

BREE 495 - Design 3
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Smart Produce Packaging for Optimization of Quality and Safety

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Abstract

The packaging of bulk fruits and vegetables (F&V) is a complex step in the delivery of fresh produce. The Rwandan company, Food Bundle, is currently facing several issues with the packaging technology they currently use, which is paper bags, mostly due to its lack of effectiveness at retaining F&V's moisture content, directly impacting its freshness. Other factors induced by the current packaging, such as low mechanical strength and lack of products separation are also decreasing the quality of the fresh produce and causing the company to receive a high number of complaints from the customers. This repeated unsatisfactory feedback has led the company to reach out for innovative solutions and thus, the purpose of our project is to design a sustainable packaging material that should address these problems. Our design 3 journey involved a lot of iteration and prototype development based on the research conducted during our design 2. After comparing the social, economic, and environmental sustainability aspect of both cardboard and paper pulp materials using a Pugh chart, cardboard was selected as a viable solution suitable for Food Bundle. The samples were bought from Canadian Tire and the prototype was iteratively built which then was used to conduct an experiment. The purpose of the experiment was to analyse the performance of the cardboard material in maintaining the quality of fruits and vegetables- bananas, green peppers, cucumbers, mushrooms, and mangoes were tested- compared to a paper bag. After three days of experimentation, it was observed that commodities stored in a paper bag experience more heat injuries, severe moisture loss, decolouration, and overall lower market quality compared to those stored in cardboard. The thickness of the cardboard acted as a temperature barrier to the commodities inside and the perforation on it provided air circulation which controlled the gasses exchange inside the package. The design of the cardboard which contains inner separations avoided mechanical injuries and transmission of pathogens from one item to the other.

Keywords: packaging, fruits and vegetables, Food Bundle, moisture content, polylactic acid, cellulose-based cardboard, PLA biofilms, social, environment, economic, sustainability

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I. Introduction

In an era of rapid demographic expansion and global shift towards healthier lifestyles, fruits and vegetables have become a staple of our everyday diet, providing us with essential nutrients like vitamins, minerals, and dietary fiber. Due to the increase of F&V market, there have been emerging technologies in the packaging design industry to facilitate proper transportation and protection between all stakeholders involved, from farm to table. These include revalorized technologies such as recycled materials and newer solutions like biopolymers, such as polylactic acid plastic. As climate change justice movements continue to skyrocket, a lot of food manufacturing and delivering companies are driving towards greener packaging materials. Food delivery companies and grocery retailers adapted the use of other packaging materials that are recyclable, such as paper and plastic bags. However, these types of materials lack important properties that are crucial to maintain the quality of the commodities, for instance, barrier and mechanical properties. When Food Bundle, a new start up, entered the fruits and vegetables market in Rwanda in 2020, they delivered the products to their customers in paper bags which did not maintain the quality and led to customer complaints. Our group identified this problem as an opportunity for our capstone project and took on a challenge to design a solution for Food Bundle. The purpose of our project is to design a sustainable F&V packaging material for Food Bundle that meets their requirements in terms of quality and that contributes to their shift towards more eco-conscious practices.

This report outlines the steps followed in the design of our final packaging solution, starting with an overview on the client's issue and solution requirements in terms of quality, operational and health safety. Furthermore, the report explains post-harvest considerations, design approach, prototype building and testing, as well as the solution's sustainability analysis in terms of socio-economic and environmental aspects.

II. Problem Analysis

Area of study

Our client is currently based in Rwanda, a country located in the great lakes' region of central-east Africa (Lamek Nahayo, 2018). The country is well known for its quick recovery of the economy after the tragedy of the 1994 genocide. The government has put the goal of a healthy and clean environment a priority and since then, has made many drastic changes (Danielsson et al., 2017). They have banned single-use plastic bags in the whole country since 2008 (Behuria, 2021). In 2008, Kigali (Rwanda's capital) received a Scroll of Honor Award from the UN-Habitat in recognition of this environmental stewardship (Danielsson et al., 2017). The decision to eliminate

the use of plastic bags was fueled by harmful environmental and social impacts of the material, in addition to lacking proper recycling facilities in the country. This has had an impact on business in terms of packaging, including Food Bundle.

Plastic Bags

Plastics consist of about 60% to 80% of the global litter (Behuria et al., 2019). The majority of these wastes end up in aquatic habitats and only a small fraction gets recycled despite the growing public attention to the issue. Furthermore, “plastic bags take up to 1000 years to break down and photodegrade (rather than biodegrade)” (Behuria et al., 2019). They ultimately become microplastics which are very small pieces that are a threat to human life and the ecosystems. Thus, Rwanda has prohibited all manufacturing and importation of polythene bags which are the most commonly used types of plastic bags (Danielsson et al., 2017).

Furthermore, plastic bags are made of polyethylene which comes from petroleum, a non-renewable resource, that needs to be extracted and separated. It then undergoes multiple processes such as mixing, melting, and heating. During these stages, many toxic chemicals are released into the atmosphere (acetone, methylene chloride, trichloroethane). These toxic chemicals being emitted should not be disregarded since about a trillion plastic bags are produced each year due to their cheap prices and multipurpose form (Soomro et al., 2020). However, their waste is the most worrying aspect. In order to meet the requirements needed such as resistance to sunlight, many antioxidants are added during production which causes them to take longer to decompose. When thrown in landfills, the process takes even longer because they are less exposed to sunlight. This makes their impact worse as it increases their chances of piercing animal organs and causing deaths, especially in sea animals. Moreover, plastic bags have also been proven to clog sewage systems. Runoff water carries plastic bags from landfills and leads them to storm sewers which eventually get clogged and prevent correct drainage. Bad drainage leads to flooding, loss of agricultural crops, increased levels of pests and other socially unpleasant situations such as the disruption of traffic movement, water pollution leading to water borne diseases, and breeding sites for mosquitoes (Alom et al., 2014).

As-Is/ paper bags

Although paper bags have been claimed to be better alternatives than plastic bags, they still generate environmental impact during their production (Kristy Bell, 2011). The emission of toxic chemicals and use of fossil fuels is a source of distress in paper bag manufacturing. Even though paper bags are recyclable and compostable, it takes 91% less energy to recycle a pound of plastic bags than it takes to recycle a pound of papers (Bell et al., 2011). Moreover, due to their heavy weight, a lot of fuel is consumed during their transportation; “it would take 7 trucks to transport the same number of paper bags compared to a single truck full of plastic bags” (Ministry of Environment and Food of Denmark, 2018). The exact impact depends on the level of sustainability of the forest that is exploited and the way of handling as well as other factors.

Currently Food Bundle uses paper bags as an alternative to plastic bags for delivery of products to their customers. Although paper bags have better environmental benefits compared to plastics such as recyclability and composability, they have not been serving the company well due to their limitations in maintaining the quality of the products. It was reported that fruits packaged in paper bags can lose up to 9% of their sugar content Hong-xia Xu et al. (year). Fruits and vegetables contain many nutrient and non-nutrient molecules that have antioxidant properties. Paper bags can significantly reduce the amount of these antioxidants, which leads to discoloration and spoilage of the produce, not to mention reduction in organoleptic properties such as taste (Wohner et al., 2019). FoodBundle's customers have experienced these drawbacks of paper bags and complained to the company. In response, the founders called on for design proposals of a sustainable packaging material that would address these issues. Our team has been prototyping the material that is suitable for Food Bundle throughout the winter semester.

III. Post-Harvest Considerations

Due to their biological nature, fruits and vegetables can easily be subjected to spoilage as a result of physical, chemical and microbiological processes (Somogyi, Ramaswamy, & Hui, 1996). In addition to the fact that horticultural products are living organisms, the different steps underwent for post-harvest handling and distribution can also highly impact the quality and freshness of fruits and vegetables.

A. Moisture Loss

When dealing with fresh produce, the main parameter to assess remains moisture loss. Fruits and vegetables are high-moisture food items with a water content of approximately 90% (Robertson, 2010). Fresh produce with high moisture content are extremely prone to moisture loss once harvested since there is no water uptake system able to compensate for the water lost (Robertson, 2010). Loss of water content mainly occurs because of transpiration performed through the stomata, cuticle as well as through the periderm of the plant (tissue enveloping secondary stems) (Wu, 2010). For horticultural commodities, transpiration consists of the evaporation of water from produce's tissue to the surrounding environment, in accordance with physics principles of water vapor diffusion from a high-concentration medium to a low-concentration medium (Díaz-Pérez, 2010). Very little moisture loss is sufficient to cause water stress in horticultural produce tissues and seriously lower its quality. According to Robertson (2010), a decrease of 5% in water content is enough to cause significant damage to the textural properties of fruits and vegetables. Desiccation is responsible for a major decrease in the physical and nutritional properties of fruits and vegetables, weight loss, colour change, softening, wilting and shrinkage, in addition to loss of

flavour, aroma as well as a deterioration of the nutritional value of horticultural goods (Somogyi, Ramaswamy, & Hui, 1996).

Moisture loss differs from one horticultural product to another, as there are many parameters such as morphology, maturity stage, surface area to volume ratio, injuries that impact the rate of transpiration (Díaz-Pérez, 2010). Transpiration, for example, is inversely correlated to produce size, thus large fruits and vegetables will tend to transpire less than smaller products (Díaz-Pérez, 2010). In addition to these biological factors, environmental factors such as temperature and relative humidity have an impact on transpiration rates of horticultural commodities. High temperatures and a low relative humidity in post-harvest handling facilities and packaging, can lead to a significant increase in transpiration rates (Díaz-Pérez, 2010). Thus, leading to significant moisture loss.

B. Temperature

Temperature is another factor responsible for the disturbance of horticultural products quality. As previously mentioned, temperature can negatively impact the shelf-life and freshness of fruits and vegetables because of its ability to enhance the transpiration and respiration processes, leading to senescence (Díaz-Pérez, 2019). Robertson (2010) explains that an increase of 10°C is enough to significantly increase rates of respiration for raw fruits and vegetables. Moreover, an increase in temperature likely leads to an increase in enzymatic reactions and production of ethylene, which eventually hastens the maturation process, leading to over-ripening and a degradation of fruits and vegetables' quality (Somogyi, Ramaswamy, & Hui, 1996). On the other hand, if high temperatures pose a problem, low temperatures can also have a negative impact on horticultural commodities' freshness. Storing raw fruits and vegetables at temperatures lower than its freezing points might cause chilling injuries and lead to irreversible damages of textural, sensorial, and nutritional properties (Wu, 2010). Thus, when dealing with freshness of produce it is important to find a temperature balance that will prevent the increase of the rates of biological reactions, such as transpiration and respiration, while ensuring a high enough temperature to prevent freezing damages.

C. Respiration and ripening

Another important process impacting fruits and vegetables quality and correlated to temperature is respiration. Horticultural products such as climacteric fruits are able to continue the respiration process even after harvesting. Respiration is the reaction during which living organisms oxidize organic substrates (oxygen and glucose) to produce energy, releasing water and carbon dioxide (Somogyi, Ramaswamy, & Hui, 1996). The quality and freshness of these products is inversely correlated to the rate of respiration: the higher the rate, the lower the shelf-life and the quicker the senescence of the product (Wu, 2010). It is crucial to control the surrounding gas composition of the product, as quantities of O₂, CO₂ and ethylene can significantly slow down or increase the respiratory rate of fruits and vegetables (Wu, 2010). High amount of surrounding O₂ will lead to an increase in the respiratory rate and product deterioration; on the other hand, a lack of oxygen will cause spoilage, because the horticultural product will perform fermentation rather than respiration (Somogyi, Ramaswamy, & Hui, 1996).

Additionally, a high respiration rate is accompanied by a high production of ethylene through several enzymatic reactions, which will accelerate ripening of fruits and vegetables (Robertson, 2010). Ripening is the process occurring after the last stage of maturation and during which horticultural products undergo significant biochemical and physiological changes through metabolic reactions (Wu, 2010). The ripening process has been classified into two groups of fruits and vegetables: climacteric and non-climacteric. The first group's ripening is characterized by a high respiratory rate and ethylene production, meanwhile the latter consists in a stable decrease in respiration with no significant ethylene production (Wu, 2010). Ripening is responsible for the decline in extrinsic (colour and texture) and intrinsic (nutritional value) properties of fruits and vegetables (Robertson, 2010). Therefore, in order to decelerate ripening, the main challenge remains to control and ideally slow down the rate of respiration of horticultural products, which can be done by thoroughly assessing the surrounding environment's composition.

D. Physical injuries

Another risk factor to mitigate in order to enhance post-harvest quality of fruits and vegetables is physical damage. Mechanically induced damages often occur during handling and distribution; these are responsible for the deterioration of the physical aspect of the product, making it much less attractive to the consumer. In response to these tissue injuries, horticultural products have the tendency to increase their respiration rate and produce ethylene in much higher quantities, thus

accelerating the ripening process (Wu, 2010). Finally, the main issue caused by physical damage is an increased vulnerability to infections; pathogens penetrate plant tissues through lesions and bruising, leading to microbial spoilage (Somogyi, Ramaswamy, & Hui, 1996).

E. Microbial safety

The microbial control for fruits and vegetables is impacted by most of the parameters above and is one, if not the most important factor to control when it comes to the safety of these products. Microorganisms can either grow on the surface of the products or reach their inside, which poses a much bigger threat to their quality and safety for consumption (Somogyi, Ramaswamy, & Hui, 1996). In most cases, the microorganisms likely to infect produce are moulds and bacteria that will cause spoilage of produce but are unlikely to harm human health (Robertson, 2010). Fresh produce with enclosed tissues are considered to be resistant to microbial infection; however, when subjected to poor post-harvest handling conditions such as dehydration, temperature fluctuations, physical damage, and unbalanced air circulation, commodities become highly prone to pathogenic infection (Somogyi, Ramaswamy, & Hui, 1996). Pathogenic infection is usually made possible by the penetration of microorganisms inside the product through cuts and injuries; although, some rare pathogens possess the ability to directly permeate plant tissue (Wu, 2010). In even rarer cases, pathogens can infect the product before harvest and remain latent until they reactivate under their favourable growth conditions. This infection is referred to as quiescent infection (Wu, 2010). However, proper post-harvest handling practices can minimize or eliminate the risks of fresh produce being contaminated by microorganisms.

G. Handling and Storage Conditions

Climacteric fruits such as bananas, mangoes, and avocados, which are among Food Bundle's products, do not stop ripening after harvest. Their respiration rate increases with the increase of temperature. Maintaining the optimal temperature throughout the postharvest handling of fruits and vegetables has been a global challenge to attain (Brecht et al., 2003). Although Food Bundle receives most of their products ripe and ready to eat, it is important to consider storage and ripening conditions for some fruits since they keep the products at their warehouse for a short period of time, and the orders at the retailers for a few days before the customer picks them up. The average storage duration of Food Bundle products is 3 days and maximum 5 days. The products that stay

at the warehouse for five days are sold at a discount (Shikama, the founder). Since Food Bundle sources their products directly from different local farmers, they send quality controllers on field to check the quality and run the sorting procedure before supplying products to the company. Controlling the quality of fresh produce during harvesting ensures that the temperature is well-managed, such as shading the fruits to minimize heat exposure because fruits and vegetables respire at relatively higher rate at field temperatures (USDA handbook 66, reading material BREE 532). Once the products reach the warehouse, they undergo the handling process indicated in figure below; then, get delivered to the customers immediately. The products can be sold at a regular price within three days of reception while the quality is still high. However, some fruits come unripe and are kept at the warehouse until they are ready to be shipped. After completing the prototype of our designed cardboard, an experiment was carried out to analyse the impact of storage conditions on the packed fruits and vegetables. We compared the performance of a cardboard and a paper bag (current client's packaging) the same storage-environment conditions.

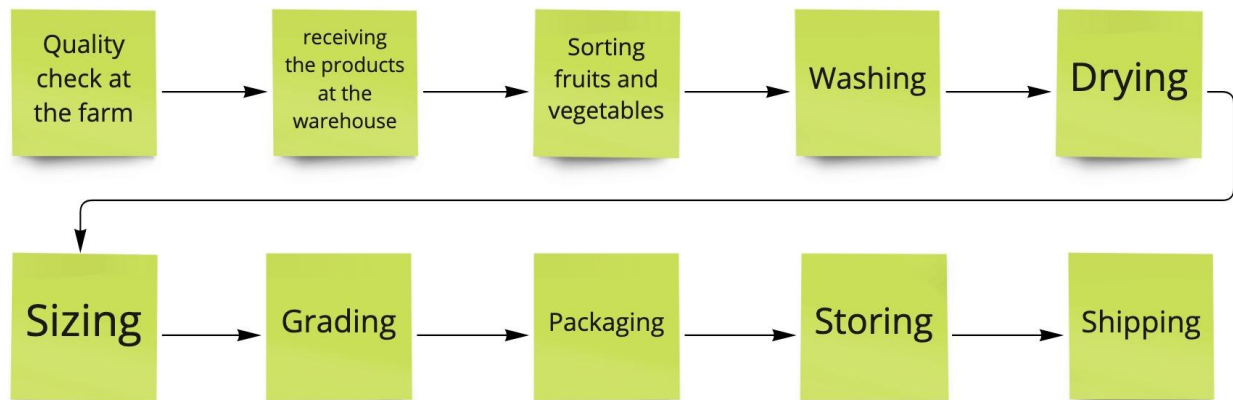


Figure: Packing House Operations of FOOD BUNDLE

IV. Design Approach

Last year, we weren't sure which material to choose between two; melded pulp, cellulose-based cardboard. The following paragraphs point out the reasons why we were interested in using them.

A. Materials

1. Moulded-Pulp Packaging

Moulded paper pulp packaging was first invented in 1903 by Canadian inventor Joseph Coyle, who designed it for packing eggs (Dey, Sengupta, Paramania, & Alam, 2020). This technology has ever since been widely used in the food industry for packaging bulk fruits and vegetables (Kim & Min, 2014). Food grade melded pulp articles mostly rely on the pulping process which consists of the extraction of cellulose fibers from raw material (Kim & Min, 2014). The technology is generally manufactured in four distinct steps as shown in Figure 2. The first step consists of slicing and mixing plant fibers (wood or sugar beet for example) or paper residues (recycled cardboard, newspaper...priorly purified to prevent contamination) with water in order to obtain a pulp paste (Dey, Sengupta, Pramanik, & Alam, 2020). Next, this fibrous paste, which contains approximately 96% of water, is pumped and spread in a meld of the desired shape before being wet pressed, which significantly reduces moisture content and leads to the compaction of the fibers into the packaging's shape. The final step is the drying of the meld to rid of any remaining water, the most used method being oven drying (Dey, Sengupta, Pramanik, & Alam, 2020).

Food grade paper pulp provides the food industry with many opportunities for quality preservation as well as significant socio-economic and environmental advantages, most especially for bulk fruits and vegetable packaging. Indeed, pulp packaging is extremely versatile and flexible, thus enabling the manufacture of specific shapes and dimensions able to meet the design requirements. Moreover, this technology has good mechanical characteristics while remaining low weight, easily printable, and customizable (Somogyi, Ramaswamy, & Hui, 1996). In addition to that, paper pulp containers are considered inexpensive to manufacture and possess lots of eco-friendly attributes like biodegradability, recyclability, and biocompatibility (Dey, Sengupta, Pramanik, & Alam, 2020).

The main drawback of this technology is its hydrophilicity, like most other paper-based packaging technologies. Indeed, moisture absorption and retention cause the packaging to become more vulnerable to physical damage, as the container loses rigidity and impact strength, thus significantly decreasing the quality of the products packaged (Somogyi, Ramaswamy, & Hui, 1996). There are, however, many features that can be added to the pulp packaging in order to make it waterproof and enhance its quality preservation attributes, some of these features include water-repellent waxes and coatings, as well as protective films (Somogyi, Ramaswamy, & Hui, 1996).

2. Cellulose-based cardboard

The development of extracting the useful cellulose fiber from wood pulp was established in 1867 (Kenneth R. Berger, 2000). Put simply, paper is a thin sheet of these cellulose fibers. Multiple advances and research on cellulose-based paper led to cardboard boxes and the corrugated cardboards we currently use in packaging. They are considered very practical for storing and transporting due to their lightweight, their strength, and their low cost.

According to Ayan Dey et al., cardboard packaging is made by mechanical and/or chemical processes. The mechanical process involves cleaning, grinding, and compacting (Dey Ayan, 2020). The first step is to wash the wood chips to remove impurities. The second step involves grinding which separates the fibers and reduces their length while also decreasing their strength. When the chemical process is done, the second step also involves the separation of the fibers with the lignin by heating and treating with chemicals. The chemical process also involves the addition of substances to increase the strength and purity of the item. For fresh F&V packaging, the sulphite additive process is used (Ayan et al., 2020). Food grade cellulose-based cardboard packaging for F&V has its sustainable benefits and disadvantages just like any other packaging product. It is greatly used for its strength which protects the fresh products from any mechanical damage during handling and delivery. However, due to its high-water absorption characteristic, any moisture retention can decrease its strength efficiency and injure the products. Nevertheless, this issue can be solved by adding coatings that will be discussed later. In addition, they are printable as well as recyclable, relatively compostable, and biodegradable making them low-cost eco-friendly packaging.

3. Final Choice of Material

By using the Pugh Chart analysis engineering tool, the 3 materials we were initially interested in (PLA, Cellulose-based cardboard, and Moulded-pulp), were ranked based on criteria that were placed from most important to least important, with a weight ranging from five to one. The criteria were ranked as such; microbial safety, moisture retention, maintenance of quality, and hardness, followed by environmental impact, cost-effectiveness, and manufacturability, and finally, with the lowest score, aesthetics, and printability.

After rating each material for each criterion, the winner of the Pugh Analysis was cellulose-based cardboard and the material clearly discarded was PLA. Even though the cardboard was clearly ranked higher, we were still leaning towards the moulded pulp as we believed some drawbacks, that have prevented the paper-pulp technology from ranking first in this analysis, could be mitigated through the addition of preservation enhancing features like protective coatings and films. However, this year, when we were looking for manufacturers, we found that creating a unique shape with the moulded-pulp material was too costly and some manufacturers said that for our design, it would not even be possible to mould such a structure.

We thus made the decision to go with **cellulose-based cardboard for our design**. Its characteristics will be enhanced by the addition of a biofilm which is explained in the next paragraph:

Biofilm

Biodegradable films are used for their gas permeability, nuclear magnetic resonance, antioxidant activity, microbiological and water activity characteristics (Di Matteo et al., 2021). They provide unique physical, mechanical and chemical properties such as simple processing, good functionality and their light weight (Bourakadi et al., 2021). A study done by Matteo et al. showed that biofilms made of polylactic acid (PLA) from corn starch are most suitable for fruits and vegetables packaging. The reason is that it has the lowest level of microorganisms' growth as compared to other alternatives, it keeps the total phenolic content and carotenoids of F&V preserved and overall, it increases time before spoilage. Moreover, it has moisture preservation characteristics as well as good mechanical strength. One downside is its low mechanical flexibility, but our final structure is stiff and does not require bending, thus, the lower mechanical flexibility is not an issue. PLA is an aliphatic polyester derived from 2-hydroxy propionic acid extracted from plant sources (Bourakadi et al., 2021); in the case of our project we went for a corn source based on the multiple studies that proved it to be most efficient cost-wise, antimicrobial-wise and physically.

In our design, the binding quality of the biofilm and the fact that they cannot be easily removed adds to its durability. The PLA biofilm will be coating the inside walls of our design as well as the separations that will be explained in the structure section of the report.

B. Structure

For the structure, we had to consider multiple aspects stated by our client. As previously mentioned, it is a delivery company of F&V bundles. The important features of their business that need to be carefully thought of when it comes to the structure of the packaging are the following:

(1) Bundles are **custom-made** and **unique**:

This feature can be classified as the most complex aspect of our design structure. Indeed, each customer of the Food Bundle company can make their own unique bundle with different types of F&V and different amounts of each chosen F&V. For example, one order can have 4 types of products with half a kilo each, whereas another can contain 4 kilos of 1 type of product. For this reason, as well as previously mentioned ones, it was practical for them to use plastic bags. Plastic bags are flexible in size and depending on how small or big the delivery, more or less plastic bags can be used without worrying about costs given their affordability. Thus, our structure will have to be as flexible as possible as to the amount of F&V and their separability. We also needed to keep in mind that the customizability needs to be quite simple to adjust so that the people assembling the bundles do not spend too much time on it.

(2) Orders are delivered in **bulk**:

This information is one reason why paper and plastic bags were not their best options. They currently deliver about 25 boxes, thus, during transportation, the F&V needs to resist weight and impact when the orders are stacked next to and on top of each other. The company is planning on expanding; this will lead to an increase in their orders and even more packages stacked more tightly during the process of delivery. For that reason, our structure will need to be impact resistant and able to support the weight.

(3) F&V can get **damaged** when in contact with each other:

For that reason, there is a need for separation between soft with high moisture content F&V and harder ones. For example, tree tomatoes can get damaged easily if smashed by avocados. A separation would decrease these risks. Moreover, the moisture loss of one fruit can damage the quality of another's. A sort of barrier is thus needed.

(4) **Handling** should be as little time-consuming as possible and should be suitable to all genders.

At the beginning of the winter 2022 semester, figure XX was our design suggestion. However, after building the prototype and testing it, we ended up with figures XXX as our final design.

As is shown in the figure, the overall structure is a simple box. When coming up with ideas, a unique shape with a puzzle-like structure for customizability was suggested, but later, when we started looking for manufacturers in the region close to our client we realized that the cost would be much higher if we didn't go for the original shape of a cardboard box. The reason is that manufacturers already have the equipment for that shape and creating a more complex one in bulk would require new machines that the small business we are working with are not yet able to pay for. Thus, we went for a cubic box and added the needed features to it.

Before discussing the special features, it is important to state that our client does not know what sizes he will need for the boxes. We had suggested 2 standard box dimensions based on the weight and size of the orders but when we met with the client, he asked us to provide him with a unit scale sketch. Thus, we removed our focus from the exact size of the final designs and went on with the special features.

For the ease of carrying we have two holes facing each other. They also serve as the aeration component for the upper part of the box. Holes in the bottom were also a necessity in case a separation was added in the middle. These holes' shape and size should be functional and practical without weakening the box to an unwanted extent. For the shape, an elongated oval was chosen as the design does not need a more complex shape. For the size, women's and men's hand sizes should be considered as well as potential gloves added during handling. The final dimensions chosen for the holes after researching standards as well as suitability for all genders are a length of 8.8 cm and a width of 3 cm.

When it comes to separation and compartmentalizing, it is of particular importance as it truly affects the quality of the F&V. In our initial and final designs, we have the same horizontal separation which was validated when we built the prototype. It is placed in the middle inside a hole in a very smooth, practical, and quick way and can also be omitted easily. Moreover, the separation is well supported due to the strength of the material chosen and its thickness. Thus, vertically, the box will only have the option to be divided in two.

However, for the vertical separations, we had planned on having some friction on the walls that would keep the added parts in place. They were quite stable but not to the point that could withstand a sudden severe break during transportation for example. For that reason, we changed our design to be separated diagonally which allowed the corners to assure the separations stability. These separations will come in 2 sizes; one that is the length of the box's side and another that is just half as long. That way, regardless of if the vertical separation is placed or not, the horizontal ones can fit.

Finally, based on the largest order in terms of weight and volume and after calculating the forces that will be applying pressure to the packaging, as well as testing the material (next section), we found that the needed thickness is about 2 cm for the box and the horizontal separation. However, for the diagonal separations, we found that the needed thickness is 2.5 cm to assure that it does not bend or move in any direction.

V. Package testing

Purpose and importance:

The most important part of the packaging is to ensure that the contents stay safe and of high quality during transportation and warehousing. In the case of our project, warehousing can last as long as 3 days with the worst conditions being in a market with no air conditioning in Rwanda where the temperature can reach a maximum of 30 degrees Celsius during the year.

If the products do not keep their quality before reaching the customer, the packaging is not considered efficient.

For that reason, testing the packaging is a crucial step to ensure that the company does not face rejections or a decrease in customers and purchases. Moreover, testing the design before manufacturing it on full scale and using it for deliveries can save time, and money and keep the customers happy.

We did two types of tests:

A) Testing for the moisture retention and physical appearance of the fruits and vegetables:
This can validate the performance of the material and air circulation that the packaging offers.

B) Testing for the strength of the box:
This assures no damage is done to the fruits and vegetables when encountering impacts during transportation and handling. It is important to make sure the fruits and vegetables don't smash into each other brutally or get smashed by the box itself.

A. Testing for the moisture retention and physical appearance of the fruits and vegetables

Materials & Methods

Six fruits and vegetables were chosen; mangoes, bananas, tomatoes, cucumbers, mushrooms and green peppers. They were bought in pairs at IGA and Provigo and washed to remove any coated chemicals since our client is looking for a packaging that does not require the fruits and vegetables to be coated with preservatives. They were then dried with a towel. Two types of packages were tested- the box that we created without the biofilm (since we did not acquire the material because of covid-19 and delays in delivery) and a paper bag, which is the current package used by Food Bundle- to compare their performance in maintaining the market quality of the commodities. The fruits and vegetables were then divided in two groups (with each group having identical types and number of F&V). We then took pictures of each product before placing each group in a different package. As mentioned previously, the warehousing can last as long as 3 days with the worst conditions being in a market with no air conditioning in Rwanda where the temperature can reach a maximum of 30 degrees Celsius. We carried our experiment at room temperature. The room

temperature varied with the outside ambient temperature which had an impact on the heat transferred through the packages. Then, the fruits and vegetables were taken out of their respective packages every day at the same hour (6 pm) for 3 consecutive days and photographed individually to observe the change in colour, texture, firmness and appearance (as shown in the results section). Moreover, the same types of products from the different packages were felt to compare how the moisture and stiffness had been affected by each of the 2 packages. (Optimally, if we had had the packaging material earlier, more professional materials would have been used for the testing of the moisture content of the fruits).

Results:

Day 0:

Cardboard Box	Paper Bag
 Same softness	 Same softness
 Same softness	 Same softness

 Same softness	 Same softness
 Same softness	 Same softness
 Same softness	 Same softness
 Same softness	 Same softness

Day 1:

Cardboard Box	Paper Bag
----------------------	------------------



Same softness



Same softness



Less soft than paper bag tomatoes



Softer than cardboard box tomatoes



Same softness



Same softness



Less soft than paper bag cucumber



Softer than cardboard box cucumber



Less soft than paper bag mango



Softer than cardboard box mango



Harder than paper bag mushrooms



Softer and their colour much darker + white hair like texture coming out of mushrooms

Day 2:

Cardboard Box

Paper Bag



Less soft than paper bag cucumber



Softer than paper bag cucumber



Less wrinkles and less soft than paper bag pepper



More wrinkles than cardboard box pepper and softer



Same softness, still having some green



Same softness but more ripe and yellow

 Less soft than paper bag mango	 Softer than cardboard box mango
 Less soft than paper bag tomatoes	 Softer than cardboard box tomatoes
 No white hair like texture coming out of mushrooms	 Softer than cardboard box and their colour much darker + white hair like texture coming out of mushrooms increased since day 1

Day 3:

Cardboard Box	Paper Bag
 Less soft than paper bag cucumber	 Softer than paper bag cucumber



Less wrinkles and less soft than paper bag pepper



More wrinkles than cardboard box pepper and softer



Same firmness



Same firmness but more ripe and yellow



Less soft than paper bag mango



Softer than cardboard box mango and colour has been damaged



Less soft than paper bag tomatoes



Softer than cardboard box tomatoes and more wrinkles

 No white hair like texture coming out of mushrooms	 Softer than cardboard box and their colour much darker + white hair like texture coming out of mushrooms increased since day 2 and a very strong door
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B. Testing for the strength of the box

Materials and methods

The drop test is important to make sure the packaging can bear accidental drops which are very common in handling practices and evaluate its capability of protecting the inner products from a shock too. This is how we proceeded to do the experiment; we let go of the box from a height of 2 meters. This is the height we chose because the box is too heavy to be stored higher and during transportation, our client currently only uses small trucks which have a maximum height of 2 meters. The box was thrown from different angles to make sure it doesn't tear apart or gets folded due to impact. This will assure that if ever it were to fall during transportation it does not get fully damaged and can still be delivered presentably to the customer. Moreover, given that the highest weight delivered by our client is 15 kg, we filled it up with 15 kg of products before testing it.

Unfortunately, due to delays in acquiring the material for the design, we were not able to do the following tests that would have been quite useful, but we plan on doing them before sending the final proposition to our client; the compression test and the transport worthiness and vibrations tests. These are done using specific machines and can further validate the package.

Results

Fortunately, before the 5th fall, our packaging did not get damaged and the inner separations did not move.

VI. Discussion

The results from day one revealed insignificant differences between the firmness, colour, and texture of peppers packaged in cardboard and those in a paper bag. Implying that the moisture loss was insignificant for the peppers due to less variation in room temperature on that day.

Tested tomatoes in both packages were red (full-ripe) uniform and shiny colour, no signs of mechanical injury, shrivelling, or decay. However, it was observed that tomatoes stored in paper bags were softer than in cardboard. The firmness of tomatoes in cardboard compared to those in a paper bag can be attributed to the retardation of ripening in cardboard due to the heat-barrier property of the material. The thickness of the cardboard is bigger than that of paper bag, which minimised the heat transferred through it; hence, ethylene produced by the tomatoes inside the paper bag was high which enhanced the ripening process. Thus, leading to the softness reported.

Similarly, bananas in the paper bag appear to be more ripe and yellow compared to those in cardboard due to the same factors of increased heat inside the paper bag regardless of both packages being stored at the same room temperature. Ethylene production of bananas increases with temperature which explains why the bananas inside the paper bag look riper and the colour grade is 6 (fully yellow) compared to 5 (yellow with green tips) of bananas in cardboard (USDA Handbook, Eduardo Kerbel).

For mangoes, the only difference observed was the firmness on the first two days. However, the real difference in appearance and coloration was observed on day 3. According to USDA Handbook (66, pg 408), ripe mangoes can be stored at 7- 8°C, whereas the ones we experimented with were stored at a higher temperature. The ripening decolouration observed on a mango kept in the paper bag could be attributed to the heat injury.

Although photos of mushrooms in both packages show browning of the product from day 1 to day 3, those in paper bags appear to be browner, in addition to wrinkles and white hair observed. Mushrooms being a high-water content commodity, storing them at room temperature leads to a quick and severe deterioration of colour, texture, and appearance. However, the cardboard indicated less deterioration of mushrooms compared to the paper bag because it was perforated which allowed air circulation and reduced colour loss as well as the condensation inside the package.

Cucumber is another water-rich non-climacteric vegetable which experiences a rapid desiccation when unrefrigerated. The softness observed from day 1 to day 3 on the cucumber

packed in the paper bag was due to moisture loss as the temperature inside that package was higher than that inside the cardboard. Overall, cardboard performed better in controlling decay and keeping the quality of the produce compared to the paper bag.

The rigidity and strength test indicated that the cardboard box was stronger than the paper bag. Its strength protects the items inside from mechanical injuries, which was the most frequently received complaints from the customers, during transportation.

VII. Design Sustainability Analysis

Economic Considerations

From the beginning of this project, budget has been a critical aspect we took into consideration for our design process and materials' selection. Food Bundle being a small start-up company located in a developing African country, we needed to come-up with an economically sound solution that would not burden them, but help the company increase its profit margins from increased orders. We had to ensure that the package can keep high quality of the product; thus, attracting the customers. However, the main issue in determining our solution's optimal cost resided in the inability to obtain a clear and defined budget from our client. In addition, we were given no substantial data to help us make financial projections. The current packaging used by the company is extremely competitive as it is a low-cost solution, thus, to reduce the cost of our product to the lowest price was a challenge. The materials' choice was the crucial factor to consider. We selected a cost-effective such as recycled cellulose-based cardboard, which would allow us to incorporate a coating material such as a PLA biofilm to enhance the performance of the entire package. According to several entrepreneurship and business specialists, an acceptable range for the cost of a packaging would be about 10 to 40% of its retail price (Wicks, 2016). Given the financial resources of our client we decided to aim for less than or 10% maximum, and proceeded to figure out the highest product available for retail and figure out what that 1 to 10% range would be:

- Highest bundle cost: 18500 Rwf = 22.91CAD\$
- So: $10\% \times 22.91\$ = 2.291\text{CAD\$}$

Such total price seemed high but helped us guide our research, as we were able to figure out a very acceptable budget by using estimates from online bulk retailers, which resulted in the following pricing scheme, providing a realistic estimate of the total cost of each unit to the client.

Component	Bulk Retail Price (CAD\$)
Custom Cellulose-Based Cardboard Box (36x36x36cm)	0.91
PLA Biofilm (0.881m ²)	0.30
Biodegradable Tape (50cm)	0.01
TOTAL per packaging unit	1.22

Such price seems acceptable to us as it falls below the projected 10% and given the fact that the client is likely going to work with their current paper bag supplier for the manufacturing of the box, which will probably lead to some savings. Finally, we believe the positive impact of the package's implementation will help the company make enough profits to offset any high cost invested in the manufacturing process.

Social Considerations

We believe that the implementation of this packaging will elevate the company's external positioning and their reputation will be centred around the consumer's point of view. They will be known for selling fresh produce packed in a sustainable, aesthetic, and unique cardboard box. That will achieve customer's satisfaction. The structure of our solution (with its practical handles) makes it highly ergonomic, regardless of gender, which will benefit the company's delivery workers and enhance the consumers' experience as the products will be easily carried and maintain their quality. Moreover, the fact that our box is printable and customizable will allow better communication between different departments in the company, as well as between clients and

company and will enhance its marketing strategy. This packaging will have another societal benefit as it will contribute to maintaining the freshness and quality of the F&V, decreasing post-harvest losses, preventing food waste; thus, contributing to food security. The durability aspect of the cardboard box will help the company's workers increase performance and raise overall packaging efficiency, which will help the start-up grow faster. Lastly, there are no harmful chemicals incorporated in the material that could threaten the health of the Food Bundle employees or that of their customer. Therefore, it will be socially acceptable.

Environmental Considerations

As a team of environmentally conscious individuals, the ecological impact of the package we designed was at the core of the process. Our client has also been clear on their desire to shift towards a more environmentally friendly business approach. Since then, we have only worked on creating a solution which would have the lowest environmental impact possible. Indeed, all the materials selected are plant-based eco-friendly ones, as they can all be recyclable, biodegradable, and compostable making the overall solution a truly green product. Furthermore, the smallest details possible were considered, such as biodegradable tape to seal the packages and the use of algae eco-ink, to avoid compromising the ecological aspect of the design.

Besides the positive impact of our packaging's components, our solution is going to mitigate the current quality issues faced by the company and causing the customers to waste a significant amount of F&V due to damages that occur from paper packaging. Indeed, our packaging was designed to preserve the intrinsic and extrinsic properties of the produce packaged, which will achieve product protection and food waste reduction, thus minimising environmental impact.

VIII. Conclusions & Recommendations

This section contains a few recommendations based on our retrospective of the design process. It includes suggestions on what can be done to improve design and what we should have thought of and done to make it and the whole design process better.

Due to the current pandemic context, this semester we have struggled a lot to source the final materials selected to build our current prototype, as most suppliers were either unable to send us the materials or due to shipping delays and issues, the materials never got to Montreal. Such an

issue could have been avoided or mitigated had we ordered as earlier as last semester. In addition to that, we feel we should have started prototyping earlier than we did to have more opportunities for iteration and adjustments.

Another aspect we have thought of at the end of the project was the issues in terms of budgeting and dimensions we faced due to lack of data from and clarity from our client, as it is a recent start-up. We feel we should have insisted more to obtain precise data, which would have overall improved our current design and made us more time efficient.

A long-term suggestion for our client consists in continuing efforts to locally source the materials to further enhance the solution's sustainability. We were unable to find in Rwanda suppliers for our materials, however such a thing is not excluded from happening in a short-term future, as the country's undergoing major socio-economic development. Once Food Bundle is able to manufacture part or all of its materials in Rwanda, the socio-economic and environmental benefits will be significant for both the company and the local community.

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X. Figures



FigureXX



Figure XXX.1



Figure XXX.2



Figure XXX.3