KCl needed to regulate the humidity needs to be discovered.

3.4.1.1 Flow rate measurement. Based on the design variables mentioned in the experimental design, the gas cylinders for both Argon and Carbon will have to be opened or closed depending on the variables specified in each run, therefore, the flow rate for each of the cylinders needs to be measured. To measure the volumetric gas flow rate, a 40-liter Argon cylinder was borrowed and used from the AUS manufacturing lab, while a 2-liter Carbon cylinder was purchased via an aquarium company (Discus) online along with a flow regulator. A simple method of measuring the gas flow rate used was where a small tank filled with water was used along with an inverted graduated measuring cylinder (Yardwe 250ml) dispatched inside it, and was placed a few centimeters above the surface of the water tank where the gas tube was placed right beneath it. For the argon cylinder, the gas was run through a 3.5-meter-long hose with 10 x 6mm diameter right into the water tank for the duration of exactly a minute. As for the Carbon cylinder, the gas flowed through a 2.5-meter-long hose with a 6 x 4mm diameter for the duration of also a minute. Afterward, the gas flow rate was measured as the water is forced out of the measuring cylinder using a stopwatch, and was converted from (ml) to (cm^3) per minute. For the argon cylinder at 31.9 seconds, the water was forced completely to exit the measuring cylinder, hence using simple calculations where [60s x 250ml = 31.9s x [X]ml] gave a gas flow rate of 470.22cm^3 per minute for Argon. Additionally, the amount of time it took for the water to be forced out of the measuring cylinder using Carbon gas was 25.3 seconds, hence, using the calculation formula [60s x 250ml = 25.3s x [X]ml] resulted in the gas flow rate for Carbon to be at 592.88cm^3 per minute. A rough sketch of the process can be seen in Figure 19.

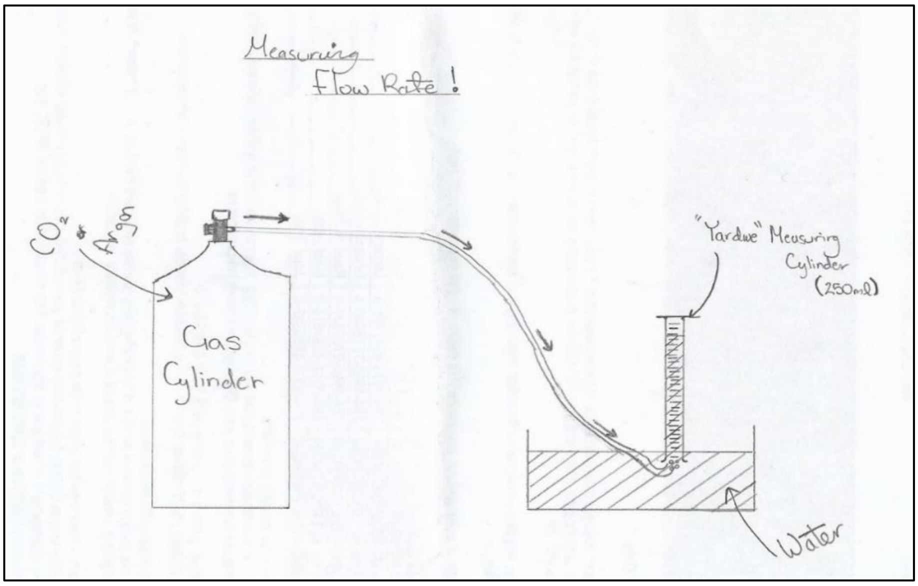

Figure 19: Measuring Flow Rate Sketch

3.4.1.2 Humidity regulation. Based on the literature review, the KCl powder can be used to regulate and control the relative humidity in a closed system, however, the amount of KCl needed to regulate the humidity within this packaging compartment is unknown, therefore, multiple experiments were conducted to test the limits of the KCl powder in different amounts. To start the experiments for extending the shelf life of the fruits, both components in terms of air composition and humidity need to be regulated. The types of fruit used for this experiment (Banana & Avocado) require an optimum range of 85 – 95% relative humidity in order to maintain maximum quality as illustrated in Table 1, and hence, that can be achieved by experimenting with different amounts of KCl powder. The spun-bounded polypropylene sachets used to hold the KCl powder was cut and collected from the first layer of surgical masks, and stapled to avoid any powder seepage. The main reason spun-bonded polypropylene film pouches are used for this experiment is because the holes in the film readily permit the movement of water vapor unlike liquid water, and therefore, over periods of time the powder inside the pouches become saturated with water depending on the amount of the compound used, hence, helping regulate the relative humidity.

Firstly, the banana fruit used for the humidity regulation experiment was of uniform size and free of visible defects, moreover, the fruit was stored inside the packaging compartment at 22C and was analyzed in terms of relative humidity change for approximately 4 days. The first experiment for regulating the humidity; tested using 25 grams of KCl powder inside the polypropylene pouch over 4 days, while having the relative humidity values monitored through an Arduino DHT11 temperature and humidity sensor. Additionally, the experiment following that used 50 grams of KCl within the pouch for 4 days, and the results of both in terms of relative humidity percentage over time can be shown in Figure 20.

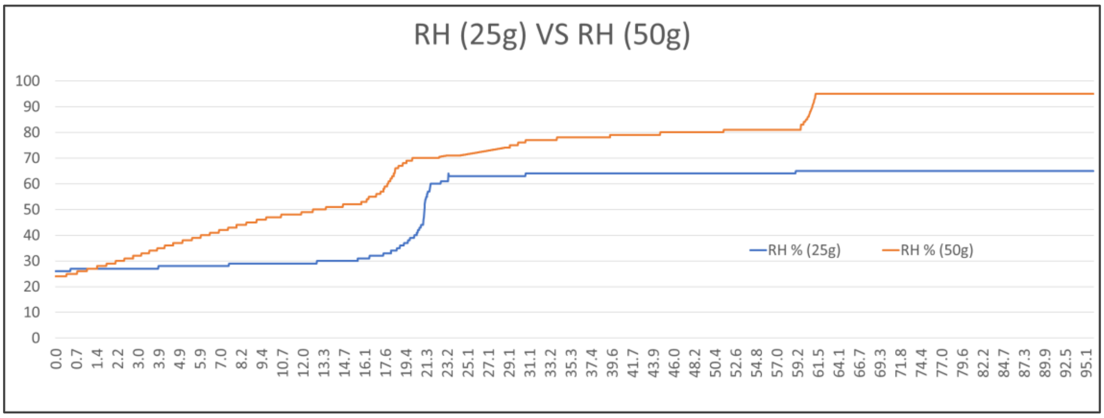

Figure 20: Humidity % comparison graph over 4 days

At the beginning of Day 1, the RH % for KCl 25g starts at 26% while the 50g starts at 24%, and over the course of 4 days, both tests increase exponentially, however, the RH% for the 25g stabilizes at 65% for half of Day 3 and all of Day 4, while the RH% for the 50g stabilizes at 95%, and therefore, it is decided that the 50g of KCl will be used for the fruit experiments onward. Additionally, the full datasheet for the relative humidity comparison is added in the appendix for reference.

3.4.2. Initial trials. Initial trial experiments were performed to ensure that the system is working properly, as well as to certify if the argon, carbon, and relative humidity can be controlled and regulated. These trials were conducted on two types of fruits (Bananas and Avocadoes), where the details of the experiments are illustrated below. Additionally, the first experiment was run over the course of a week while the second experiment was run over the course of 9 days, and this due to a holiday being present during the course of the second experiment.

3.4.2.1 Banana experiment. After analyzing the right amount of KCl to be used for further experiments, 2 bananas weighing approximately 136g each were purchased and used for the first trial experiment over the course of a week. The first banana was placed inside the compartment in the center, where the 50g of KCl was placed right behind it and the program for the air composition was run instantly as seen in Figure 21.

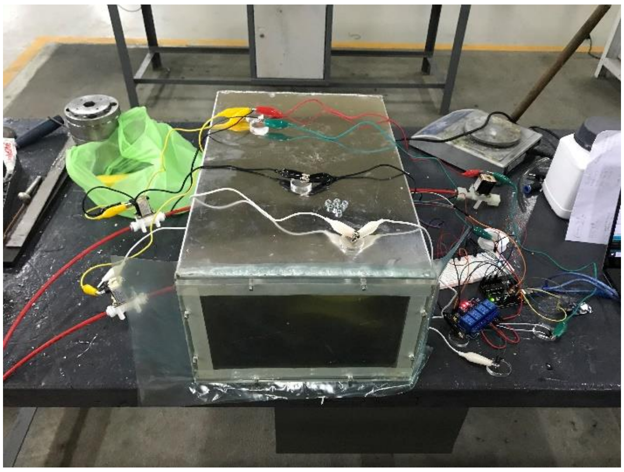

Figure 21: Banana Storage System Experiment

As displayed in Figure 21, once the program was run, the oxygen sensor within the compartment gathered that the sensor levels were above 4% as stated at the beginning of the code, hence, activating both the argon and exit valve as seen by the two lights being lit on the valve relay numbers 2 & 3. Once the oxygen levels within the compartment were regulated below 4%, both lights went off and the Carbon valve was activated, causing the first valve relay to be lit instead which can be seen in Figure 22 as well.

Once both Oxygen and Carbon levels were regulated, the second banana was added next to the compartment on the outside, while placing the outside air quality sensor next to it in order to monitor the changes to the air quality over the week. Images of both bananas were taken whenever accessibility to the lab was allowed for a week, and the changes in terms of color were notably higher for the banana on the outside compared to the banana inside the storage system, and these changes can be seen clearly in Figures 23 to 26, compared between Day 1 and Day 6 for both bananas on the inside and outside of the storage system.

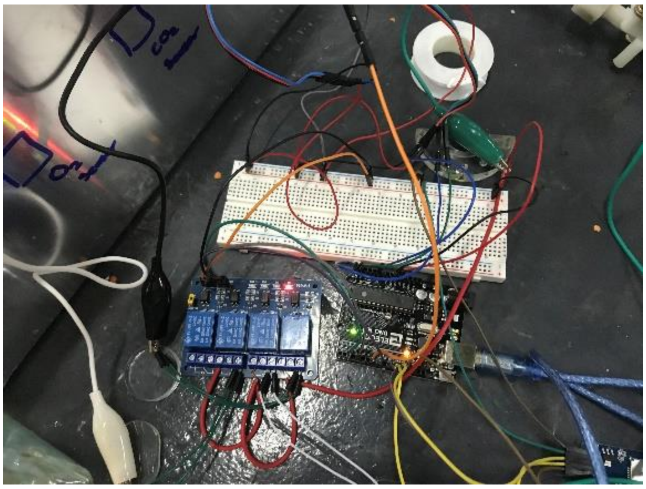

Figure 23: Carbon valve relay being activated

Figure 24: [Day 1] Banana inside the system

Figure 25: [Day 7] Banana inside the system

Figure 26: [Day 1] Banana outside the system

Figure 22: [Day 7] Banana outside the system

The change in color for both bananas helps show the major difference that air regulation and humidity within a closed compartment can play in the extension of a fruit's shelf life. Additionally, the data over the week was organized and graphed in hours to help distinguish the changes being made in terms of air quality inside and outside the system as illustrated in Figure 27.

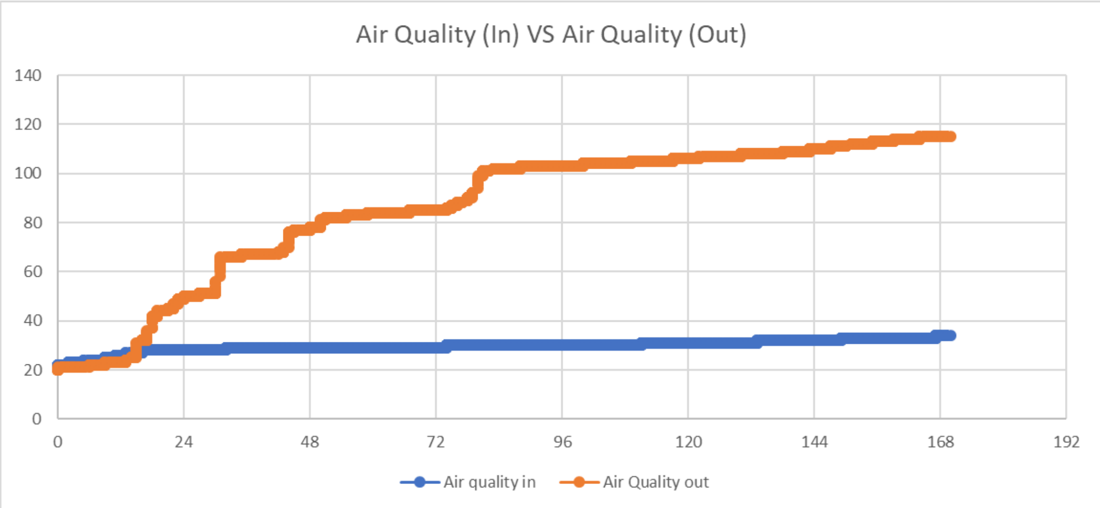

Figure 27: Air Quality Comparison for Bananas

The air quality measurements for both bananas as seen in the graph are almost the same throughout the course of the first day, however, the air quality measurements for the outside banana begin to increase exponentially in contrast to the measurements of the banana placed inside the system, and which help prove that regulating the air composition and humidity plays a major role in prolonging the shelf life of the banana.

3.4.2.2 Avocado experiment. After experimenting using both bananas, two avocadoes were used for the second trial of experiments where both weighed approximately 145g each with no visible damage, one to be placed inside the system while the other on the outside in the same manner as the banana experiment. However, the KCl pouch used in the banana experiment was left to be dried out in the open for a day, and placed back inside the compartment along with the avocado while being sealed tight to prevent any air leakage. The same process was used for this trial including the same air composition and humidity levels used for the banana experiment, however, the avocado trial was run over the course of 9 days instead of a week due to the inability to access the lab. The change in the shape and color of the avocadoes in contrast between the inside and outside the system was evident and can be seen clearly in Figures 28 to 31.

The change in color and shape for both avocadoes help show the major difference that air regulation and humidity within a closed compartment can play in the extension of a fruit's shelf life. Additionally, the data for the air quality measurements both inside and outside the system was graphed over the course of 9 days in hours as shown in Figure 32.

The air quality measurements for both inside and outside the system are almost aligned throughout the first day, however, in contrast to the air quality measurements in the banana experiment, the air quality for avocadoes seemed to rise in a linear manner over the course of the first 6 days. Besides, due to the experiment being executed over a longer period, the air quality measurements are much higher for the avocados in contrast to the bananas, and this is a result of the larger amounts of ethylene being

Figure 28: [Day 1] Avocado outside the system

Figure 29: [Day 10] Avocado inside the system

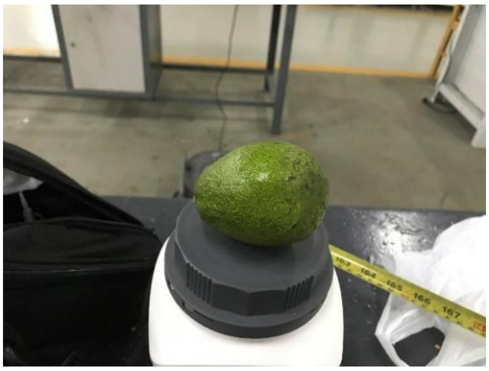

Figure 30: [Day 1] Avocado outside the system

Figure 31: [Day 10] Avocado outside the system

produced by the avocadoes over a longer trial period. Moreover, the datasheet for both banana and avocado experiments are also added in the appendix for further reference.

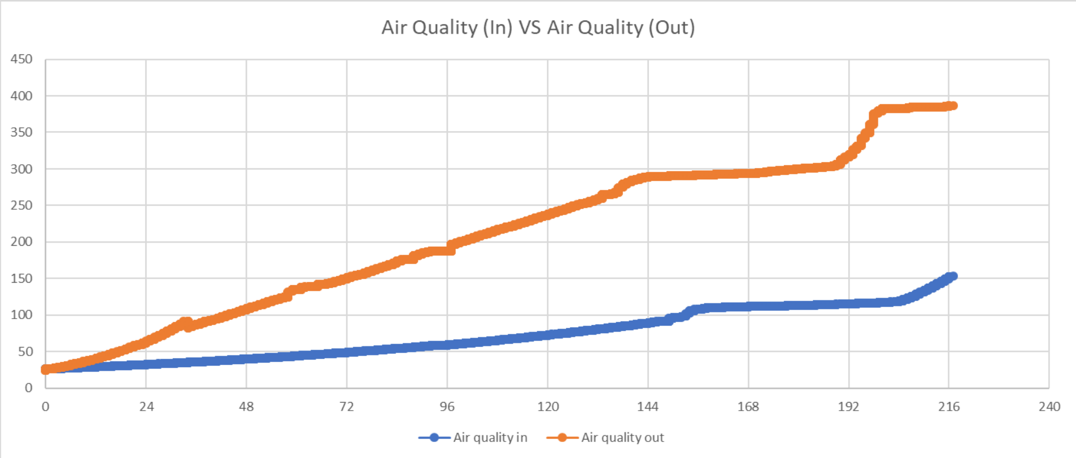

Figure 32: Air Quality Comparison for Avocadoes

3.4.2.3 Fruit deterioration measurements. As proposed in the experimental design section, in order to validate that the air quality measurements can act as an indicator for deterioration of the fruit, the data results from the trial experiments will be used to analyze the color of the fruits at 3 different points, and this was done 3 times for each of the fruits both inside and outside the storage system using the images captured. Additionally, the collection of data both inside and outside the system for the banana experiment was collected on 4 different days, while for the avocado experiment, it was done over 5 different days due to the extended period of the trial; using the images taken for both fruits during those specific days, which can be seen in Table 10 in Appendix B. All correlations and between the air quality measurements and the colors were also conducted on Minitab.

After organizing the data for each of the points taken for each fruit both inside and outside the system, the averages for each of the colors were calculated and summed at each day as well as displayed in Table 11 in Appendix B.

Using the averages and sum for each of the colors, nonlinear regression was used to fit the data points for each of the color averages to the air quality measurements taken on that day, including the sum of the averages as well. Each graph shown then displays the correlation between both variables in terms of the color and air quality measurements, which can all be seen in Figure 33 - 36. Moreover, when it comes to the color data (RGB), the higher the value of the color, the higher the quality of the fruit, and the brighter is its color, and vice versa.

As seen in the scatter plot in Figure 33 between both the average red points and the air quality measurements, the correlation between them is represented by -0.705, which shows a high negative correlation between both variables, and that much of the change in the color data in terms of red color is driven by the air quality measurements. However, the correlation between both variables is negative, meaning that as the air quality measurements increase with time as the fruits deteriorate, the color values decrease, since the color quality of the fruit is getting darker.

As for the scatter plot between the average of the green color points and the air quality measurements displayed in Figure 34, the correlation is also represented by a strong negative value of -0.694, meaning much of the change in the color data in terms of the green values is also driven by the air quality measurements. Also, since the correlation between both variables is also negative, this means that as the air quality measurements increase, the green average values decrease and vice versa.

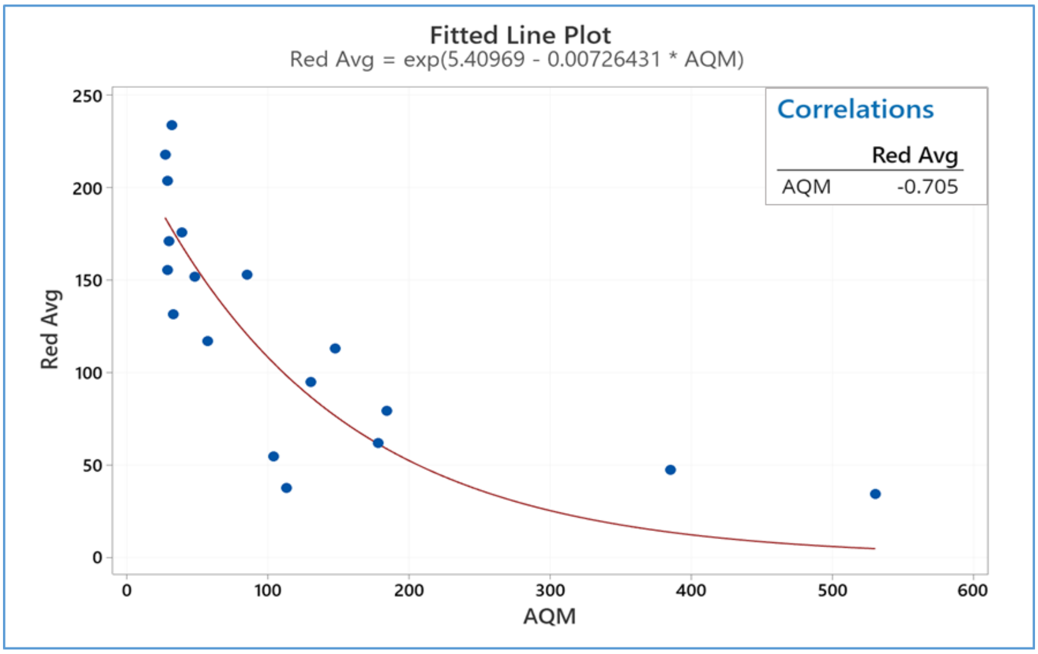

Figure 33: Average Red points in comparison to AQM

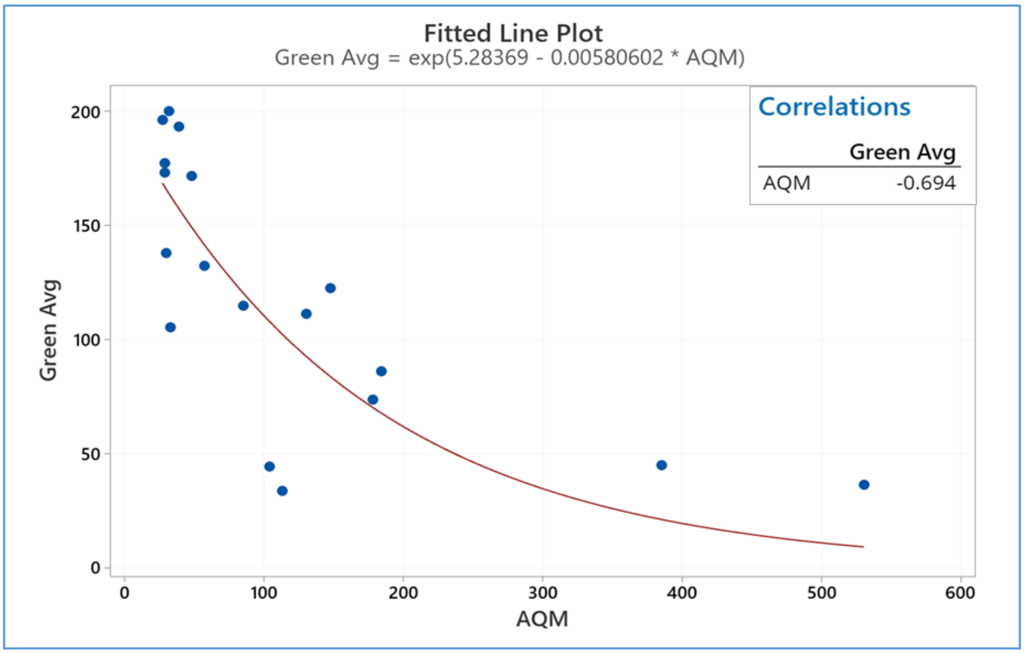

Figure 34: Average Green points in comparison to AQM

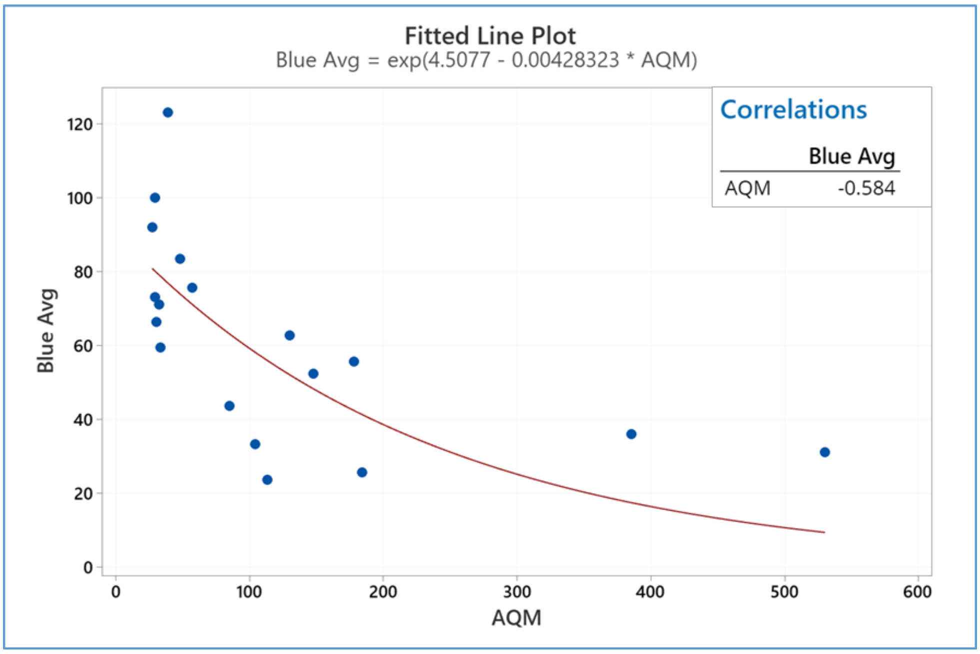

Figure 35: Average Blue points in comparison to AQM

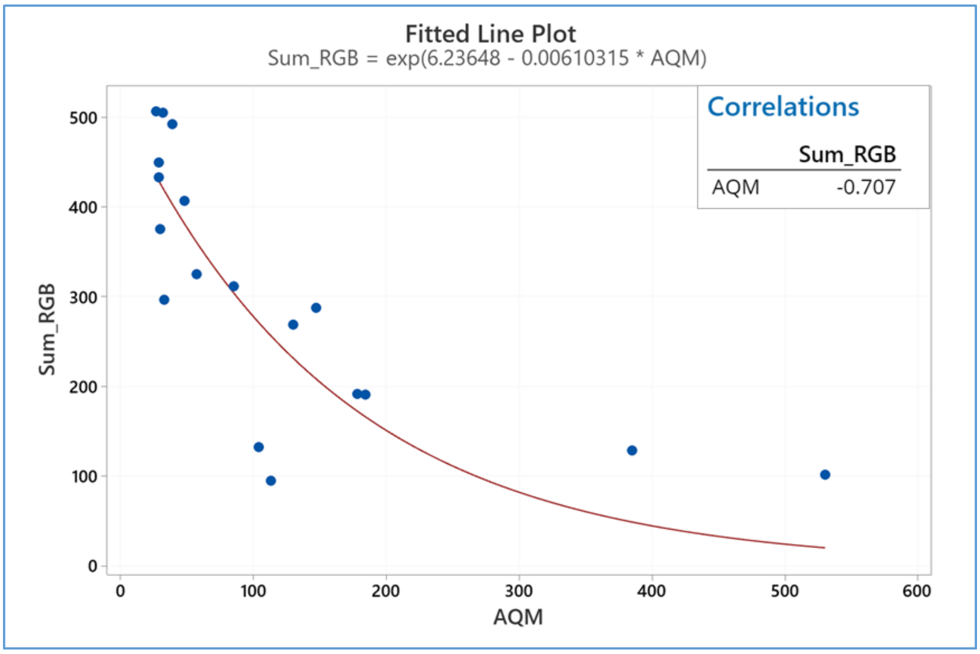

Figure 36: Sum of RGB points in comparison to AQM

Out of all 3 colors being correlated with the air quality measurements, the blue color points have the lowest negative correlation with a value of -0.584 as illustrated in Figure 35. This means that roughly 58% of the change in blue color points are being driven by the air quality measurements, however, unlike the red and green colors where the mean values fall between 0 and 255, the blue color values in terms of RGB, have a limited mean range that is spread between 0 and 128, which explains why the blue color values have a weaker correlation to the air quality measurements, unlike the other colors.

After summing all 3 color values and correlating them against the air quality measurements as shown in Figure 36, the final correlation between the RGB Summed values and the air quality measurements are represented by a value of -0.707. This means that almost 70% of the change in the data points are being influenced by the air quality measurements through a negative relationship, in which as the fruit deteriorates with time and increases the air quality measurements, the sum of the RGB colors decreases, and hence, these averages color values will be used to act as a measure for the fruit deterioration.

3.4.3. Actual DOE runs. Based on the planned DOE for all 8 runs, the actual experiments were conducted while adding an additional design variable to the runs in the form of time. Each of the runs was then conducted over the course of 2 days while having the data being collected, therefore, any non-linearity occurring during the experiments with the time variable is then captured. A sample of the results for one of the factorial runs is shown in Table 12 in Appendix C, and the entire results sheet for all the runs is included in the appendix for reference.

The results in Table 12 in Appendix C form a sample from the first run performed during the experiments, and in which both Argon and Carbon variables had to be used, as well as the KCl powder. Additionally, the type of fruit specified for this experiment had to be an avocado, while the time is used in the form of minutes and seconds, and in which this run is shown in Table 9 as the first run order. Moreover, the results of the experiments in terms of the Oxygen % Carbon ppm, and Relative Humidity % throughout the experiment is shown, in addition to the air quality measurements for the avocado both inside and outside the compartment. The analysis performed on Minitab for all the runs is then analyzed and explained in detail in the next chapter, while the full data results for all the runs are added in the appendix for reference.

Chapter 4. Statistical Analysis

In this chapter, a statistical analysis will be implemented and analyzed in the form of regression analysis using Minitab, where it will be used to help predict the continuous dependent variables from a number of independent variables. as well as to estimate the effect of the design variables on the response variables.

4.1. Regression Analysis

Based on the results from the actual DOE runs, a regression analysis will be conducted in order to show the variability and correlation between the design variables and the response variables. The design variables will consist of the rate of Argon used, the rate of Carbon used, the amount of KCl, the type of fruit, and the time for each run. Moreover, the program Minitab is used where the DOE (Design of Experiments) is conducted in the form of a 2-level factorial, at which the design will be a half-fraction consisting of 8 runs as explained in the planned DOE.

In terms of these runs, the values 470 and 592 are the flow rates for each of the gas cylinders and represents when the gas cylinder should be used as shown for the first run in Figure 35, additionally, the 50 KCl also represents when KCl should be used as well as the type of fruit for each trial. This design will help show the variability between each of the 5 design factors, and how each of them is influencing the response factors.

Moreover, after performing the 8 runs using the design factors over the course of 2 days for each, the data results were inserted into Minitab and used for different types of analysis as demonstrated in the figures below. The 3 responses that will be examined using response surface regression analysis and factorial plots, consist of the air quality measurements inside the compartment, the Oxygen, Carbon, and Humidity variables, as well as the air quality measurements outside the packaging system. These responses will be examined to view the effects of the process parameters on the deterioration of the fruit, and how these parameters can be selected to elongate the fruits' shelf life. The Oxygen, Carbon, and Humidity variables are also monitored to ensure they are properly controlled using the design variables that are constantly changing in the experiment depending on the type of run.

4.1.1. Response variables (Oxygen %, Carbon ppm, & RH %). As for the response variables such as the Oxygen and RH percentage values as well as Carbon ppm values, a response surface regression analysis is executed for each in order to calculate its regression equations as well as correlations in terms of the same 5 design variables, which can all be demonstrated in Figure 37 and Figure 38 starting with the oxygen % as a response variable.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.45563	91.72%	91.72%	91.71%

Regression Equation in Uncoded Units

Fruit			
Avocado	Oxygen %	=	24.5940 - 0.019055 Argon - 0.001695 CO2 + 0.00402 KCL - 0.007367 Delta T Orig + 0.000002 Delta T Orig*Delta T Orig - 0.000001 Argon*CO2 - 0.000012 Argon*KCL - 0.000009 Argon*Delta T Orig + 0.000001 CO2*Delta T Orig - 0.000003 KCL*Delta T Orig
Banana	Oxygen %	=	24.4274 - 0.018493 Argon - 0.001695 CO2 + 0.00402 KCL - 0.007242 Delta T Orig + 0.000002 Delta T Orig*Delta T Orig - 0.000001 Argon*CO2 - 0.000012 Argon*KCL - 0.000009 Argon*Delta T Orig + 0.000001 CO2*Delta T Orig - 0.000003 KCL*Delta T Orig

Figure 37: Model Summary & Regression Equations for Oxygen %

According to the regression equations illustrated in Figure 37, depending on the type of fruit whether it is a banana or an avocado, the Oxygen % can be calculated using these equations as a function of the Argon, Carbon, KCl, and time variables. As for the model summary depicting the strength of the fit, almost 92% of the change occurring to the oxygen % values inside the compartment is being driven by the 5 design variables, however, correlations depicting the relationship between each of the variables and their strength can be seen in Figure 38.

The variable with the greatest effect on the Oxygen % is the Argon, where the correlation between the Argon and Oxygen values is represented by a strong negative relationship value of -0.894, meaning that as the Argon is pumped into the system, the Oxygen values decrease. This also shows that almost 90% of the change in Oxygen %, is being driven by the use of Argon, which makes sense.

Correlations

	Argon	CO2	KCL	Delta T Orig	Oxygen %	CO2 ppm
CO2	0.000					
KCL	-0.000	0.000				
Delta T Orig	-0.000	0.000	-0.000			
Oxygen %	-0.894	-0.014	-0.009	-0.206		
CO2 ppm	-0.022	0.832	0.067	0.295	-0.080	
KCL %	-0.007	-0.029	0.690	0.574	-0.104	0.209

Figure 38: Correlations for all design variables

Additionally, in terms of the type of fruit either being a banana or an avocado, the optimal Carbon ppm within the compartment can be calculated using the regression equations shown below in Figure 39, as a function of Argon, Carbon, KCl, and time variables.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2470.17	88.99%	88.98%	88.97%

Regression Equation in Uncoded Units

Fruit			
Avocado	CO2 ppm	=	-435.0 - 0.242 Argon + 9.439 CO2 - 4.98 KCL + 3.3221 Delta T Orig - 0.001441 Delta T Orig*Delta T Orig - 0.004111 Argon*CO2 + 0.01999 Argon*KCL + 0.001580 Argon*Delta T Orig + 0.008676 CO2*Delta T Orig + 0.014065 KCL*Delta T Orig
Banana	CO2 ppm	=	-161.5 - 4.273 Argon + 9.439 CO2 - 4.98 KCL + 3.6610 Delta T Orig - 0.001441 Delta T Orig*Delta T Orig - 0.004111 Argon*CO2 + 0.01999 Argon*KCL + 0.001580 Argon*Delta T Orig + 0.008676 CO2*Delta T Orig + 0.014065 KCL*Delta T Orig

Figure 39: Model Summary & Regression Equations for Carbon ppm

As demonstrated in the regression equations in Figure 39, the optimal Carbon values within the packaging system while using either an avocado or a banana can be calculated using these equations as a function of the Argon, Carbon, KCl, and time variables. In addition, the R-squared for the Carbon ppm shows a high value of 88.98%

as a function of the design variables, meaning that roughly 89% of the change in Carbon ppm values are driven by the Argon, Carbon, KCl, time, and type of fruit. Moreover, the variable with the strongest effect on the Carbon ppm is the Carbon gas itself, which is represented by a strong positive correlation with a value of 0.832, as displayed in Figure 38. This positive relationship also shows that as Carbon gas is pumped into the packaging system, the values for the Carbon ppm rises as well.

Lastly, a response surface regression analysis for the relative humidity was performed where the design variables chosen were Argon, Carbon, KCl, time, and the type of fruit, and at which the analysis results can be seen in Figure 40.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.838930	99.32%	99.32%	99.32%

Regression Equation in Uncoded Units

Fruit			
Avocado	RH %	=	23.2147 + 0.001792 Argon - 0.003896 CO2 - 0.010002 KCL - 0.001448 Delta T Orig + 0.000001 Delta T Orig*Delta T Orig + 0.000003 Argon*CO2 - 0.000037 Argon*KCL - 0.000001 Argon*Delta T Orig + 0.000002 CO2*Delta T Orig + 0.000209 KCL*Delta T Orig
Banana	RH %	=	22.6222 + 0.001307 Argon - 0.003896 CO2 - 0.010002 KCL - 0.001043 Delta T Orig + 0.000001 Delta T Orig*Delta T Orig + 0.000003 Argon*CO2 - 0.000037 Argon*KCL - 0.000001 Argon*Delta T Orig + 0.000002 CO2*Delta T Orig + 0.000209 KCL*Delta T Orig

Figure 40: Model Summary & Regression Equations for RH %

In order to calculate the optimal relative humidity value within the compartment depending on the fruit being a banana or an avocado, the regression equations as a function of the design variables are shown in Figure 40. Moreover, the model summary for the equations illustrates a high R-squared value of 99.32%, showing that almost all changes in the relative humidity are a function of the design variables. Additionally, the design variable that showed the highest correlation to the relative humidity, as well as a positive relationship, was the use of KCl powder, followed by the time variable as shown in Figure 40. With the correlation between the RH % and KCl powder being a high positive value of 0.69, this shows that by increasing the amount of the powder inside the packaging system, the values for the relative humidity increases. Moreover, time also seems to play a major role since as time progresses, the humidity within the compartment increases due not only to the effects of the KCl powder, but also the deterioration of the fruit, and this is depicted by the positive correlation value of 0.574.

Lastly, a response surface regression analysis was also executed in terms of the air quality measurements both inside and outside the compartment as a response variable, however, unlike the measurements inside the system where the design variables such as Argon, Carbon, and KCl plays a major role as will be displayed in the sections below, the design variables that are used for the outside measurements consist of only the time and type of fruit.

4.1.2. Response variable (AQM IN). For the first type of air quality analysis inside the packaging compartment, a Pareto chart in Figure 41 helps display which design variables had the strongest effect on the air quality measurements in order, including which interactions between variables as well.

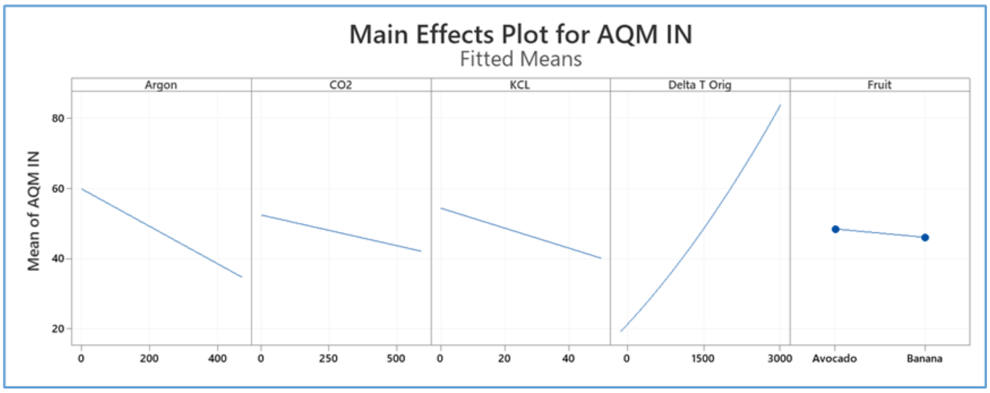

Figure 41: AQM IN Factorials Plots

As illustrated in Figure 41, the design variable with the highest effect on the AQM inside is time, which makes sense since as time progresses, so do the measurements for the air quality. Afterward, Argon comes next which shows that reducing the oxygen within the compartment played a major role in reducing the air quality measurements and had a large effect, followed by the use of KCl powder. Afterward, the interaction between the Argon and time, as well as the Argon and the type of fruit have strong effects on the air quality measurements, followed by the pumping of Carbon gas, and the variable with the least effect is concluded to be the interaction between Carbon and time. Moreover, the relationships between each of the design variables and the AQM IN can be seen in Figure 42 in the form of the main effects plot.

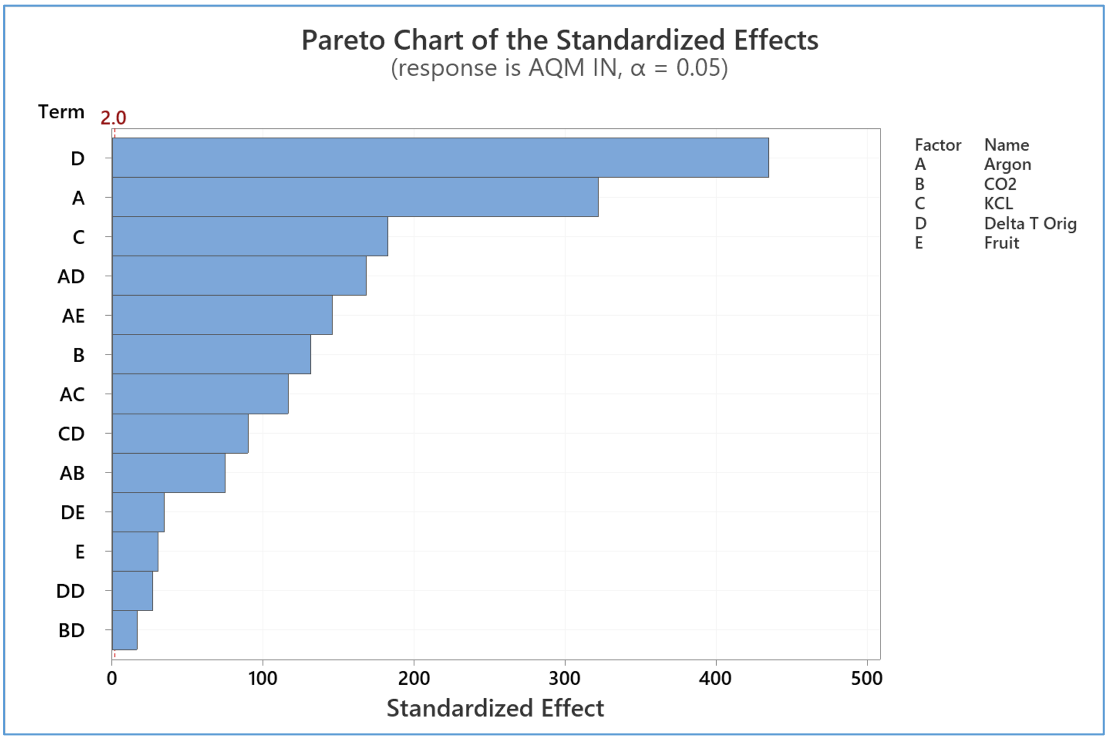

Figure 42: Pareto Chart for the Standardized Effects

Argon, Carbon, and KCl variables all follow a negative relationship in the main effects plot against the air quality measurements, which is correct since by increasing the Argon, Carbon, and KCl, the deterioration of the fruit decreases, and hence, the air quality measurements decrease as well. Additionally, time as a variable follows a positive relationship since as time progresses, so does the air quality measurements, while in terms of the type of fruit, the avocadoes respire and deteriorate faster than bananas, which is shown by the mean value of the avocado being higher than that of the banana. As for the interactions between each of the design variables, they are displayed in Figure 43.

Most of the design variables have no interaction with each other, however, the most notable interactions are revealed to be between the Argon and time each; in terms of the type of fruit. The first interaction between the Argon and the type of fruit helps show that as the Argon increases, its effects are on reducing the air quality is much higher on the banana than the avocado, which also supports the results in the main effects plot since it was proven that avocadoes respire and deteriorate faster than bananas as shown in Figure 43.

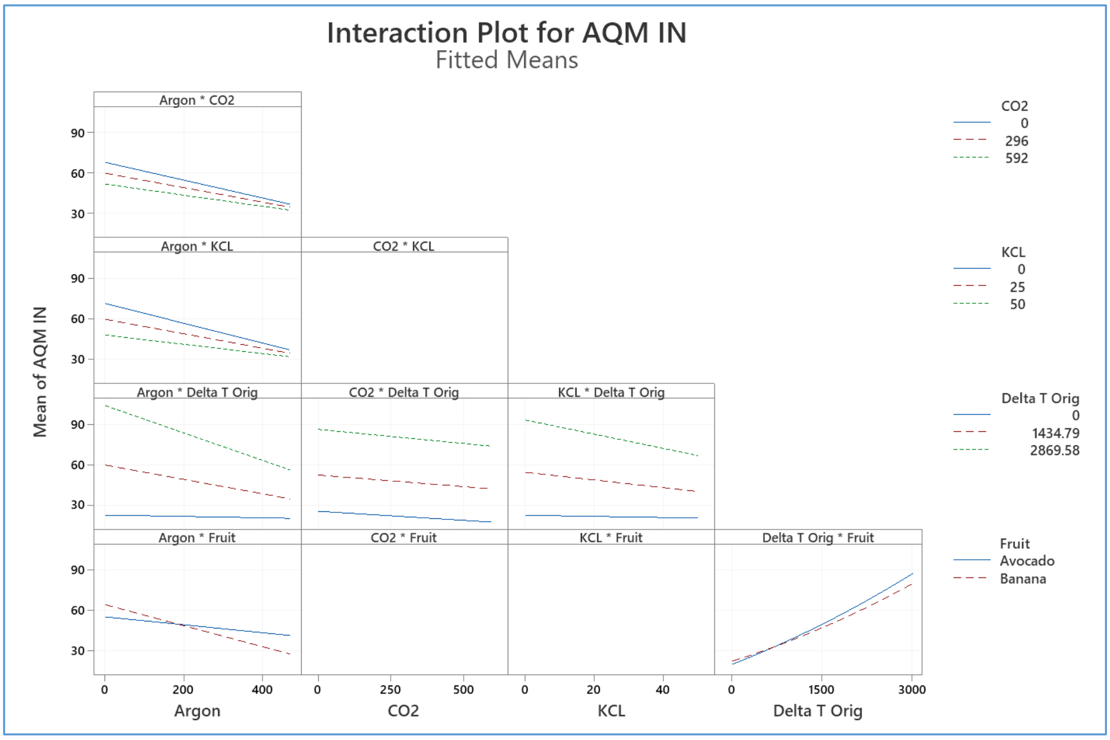

Figure 43: Interaction Plot for AQM IN

This is also proven in the interaction plot between time and the type of fruit, which shows that as time progresses, avocadoes respire more quickly than bananas. As for the regression equations for each type of fruit in terms of AQM IN, they are illustrated in Figure 44.

Regression Equation in Uncoded Units

Fruit			
Avocado	AQM IN	=	28.276 - 0.012634 Argon - 0.023476 CO2 - 0.22350 KCL + 0.030142 Delta T Orig + 0.000002 Delta T Orig*Delta T Orig + 0.000042 Argon*CO2 + 0.000775 Argon*KCL - 0.000034 Argon*Delta T Orig - 0.000003 CO2*Delta T Orig - 0.000170 KCL*Delta T Orig
Banana	AQM IN	=	41.937 - 0.061082 Argon - 0.023476 CO2 - 0.22350 KCL + 0.026902 Delta T Orig + 0.000002 Delta T Orig*Delta T Orig + 0.000042 Argon*CO2 + 0.000775 Argon*KCL - 0.000034 Argon*Delta T Orig - 0.000003 CO2*Delta T Orig - 0.000170 KCL*Delta T Orig

Figure 44: AQM IN Regression Equations

According to the regression equations, depending on the type of fruit whether it is a banana or an avocado, the air quality measurements by which we measure the deterioration of either fruit can be calculated using these equations as a function of the Argon, Carbon, KCl and time variables. Therefore, if a type of fruit (Banana or Avocado) is required to last 4 or 5 days, the optimal settings for each of the Argon, Carbon, and KCl values can be calculated using these regression equations. As for the model summary showing the fit for the equations in terms of the air quality measurements, it is illustrated in Figure 45.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.43554	95.62%	95.62%	95.62%

Figure 45: AQM IN vs All 4 Design Variables Model Summary

The R-squared between the air quality measurements inside the compartment and the design variables shows a strong fit with a high value of 95.62%, meaning that almost 96% of the changes in the AQM is being driven by the Argon, Carbon, KCl, time, and type of fruit variables.

4.1.3. Response variable (AQM Out). For this response surface analysis, a new DOE was created since the only variables that had an effect on the air quality measurements outside the packaging system were the type of fruit and time. Afterward, the Pareto chart for the standardized effects was measured for the air quality measurements outside the compartment as a response variable to the time and type of fruit factors and can be seen in Figure 46.

The Pareto chart in terms of the effects and their magnitude, also determined that time played the prime role in affecting the air quality measurements outside the compartment, followed by the type of fruit, and ending with the interaction between both the time and type of fruit. Additionally, the factorial plot for both variables can be seen in Figure 47.

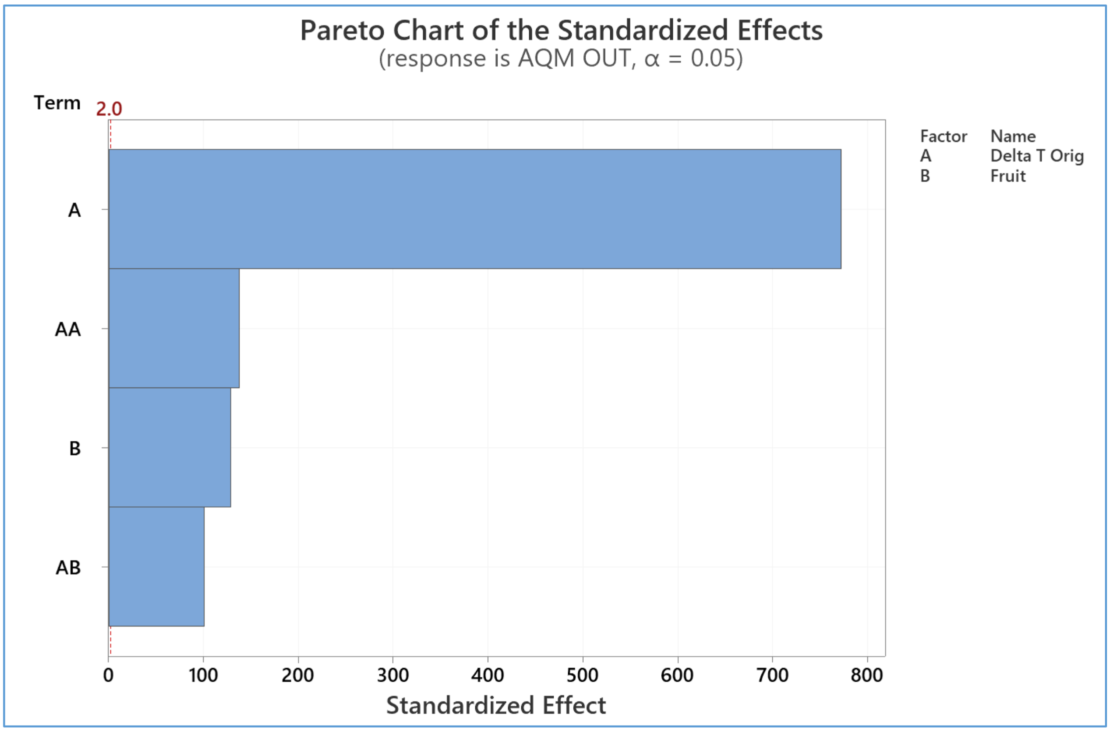

Figure 46: Model Summary & Pareto Chart for AQM Out

As illustrated in Figure 47, there is a positive relationship between time and the air quality measurements outside, which is correct since as time progresses, so does the air quality measurements. Also, the type of fruit plot shows that avocadoes deteriorate and respire faster than bananas, which is also supported in the factorial plots for the AQM In displayed in Figure 38. As for the regression equations for each of the fruits in terms of air quality measurements outside the packaging system, as well as the model summary depicting their fit, are all illustrated in Figure 48.

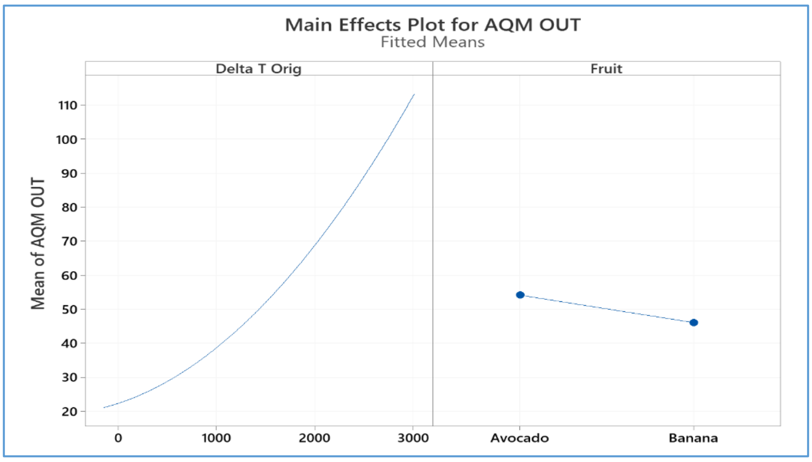

Figure 47: Factorial Plot for AQM Out

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.38068	98.30%	98.30%	98.30%

Regression Equation in Uncoded Units

Fruit			
Avocado	AQM OUT	=	20.923 + 0.013275 Delta T Orig + 0.000007 Delta T Orig*Delta T Orig
Banana	AQM OUT	=	23.770 + 0.005663 Delta T Orig + 0.000007 Delta T Orig*Delta T Orig

Figure 48: Model Summary & Regression Equations for AQM OUT

According to the regression equations, depending on the type of fruit whether it is a banana or an avocado, the air quality measurements by which we measure the deterioration of either fruit outside the compartment can be calculated using these equations as a function of time. The model summary also concluded that 98.3% of the change occurring to the air quality measurements outside the compartment; are a direct result of the design variables being only the time, which makes sense since no other variable had a hand in affecting the fruits’ respiration but the progression of time itself.

4.1.4. AQM (In vs. Out) comparison. Moreover, to prove that the average value for the air quality measurements outside the system is much higher than the values of the measurements inside, a Paired T-Test was conducted using Minitab, where the results are shown in Figure 49.

In the Paired T-Test results displayed above, the null hypothesis states that the mean difference of the air quality measurements is 0, whereas the estimate for the paired difference in the means of air quality measurements is -14.905. In addition, the results state that there is a 95% confidence that the paired difference in the means is between -15.176 and -14.634, especially since that the p-value shown is less than the significance level of 0.05, meaning that the null hypothesis is rejected and that there is a significant difference between the air quality measurements inside and outside the packaging system. This can also be seen in the descriptive statistics section of the paired-t test results, where the mean of the air quality measurements outside the system (55.622) is much higher than the measurements inside the compartment (40.717), concluding that the packaging system implemented not only improved the air quality within the compartment but also helped extend the shelf life of the fruit.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
AQM IN	12129	40.717	20.928	0.190
AQM OUT	12129	55.622	25.910	0.235

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
-14.905	15.228	0.138	(-15.176, -14.634)

μ_difference: population mean of (AQM IN - AQM OUT)

Test

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference ≠ 0

T-Value	P-Value
-107.80	0.000

Figure 49: Paired-T Test for both Air Quality Measurements

Chapter 5. Economic Analysis

For this chapter, we will be conducting an economic analysis in which we attempt to estimate the public price for the packaging compartment if sold to large families, particularly a family of 5, as well as the benefits those families would receive from purchasing it in terms of savings. The economic analysis will help determine the Internal Rate of Return (IRR) as well as the Net Present Value (NPV) for the packaging compartment. The period for the analysis was done over 4 years in terms of 3 months each (Quarterly), and the Minimum Acceptable Rate of Return (MARR), as well as the Inflation, were taken into consideration in terms of a Quarterly period instead of Annually. Moreover, the device parts costs', operations, and maintenance costs, as well as savings will be calculated individually as seen in the sections below.

5.1. Investment

The total estimated selling price for the whole system consisted mainly of 3 measures, the purchasing costs of the parts, the material, and manufacturing costs, as well as packaging costs, which are all illustrated in Table 8.

In terms of the device parts, the costs of all the components consisted mainly of the Gas cylinders used for the air composition regulation, the sensors used for monitoring the variables, the gas valves, KCl powder for RH regulation, and other parts including insulation tape, hoses, and fittings. Also, the original prices were added for the gas cylinders and sensors as well as the discounts if the products were bought in bulk, which consists of 10% given by the gas cylinder suppliers, and 5% for the sensors.

Moreover, the materials considered for building the compartment consisted of aluminum sheets roughly [92 x 92cm] priced at 80 dirhams, while also using a [24 x 36cm] hardened plexiglass for visibility; priced at 35 dirhams. In terms of manufacturing costs, labor costs were approximated at 2000 AED a month for the worker, hence, 9.5 AED per hour, which totaled 38 AED as a result of requiring 4 hours in total to build and assemble the compartment. Additionally, manufacturing overhead averaged at 35% of production costs as stated by the Harvard Business Review [34], therefore, the overhead costs were calculated by summing the material and manufacturing costs, while taking 35% of it. Moreover, according to a study from Ohio State University, nowadays the cost of the packaging for the total product price varies greatly between 1.4 percent to 40 percent, hence, the average cost of packaging was defined at 9% of the amount you spend on any product [35].

Table 8: Estimated Total Cost for the Packaging

	Total Cost Investment							
1-	**Parts**				**Bulk Discount**			
	Argon Cylinder (2l)	110	aed		99	aed	**10%**	Gas Cylinders
	Carbon Cylinder (2l)	119	aed		107.1	aed	**10%**	Gas Cylinders
	Sensors	395	aed		375.25	aed	**5%**	Sensors
	Gas Valves, Gas hoses	85	aed					
	KCL Powder	25	aed					
	Insulation tape, Controller, Reducers & Fittings	70	aed					
2-	**Material Costs**							
	(Aluminum Sheets)	80	aed	[92 x 92cm]				
	(Plexi Glass)	35	aed	[24 x 36cm]				
3-	**Manufacturing Costs**							
	Labors cost - hourly wage	38	aed	[9.5aed/hr]				
	Overhead costs	53.55	aed			Manufacturing Overhead Average		35%
4-	**Packaging Costs**	48.395	aed			Packaging Costs		5%
	Total Investment for 1 System	**-1016.3**	**aed**			Average Margin for Appliances		20%

However, this value depends on the value of what is being packaged, hence, we considered 5% for the packaging costs. The final estimated selling price for the device totaled an amount of 1016.3 AED to build, assemble, manufacture, and package the compartment, while also including a 20% average margin for appliances over the total cost for retailers, hence, if sold, making them a profit of almost 200 AED. All in all, the estimated selling price for the packaging system falls within the budget we decided on in section 3.1.3 for the system requirements.

5.2. Operations and Maintenance Costs

To keep the system operating smoothly without any problems over the course of 4 years, multiples changes need to be implemented following cylinder refill and sensor changes which are shown in Table 9.

The time to regulate the air composition within the compartment was measured for each of the Argon and Carbon gases and was measured at approximately a minute each. Assuming that households will open the compartment 3 times a day, it was calculated that each of the gas cylinders will be opened and used for approximately 90 minutes each month, and hence, will require refilling each month once (Argon – 30

AED & Carbon – 35 AED). Therefore, a total of 65 AED will be spent each month or 195 AED each Quarter.

Table 9: Operations & Maintenance Costs

Operating & Maintenance Costs			
1-	**Cylinder Refills**		
	Argon Cylinder (2l)	30	aed
	Carbon Cylinder (2l)	35	aed
	SUM (per month)	**65**	**aed**
	SUM (per quarter)	**-195**	**aed**
2-	**Sensor Change**		
	Oxygen Sensor	165	aed
	Carbon Sensor	135	aed
	RH Sensor	15	aed
	SUM	**-315**	**aed**

As for the Arduino sensors, their life spans between an average of 2-3 years, therefore, the sensors are to be changed every 2 years or 8 Quarters. Additionally, the estimated total price for changing each of the sensors (Oxygen, Carbon & RH) will be totaled at 315 AED every 2 years.

5.3. Savings

For this analysis, each week over the course of a month, a different mixture of fruits is bought for a family of 5, where according to ReFED, fruits account for 19% of the waste produced by families' monthly, therefore, Table 13 in Appendix D displays 4 examples of fruits combinations for each week of the month in terms of the price, as well as savings in terms of petrol and time.

The total price for the fruits bought each week is at first summed, then multiplied by 19%, and that value is counted as the savings for that particular week. Moreover, the savings are all added for that month and multiplied by 3 to calculate the Quarterly savings. As for the savings in terms of petrol and time, we assumed a value of 20 AED to be the savings each week in terms of saving petrol as well as time to go out and shop for extra fruits, where the monthly savings are calculated at 80 AED. Hence, the total value in terms of quarterly savings amount to a value of 429.012 AED saved each Quarter. Last but not least, Table 14 in Appendix D shows the calculations for both NPV and IRR by adding the investment costs, operations and maintenances costs, and savings over the course of 4 years.

According to the final calculations at the end of the 4 years, the NPV value of 2,118 AED helps show that the projected earnings generated by this packaging system exceed the anticipated costs and that it will be profitable. In addition, with an IRR being positive with a value of 21.43%, it means that the system expects to return some value, and which shows that the fruit packaging system is an investment worth making and selling.

5.4. Sensitivity Analysis

After performing the economic analysis in terms of the investment costs, operations and maintenance costs, and savings, one final analysis was performed to check which inputs were the most sensitive to change in the form of a sensitivity analysis. As shown in Table 15 in Appendix D, the 3 inputs which have an effect on the output being the NPV, were Investment, O&M, and savings were highlighted. Also, the inflows and outflows similar to the economic analysis were added in order to help calculate the net cash flow as well as the NPV.

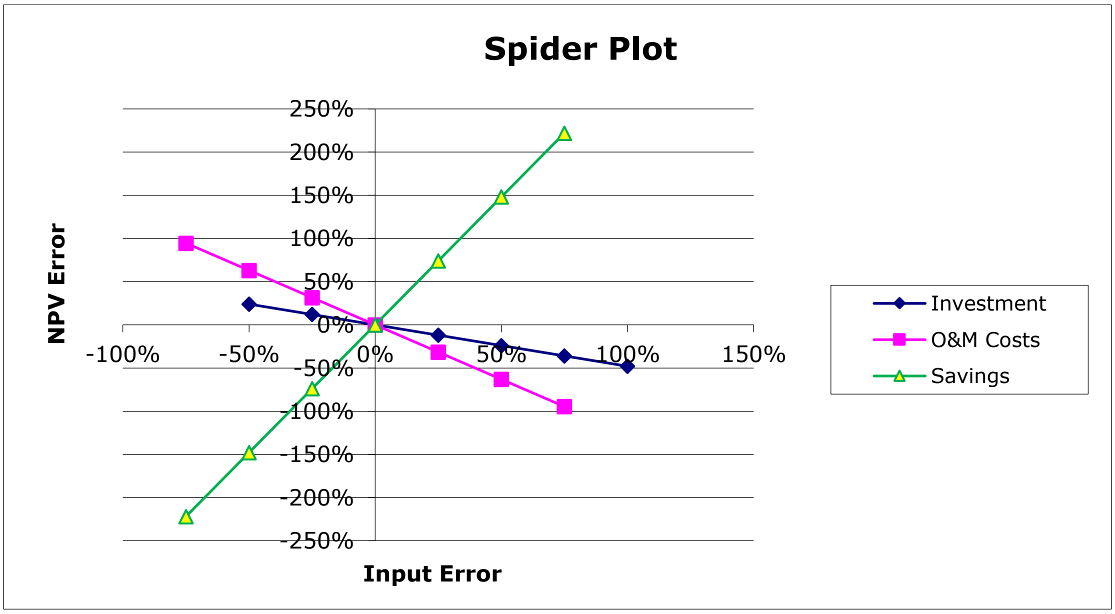

Figure 50: Spider Plot

According to the spider plot shown in figure 50 above, both inputs “Investment costs” and “O&M costs” have a negative relationship as opposed to the input “Savings”, that is due to the fact that both costs reduce the NPV as they increase while the savings increase the NPV. In addition, the input that is the most sensitive to change was the “Savings”, followed by “O&M costs” and “Investment costs” which is because the larger the slope is for a specific curve, the more sensitive that input is and vice versa. This can also be seen in the NPV error, since the higher the error is, the more that input is sensitive to change.

Chapter 6. Conclusion

In this thesis, the negative issues affecting the quality of fruits in terms of temperature, air composition, and humidity were studied along with the different types of active and intelligent packaging techniques. The fruit packaging system that was manufactured and setup using Arduino was able to regulate the Oxygen and Carbon levels as well as relative humidity through the use of gas cylinders and KCl powder. An experimental analysis was then conducted using bananas and avocadoes by which the shelf life of both fruits was doubled, and the color and quality of both fruits using RGB values were proven to act as an indicator for the fruits' deterioration.

A design of experiments (DOE) was then performed through a 2-level factorial using a ½ fraction or 8 runs, where an analysis of the data was conducted through Minitab in order to show the variability and correlation between the design variables and the response variables. The design variables assigned to the factorial runs consisted of the argon gas, Carbon gas, KCl powder, type of fruit, and time, where the response variables included the air quality measurements both inside and outside the system, as well as the oxygen %, humidity %, and Carbon ppm. The results helped display that 95.62% of the change in the air quality measurements inside the compartment are being driven by the design variables, where time had the biggest effect, and the least effective being the fruit type. As for the air quality measurements outside the system, where the design variables consisted of only time and the type of fruit, the results showed 98.30% of the change is being driven by these two variables, as well as time having the strongest effect. Additionally, the factorial plots for both air quality measurements helped show that in terms of avocadoes and bananas, avocadoes respire and deteriorate faster. Moreover, a paired t-test was conducted between the air quality measurements inside and outside the compartment and helped show that there is a significant difference in air quality between both measurements due to the null hypothesis being rejected, in addition to proving that the fruit packaging system helped reduce the deterioration of the fruits by showing that the AQM Out has a higher mean than the AQM In.

An economic analysis was also conducted to estimate the public price for the packaging compartment if sold to large families, particularly a family of 4 or 5, as well as the benefits those families would receive from purchasing it in terms of savings. The results presented a positive NPV with a value of 2,118 AED and an IRR value of 21.43%, which helped prove that the smart packaging system would return some value to the customer and that it is a positive investment worth venturing in.

In terms of commercializing the packaging system, multiple steps would be taken into consideration such as developing a marketing campaign to help target the families that can benefit from this system, create an advertising plan to analyze where do these families usually get their product information, and even develop a sales plan to help define strategies for setting sales targets for the ideal customers. As for future work, multiple other designs can be made and integrated for other food-related goods such as vegetables, dairy, fish, meat, and even pharmaceutical products. Besides, the system could also be scaled to be used within warehouses for different cold supply chain companies in order to continually help reduce the major issue of food wastage and greenhouse emissions on a global scale.

References

[1] J. Gustavsson, C. Cederberg, U. Sonesson, R. V. Otterdijk and A. Meybeck. *Global food losses and food waste – Extent, causes and prevention.* Rome, Italy: FAO, 2011, pp. 29.

[2] A. Stenmarck, C. Jensen, T. Quested and G. Moates. “Estimates of European food waste levels.” FUSIONS EU, Stockholm, Sweden, Rep. 23-29 , 2016. [Online]. Avalible: https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf

[3] D. Gunders. “Wasted: How America is Losing Up to 40 Percent of Its Food from Farm to Fork to Landfill.” *Natural Resources Defense Council,* vol. 24, pp. 26-29, 2017.

[4] G. Gerlock. “To End Food Waste, Change Needs to Begin at Home.” Internet: https://www.npr.org/sections/thesalt/2014/11/17/364172105/to-end-food-waste-change-needs-to-begin-at-home, Nov. 17, 2014 [Apr. 12, 2020].

[5] K. Yam, P. Takhistov and J. Miltz. “Intelligent packaging: concepts and applications.” *Journal of Food Science,* vol. 70, no. 1, 2005.

[6] T. Janjarasskul and P. Suppakul. “Active and intelligent packaging: The indication of quality and safety.” *Critical Reviews in Food Science and Nutrition,* vol. 58(5), pp. 808-831, Mar. 2018.

[7] J. Ayala-Zavala, S. Wang, C. Wang and G. Gonzalez-Aguilar. “Effect of storage temperatures on antioxidant capacity.” *LWT - Food Sci. Technol,* vol. 37, pp. 687-695, Dec. 2004.

[8] “Storage of fresh fruit and vegetables | Agriculture and Food.” Internet: https://www.agric.wa.gov.au/fruit/storage-fresh-fruit-and-vegetables?page=0%2C0, Aug. 10, 2016 [Feb. 2, 2020].

[9] A. Shirazi and A. C. Cameron. “Controlling Relative Humidity in Modified Atmosphere Packages of Tomato Fruit,” *HORTSCIENCE,* vol. 27, no. 4, pp. 336-339, Oct. 1992.

[10] M.-J. Dumont, V. Orsat and V. Raghavan. “Reducing Postharvest Losses.” *Emerging Technologies for Promoting Food Security,* vol. 7, pp. 135-136, 2016.

[11] S. Bodbodak and M. Moshfeghifar. “Advances in controlled atmosphere storage of fruits and vegetables.” *Eco-Friendly Technology for Postharvest Produce Quality,* vol. 2, pp. 39-76, Dec. 2016.

[12] L. Vermeiren, F. Devlieghere, M. v. Beest, N. de Kruijf and J. Debevere. “Developments in the active packaging of foods.” *Trends in Food Science & Technology* , vol. 10(3), pp. 77-86, Oct. 1999.

[13] E. Han. "Food Science: Ethylene." Internet: https://www.thekitchn.com/food-science-ethylene-gas-130275, Oct. 21, 2010 [Feb. 2, 2020].

[14] K. Gast. "Storage Conditions: Fruits & Vegetables." *Postharvest Management of Commerical Horticultural Crops,* vol. 3, pp. 1-8, June 2001.

[15] S. Singh and M. S. Alam. "Preservation of fresh-cut fruits and vegetables: current status and emerging technologies," *Stewart Postharvest Review,* vol. 8, pp. 2-11, Mar. 2018.

[16] S. Sengupta. "Storing Your Vegetables In Plastic Bags? Here's Why You Need To Stop," Internet: https://food.ndtv.com/facts/storing-your-vegetables-in-plastic-bags-heres-why-you-need-to-stop-1729511. July 26, 2017. [May. 3, 2020].

[17] M. Ozdemir and J. D. Floros. "Active Food Packaging Technologies." *Crit. Rev. Food Sci. Nutrition,* vol. 44, no. 3, pp. 85-93, Feb. 2004.

[18] J. P. Smith, H. S. Ramaswamy and B. K. Simpson. "Developments in food packaging technology. Part II. Storage aspect.," *Trends in Food Science & Technology,* vol. 5, pp. 111-118, 1990.

[19] A. Blanco. "Oxygen Scavenger Technologies, Applications, and Markets: A Strategic Analysis for the Packaging Industry." *Plast. Eng.,* vol. 57, no. 8, p. 97, July 2001.

[20] N. Pathak, O. J. Caleb, C. Rauh and P. V. Mahajan. "Effect of process variables on ethylene removal by vacuum ultraviolet radiation: Application in fresh produce storage." *Biosystems Engineering,* vol. 15, pp. 33-45, Apr. 2017.

[21] M. L. Rooney. "Introduction to active food packaging technologies." *Innovations in Food Packaging,* pp. 63-79, Dec. 2005.

[22] J. P. Smith, J. Hoshino and Y. Abe. "Interactive packaging involving sachet technology." *Active Food Packaging, Springer US,* pp. 143-173, 1995.

[23] Anon. "Ensuring product freshness with new desiccant product." *Food Marketing and Technology,* vol. 10, pp. 75-77, 1995.

[24] A. Shirazi and A. C. Cameron, "Controlling Relative Humidity in Modified Atmosphere Packages of Tomato Fruit." *HortScience,* vol. 27, no. 4, pp. 336-339, Oct. 1992.

[25] C. L. Wilson. *Intelligent and Active Packaging for Fruits and Vegetables.* Florida, US: CRC Press, July 2007, pp. 75-77.

[26] M. Vanderroost, P. Ragaert, F. Devlieghere and B. (. i. F. S. &. T. 3. 4.-6. De Meulenaer, " Intelligent food packaging: The next generation." *Trends in Food Science & Technology,* vol. 39, no. 1, pp. 47-62, 2014.

[27] L. S. J. and A. T. Rahman. "Intelligent Packaging for Food Products." *Innovations in Food Packaging,* vol. 16, pp. 171-209, June 2014.

[28] J. P. Kerry, M. N. O'Grady and S. A. Hogan. "Past, current and potential utilization of active and intelligent packaging systems for meat and muscle-based products: A review." *Meat Science,* vol. 74, no. 1, pp. 113-130, Jan. 2006.

[29] M. Smolander. "Freshness Indicators for Food Packaging." S*mart Packaging Technologies for Fast Moving Consumer Good,* vol. 17, no. 1, pp. 111-127, 2008.

[30] A. I. S. and A. C. Stratakos. "Application of Modified Atmosphere Packaging and Active/Smart Technologies to Red Meat and Poultry: A Review." *Food Bioprocess Technol,* vol. 5, no. 5, pp. 1423-1446, May 2012.

[31] E. Hurme. "Detecting leaks in modified atmosphere packaging." *Novel Food Packaging Techniques,* vol. 13, pp. 276-186, Jan. 2003.

[32] T. Hareendran. "How To Use MQ-135 Gas Sensor." Internet: https://www.codrey.com/electronic-circuits/how-to-use-mq-135-gas-sensor/. July 2, 2000 [Sept. 27, 2020].

[33] D. Reneker. "PLC vs. Arduino for industrial control." Internet: https://www.controldesign.com/articles/2017/arduino-vs-plc-for-industrial-control, July. 13, 2017 [May 13, 2020].

[34] T. Arwal. "EDGEFX Kits." Internet: https://www.edgefxkits.com/blog/arduino-technology-architecture-and-applications, Sept. 18, 2017 [Apr. 26, 2020].

[35] J. G. Miller and T. E. Vollmann. "The Hidden Factory." *Harvard Business Review,* vol. 22, no. 4, pp. 1-12, Sept. 1985. Accessed on: Nov. 24, 2020. [Online]. Availible: https://hbr.org/1985/09/the-hidden-factory#.

[36] P. Hook and J. E. Heimlich. "Purposes of Packaging." *A History of Packaging,* vol. 7, pp. 17-23, May 2017.

Appendix A

Arduino Code for the Packaging Compartment

```
#include <dht.h>
//Library for the Humidity & Temp. Sensor
//#include "CarbonSensor.h"   //Library for the Carbon Sensor
#include "DFRobot_OxygenSensor.h"
//Library for the Oxygen Sensor
#include <SD.h>   //Library for the SD card
#include <SPI.h>  //Library for the SPI function

#define COLLECT_NUMBER    10
// Input function for the SD card adaptor
#define Oxygen_IICAddress ADDRESS_3

// Outputs
#define Ar_VALVE 4
#define Carbon_VALVE 2
#define EXIT_VALVE 8

// Inputs
#define HUMIDITY_SENSOR 7
dht DHT;
DFRobot_OxygenSensor Oxygen;


#define BASE 0          //State of perfect equilibrium so all valves are
closed
#define EXHAUST_Oxygen 1    //State of high Oxygen, so open exit and argon
valves
#define RAISE_Carbon 2     //State of low Carbon, so open Carbon valve


// CODE FOR Carbon SENSOR
#define         MG_PIN                       (A0)
//define which analog input channel you are going to use
#define         BOOL_PIN                     (2)
#define         DC_GAIN                      (8.5)
//define the DC gain of amplifier

/***********************Software                                  Related
Macros************************************/
#define         READ_SAMPLE_INTERVAL         (50)
//define how many samples you are going to take in normal operation
#define         READ_SAMPLE_TIMES            (5)
//define the time interval(in milisecond) between each samples in
//normal operation

/**********************Application                               Related
Macros**********************************/
```

```
//These two values differ from sensor to sensor. user should determine
this value.
#define         ZERO_POINT_VOLTAGE           (0.220)
//define the output of the sensor in volts when the concentration of
Carbon is 400PPM
#define         REACTION_VOLTGAE             (0.030)
//define the voltage drop of the sensor when moving the sensor from air
into 1000ppm Carbon

/***************************Globals********************************
*************/
float                                            CarbonCurve[3]        =
{2.602,ZERO_POINT_VOLTAGE,(REACTION_VOLTGAE/(2.602-3))};

//two points are taken from the curve.

//with these two points, a line is formed which is
                                                     //"approximately
equivalent" to the original curve.

//data format:{ x, y, slope}; point1: (lg400, 0.324), point2: (lg4000,
0.280)

//slope = ( reaction voltage ) / (log400 â€“log1000)

float MGRead(int mg_pin)
{
    int i;
    float v=0;

    for (i=0;i<READ_SAMPLE_TIMES;i++) {
        v += analogRead(mg_pin);
        delay(READ_SAMPLE_INTERVAL);
    }
    v = (v/READ_SAMPLE_TIMES) *5/1024 ;
    return v;
}

int  MGGetPercentage(float volts, float *pcurve)
{
   if ((volts/DC_GAIN )>=ZERO_POINT_VOLTAGE) {
      return -1;
   } else {
      return pow(10, ((volts/DC_GAIN)-pcurve[1])/pcurve[2]+pcurve[0]);
   }
}

int state = BASE;
float Oxygen = 0;
float Carbon = 0;
int Humidity = 0;

// SD card Code
int CS_PIN = 10;
```

```
File file;

void initializeSD() {
  Serial.println("Initializing SD card...");
  pinMode(CS_PIN, OUTPUT);

  if (SD.begin()) {
    Serial.println("SD card is ready to use.");
  } else {
    Serial.println("SD card initialization failed");
    return;
  }
}

int writeToFile(String text) {
  if (file) {
    file.println(text);
    Serial.println("Writing to file: ");
    Serial.println(text);
    return 1;
  } else {
    Serial.println("Couldn't write to file");
    return 0;
  }
}

int createFile(char filename[]) {
  file = SD.open(filename, FILE_WRITE);


  if (file) {
    Serial.println("File created successfully.");

writeToFile("Oxygen,Carbon,HUMIDITY,Ar_VALVE,Carbon_VALVE,EXIT_VALVE,ST
ATE");
    return 0;
  } else {
    Serial.println("Error while creating file.");
    return 1;
  }
}

void closeFile() {
  if (file) {
    file.close();
    Serial.println("File closed");
  }
}

//Changing state
void setState(int nextState) {
  Serial.println("Exiting state " + String(state) + "... Entering state
" + String(nextState));
  //Closing all valves
```

```
  digitalWrite(EXIT_VALVE, 1);
  digitalWrite(Ar_VALVE, 1);
  digitalWrite(Carbon_VALVE, 1);
  state = nextState;
}

// Read the Carbon Sensor Data
float readCarbon() {
  int percentage;
  float volts;
  volts = MGRead(MG_PIN);
  percentage = MGGetPercentage(volts,CarbonCurve);
  return percentage;
}

// Raed the Oxygen Sensor Data
float readOxygen() {
  return Oxygen.ReadOxygenData(COLLECT_NUMBER);
}

// Read the Humidity Sensor Data
int readHumidity() {
  int chk = DHT.read11(HUMIDITY_SENSOR);
  return DHT.humidity;
}

void base() {
  Oxygen = readOxygen();
  Carbon = readCarbon();
  Humidity = readHumidity();

//If Oxygen is above 4%, activate both argon & exit valves state
  if(Oxygen > 4 && state != EXHAUST_Oxygen ) setState(EXHAUST_Oxygen);
//If Carbon is below 1% or 10000ppm, activate Carbon valve state
  else if (Carbon < 10000 && state != RAISE_Carbon && state !=
EXHAUST_Oxygen) setState(RAISE_Carbon);
}

//If Oxygen is above 4%, close both exit & argon valves, and move to the
Carbon stage
void exhaustOxygen() {
  if (Oxygen <= 4) {
    setState(RAISE_Carbon);
    return;
  }
  digitalWrite(EXIT_VALVE, 0);  // Exit Valve Valve close
  digitalWrite(Ar_VALVE, 0);    // Argon Valve close
}


void raiseCarbon() {
  if(Carbon >= 10000) {    //If Carbon is greater than 1%, close Carbon
valve andmove to the BASE stage [Equilibrium]
    setState(BASE);
```

```
    return;
  };

  digitalWrite(Carbon_VALVE, 0);   // Carbon Valve Close
while(readCarbon() < 10000) {      // Wait for Carbon levels to rise if
above 10000ppm

    Serial.println(String(readOxygen())+ " " + String(readCarbon()) + "
"   +   String(readHumidity())   +   "   "   +   "$"   +   "   "   +
String(digitalRead(Ar_VALVE)) + " " + String(digitalRead(Carbon_VALVE))
+ " " + String(digitalRead(EXIT_VALVE)));
    delay(200);                 // Print the data in this manner
  }
}

void setup() {
  Serial.begin(9600);     //Baud Rate
  pinMode(BOOL_PIN, INPUT);
//set pin to input
  digitalWrite(BOOL_PIN, HIGH);
//turn on pullup resistors
  pinMode(EXIT_VALVE , OUTPUT);
  pinMode(Carbon_VALVE , OUTPUT);
  pinMode(Ar_VALVE , OUTPUT);
  digitalWrite(EXIT_VALVE, 1);
  digitalWrite(Carbon_VALVE, 1);
  digitalWrite(Ar_VALVE, 1);
  while(!Oxygen.begin(Oxygen_IICAddress)) {
    Serial.println("I2c device number error !");
    delay(1000);
  }
  Serial.println("I2c connect success !");
  //initializeSD();
  //createFile("data.csv");

}

// State check and control
void loop(){
  base();
  switch(state) {
    case EXHAUST_Oxygen:
      exhaustOxygen();
      break;
    case RAISE_Carbon:
      raiseCarbon();
      break;
    default:
      Serial.println("Perfect STATE");
  }

// Final code print for all the data variables
  Serial.println(String(Oxygen)+  ",  "  +  String(Carbon)  +  ",  "  +
String(Humidity)  +  ",  "  +  String(digitalRead(Ar_VALVE))  +  ",  "  +
```

```
String(digitalRead(Carbon_VALVE))        +        ",         "        +
String(digitalRead(EXIT_VALVE)) +", "+String(state));
  delay(3000);
```

Appendix B

RGB Values for each of the colors and their averages

Table 10: RGB Data points for each fruit

Date	Day	Fruit Type	In or Out	AQM	Red1	Green1	Blue1	Red2	Green2	Blue2	Red3	Green3	Blue3
15-Oct	Thursday	Banana	IN	**27**	222	196	92	195	188	68	236	205	116
18-Oct	Sunday	Banana	IN	**29**	197	167	67	192	159	63	222	193	89
19-Oct	Monday	Banana	IN	**30**	185	142	55	156	145	61	172	127	83
22-Oct	Thursday	Banana	IN	**33**	121	78	48	130	126	55	144	112	75
15-Oct	Thursday	Banana	OUT	**32**	246	216	75	226	198	59	229	186	79
18-Oct	Sunday	Banana	OUT	**85**	141	100	27	156	119	47	162	125	57
19-Oct	Monday	Banana	OUT	**104**	74	62	39	51	42	30	39	29	31
22-Oct	Thursday	Banana	OUT	**113**	51	43	31	31	30	24	31	28	16
22-Oct	Thursday	Avocado	IN	**29**	157	179	117	154	180	77	155	173	106
25-Oct	Sunday	Avocado	IN	**48**	164	177	89	148	174	74	143	164	87
26-Oct	Monday	Avocado	IN	**57**	123	142	85	129	146	87	99	109	55
1-Nov	Sunday	Avocado	IN	**130**	101	115	69	108	133	66	76	86	53
5-Nov	Thursday	Avocado	IN	**178**	67	76	59	65	83	45	54	62	63
22-Oct	Thursday	Avocado	OUT	**39**	181	197	122	172	191	118	174	192	129
25-Oct	Sunday	Avocado	OUT	**147**	120	131	68	102	124	45	117	112	44
26-Oct	Monday	Avocado	OUT	**184**	75	81	22	88	104	21	75	73	34
1-Nov	Sunday	Avocado	OUT	**385**	51	46	35	43	48	40	48	41	33
5-Nov	Thursday	Avocado	OUT	**530**	42	43	36	32	35	32	29	31	25

Table 11: Average and Sum for each RGB data color

Red Avg	Green Avg	Blue Avg	Sum_RGB
217.67	196.33	92.00	506.00
203.67	173.00	73.00	449.67
171.00	138.00	66.33	375.33
131.67	105.33	59.33	296.33
233.67	200.00	71.00	504.67
153.00	114.67	43.67	311.33
54.67	44.33	33.33	132.33
37.67	33.67	23.67	95.00
155.33	177.33	100.00	432.67
151.67	171.67	83.33	406.67
117.00	132.33	75.67	325.00
95.00	111.33	62.67	269.00
62.00	73.67	55.67	191.33
175.67	193.33	123.00	492.00
113.00	122.33	52.33	287.67
79.33	86.00	25.67	191.00
47.33	45.00	36.00	128.33
34.33	36.33	31.00	101.67

Appendix C

Sample of the first factorial run results.

Table 12: Results Sample for a factorial run

Argon	CO2	KCL	Fruit	Delta T Orig	Oxygen %	CO2 ppm	KCL %	AQM IN	AQM OUT
470	592	50	Avocado	0.00	20.74	1899	23	27	25
470	592	50	Avocado	1.18	20.74	1281	23	27	25
470	592	50	Avocado	2.37	20.74	1938	23	27	25
470	592	50	Avocado	3.55	20.74	1950	23	27	25
470	592	50	Avocado	4.73	20.74	1408	23	27	25
470	592	50	Avocado	5.92	20.74	1789	23	27	25
470	592	50	Avocado	7.10	20.74	1375	23	27	25
470	592	50	Avocado	8.28	20.74	1925	23	27	25
470	592	50	Avocado	9.47	20.74	1483	23	27	25
470	592	50	Avocado	10.65	20.74	1847	23	27	25
470	592	50	Avocado	11.83	20.74	1191	23	27	25
470	592	50	Avocado	13.02	20.74	1608	23	27	25
470	592	50	Avocado	14.20	20.74	1620	23	27	25
470	592	50	Avocado	15.38	20.73	1178	23	27	25
470	592	50	Avocado	16.57	20.73	1971	23	27	25
470	592	50	Avocado	17.75	20.73	1563	23	27	25
470	592	50	Avocado	18.93	20.73	1450	23	27	25
470	592	50	Avocado	20.12	20.73	1109	23	27	25
470	592	50	Avocado	21.30	20.73	1666	23	27	25
470	592	50	Avocado	22.48	20.73	1200	23	27	25
470	592	50	Avocado	23.67	20.73	1358	23	27	25
470	592	50	Avocado	24.85	20.73	1646	23	27	25
470	592	50	Avocado	26.03	20.73	1799	23	27	25
470	592	50	Avocado	27.22	20.73	1879	23	27	25
470	592	50	Avocado	28.40	20.73	989	23	27	25
470	592	50	Avocado	29.58	20.73	1230	23	27	25
470	592	50	Avocado	30.77	20.73	1444	23	27	25
470	592	50	Avocado	31.95	20.73	1454	23	27	25
470	592	50	Avocado	33.13	20.73	1423	23	27	25
470	592	50	Avocado	34.32	20.73	1647	23	27	25
470	592	50	Avocado	35.50	20.73	1259	23	27	25
470	592	50	Avocado	36.68	20.73	1689	23	27	25
470	592	50	Avocado	37.87	20.73	1883	23	27	25
470	592	50	Avocado	39.05	20.73	1229	23	27	25
470	592	50	Avocado	40.23	20.73	1161	23	27	25
470	592	50	Avocado	41.42	20.73	1857	23	27	25
470	592	50	Avocado	42.60	20.73	1556	23	27	25
470	592	50	Avocado	43.78	20.73	1898	23	27	25
470	592	50	Avocado	44.97	20.73	1681	23	27	25
470	592	50	Avocado	46.15	20.73	1379	23	27	25
470	592	50	Avocado	47.33	20.73	1446	23	27	25

Appendix D

Economic Analysis Calculations

Table 13: Fruit, Petrol & Time Savings

1-	**Fruit Saving (Week 1) - Fruit Cake**					
	1 kg of apples	14	aed			
	1 kg of bananas	4.5	aed			
	1 kg of clementine	18	aed			
	1kg of kiwi	20	aed			
	340g of blackberries and rasberries	49	aed			
	SUM	**105.5**	**aed**	Saving	**20.045**	**aed**
				19%		
2-	**Fruit Saving (Week 2) - Fruit Salad**					
	1kg of oranges	8.5	aed			
	1kg of kiwi	20	aed			
	170g of blueberries	21.25	aed			
	1kg of mangoes	30	aed			
	250g of strawberries	17	aed			
	SUM	**96.75**	**aed**	Saving	**18.3825**	**aed**
				19%		
3-	**Fruit Saving (Week 3) - Main Dishs**					
	2 pineapples	11.7	aed			
	2kg of pomegranates	21.25	aed			
	2 coconuts	10	aed			
	1kg of lemons	6.25	aed			
	SUM	**49.2**	**aed**	Saving	**9.348**	**aed**
				19%		
4-	**Fruit Saving (Week 4) - General**					
	1kg of plums	13.5	aed			
	1kg of nectarine	37	aed			
	1kg of pomelo	10	aed			
	0.5kg of avocadoes	14	aed			
	0.5kg of grapes	5.65	aed			
	SUM	**80.15**	**aed**	Saving	**15.2285**	**aed**
				19%		
5-	**Petrol & Time**	4	times per week			
	Petrol & Time	20	aed			
	SUM (monthly)	**80**	**aed**			
	Total Saving	**143.004**	**aed**	per month		
	Quarterly Savings	**429.012**	**aed**	per quarter		

Table 14: Economic Analysis

					Quarterly	**Monthly**	**Annually**
				MARR	0.0175	0.005833333	0.07
				Inflation	0.0075	0.0025	0.03
				Operating and Maintenance costs	-195		
				Savings or revenue	429.012		
				Investment	-1016.295		
Total of 4 years	Total Cost	None	Cylinder Refills, Sensors Life, etc..	Less Fruit wastage, Less trips (save petrol & time)			
Period Quarterly	Investment (Aed)	Annual payment	Operating and Maintenance costs	Savings	Net cash flow	Cum NPV	Note
0	-1016.295	0	0	0	-1016.295		
1		0	-195	429	234	-786.31	
2		0	-196	432	236	-558.58	
3		0	-198	435	238	-333.09	
4		0	-199	439	239	-109.82	
5		0	-201	442	241	111.26	
6		0	-202	445	243	330.16	
7		0	-204	449	245	546.92	
8		0	-205	452	247	761.54	
9		0	-541	455	-86	687.99	Added the New Sensors
10		0	-209	459	250	898.42	
11		0	-210	462	252	1,106.78	
12		0	-212	466	254	1,313.09	
13		0	-213	469	256	1,517.37	
14		0	-215	473	258	1,719.65	
15		0	-217	476	260	1,919.93	
16		0	-218	480	262	2,118.25	
					NPV	2,118	
					IRR	21.43%	

Table 15: Sensitivity Analysis

Input			Error
Investment Cost	1016.30	aed	0
O&M Costs	195.0	aed	0
Fixed OM (g)	7.5%	per quarter	0
Savings	429.00	aed	0
Fixed Savings (g)	7.5%	per quarter	0
Inflation	0.75%	per quarter	0
MARR	1.75%	per quarter	0
Periods	4	years	0
Output			
NPV	2118.43		

Sensitivity Analysis: Investment

Investment	Error	NPV	Error
508.15	-50%	2626.58	24%
762.22	-25%	2372.50	12%
1016.30	0%	2118.43	0%
1270.37	25%	1864.36	-12%
1524.45	50%	1610.28	-24%
1778.52	75%	1356.21	-36%
2032.60	100%	1102.13	-48%

Sensitivity Analysis: O&M Costs

O&M Costs	Error	NPV	Error
48.8	-75%	4122.70	95%
97.5	-50%	3455.06	63%
146.3	-25%	2786.06	32%
195.0	0%	2118.43	0%
243.8	25%	1450.11	-32%
292.5	50%	781.79	-63%
341.3	75%	113.47	-95%

Sensitivity Analysis: Savings

Savings	Error	NPV	Error
107.25	-75%	-2584.67	-222%
214.50	-50%	-1016.97	-148%
321.75	-25%	550.73	-74%
429.00	0%	2118.43	0%
536.25	25%	3686.13	74%
643.50	50%	5253.82	148%
750.75	75%	6821.52	222%

Period Quarterly	Outflows	Inflows	Net Cash Flow
0	1016.30	--	-1016.30
1	195.00	429.00	234.00
2	196.46	432.22	235.76
3	197.94	435.46	237.52
4	199.42	438.73	239.30
5	200.92	442.02	241.10
6	202.42	445.33	242.91
7	203.94	448.67	244.73
8	205.47	452.04	246.56
9	541.00	455.43	-85.57
10	208.56	458.84	250.28
11	210.13	462.28	252.15
12	211.70	465.75	254.05
13	213.29	469.24	255.95
14	214.89	472.76	257.87
15	216.50	476.31	259.80
16	218.13	479.88	261.75

Vita

Raed Zeabi was born in 1995, in Sharjah, United Arab Emirates. He received his primary education in Dubai, UAE, and his secondary education in Michigan, US. He received his B.Sc. degree in Mechanical Engineering from the American University of Sharjah in 2017.

In September 2018, he joined the Engineering Systems Management master's program at the American University of Sharjah as a graduate teaching assistant. His research interests are in materials sciences, cold supply chain management, and sustainable system development.