Combining the strength of reusable and one-way systems into a secondary packaging design

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Preface

My educational journey to become a product designer began in Rotterdam. This is where I learned all the hard skills and soft skills needed for this craft and where I discovered my love for designing. I developed as a person, but I was not ready yet to start my career. I was still too eager to learn more about the ins and outs of different product design perspectives and strategies and most of all to learn about myself as a product designer but also as a person in my free time. That is why I moved to Enschede in 2019. Here, I started a new life. At the beginning of this journey, I joined the Twentse Student Alpine Club where I discovered my great love for mountains and with that the sports mountaineering, climbing and bouldering. This part of my development helped me a lot with overcoming fear, being brave, and discovering where life is about: challenging yourself and enjoying the journey.

This is something that I take with me every day, including in pursuing my master's degree. To switch from doing a bachelor's in applied sciences to an academic master was a challenge, but a very enjoyable one. During the way I discovered my strengths and weaknesses and most important, my topic of interest and my core values in being a product designer. Something what I will take with me in the rest of my career. I want to work on solutions for every kind of industry which will make the world a better place, considering the environment but also human rights. I want the production of the millions of products that are used all over the world to become fairer to people and the environment, so we can work towards a long-lasting and livable world.

It has been a year that I had the privilege to work on this research for my master thesis, diving into the differences between reusable and disposable packaging systems. I was able to execute the first six months of my research at CalPoly, located in San Luis Obispo, California. For that I want to thank CalPoly for having me and making their recourses available for my project. I also want to thank PepsiCo, who made a scholarship available for a student to execute research of six months abroad, and a big thanks to the members of the IAPRI board for accepting my research proposal, I am very grateful. It gave me the opportunity to discover a new country and a new culture during the way. Special thanks go out to prof. Jay Singh, for the guidance and support during that time, for finding my way in the project, at the university, but also in finding my way living in a new city. I learned a lot about the craft packaging design, the American culture, but also thank you for the introduction to the Indian culture. It was lovely to get to know your family and especially taking that knowledge with me, when we travelled to Mumbai for the annual IAPRI conference. For this I want to thank the University of Twente for funding my travel expenses, which made it possible for me to learn from yet another culture and to meet new people in the packaging field. It was an inspirational week to be delved into this small community and learn from everyone. I even had the opportunity to present my research of the six months at CalPoly to all the researchers of which I read their publications of.

Already during my time in the states, but especially back in the Netherlands, I had a lot of support from prof. Roland ten Klooster, who was my daily supervisor. Thank you, for the many meetings we had, always helping me forward and making me see my own progress. I learned a lot by talking to you about the project and all related things in the field of packaging. Fun fact, my choice for starting the study product design in Rotterdam, came from the wish to design packages that would end up in general grocery stores, i.e. Albert Heijn, when I was 18. Looking back at the process from then to now, being 25, it is super nice to see how this master made that dream become reality and a real opportunity.

It took me some effort to get back on track with studying and gaining results once I was back in my home country, a lot had happened and I needed some time to be able to regain my old rhythm, but especially the past months I succeeded again in studying hard. I am very proud on the report that you are about to read, and I am excited for finishing up my master's degree and start my career, wherever it leads me. I want to thank all my friends, both living in the states and in the Netherlands, for helping me enjoy the whole process from beginning to end. Going for climbing trips all over California was a dream come true, and thanks for all the good conversations we held, day and night. A special thanks goes out to Jens Boer, who has been the best partner I could wish for, brightening up my mood anytime and being patient with me when I did not have much energy left in my system. And at last, thanks to my parents who made this whole educational journey possible and believing in me, making the right decisions that helped me further, and discovering myself.

Abstract

The distribution of fresh fruits and vegetables is currently done using single-use cardboard boxes or reusable plastic crates. A debate is going on for a long time now as to which one is better in terms of environmental impact. It appears that this is very case specific and both secondary packaging systems have their benefits compared to each other. These benefits inspired to challenge the current secondary packaging systems and explore the possibilities of a combined packaging that incorporates the best of both worlds. The proposed design features a reusable plastic bottom that provides the strength to the base, combined with a single-use cardboard sleeve that utilizes its strength in vertical direction while maintaining its light weight, and advantages in printability. The goal of this research is to investigate the technical possibilities of this concept, along with its environmental impact.

A broad ideation was carried out to discover a wide range of possibilities for the design of this concept, from which two concepts were selected. In addition, the compression strength of a cardboard sleeve is tested which shows that it is strong enough to act as the supporting part of the secondary packaging during stacking. Also, a tensile test is performed with cardboard to determine the potential of a connection method between the cardboard sleeve and the plastic bottom, using snap systems. These activities are defined as the design phase of this research and were executed at CalPoly University in San Luis Obispo, California, which has lots of experience in packaging design and testing and facilitated all testing facilities. Full-sized prototypes of these two concepts were made to evaluate the assembly methods and get a general feel for the ideas. A Life Cycle Assessment was performed to evaluate the environmental impact of the hybrid secondary packaging system, compared to the current packaging systems. The results of this analysis were favorable for the hybrid packaging system in a wide range of scenarios.

The hybrid packaging system shows great potential to be implemented as a secondary packaging system for the fresh produce distribution with lower environmental emissions than the current cardboard box or plastic crate. The packaging design concepts require further development testing to meet all design and strength requirements before implementation.

List of Abbreviations

LCA:	Life Cycle Analysis
RPC:	Reusable Plastic Crate
CB:	Cardboard Box
HB:	Hybrid Box
Cb:	Cardboard

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1. Introduction

This thesis report describes the preliminary research executed into the design possibilities of a hybrid packaging system, in which the strength of reusable packaging is combined with the strength of one-way systems.

1.1 Background

To be able to buy fruits and vegetables in the grocery store, they need to be transported from the field they grew in, to the grocery store. Most kinds also need to be washed and sorted before they can be sold. The transport of these so-called fresh produce is mostly done in recyclable cardboard boxes or reusable plastic crates. Research is beinghas been done for many years now to see which system is environmentally better to use, but the conclusion is that it is very case specific (Chonhenchob & Singh, 2003, 2005; S. P. Singh et al., 2006; Levi et al., 2011; Accorsi et al., 2022) . In some cases, a more durable reusable system can be desirable, but in other cases a light disposable box can be more beneficial, for example for transport over seawith light produce or great transport distances.

1.2 Project aim and scope

The aim of the project is explorative research into a transport box for fresh produce, combining two materials, cardboard, and plastic, and with that, combining two end of life systems, reuse, and recycling.

The goal is to be able to say at the end of the executed research if this hybrid box has the potential of being developed and implemented in industry, or if it is not worth it to invest in. At the end a recom-mendation will be given for further development of the idea, and in which markets it could be implemented.

"Is it possible to design a packaging system to distribute fresh fruits and vegetables, combining reusable packaging systems and recyclable single use materials, to create a more sustainable product-packaging combination by using best of both worlds?"

During the research there are two main factors of focus. One is the design possibilities of the hybrid transport box, using a plastic reusable bottom with a single use cardboard sleeve. Bottoms of plastic crates function better than bottoms of cardboard boxes, while for the wall of injection molded crates, a lot of material is needed. Using cardboard, the carrying function can be fulfilled with a very little amount of material. Different directions of how the two parts can be connected to each other and how they can work together to function as a transport box will be discovered, and possible solutions will be proposed. The second important research aspect is the environmental impact of the proposed design(s), compared to the impact of the currently used transport boxes. The motivation of the research is that this design will potentially have better environmental behavior, which will be investigated in the validation stage of this project.

The market the project focuses on is fresh produce. In this business field both packaging systems, one-way as well as reusable, are used. Because of this the curiousness grew if these systems can be combined with this market as focus point. The current situation will be explained in the next chapter.

1.3 Methodology

In the double diamond framework (Dawgen Global, 2023), the divergent and convergent stages of a design development process with its iterative process is visualized (figure 1). Research is divergent: a broad perspective about a subject is gained, and different scenarios are covered. In this research literature research is executed and interviews with farmers and different experts are done. Then this information is converged into documented insights and a problem statement which is used for the development of a solution. This development starts with diverging again through an ideation phase, followed by converging, searching for specific solutions using prototyping. This development phase is an iterative process, in which the ideas are continuously tested with the market requirements. This iterative process can be within the ideation/prototyping phase, within the research/insights phase, or in between those two phases.

To develop a first concept of the hybrid box design to see if the combination between the two systems is technically possible, and to be able to execute some preliminary tests to make an estimation of the impact on the environment, a design thinking and scrum-based method is used. Design thinking is a framework which explains the development of designing a product (Karl, 2020) , see figure 2. It starts with defining the problem, what to design for, what is the goal, etcetera. Then ideation can take place to generate ideas. At the beginning of a project this is focused on diverging, generating ideas in multiple directions, so in a later stage a basis of ideas is available on which can be resorted to through the entire project. After the ideation stage, prototyping can be the next step of making ideas tangible and iterating on the first ideas, with the goal of generating more ideas, or converging the ideas to specific concepts. In this project a scrum-based method and rapid prototyping is used for prototyping and converging the ideas. Rapid prototyping makes it possible to make first ideas tangible fast which makes it easy to discuss these ideas with different stakeholders not closely involved in the project. Their opinion can be considered quickly, and small loops of iteration can follow, to get to some first concepts. Then, these concepts can be tested and compared to the framework that was developed at the beginning of the project to see if it aligns with the initial thoughts. With new insights from the developed concepts, the framework can be adjusted or more research can be done into a specific direction, after which development can continue. This is visualized by the endless loop in the design thinking method. These loops can continue until a valid concept is presented, or until a final product can be introduced to the market, depending on the goal of the design thinking project.

This report has devided the research process into the following main parts:

- Analysis phase
- Design phase
- Evaluation phase
- Conclusion

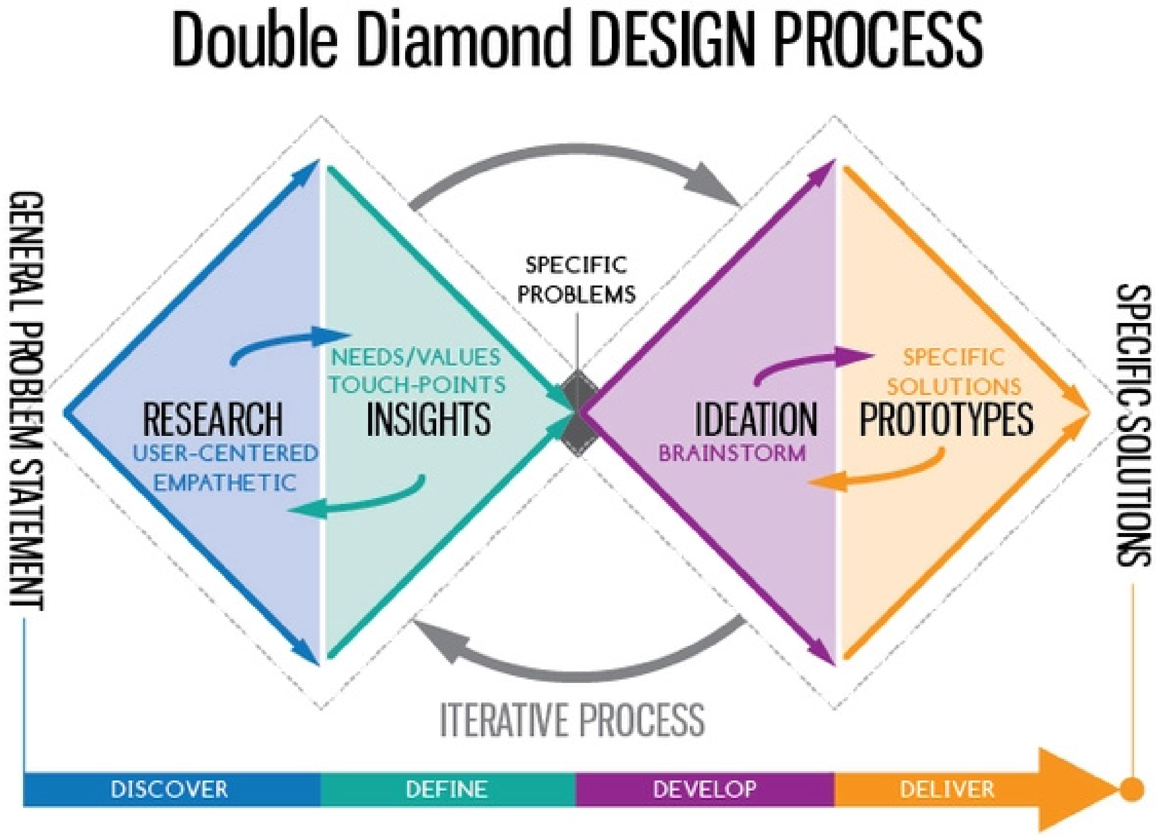


Figure 1 | Double Diamond Framework (Dawgen Global, 2023)

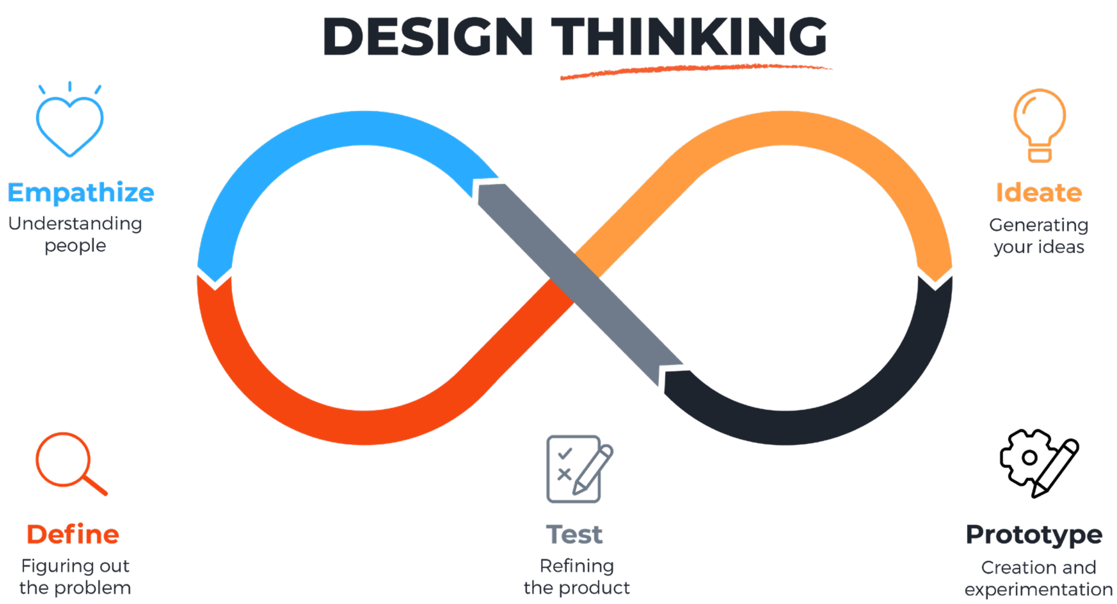


Figure 2 | Design Thinking Framework (Karl, 2020)

2. Fresh produce

This chapter provides an explanation of fresh produce distribution concepts and its packaging methods currently in use. The project aims to integrate the “best of both worlds” of both single-use and reusable packaging systems with a hybrid approach. Previous studies comparing the two systems were analyzed to identify their benefits and drawbacks, which were considered during the development of the hybrid packaging system.

2.1 Distribution of fresh produce

Before consumers can buy food products in the grocery store, the products have already undergone various processes and are transported to various places. Especially with fresh fruits and vegetables, the process from harvest to grocery store is important and needs to be fast to ensure the products can be sold while still fresh.

Figure 3 | Fresh produce harvest

2.1.1 Fresh produce

The focus of this research is on the distribution chain of fresh produce. Produce is a collective name for farm-produced goods, which includes and is referred to as fruits and vegetables in this research. Fresh produce implies that the products involved maintain the same quality as when harvested (figure 3), so they have not been treated before being sold (Chonhenchob et al., 2017).

2.1.2 Distribution chain

The distribution chain of fresh produce encompasses all the activities and processes that facilitate the fresh produce to end up at its final destination, in this case the consumer, see figure 4 (J. Singh et al., 2016) . Fresh produce starts at the harvest. From the farm it is transported to a distribution center to be sorted or cleaned, or packed in smaller packaging, depending on the kind of produce. Then it is ready to be transported to the retailer, f.i. a grocery store, and it can be sold.

2.1.3 Reason of packaging

The goal of using packaging in the distribution chain is to preserve the quality of the fresh produce so it can be sold to markets different distances from the location it is harvested. Packaging adds a layer of **protection** to create a barrier from outside factors, such as vibration, dropping and compression during transport. It also respects hygienic requirements (Battini et al., 2016). Since it **contains** the products, it

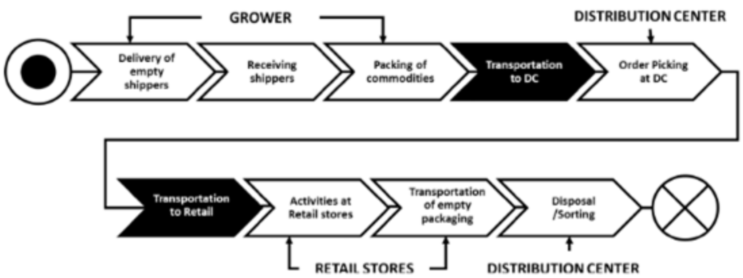


Figure 4 | Typical deployment of bulk containers in North American supply chains enables efficient handling and simplifies its management (Battini et al., 2016; J. Singh et al., 2016). It can also be used to **inform** consumers about the products inside (Bortolini et al., 2018; Chonhenchob et al., 2017). If fresh produce gets bruised or damaged, the aging process is speeded up fast, which shortens the shelf life drastically, and causes a higher percentage of food loss. Packaging helps protect the produce during the whole distribution chain, but there is a tradeoff that needs to be considered. Adding material to the packaging of every sort, will have the purpose of protecting the product better against **damage or shortening of shelf life**, while reducing the amount of packaging will reduce the **environmental impact** (and costs) of the **materials/recourses** used (Chonhenchob et al., 2017).

2.1.4 Packaging of fresh produce

Figure 5 | Plastic crate (left) and cardboard box (right)

The packaging in the distribution chain of fresh produce is used mostly to make handling of the loose products more efficient during transport and storage and to protect the produce during transport from forces from outside. In this research there is a focus on secondary packaging, which can be a cardboard box, plastic crate or wooden box, or even bigger bulk containers. The bulk containers are used to make a big amount of loose produce possible to handle efficiently through the distribution chain for products that are strong enough to protect themselves from outside forces. The produce on the bottom of such a container must carry the weight of all the produce that are above, putting weight on the layers below. For produce that is more vulnerable, smaller crates or boxes are used to store smaller amounts of produce. These boxes or crates can be stacked on each other and take over the weight carrying function. Sometimes an extra inlay can be added to the box or crate to improve the protection. In figure 5, a cardboard box and a plastic crate are shown.

Figure 6 | Packing fresh produce in shade to preserve quality

2.1.5 Cold chain

Another factor to keep produce fresh during its distribution is the cold chain. With this, during the distribution of the fresh produce, the produce is chilled continuously through various stages of the distribution chain, to extend the shelf life of fresh produce. There are various ways to achieve a cooled chain, using refrigerators using wind or moist for cooling. Another method is used for broccoli, which can be cooled by adding ice on the top layer of a pallet of plastic crates filled with broccoli. The melting ice cools the produce in the lower layers. Depending on the kind of produce and packaging method, the most efficient way can be chosen. Using moist or ice for cooling, a plastic crate is more suitable than a cardboard box, because cardboard deforms in a high moisture environment (Chonhenchob et al., 2017).

Ventilation holes are added to secondary boxes to enhance the cold in the surroundings of the transported goods to be transmitted to the produce inside the secondary boxes, and for refreshment of air inside the packages (Berry et al., 2022). The ventilation flow can be optimized per different kind of produce for example, bananas need more ventilation to stay fresh than apples. Figure 6 shows a packing scenario on a farm, where the produce is stored in the shade when it is waiting before being transported.

2.2 Sustainability in packaging

Sustainable development is a subject what is receiving heightened attention across various fields, including packaging. It is a guiding principle that aspires development **to meet the needs of the present without compromising the ability of future generations to meet their own needs** (Brundtland et al., 1987). This requires consideration of human, natural and economic resources, also known as the three pillars: **people, planet, profit** (Elkington, 1994). Our current economy is mostly designed on the **take, make, dispose** industry (figure 7), in which materials are taken from the earth, a product is made from them and used, and is thrown away and goes to waste. This is called a linear process and is not sustainable.

It is not possible to keep doing this towards the far future. The economy must adapt, and the Ellen MacArthur

Figure 7 | Linear economy

foundation (Ellen MacArthur foundation, n.d.), among others, is introducing a new approach, the **circular economy**. This approach focusses on three principles: eliminating waste and pollution, circulating products and materials at their highest value and regenerate nature. In the linear economy when products go to waste, there is no purpose intended for the remaining material, they are designed to be disposable. The circular approach is a rethinking process where waste should be eliminated by circulating products by being maintained, shared, reused, repaired, refurbished, remanufactured, and, as a last resort, recycled, see figure 9. This can be done with a focus on the design process and is about the technical cycle (figure 9, blue lines). The circular approach also focusses on regenerating nature, but this is out of scope for this project.

Within the circular approach there are three strategies which Bocken et al. (2016) have identified, see figure 9. Slowing, closing, and narrowing loops. A **slowdown** of the used resources can be done through product-life extension by share, reuse, repair, refurbishing or remanufacturing. The produced products can be used at their highest value for a longer time. Recycling can **close** the recourse loop between post-use and production, to achieve a circular flow. **Narrowing** the recourse flow focusses on using fewer recourses per product, also referred to as recourse efficiency or reduce.

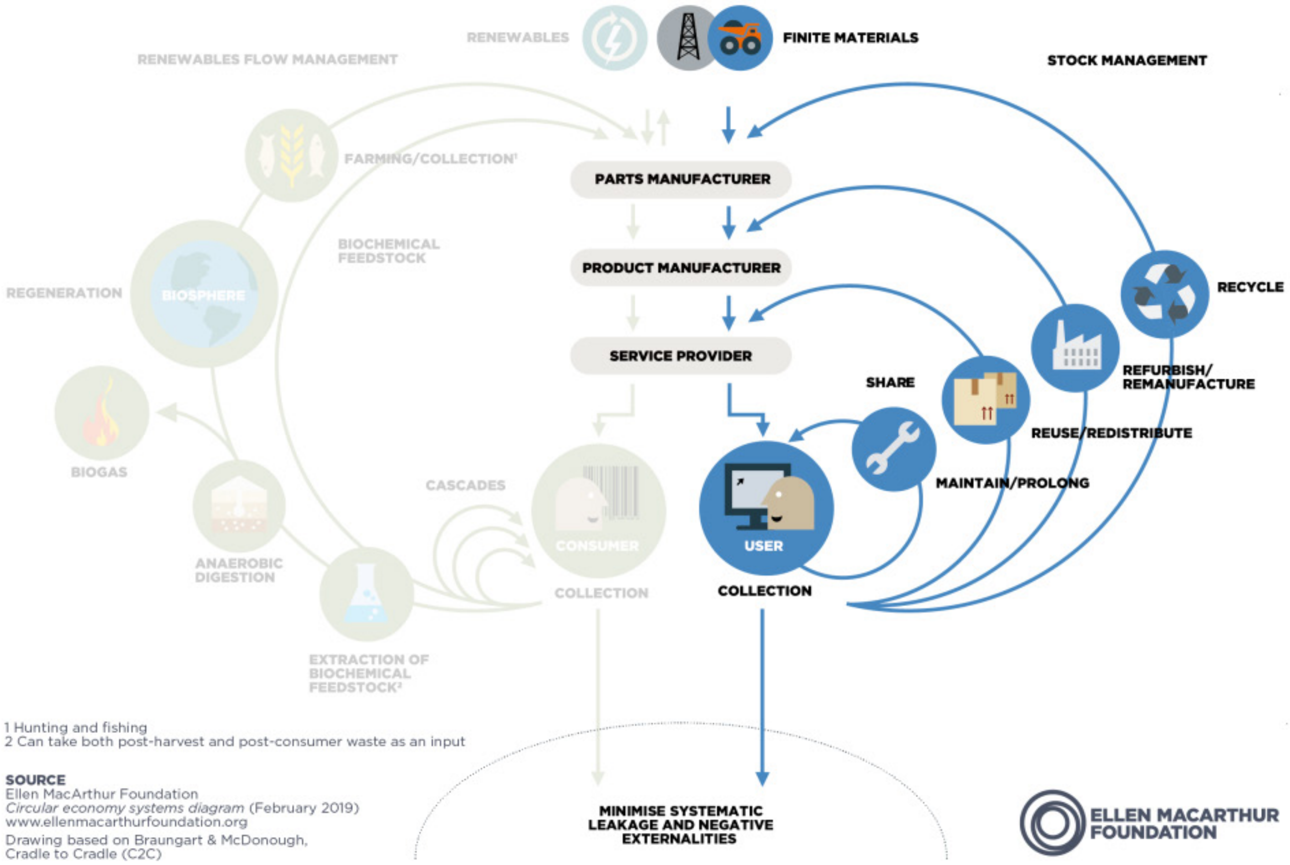


Figure 9 | The butterfly diagram: visualizing the circular economy; the technical cycle (Ellen MacArthur Foundation, 2019)

Sustainability in packaging for the food industry is about the balance between the protection level of the foods inside and the quantity of recourses used for producing the packaging. Preventing food going to waste has the highest impact on saving on economic expenses, environmental emissions (greenhouse gasses) as well as it is a social issue. Food going to waste means less food to feed the world population (J. Singh et al., 2016). Packaging causes only 1-10% of the total environmental emissions of food distribution, but there is still opportunity to move to more sustainable packaging (Tapiola et al., 2023). Packaging is a primary user of virgin materials, because of the needed quality to preserve the packed foods and beverages, so the possibility to reuse packaging reduces the environmental footprint of material use (Coelho et al., 2020), increases the recourse efficiency and can reduce the harmful impacts of littering (Tapiola et al., 2023).

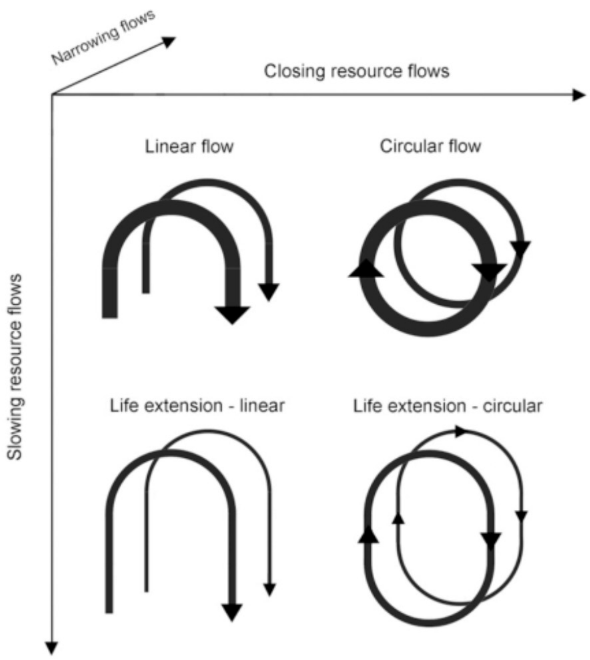


Figure 8 | Circular economy framework (Bocken etl al., 2016)

2.2.1 Recycling of packaging

The ultimate goal is to close the loop of a recourse flow. This can be done through recycling the used materials. To be able to recycle the materials, packages need to be collected and transported to a central point. For consumer products, this happens in homes, on their work or in local areas in neighborhoods. For industrial packaging this happens at a bigger scale, for fresh produce packages in the grocery stores where the packaging is disposed. To be able to use the collected materials, it is important they get sorted, which is done at a central point. For this it is important packaging existing of more than one material is able to be disassembled. Materials are sorted to achieve an even mixture of the to be recycled material, to preserve the quality of that material as good as possible. Before using the recycled material in another production process, they need to be cleaned and transported to the manufacturer. If this process is able to stay in the same value chain as the collected package it is closed circle, but recycled material often loses some of its quality by uneven mixture of the material (N. Silva & Pålsson, 2022), additives/adhesives that influence the quality when mixed or a breakage of chains on molecular level of the material. Because of the high-quality packaging material needs, the preference goes to virgin material and so the recycled material goes to another product. This phenomenon is called downcycling and a part of the value gets lost of the virgin material. Also, food packaging has strict food safety regulations. To use recycled materials, it must be proven the material never came into contact with harmful/toxic substances. That is also a reason the recycled content of packages doesn't come back into the same value chain and so is downcycled. Downcycling is a leakage in the circular process, the value of the virgin material gets lost and can never be used for the same purpose again.

For the best recycling opportunity, the package already needs to be designed upon making it possible to recycle a package at the end of its life, by choosing the material, not adding additives or such to it, and making the package easy to disassemble (Coelho et al., 2020).

2.2.2 Reuse of packaging

Making packaging reusable increases the recourse flow of the package extensively. The material used for the package is used at their highest value for a longer time, compared to single use packages. To be able to reuse packages, they need to be collected and transported to a central point. There they are sorted and checked if the quality is still sufficient. That is a decision point if the package can be reused again or if it should be repaired or disposed and recycled. Reusable packages need to be cleaned thoroughly before they are ready to be used again. Before new use they are stored and then transported to the farm, and it starts its new use cycle. The logistics of getting the package ready for a new use cycle, all the extra steps compared to a linear process, is called reverse logistics. This includes extra transport distances, decision of who owns the packages, and number of necessary stocks. The increased complexity of the logistics process is often the biggest challenge in introducing reusable packaging (Coelho et al., 2020), the organization of the reverse logistics and extra costs.

Like recyclable packaging, the design of reusable packaging has a big influence on how good the package can be reused. The goal of a reusable design is an as long as possible life cycle using as little as possible material, to extend the loop but keep it narrow too. There will be more material necessary compared to a single use package to ensure a longer lifetime and to be able to clean the package, but through reusing the material divided through all cycles, the material cost will still be less. Also, the package should be designed on repairing possibilities to extend its lifetime even more (Coelho et al., 2020).

2.3 Current packaging methods fresh produce

The current used secondary packaging methods most used in this field are reusable plastic crates (RPC) and corrugated cardboard boxes (CB) (S. P. Singh et al., 2006). Both mostly use virgin materials but are recyclable at the end of its use. Especially the RPC uses a lot of material per crate but can be endlessly reused and recycled (Accorsi et al., 2020). Packaging reuse contributes significantly to the reduction of **virgin material** extraction, waste and associated environmental impacts, especially in the food industry, which is characterized by fast and high consumption (Accorsi et al., 2020). This means that both these secondary packaging options are already designed towards sustainable solutions, but there is still discussion going on which one of these two is "better" to use. Lots of comparisons have been done and the conclusion of these is not one of them is better in all cases. It is very case dependent to conclude which one is better. In the next subchapters an elaboration will be done about the use of the specific packaging methods, and elaboration on specific comparison subjects will be done to make clear what the current state of knowledge is about this comparison and what hazards come up with using the different systems. Exploring the current state will function as a starting point of deciding where this research will contribute in.

In the fresh produce distribution chain, boxes and crates are used to transport the freshly harvested produce. The boxes and crates can take over the weight of the produce when stacking, to protect the produce from damage. Packaging produce in separated packages also provides for easier handling of the produce in bulk, instead of loose products. Mostly used as packaging materials for this application are cardboard boxes, plastic crates (foldable or stiff) and wooden crates. The cardboard boxes and wooden crates are single use, the stiff plastic crates can be single use or reusable and the foldable crates are reusable. The option to fold it allows for easier transport when not filled, mostly for the reverse logistics. The cardboard box is being recycled after usage, while the wooden crate can only be used once, and the used wood goes to waste. The reusable plastic crate is getting more popular over the years, because of different benefits and is competing against the simple to use cardboard box. These two options are the most used in the fresh produce distribution chain and already compared with each other a lot in research. Because of their convenience for most packaged fresh produce, these two are used in this research as inspiration and for comparison.

2.3.1 Recyclable corrugated cardboard box

A cardboard box is a very commonly used method to transport products of all types. It is a single use system, which makes it very convenient to customize the box for specific applications and adapt size, strength, shape, or print. Corrugated cardboard is a cheap to produce material and easy to adjust smaller or bigger production sizes. The strength of the corrugated cardboard originates from the type of flute used, the density of waves in between the outside walls, and the number of layers in the cardboard plate. After the box is used, so at the end of its life cycle, the used material can be collected and recycled. The recycled cardboard can be used for new applications, but the quality of the recycled content (strength) reduces, so the collected cardboard cannot be used for the same application again. To use recycled material as a cardboard box again, it is mixed with virgin material to achieve the necessary strength. This implies that the circle can't be fully closed.

In the distribution chain of fresh produce, the foods are packed in secondary boxes, often without an extra layer between the produce and the package material. This is beneficial to save packaging material, but means the food touches the packaging material directly. This is not accepted for processed foods, which is the reason that these foods are often packed in separate plastic packages. Unprocessed foods, which is the focus of this research, may touch recycled fibers in cardboard boxes.

Another reason for the use of virgin material in cardboard boxes used to transport fresh produce is the need to achieve sufficient strength to support stacking. The strength of corrugated cardboard is affected by several factors, including component properties and orientation, the board manufacturing process, and environmental conditions, the most significant of which is moisture. Moisture absorption in paperboard containers can cause dimensional changes and affect the strength of the corrugated board (Chonhenchob et al., 2017). In the fresh produce chain, the cardboard boxes are subjected to moisture variation throughout the supply chain which leads to considerable changes in the package performance. A higher moisture content in the corrugated cardboard leads to a lower compression strength and lower shock absorption characteristics. The water resistance of corrugated cardboard can be improved by applying a coating based of polymers or waxes, laminating the board with polymers, or internal sizing agents can be added to the paper pulp in the production process of corrugated cardboard. A downside of using a coating is the recyclability of the discarded box. Not all coatings are recyclable, like wax, and the recycle process gets more complicated from it, so coatings should be tried to be avoided, but can be a solution when there is no other option.

The single use system of the cardboard box offers the opportunity to have branding on the box (figure 10). Cardboard is easy to print and because it's used only once, the material can be printed without affecting the next user of the box. Through branding using printing the box there can be communication to the consumer. In the fresh produce chain, the quality of the produce bought by consumers in the store is important for the consumer. This perception of good quality fruits and vegetables can be linked to a brand if the brand name is communicated towards the consumer. This communication can go through printing the cardboard box which is displayed in the grocery store or via a label/small sticker on products, like a banana or apple. When the consumer knows the brand name of the produce they had before and of which the quality was good, the consumer will return easier to the fruit or vegetable of the same brand, which is profitable for the brand owner/farmer (Chonhenchob et al., 2017).

Figure 10 | Branding California Strawberries

2.3.2 Reusable Plastic Crate

The reusable plastic crate is a sturdy alternative for cardboard boxes, of which its popularity has grown over the years. The crates are made from plastic, which is a durable material, which lends itself to being used multiple times in a row, remaining the same structure and shape. Therefore, the plastic crate is used in a reuse system, where the crates are collected and cleaned after being used to transport the fresh produce from farm to grocery store. The crates are cleaned before they are shipped to a new farm to be used for transportation, to ensure the food safety of the crates. When transporting the crates back from the grocery store, they are empty. To make this process, which is called reverse logistics, efficient, the crates are designed to be able to fold the sides down, so there is no empty space left during transport and the truck space is used efficiently. The reverse logistics process includes all the steps necessary for a reusable product to be used another time, so all the steps that are not involved in a linear single use process. This includes, transport of empty packaging, cleaning, sorting, quality control, repair, and storage. The reverse logistics of reusing crates is an added complexity in the distribution process of fresh produce, compared to single use boxes, with rising costs and environmental emissions, but a strong reduction of raw material usage saves the use of virgin resources and reduces waste ending up in incineration or landfill (Bortolini et al., 2018). When a crate isn't usable and repairable anymore, the crate gets discarded, and the material used for the crate can be recycled. In theory this loop of reusing and recycling could go on infinitely (Accorsi et al., 2020). The recycled material could be used for the production of new crates. In reality, keeping material in the same process loop is hard, material or crates get lost and recycling material can cause quality loss, dependent on the type of plastic used, so recycled material gets downcycled and is lost out of the circle.

The plastic crates that are used in industry are owned by a pooling company. This company rents the crates out to companies who are in charge of the transportation of the fresh produce and supply the reverse logistics, inspection and cleaning, of the collected crates. These companies can take over a big part of the added complexity of using reusable crates (J. Singh et al., 2016).

2.3.3 Environmental comparison

Comparing the environmental impact of using a corrugated cardboard box or a reusable plastic crate for the distribution of fresh produce, multiple factors have an influence on the emissions. To be able to reuse the plastic crate, the reverse logistics process is added on top of the distribution logistics of the fresh produce. This adds up to the environmental impact of the reusable crates, but the production process of the crates can be divided over the times the crates are used. On the other hand, the production process of the cardboard boxes is per box and has therefore a higher impact on the total environmental impact then the plastic crate. To get an understanding of the environmental benefits and drawbacks of crates compared to boxes, Life Cycle Analyses are done in the past, mostly to discover which of the two is "better" to use for specific distribution processes, based on real cases.

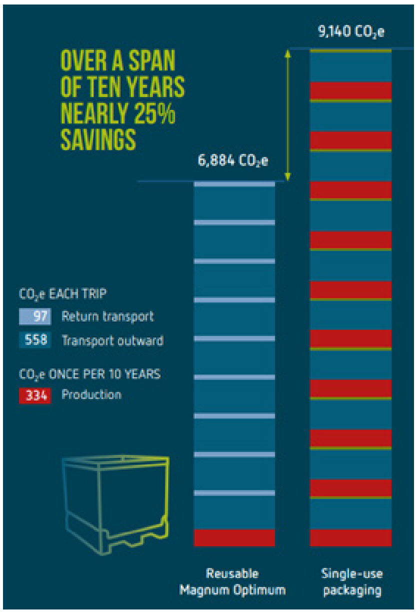


Figure 11 | LCA RPC vs. CB (Jung, 2022)

A Life Cycle Analysis, often called LCA, is a tool to calculate and compare the environmental impact of specific products. In this assessment it is the goal to make a complete as possible assessment of all processes needed in a life cycle of a product, from extraction of materials and production to the use phase of the product, including reuse, ending at the end-of-life treatment, including recycling and incineration of the used materials. To get reliable results, the data that is used as input for an LCA is important to be reliable itself. The LCAs done in former research to compare the environmental impact of RPCs with cardboard boxes is based on specific cases on how the transport boxes are used in real life, with input data coming from reliable sources and is based on realistic cases.

Different studies ended up with different conclusions about which transport box has a lower environmental impact. This is because for all the executed LCAs, different case studies are used. These differences lie in the kind of fresh produce that is distributed, the transport distances it needs to cover or how much recycled material is used in the production of the boxes. Because in one study the cardboard box turns out to be more environmental efficient and in another case the RPC is, it means that it is not possible to draw one conclusion of which one is "better", regarding environmental impact. Figure 11 shows an example on how the impact can look like. The RPC needs to be produced only once, which results in that the biggest impact of the RPC is in the transport of the goods. The CB is single-use and therefor needs to be produced for every single cycle of transporting goods. This results in a high impact of the production phase. Together with the impact of transporting the goods, the CB turns out to have more emissions than the RPC in this case.

Koskela et al. (2014) had an important study in this field. They did an LCA on the distribution of bread in Sweden. Bread is a light product and the transport distances in Sweden are high. An RPC is heavy compared to a CB, which results in higher emissions during long transport and because of the low weight of the to be distributed product, the emissions of transport are mostly caused by the weight of the RPC, not of the distributed product. This resulted in the CB being more environmentally beneficial in this case than the RPC.

Multiple researchers have concluded that transport distance plays an important part in the environmental impact of RPCs, under which Accorsi et al. (2022). They did a literature review of the results of LCAs done in the past between different secondary packaging systems for the fresh produce distribution chain. Together with their research about highlighting the importance of using primary data for the logistics for the analyzed case because of its sensitivity in an LCA, they conclude that the trade-off between RPC and CB remains unclear. Also, regarding the importance of transport distance, Accorsi et al. (2020) proposed a closed-loop network design model, mostly aimed at the optimalisation of transport paths for closed-loop secondary packaging systems.

A noticeable result in LCAs done for industry, is the varying results of impact of the RPC versus the CB. Taking a study which compares the results of two LCAs done for two different studies (Albrecht et al., 2022). The SIM study was executed for IFCO, which is the world leader in RPCs. The FEFCO study was executed for FEFCO, world leader in cardboard box designs. The results of the LCAs were both in favor of their own packaging system. Not only in this example, but this happens in various cases. The difference originates in the input data that is chosen in favor of the packaging systems. This implies again the importance of the data used in such studies and importance of being critical to the results, taking into account for what company the analysis is done and if the shown input data is based on realistic case studies.

2.3.4 Other comparisons

2.3.4.1 Damage during distribution

Another aspect which plays an important role in the environmental impact of the total life cycle of fruits and vegetables is the percentage of damaged products which leads to food loss or shortened shelve lives. It is all about the balance between the amount of packaging used. The more materials the higher impact on environmental emissions, and the amount of damage occurring during transport of the fruits and vegetables. In literature three different types of damage are found. Damage on the packaging system itself, resulting in damage to the transported goods, damage due to the internal surface of the packaging systems, and longer freshness due to humidity control.

Reusable crates appear to be strong and have a good stack stability, which results in less damage during the distribution of fruits and vegetables (Albrecht et al., 2013). In a comparison between an RPC and CB, the RPC had only 0.15% damage to the crates, while the CCB boxes saw a damage percentage of 4.15%. Using standardized packaging can result in lower damage rates as well (J. Singh et al., 2016).

CBs are found to have a softer internal surface than RPCs, which could function as a cushioning element with a higher protection ability for packed peaches, a fruit with a soft internal surface (Sasaki et al., 2022). This contributes to the quality the produce will be delivered into the grocery store. The switch of wooden crates to cardboard boxes and RPCs has been made in the past because of their smoother surface, resulting in less damage to the surface of soft produce.

A third damage preventive aspect in the transport packaging of fruits and vegetables is humidity control. Vegetables such as radish and green onions have been found to stay fresh longer in wooden boxes because of the more suitable humidity conditions (Albrecht et al., 2013). RPCs are impermeable to moisture, which gives it the application method in wet or humid environments. Cooling methods in a humid room or using (melted) ice can be used, using RPCs, while CCB boxes would collapse (Chonhenchob et al., 2017). Cooling during storage is an important step in the distribution of the fruits and vegetables from farmer to grocery store. The fruits and vegetables are stored in the distribution center, waiting until the grocery stores requests them. The optimal cooling method differs between fruit and vegetable kinds, but for kinds with a preference to wet/humid cooling method, plastic crates have an advantage. Cardboard boxes could be used too, when they are coated, but this kind of coating is often not recyclable or poorly recyclable, which has a big impact on the environmental emissions of the CBs. So, this is not wished when we're looking into the environmental impact of the boxes.

2.3.4.2 Social aspect

Continuing, the benefit of humid/wet handling of plastic crates, a social aspect comes up at the very beginning of using the transport boxes: packing the just harvested foods in the field into the boxes, ready for transporting the goods. RPCs are beneficial while packing in the rain and are sturdy so easier to stack. Cardboard boxes can have more ergonomic designs for handhelds, though plastic crates are seen as easier to hold because of the thicker material in the handholds.

Stacking the transport boxes is another social aspect during the use phase of the boxes. RPCs have a locking system when stacking them together on a pallet. This locking system assures employees/workers the boxes are stacked well, functioning as feedback system. A problem with cardboard boxes is that they don't interlock in each other and transporting the pallet sometimes causes the pallet to collapse. With an interlocking system, employees who stacked the pallets cannot be blamed on wrongly stacking. While this makes sense, especially from a designer's perspective, the real use of a designed product doesn't turn out to be as expected. An interview with a farmer revealed that his employees are working so fast, that sometimes one locking nock is not in place which makes the stacked pallet as weak or even weaker than the CCB box stacked pallet. So, the intended use of the interlocking nocks is a great idea, but it doesn't seem to work 100% of the time. This is something to consider in future designs.

2.3.4.3 Economic aspect

The increase of the use of standardized packaging (RPCs) has resulted in lower costs in multiple studies. J. Singh et al. (2016) has found 9-226% faster processing times, using standardized RPCs in DC activities, improved handling efficiency between 5-53% at retail locations, increased unloading, and sorting/securing activities in the asset recovery centers between 16-154% and reduced damage rates by 4%, which is a clear economic as well as social benefit. Albrecht et al. (2013) analyzed three fruit and vegetable transport packaging systems on costs and concluded that the reusable system is the most cost effective over its life cycle. In this analysis, extra transport of the return system, washing, sorting and crate replacement, etc. is included in this study. The biggest difference is seen in the box/crate production. Over the full life cycle of the transport boxes/crates, in single use boxes, the production costs of the box/crate, have a bigger impact on the total costs, than of reusable crates, because for single used boxes the full costs have an impact on every single cycle, while the production costs for reusable crates are divided over every cycle the crate is used, in this study 50 times.

2.4 Combining two end of life systems

2.4.1 Reuse over recycling?

In a study comparing the use of the reusable vs the single-use packaging system (Coelho, Corona, & Worell, 2020), the statement is made: "reuse over recycle". This refers to that using used materials in the same context repeatedly, will have less emissions than recycling the materials after a single use, which is in true in multiple cases, but it has its limitations too, as showed in paragraph 2.3.3. To be able to use one product multiple times in a row, means that the product needs to be stronger than single use products, so it can handle more impact for a longer time. In the food packaging industry, an added factor is it needs to be cleaned before the next use cycle, so the packaging needs to be able to be cleaned too. This means that in general reusable packaging consists of more material than disposable packaging, which means they will be heavier. In packaging for distribution, the weight of the packaging has a significant influence on the emissions during transport, but also during the reverse logistics of the reusable packaging. So, in this context, a recyclable but lighter package could be more beneficial than the heavier reusable packaging, depending on the specific packaged product.

Bortolini et al. (2018) suggest that a combination of reusable and disposable packaging containers offers the best balance. In their study, the authors found that the disposable system was more cost-effective, while the reusable system was more environmentally friendly. Using both packaging systems depending on the specific use case allows for leveraging the unique benefits of each, which is in line with the findings of the comparisons between RPCs and CBs. This study suggests that integrating end-of-life systems for both materials in one package might be a potential route to the most effective packaging method. Incorporating a mix of the two materials in the initial design would achieve this goal.

Modularity of product designs is identified as a possible strategy to facilitate reuse through flexible product design. Other benefits of using modular design include reducing material usage, by having the ability to design for cases specifically. Focusing on specific cases can improve the quality of the end product by reducing the need for compromise (Machado & Morioka, 2021).

2.4.2 EU regulations

The objective of the EU is to reduce the environmental impact of packaging drastically, aiming for climate neutrality by 2050 and making all packaging recyclable by 2030 (European Commission - Press release, 2022). The currently used packaging methods of fresh produce is recyclable already, but they want to boost reusable packaging as well. Currently a small share of the market uses reusable plastic crates, but these are not adopted by all industries yet. To make the transition to more reusable crates, a hybrid form for the transport box could be an intermediate step to make the transition better manageable, using a more hybrid and still brandable design. Also, with using the hybrid design instead of CBs, a share of the used cardboard for the CB is being prevented from being used, which already saves needed virgin materials.

2.5 Conclusion

Neither packaging method is superior in all use cases. Both reusable and disposable packaging methods have advantages and disadvantages that are highly dependent on the specific use case. Both options are viable solutions for transporting fresh produce, provided that the appropriate packaging method is selected. Because of the advantages of the different materials, being light, printable, strong, and the advantages of a returnable system versus a disposable system, this research challenges the current packaging methods for fresh produce to investigate if there is another solution that takes advantage of both, designing a packaging system in a hybrid form.

3. Packaging design

This chapter describes the development of a hybrid secondary packaging system for the distribution of fresh produce, using a combination ofdisposable and reusable components. The selection of a plastic bottom as the reusable component and a cardboard sleeve as the disposable but recyclable component was based on an analysis of the identified advantages and disadvantages. The initial phase of the project involved identifying multiple design challenges and corresponding requirements. With that as a basis, a broad ideation took place which was use to develop multiple concepts and iteration on these took place.

3.1 Design challenge

To be able to answer the research question if a hybrid transport box design could be more sustainable than the current transport box options, first it must be researched if a hybrid transport box can be designed. With this there need to be looked at if it can get 'strong enough' and 'convenient enough' while using. For the design a requirement list is made, the use cases are discovered, and stakeholders are defined. After that an ideation process took place, followed by the development of multiple concepts, which are discussed with multiple stakeholders and tests are done for further development.

This part of the research has been conducted at CalPoly in San Luis Obispo, California. This university has expertise in packaging design and testing and Jay Singh was involved in this research. He has done various research in the area of secondary packaging for fresh produce distribution. Facilities for the testing conducted in this research were provided by CalPoly for the design phase of this research.

Goal of this phase:

1. Prove that a hybrid design can be developed and manufactured. It can get strong enough and the expectation is it can comply with the set-up requirements (so proof of concept) with arguments
2. If it turns out the hybrid design is feasible, the designed box can be used as input example for the comparison of this hybrid concept with the current used secondary packaging. This will be validation research to discover what a possible market position could be, and the expected benefits compared to current secondary packaging, so to be able to give an advice if it will be interesting to further develop this idea and invest in it.

Goal 1 first needs to be realized before goal 2 can be researched.

3.1.1 Design challenge

"Develop a transport box, using a combination of a single-use and reusable part, to transport fresh produce."

In the previous chapter it became clear that cardboard box or a reusable plastic crate are the most used box types for the distribution of fresh produce. These boxes both have a different end-of-life system, but both have a **circular** approach. The cardboard box is used once and then goes into a **recycling** stream and the material is used in a new product. The plastic crate can be **reused** several times until it comes to its technical end-of-life, it can't be repaired and used anymore. This reusing can go up to 50-100 times. After its usable life, it is recycled, and the material can be used in the production of new plastic crates.

These two systems both have their benefits and drawbacks. This project was initiated to discover the benefits of both systems and give it a try to combine the benefits of both in a new product. This new product will be a hybrid packaging box, existing of a reusable part and a single use part. The biggest reason for this is to make the reusable system **lighter**, making use of a single use material which tends to be light because it doesn't have to survive multiple cycles of use, and the **modularity** of a single use part. It can be printed for specific cases, and the height and strength can be varied per application.

It is determined that the bottom will be the reusable plastic part and the sides will be made of corrugated cardboard.

Expected is that a cardboard sleeve, without a folded bottom or top, is stronger than a cardboard tray with a folded bottom. If this is true, a stronger product can be realised using less material, which saves weight, costs, and emissions for the same function. Also, the benefits of the cardboard boxes are in the modularity of the sides of the box, being able to print it and vary in the height per specific case.

The plastic crate has a stiff bottom. This stiffness can be designed very specifically with ribs in the material. With the cardboard sleeve as modular part, this bottom can have one size which makes the logistics of this part easier for reuse than needing several sizes.

3.1.2 Division design problems

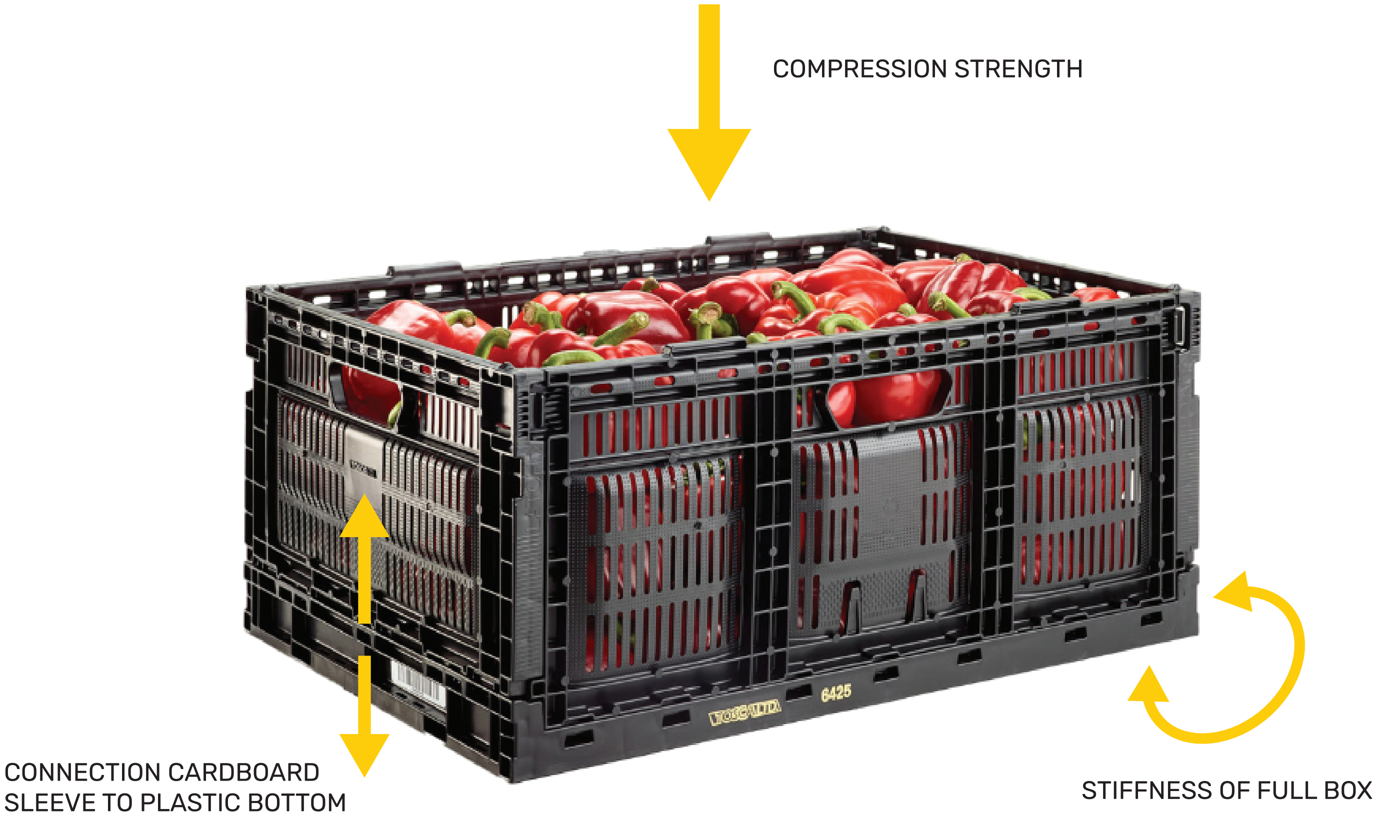


Figure 12 | Division design problems

The design challenge is divided in separate design problems. The first challenge is the attachment of the cardboard sleeve to the plastic bottom. This attachment needs to be able to carry the weight of the content in a filled hybrid box. Then the boxes will be stacked during transport, so the cardboard sleeve needs to carry the vertical compression strength. Also, the stiffness of the full box is a factor that needs to be designed upon, during carrying and stacking. See figure 12 for a visual representation of the design problems.

3.1.2.1 Attachment sleeve to bottom

The design challenge for the attachment of the CB sleeve to the plastic bottom has two different challenges in it. One is the **technical aspect** of the attachment. It needs to be **strong** enough while the box is carried (figure 12) [this part of the strength of the box will be addressed with the tensile strength of the box], it needs to be able to be assembled and disassembled several times (about 50-100 times). The second aspect of this design challenge is the **method of assembling** the sleeve to the bottom. The steps that need to be performed by the user. The **number of steps** should be as low as possible, the execution should be as **easy and fast** as possible. Compared to the assembly of an RPC the time it takes to assemble the hybrid box should be about the same. Shorter is better but the RPC is already very efficient so striving for the same time is already a challenge. The time of assembly is an important aspect for the hybrid box, for making a chance to be accepted into the fresh produce packaging market.

To address this design problem, some research questions are formulated which will be used in the ideation phase:

- What are possible connection methods to connect a cardboard sleeve to a plastic bottom?
- What are possible movements to assemble and disassemble a cardboard sleeve to a plastic bottom?
- How to reach the desired tensile strength for carrying the hybrid box?

3.1.2.2 Compression strength

During the distribution of the fresh produce, the boxes are stacked on top of each other on a pallet. For this, the box on the bottom of this pallet needs to be strong enough to carry all boxes on top of it. Corrugated cardboard exists of a waving pattern on the inside of two flat sheets, see figure 13. In different flutes the waving pattern differs in size. This influences the strength of cardboard. A cardboard sheet can be single walled or a double or triple wall.

For the design of the hybrid box, the strength of a cardboard sleeve compared to a folded tray needs to be discovered. With this information an estimation can be made of which type of flute is needed in the hybrid box design and if a simple sleeve will be strong enough or if the sleeve needs to be strengthened using smart designs.

The following research questions will be addressed:

- Is a sleeve strong enough to hold the load as secondary box for the fresh produce distribution?
- How can the design of the sleeve, including material choices, be optimized for the hybrid box design?

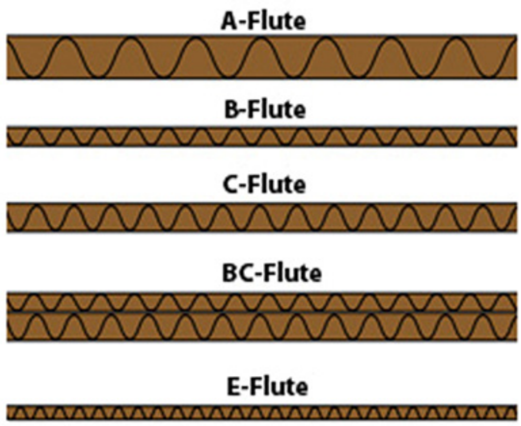


Figure 13 | Flute types cardboard

3.1.2.3 Bottom design

To make stacking of the boxes easier and stronger, the plastic bottom needs to be designed for that, in the case of stacking filled boxes as well as for empty bottoms for the reverse logistics. This is based upon the current design for RPCs, indents for the sides to fall into, and some designs of cardboard trays (figure 14 & 15).

These features enable a locking system which secures the place of the boxes on top of each other while stacking. This makes the pile of boxes/crates stronger and functions as feedback for the user who places the boxes on the pile, ensuring a straight stacked pile.

For the reversed logistics of the plastic bottoms, the bottoms should be stacked with as little as possible empty space left, to make optimal use of the space during transport and storage.

For the general design, the plastic bottom needs to be stiff and keep its designated form during use, carrying and transport. For this, ribs can be used to strengthen the bottom design. Also, ventilation holes can be added to the bottom design. Further explanation of this can be found in the next paragraph.

Figure 14 | Design features for stacking cardboard

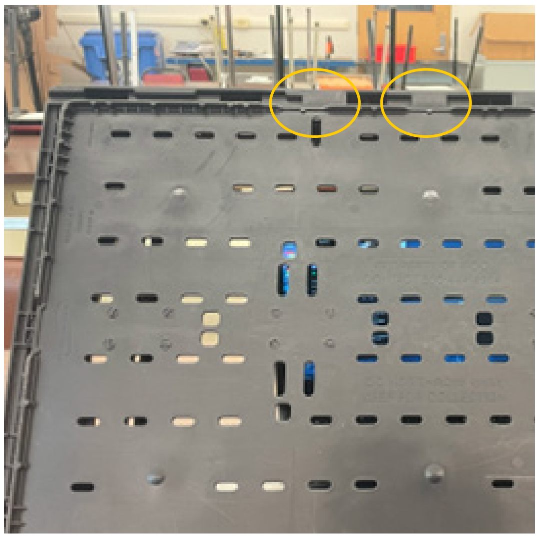


Figure 15 | Design features for stacking RPC

3.1.2.4 Ventilation design

To ensure freshness of the harvested fresh produce, ventilation holes are added into the design of transport boxes. The amount of ventilation necessary differs strongly per fruit or vegetable, but in general, the more the better applies most of the times (Chonhenchob et al., 2017). In

RPCs, ventilation holes are present in the sides as well as in the bottom of the crate, in cardboard boxes the holes are often added at the bottom of the sides of the box, where they have the most effect. Holes weaken cardboard boxes fast, so the placement of the holes is important to make them effective and be able to have as much ventilation as possible without too many holes. For the hybrid design, ventilation holes can be added in the plastic bottom and when necessary, in the cardboard sleeve, but this can be decided per use case.

3.1.3 Tentative requirements list

A requirement list is setup to function as starting point for the design development of the hybrid. The full requirements list can be found in Appendix A, but here is an enumeration of the most important onces for the beginning stage of the design process.

- C.010: The attachment of the sleeve to the plastic bottom needs to be able to withhold a tensile strength of the load it will be designed for
- C.011: The attachement of the sleeve to the plastic bottom and the disassembly of it should be possible to do in less then 3 (easy) steps
- C.013: The assembly of the hybrid should be clear without any explenation necessary
- C.020: The plastic bottom should withstand >50 cycles
- C.030: The assembled hybrid box should be able to withstand a compression strength of the load it will be filled with, times the amount the hybrid box can be stacked on a pallet
- C.042: The empty plastic bottoms should be as low as possible when stacked
- C.052: The hybrid should be able to keep the contents inside and protect them from forces from outside
- C.060: The plastic bottom must be cleanable

3.1.4 User scenario hybrid design

To get an idea in what environment the product will be used and what requirements are important in different scenarios, an overview of the life cycle of the to be designed hybrid box is made (Chonhenchob et al., 2017; J. Singh et al., 2016). The life cycle of a cardboard box is combined with the one of a reusable crate for the hybrid design. In figure 16, an overview is shown of where the box will be used and what kind of user cases it needs to be able to with stand. It starts with the production of the two different parts. These parts both need to be shipped to the farm where the boxes will be filled. This timing needs to be aligned to each other, which is the first hazard in the hybrid box design, compared to a box design using one material.

The box will be assembled on the field by the harvesters. These harvesters are paid by how many boxes they fill in a day, so the assembly time of the boxes play an important role in the possible speed the growers can fill the boxes. The faster it is, the better for the growers. This means the average assembly time of the hybrid box shouldn’t be way longer than current used crates to be able for industry to implement the box.

In the fresh produce chain, especially using reusable products, transport is a big part of the use cycle of the box. On this the hybrid box could save emissions if its lighter and smaller than a crate.

LIFE CYCLE

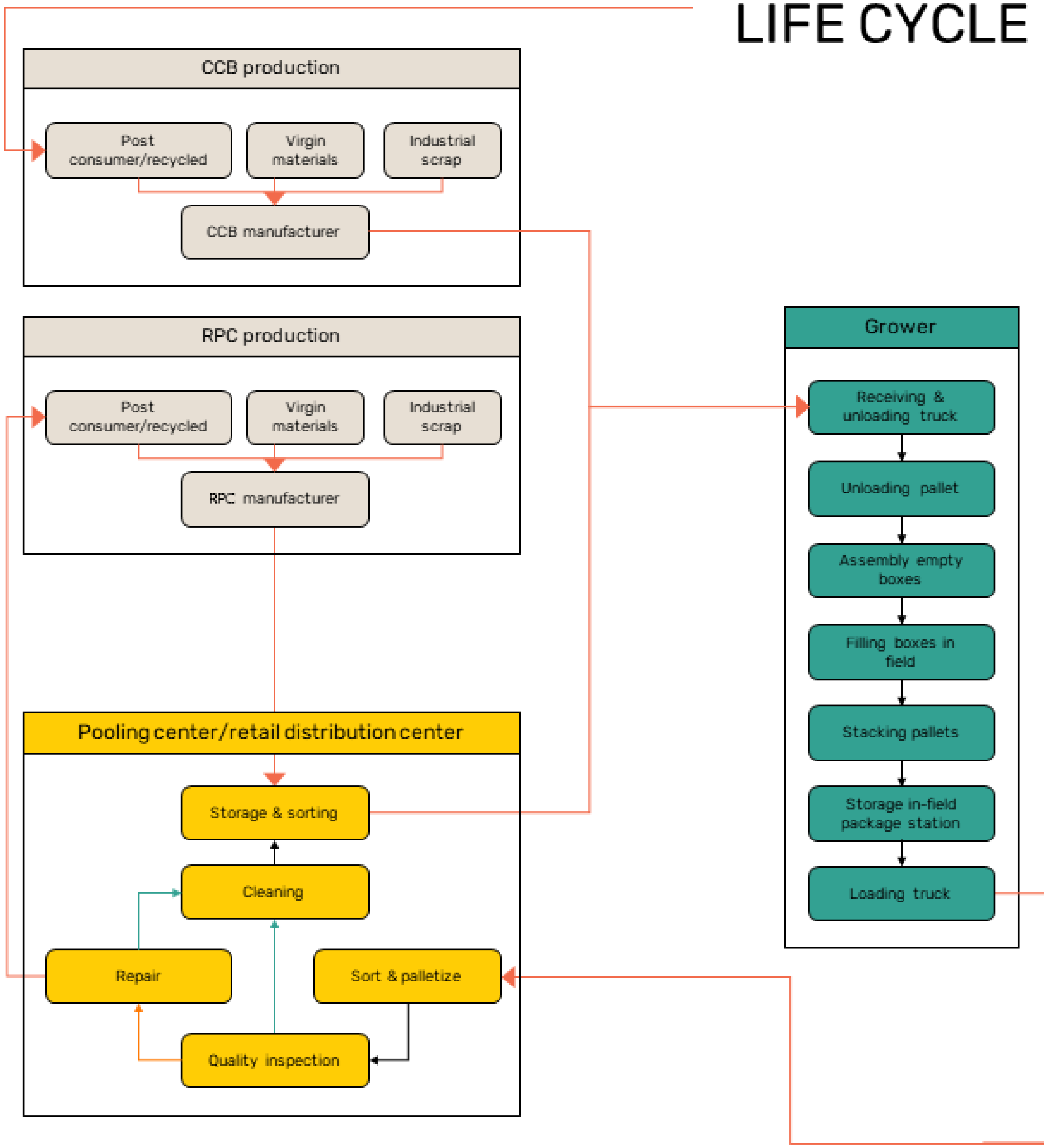
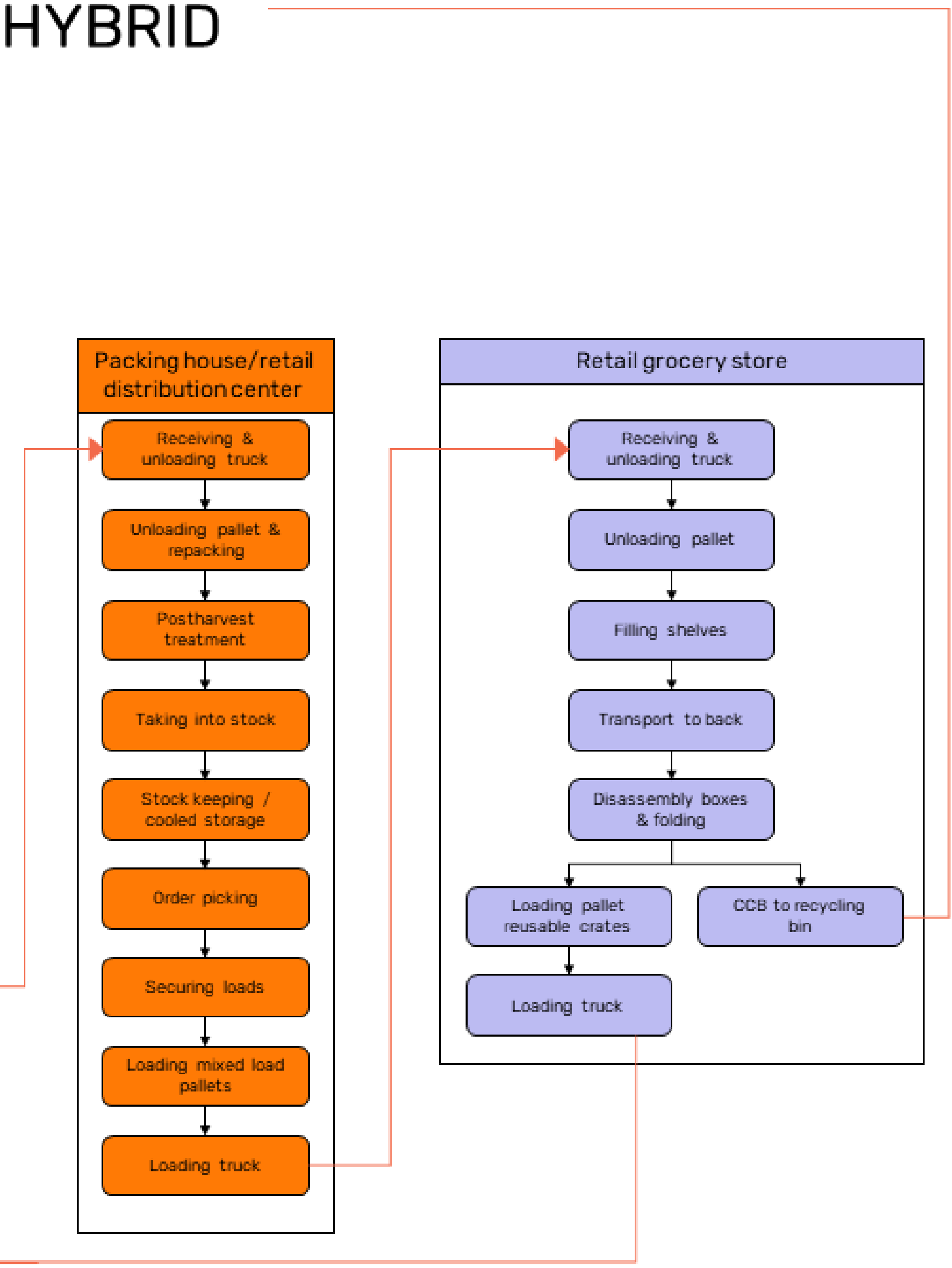


Figure 16 | Life cycle hypothetic hybrid secondary packaging

HYBRID


Packing house/retail distribution center
Receiving & unloading truck
Unloading pallet & repacking
Postharvest treatment
Taking into stock
Stock keeping / cooled storage
Order picking
Securing loads
Loading mixed load pallets
Loading truck
Retail grocery store
Receiving & unloading truck
Unloading pallet
Filling shelves
Transport to back
Disassembly boxes & folding
Loading pallet reusable crates
CCB to recycling bin
Loading truck

3.1.5 Hypothesis of pros and cons hybrid design

An enumeration and with that a summary of the expected pros and cons of the to be designed packaging combination between the RPC and CB is shown below.

Pros RPC/CB combi

- Less emission during transport of the to be distributed fresh produce
    - Due to the combination with CCB which has the possibility to reach the desired strength while keeping the design lighter, has the potential to save on transport emissions and thereby being environmentally and economically advantageous
    - Extend of difference is not known yet
- Possibility to single use branding for display ready boxes
    - Brand image promotion
    - No need of second tray for in store display (which saves material, paper?): environmental and economic benefit potential
    - Saves the step of transferring fresh produce in store to another tray: social and economic benefit potential
- Possibility to better standardization, while keeping higher modularity possibilities
    - With only changing the disposable and recyclable CCB sides, high modularity is possible while keeping a standardized RPC bottom, with emphasis on modularity in height (and brand image as explained in bullet point above)
- Less material will be “stuck” in the reuse pool of the use of one RPC
    - For one RPC in use, about 6 RPCs are needed in circulation. This is because of the waiting and transport times in the reverse logistics chain
    - An RPC bottom will exist of less material than a full-sized RPC, which has the benefit of a thinner loop (according to the circular recourse flows of Bocken et al, 2016)
    - This has an environmental benefit
- Less cardboard needed to achieve same strength
    - Using a sleeve without folding the sides
    - Less material needed to achieve the same strength

Cons RPC/CB combi

- Need for assembly in production line or in reverse logistics chain and need for disassembly and separation of materials in reverse logistics chain
    - Extra action needed by employees or in production process, which leads to possible economic and social drawback
    - This drawback can be limited by a simple to use design, which takes as little time as possible to execute
- Including a material which is designed to be disposed
    - With the future being aimed at as much as reusable products as possible, stimulated by the European (government), it is a drawback to keep using disposable material. Although it will be, to expectations, recycled, it will lose its quality and the material will lower in value.

3.2 Concept creation & iteration

3.2.1 Existing products

Existing products using a plastic/cardboard combination can be used as inspiration for ideation. In Singh et al. (2016), there is referred to a flower transport box, using a plastic crate as base with a cardboard sleeve on top of it (figure 17). This has the function of protecting long flowers, without having to make a very long plastic crate. The carboard can be adjusted to the needed height because it is used a single time. Flowers are light so the cardboard top is easily strong enough to be stacked.

Next to that, connection methods using plastic parts on cardboard boxes are studied, as well as plastic lids on top of cardboard boxes or cups (figure 18).

Figure 17 | Hybrid flower boxes

Figure 18 | Various plastic/cardboard connections

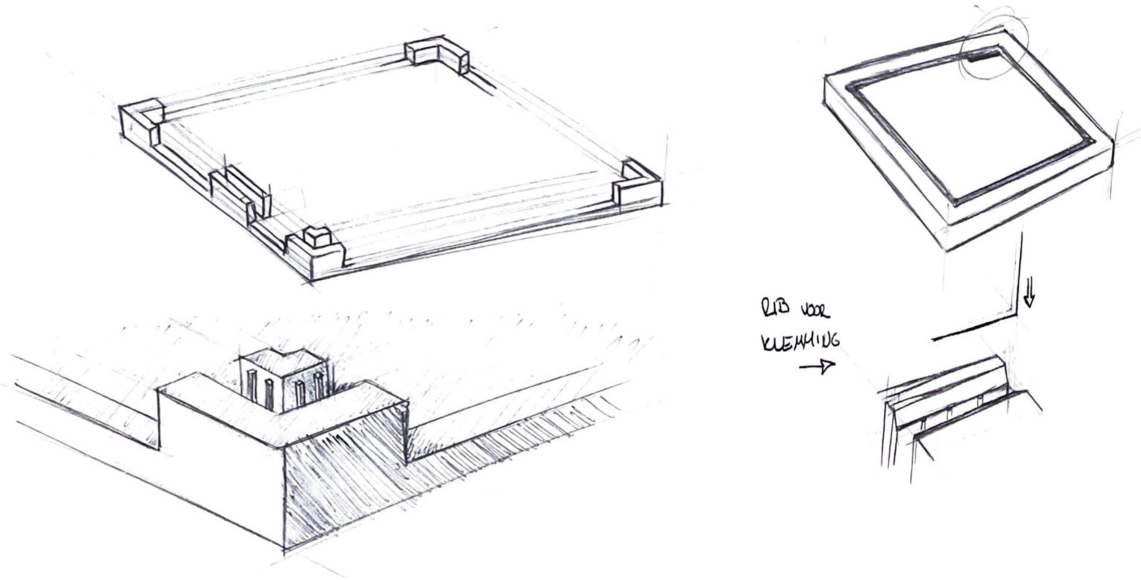


Figure 19 | Hybrid box idea Schoeller-Allibert

The idea for a hybrid design has its origin in a concept idea which was presented on a conference in the 90s (a Schoeller-Allibert concept) (figure 19). It was a plastic bottom with slots in it for the connection of a cardboard sleeve. In the slot were ribs which clams the sleeve. It was a very light weight design, but it didn't get implemented in industry. We expect the reason for this is that it was unable to be carried as a box.

This concept is used as input for a brainstorm session with the goal to use a plastic bottom existing of 1 part, like this one, and add something which makes the assembled box be able to be carried.

3.2.2 Ideation, concept creation & iteration

The design question for ideation is “How to assemble the cardboard sleeve to the plastic bottom?“

The question is divided in two different parts:

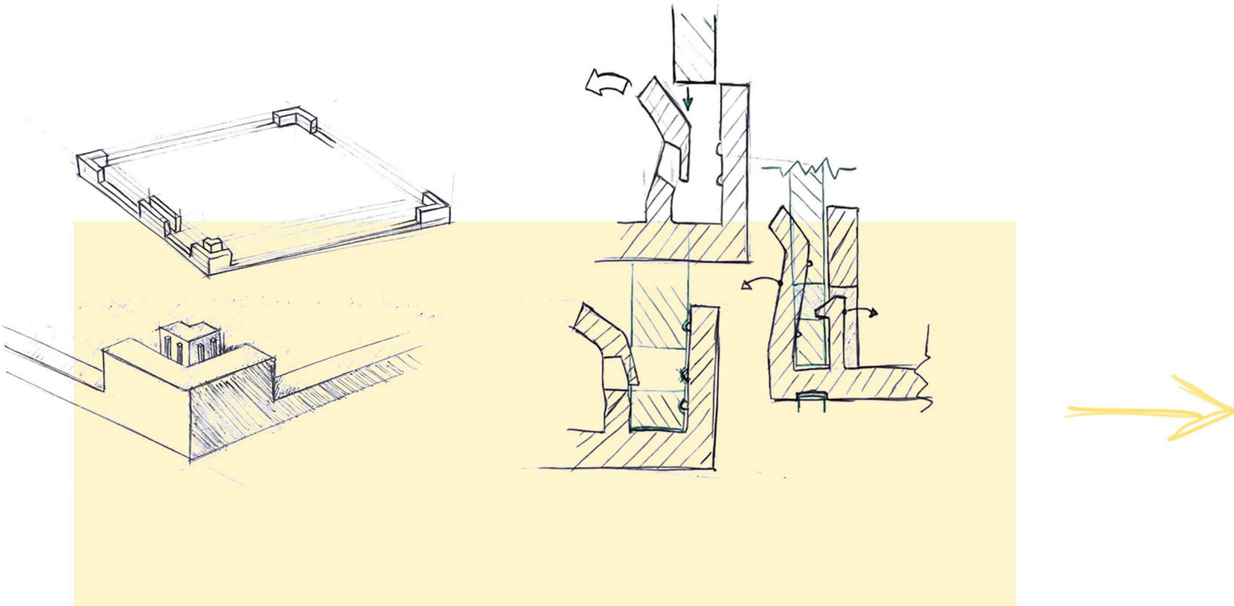
- What are possible connection methods to connect a cardboard sleeve to a plastic bottom?
- What are possible movements to assemble and disassemble a cardboard sleeve to a plastic bottom?

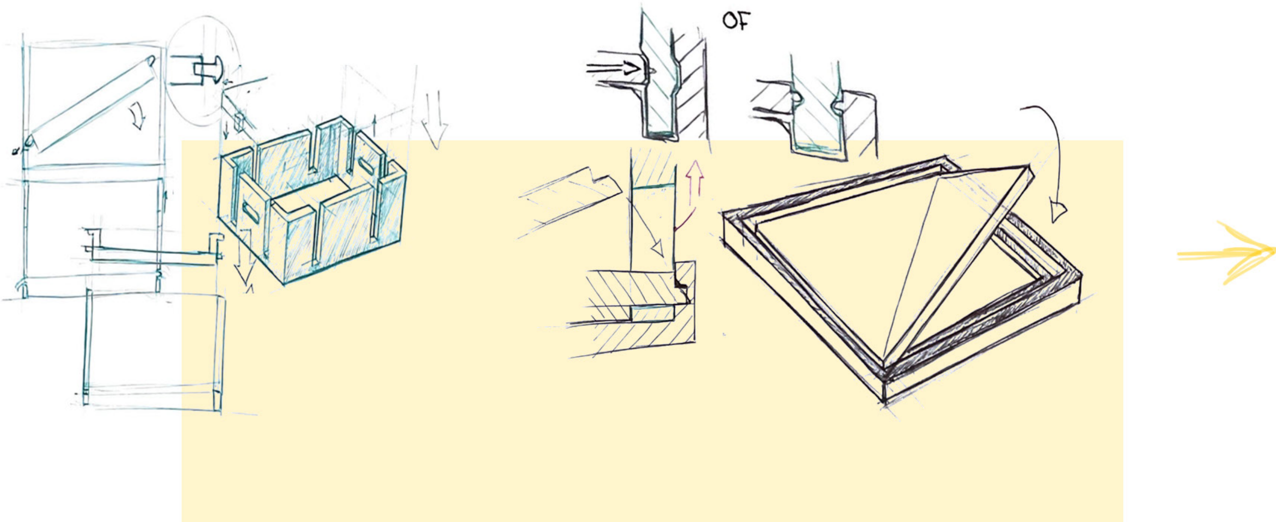
Explorative ideation will be performed for the two questions and various ideas will be combined, from which multiple concept ideas may emerge. The following steps will be taken:

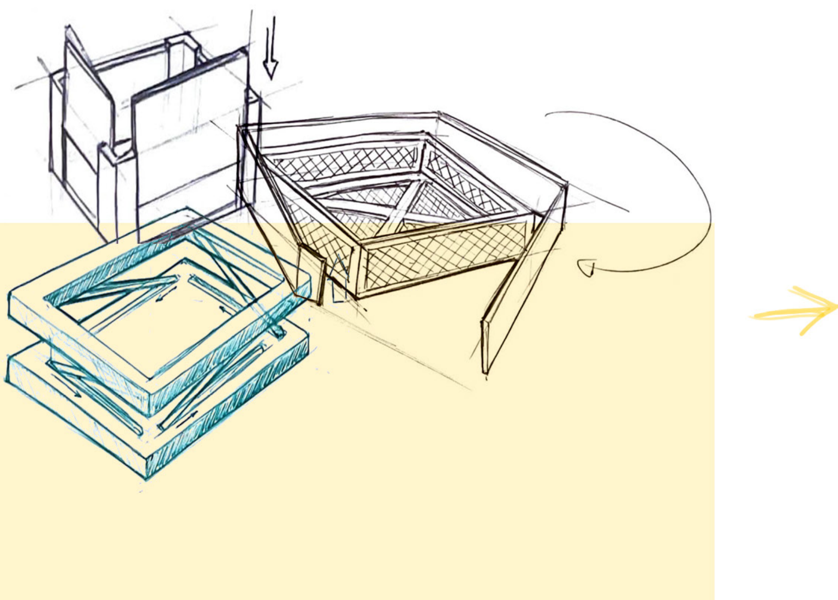
1. General ideation about possible movements
2. Ideation on technical possibilities of attachment based on the discovered movements
3. Concept creation in 3 different directions
4. Iteration upon first concepts

In order to explain the design process used in this project, sketches will be presented and the details of how the concepts were developed, and which ideas were discarded will be explained. The explanation will be organized into three concept directions for a clear and logical presentation. However, it should be noted that in reality, all idea generations did not follow a linear process but occurred together simultaneously.

Figure 20 shows an overview of the design process and the three different concept directions. The first direction is an iteration on the first idea (figure 19), but with the goal to make a connection between the bottom part and the sleeve, so the assembled box can be carried using handles in the sleeve. The second ideation process shown is based on the movement of pushing a plastic part in the sleeve to make the connection and the third is based on the current RPC design. This ideation challenged the weight of the current RPC to discover possibilities to make a concept design using cardboard as supporting part for a lighter RPC.







IDEATION SKETCHES

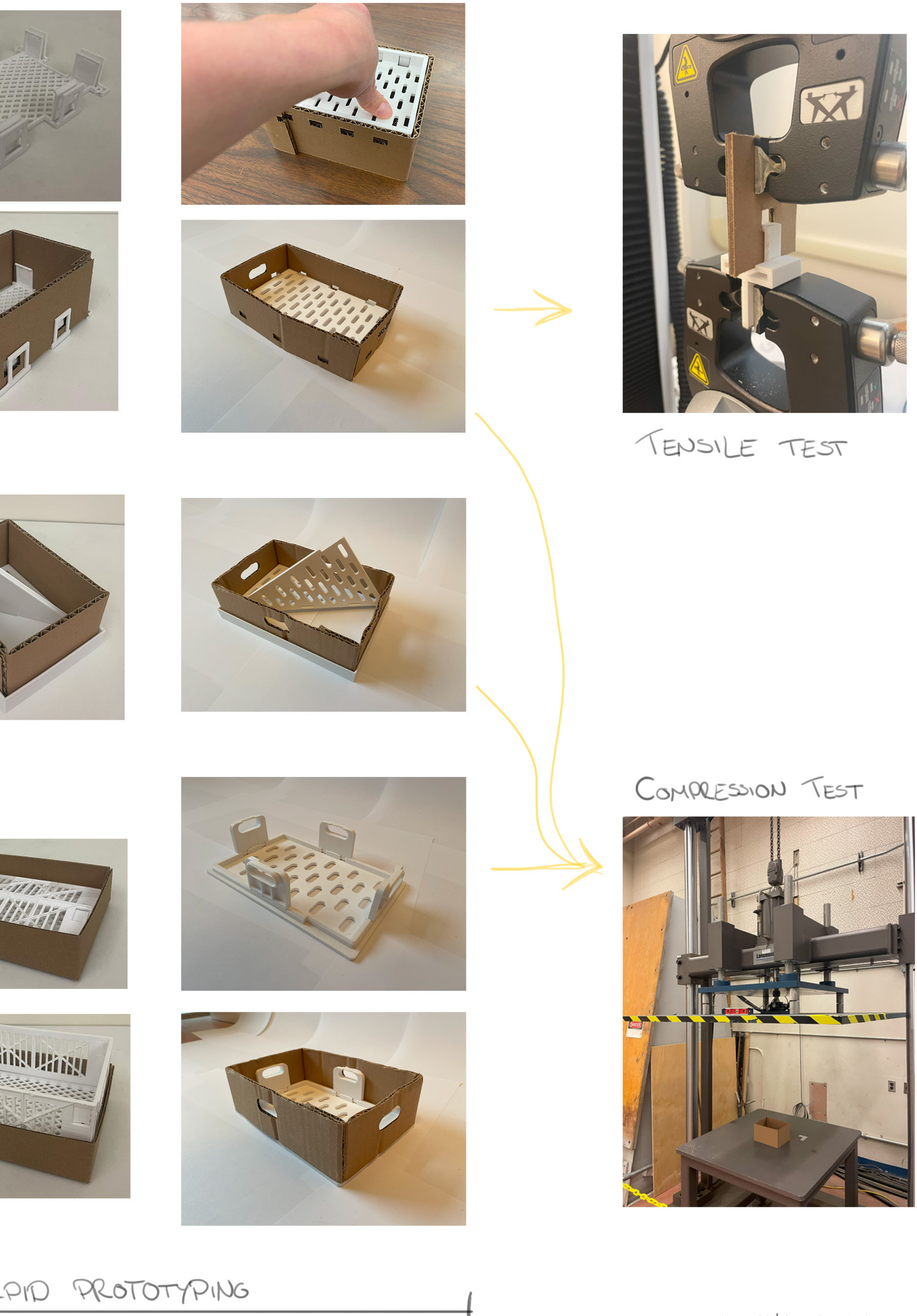


Figure 20 | Overview design process

3.2.2.1 Ideation on one solid plastic bottom part

See figure 21 for explorative sketches to discover possibilities in this point of view.

Movable parts for assembly

After the first brainstorm session a couple of ideas could already be discarded because of the requirements they need to fulfill. A plastic bottom with a system in it which turns and therefore extends some kind of pins that attach to the cardboard sleeve is a complex system with multiple parts. For a reusable product it is wished to have as less parts as possible, because the more parts the likelier one of them breaks during the use phase and therefore makes the product less durable. Also, it is harder to **clean** moving parts, or even hidden parts that might be necessary in this concept.

Requirement C.020 & C.060

So: DISCARDED

Push bottom on cardboard

This concept involves a firm plastic base that can be attached to the cardboard sleeve from the top, without any base movement. To achieve this, slots on the sleeve could be used to prevent the plastic base from disassembling while the cardboard sleeve carries the box. However, this option is not feasible because the slots would significantly weaken the box.

Requirement: C.030

So: DISCARDERD

Another idea is to push the plastic bottom in the sleeve from the top. This approach is explored further following section, paragraph 3.1.2, the clamming bottom ideation development.

Push cardboard on bottom

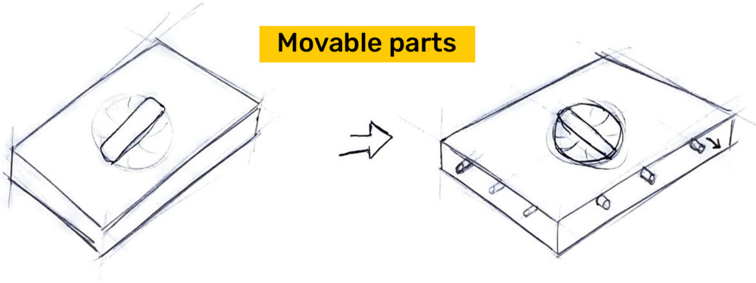
A concept involving a push through mechanism together with a flexible attachment system is explored. Based on a Tupperware container, the idea was to connect the cardboard to the plastic bottom using a movable attachment system, which can be achieved with either a film hinge, a standard moving hinge, or a flexible component that is able to grip a hole within the cardboard sleeve. A pinch in the sleeve could be a way to keep the attachment of the two materials or making a “dead point” of the plastic when it went through a cardboard hole or make the plastic attach to itself again. It is probably not possible to make this attachment with a clamming force of the plastic onto the hole in the cardboard, because cardboard is probably not strong enough.

Alternatively, this type of attachment, a plastic part going through a hole in cardboard sleeve, can also be a snapping system. Then the sleeve can be a pushed through the plastic bottom.

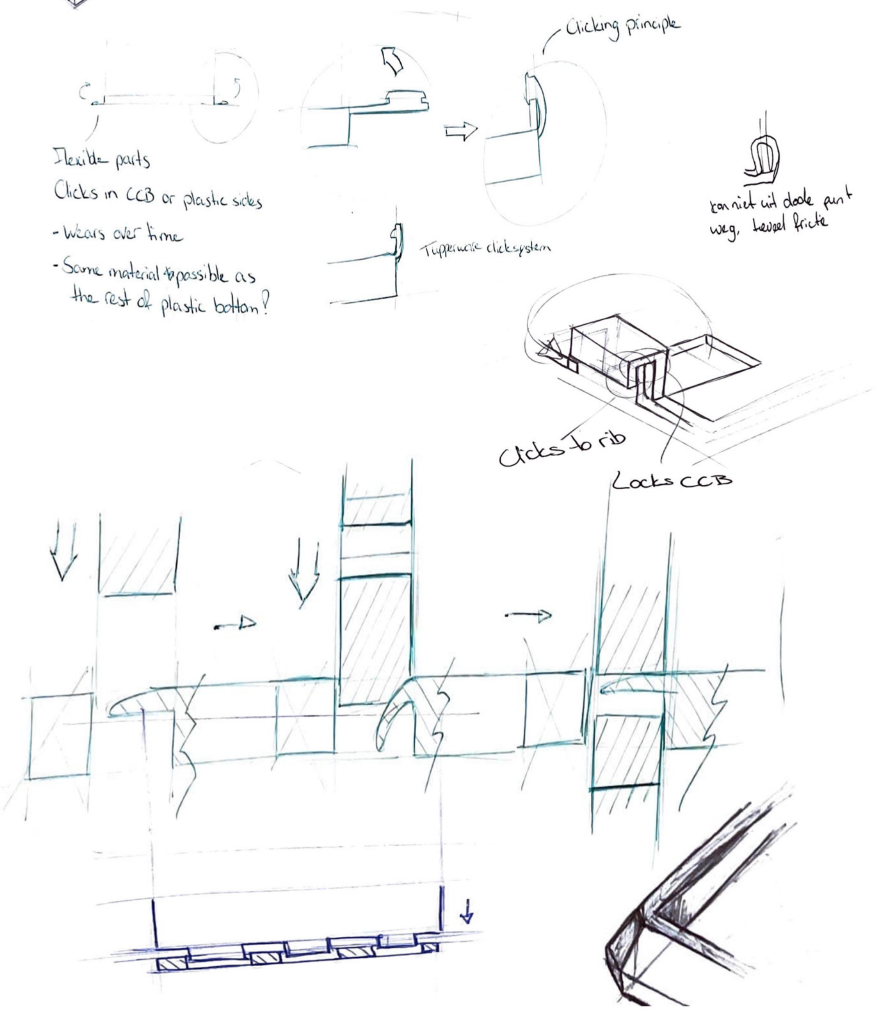
Snap system ideas

During this ideation process, the idea of the snap system appeared to be most promising and durable, resulting in further development. Various snap system shapes were explored to come to an idea with the potential to be durable enough for a reusable product. Additionally, the disassembly of the product is an important aspect that should be considered. This is a challenging aspect of the development of this concept because snap systems will only move when the force executed on them in one direction. For disassembly the product needs to move in the other way, but that is the same direction as where the snap systems are designed for to withhold the strength of the content. A first rapid prototype was created to explore additional possibilities, as shown in figure 23.

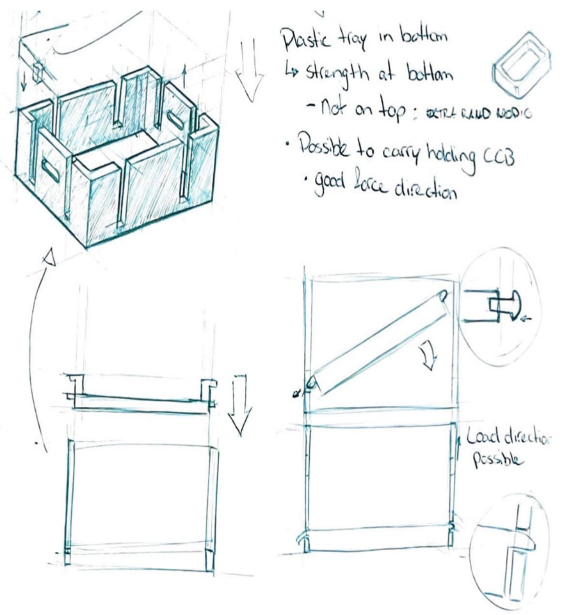
Movable parts



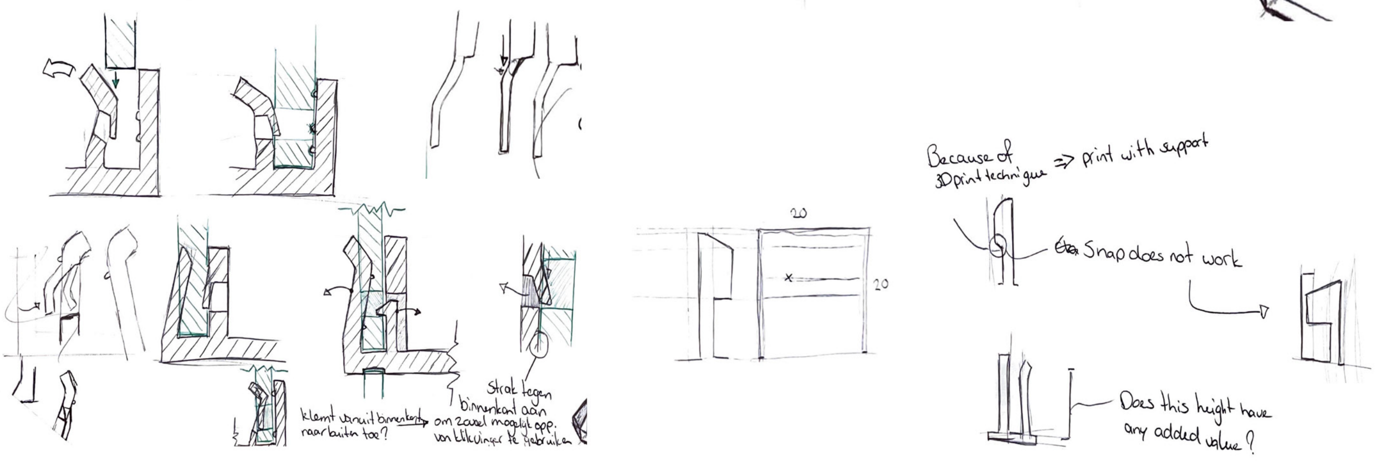
Push cardboard on bottom



Push bottom on cardboard



Snap system ideas



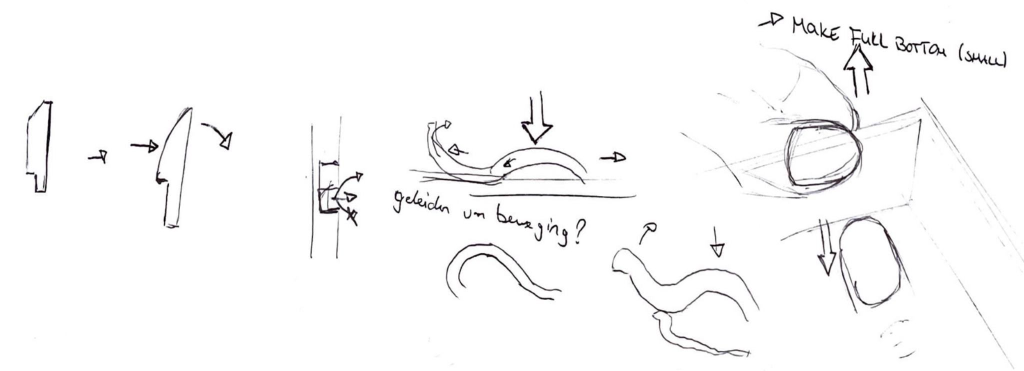


Figure 21 | Ideation on one solid bottom part

The **disassembly** method in this prototype required pushing the two corner snap systems and pulling on the corresponding corner of the cardboard sleeve. This process had to be repeated four times to disassemble the sleeve from the bottom, which presented a hazard. To continue with this concept the design challenge became making the disassembly process easier while maintaining the concept idea. Initially, the proposed solution was to press a button inside the box to relocate the snap system to its interior, thus freeing the sleeve. However, this approach proved to be even more challenging to achieve while complying with the criteria of easy cleaning and minimal number of parts, like the moveable parts for assembly ideation.

Another disassembly method could be tearing the cardboard sleeve open, see figure 22. This would require creating a puncture line on the sleeve, which would weaken its overall strength. Also, the prediction is that it would require excessive force to tear the sleeve using this method and would not be ergonomic for employees who have to repeat this process many times.

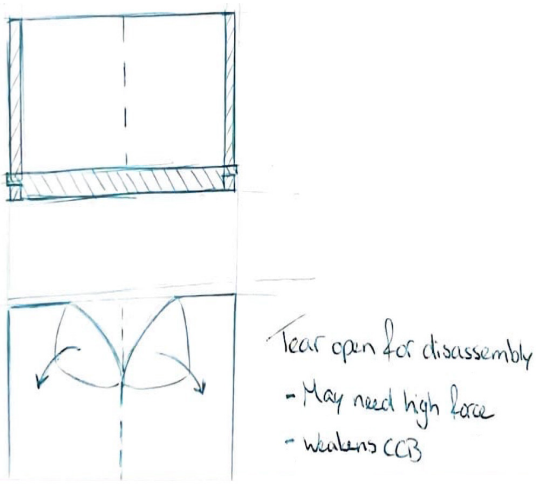


Figure 22 | Disassembly method

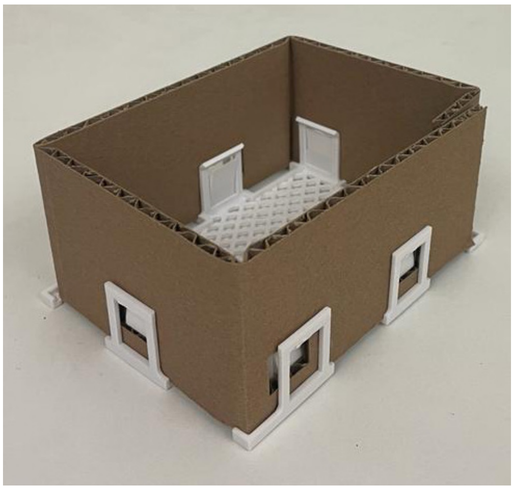


Figure 23 | First prototype of snap system concept

Snap system concept

Iterating on the disassembly possibilities, and combing the push through bottom idea, a push through disassembly idea was created. The plastic bottom has snap systems. A snap system can only be assembled in one way. For this concept, the cardboard sleeve can be pushed onto the plastic bottom from the top. The snap systems snap into the holes in the cardboard. When the box is lifted, the snap systems hold the plastic bottom attached to the sleeve. When the box is at the end of one cycle, the bottom can be pushed through the cardboard sleeve from bottom to top, allowing the snap systems to form and making room for disassembly, see figure 24.

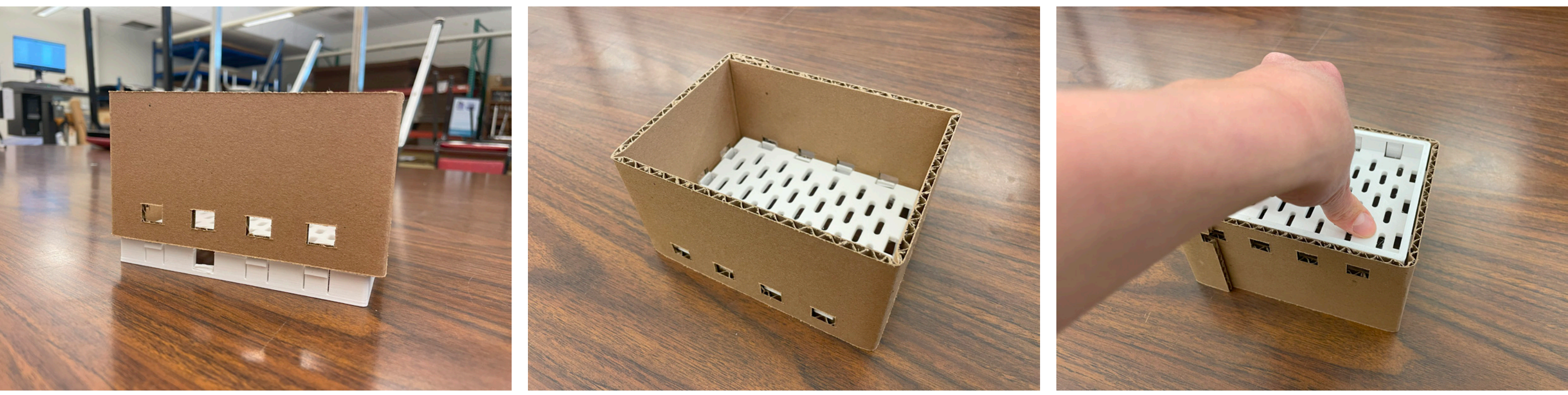


Figure 24 | Rapid prototyping of push through snap system concept (on scale)

3.2.2.2 Ideation based on pushing plastic bottom through cardboard sleeve

At a prior ideation stage, another path was conceived centered around pushing the plastic bottom through the cardboard sleeve for assembly. See figure 25 for explorative sketches to discover possibilities in this point of view.

General ideation

It could be a **stiff bottom**, but with the idea in the bottom left, I was afraid the bottom would damage the cardboard sleeve while being push into the holes of the sleeve. That's where the idea of moving plastic bottom comes from. That can put force onto the cardboard sleeve.

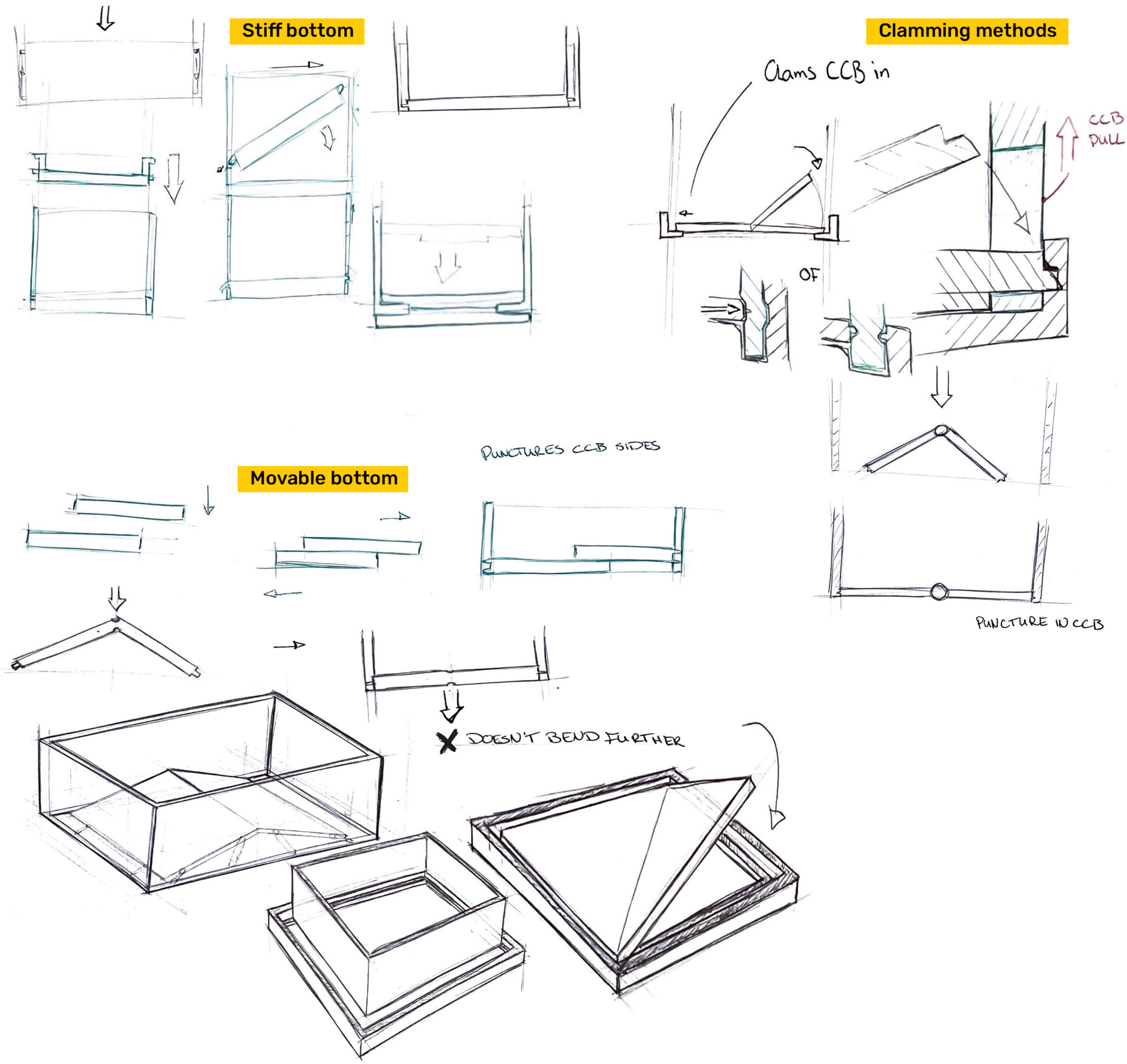


Figure 25 | Ideation on push plastic through sleeve

Clamming methods cardboard to plastic part

Multiple options for attaching the sleeve to the plastic bottom were explored. One of them having the plastic bottom puncture the cardboard sleeve, but this was discarded because of possibly loss of strength of the cardboard sleeve and kind of sharp part necessary on the plastic bottom to puncture. Also, a clamming between an inside plastic part and an outside plastic ring with the cardboard in between, or the plastic inside part clicking in the outside part through holes in the sleeve.

Clamming system concept

The choice for a concept was fallen on a plastic inside part with a hinge, film hinge or normal one, diagonal on the part, so the force distribution to the sides of the cardboard sleeve would be divided equally. An outside plastic ring/part was added so the force could be applied on it with sleeve in between. This concept was rapid prototyped too (figure 26), using 3D-prints and cut cardboard sleeve. A "normal" hinge is used. Film hinge was tried too but to apply enough pressure it was not strong enough, especially with 3D-printing. Clamming of the cardboard is done by an added edge to the inside and outside plastic parts. This influences the strength of the cardboard sleeve because it compresses the flutes of the cardboard, so it gets weakened.

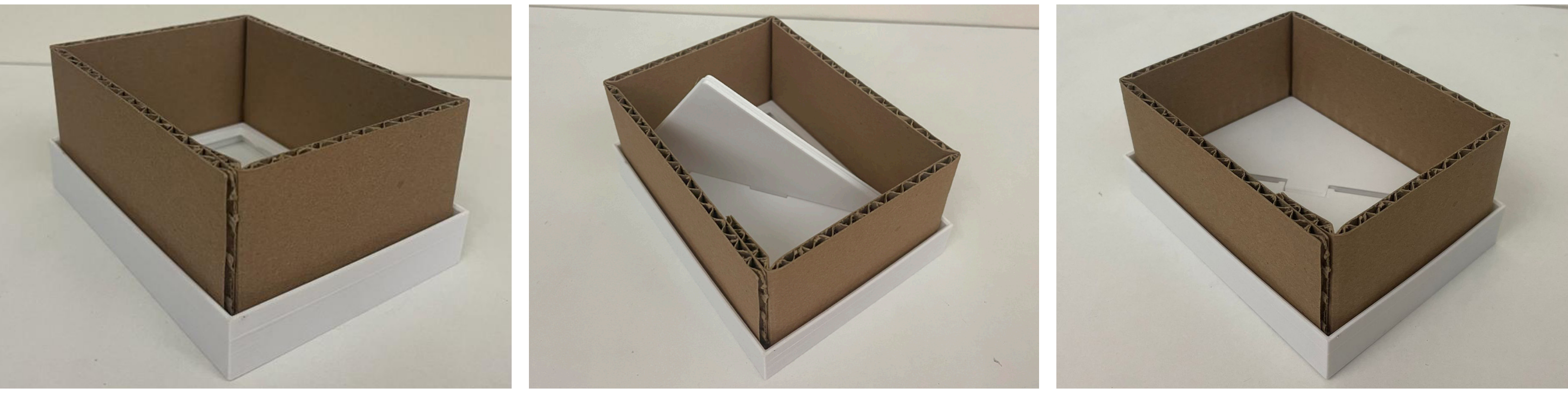


Figure 26 | Ideation on push plastic through sleeve

3.2.2.3 Ideation based on RPC

Then as another base for an ideation process, the foldable plastic crate was used as inspiration too. See figure 28 for explorative sketches to discover possibilities in this point of view. To improve upon the current RPC, the goal was to make the plastic reusable part lighter and support it with a cardboard sleeve. A couple of options were taken into consideration. Making a skeleton out of plastic, putting cardboard sides in it, or a sleeve. This skeleton would be a movable plastic product, saving a lot of material compared to an RPC. In the past a foldable plastic crate was developed using a mesh as basis for the crate. This was a very lightweight option for the transport of light fresh produce, such as strawberries or grapes in this case (figure 27). The crate was intended to be reusable, but the mesh wasn't strong enough for multiple use cycles. Therefore the idea was to combine this mesh crate with a lightweight cardboard tray outside. The lightweight cardboard tray would function as protection of the mesh, not for strength. A rapid prototype is made of this idea, see figure 29, but the potential of the idea was lost. The skeleton idea was regarded too, as the moving parts would be hard to clean and potentially hard to make durable enough.

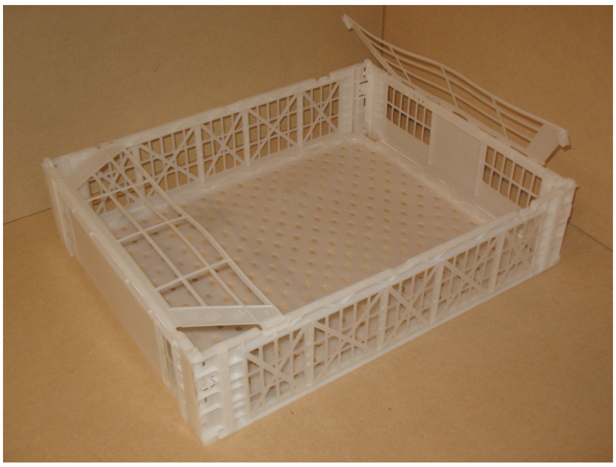
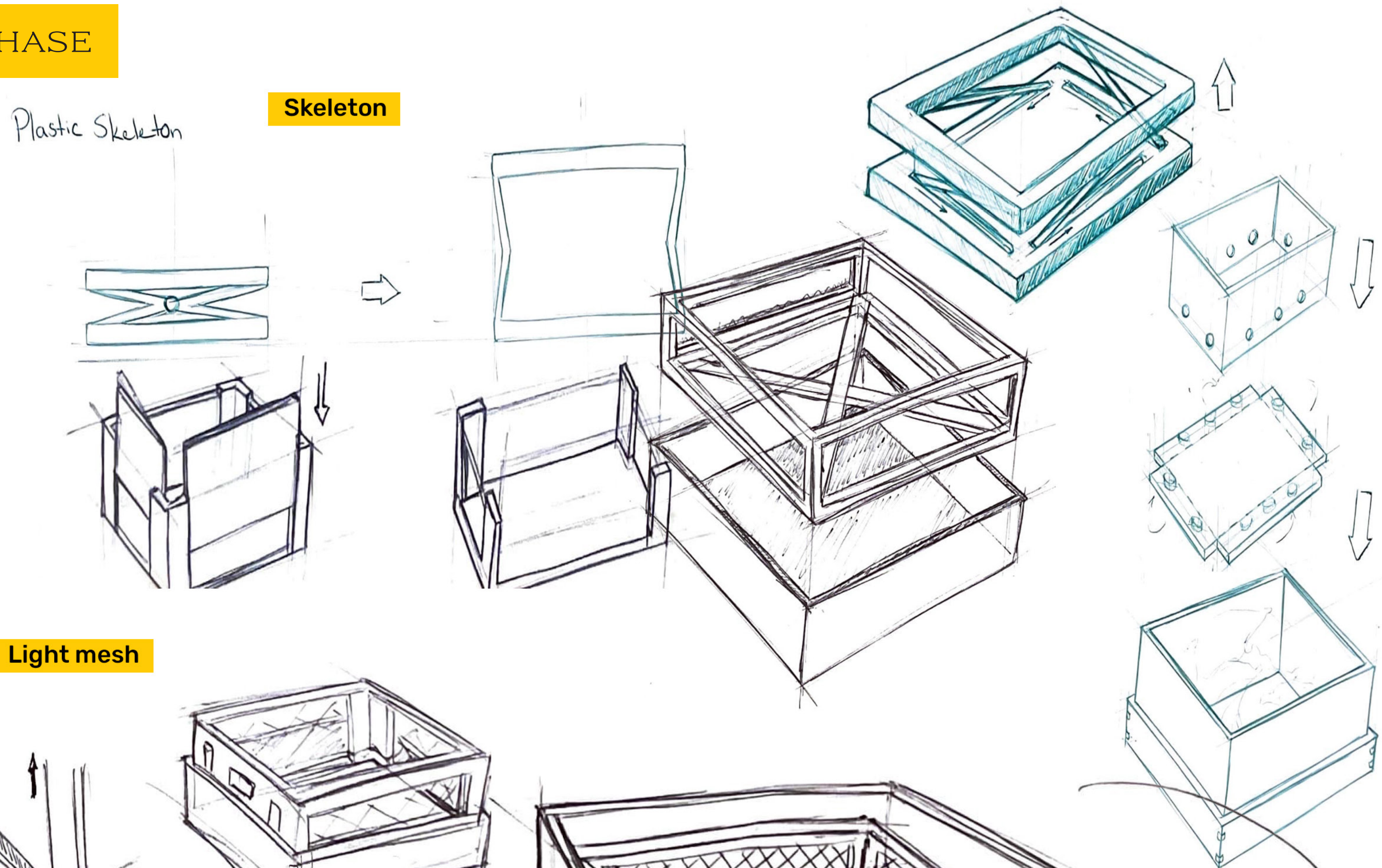


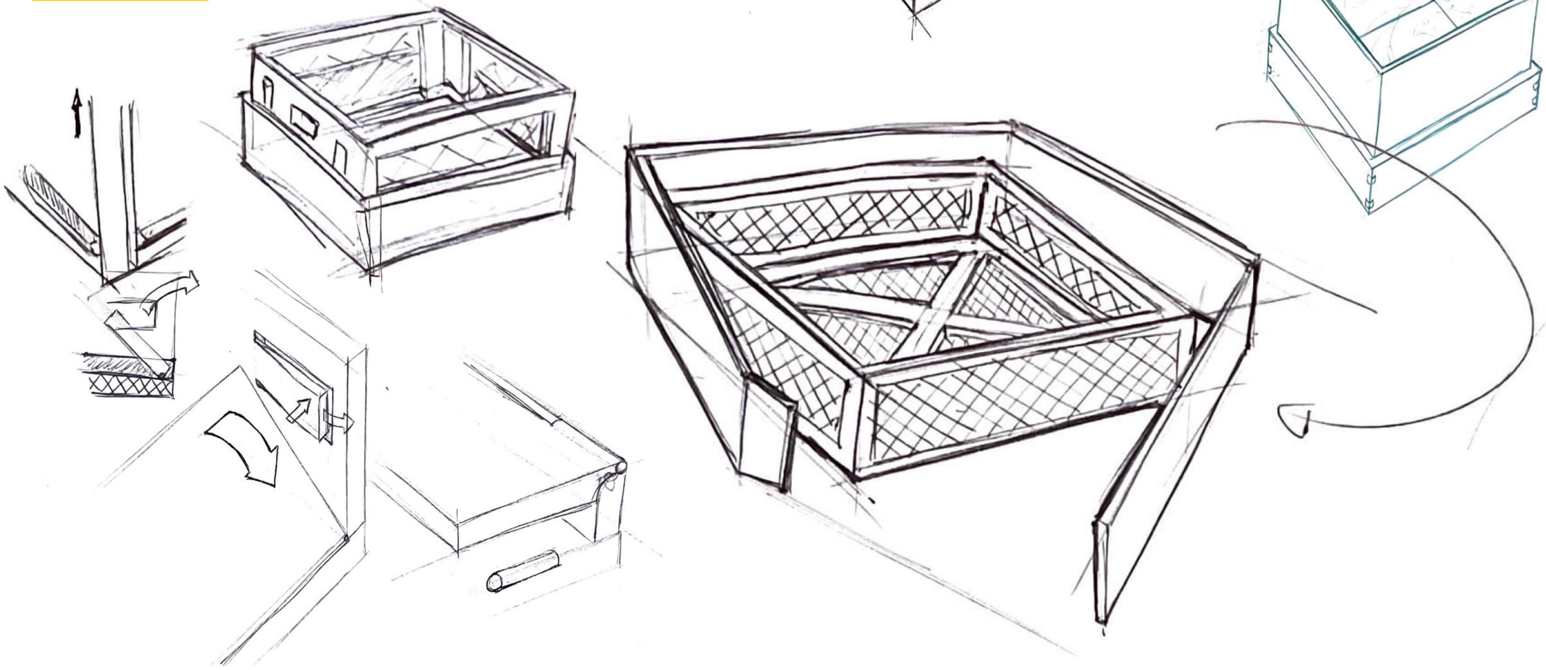
Figure 27 | Strawberry container

Further iteration on this idea let to the idea to only add material to the plastic part around the handles for carrying the box. This reduces the amount of

Skeleton



Light mesh



Handles only

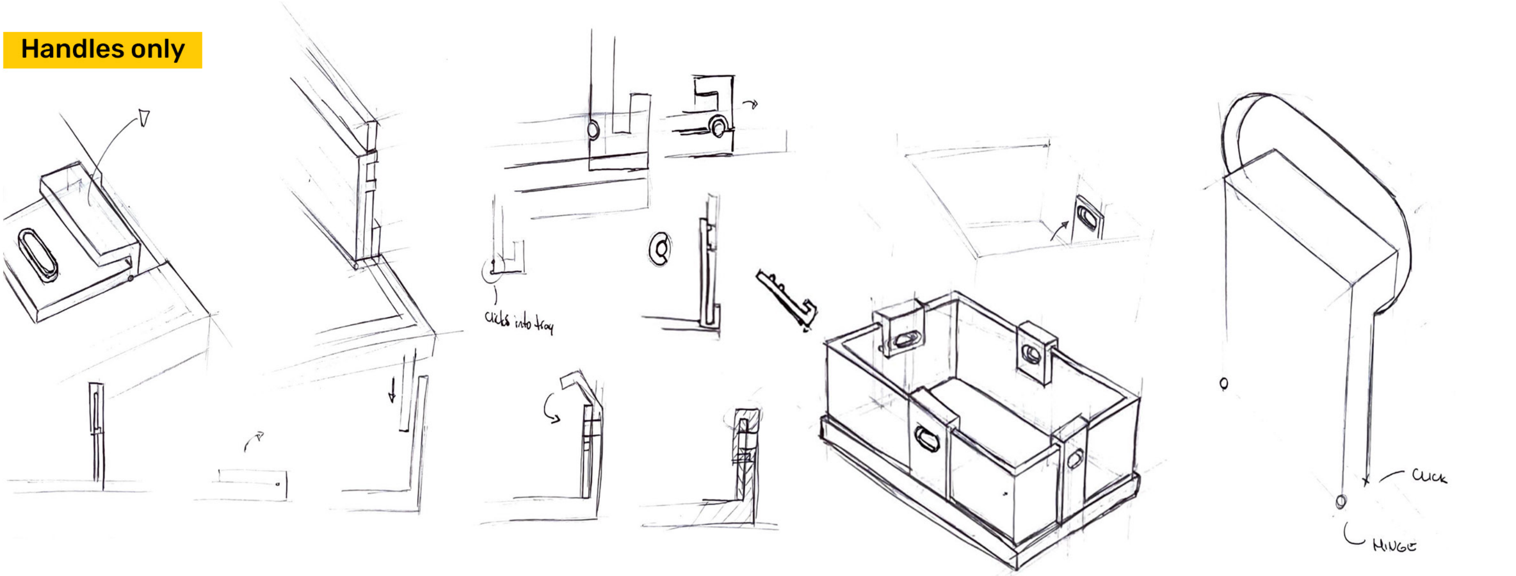


Figure 28 | Ideation based on RPC

plastic material in the reusable plastic bottom part, which makes it lighter than an RPC, but it can be made sturdy enough for repeating use cycles. Another advantage of adding plastic material there, is that when carrying the assembled box, the strength of the box is coming from the plastic parts only, instead of in the connection of the cardboard to the plastic parts. This makes it easier to develop this concept and make it strong enough. Also, from literature or from interviews with people from the field, it appears that holding a plastic handle is more preferred than a cardboard hole, which cuts into the hands of employees. To attach the handle to the cardboard sleeve is explored in the following sketches. A first idea, which is a clamming edge of the plastic part into the cardboard hole, is chosen to use for the rapid prototyping (figure 30).

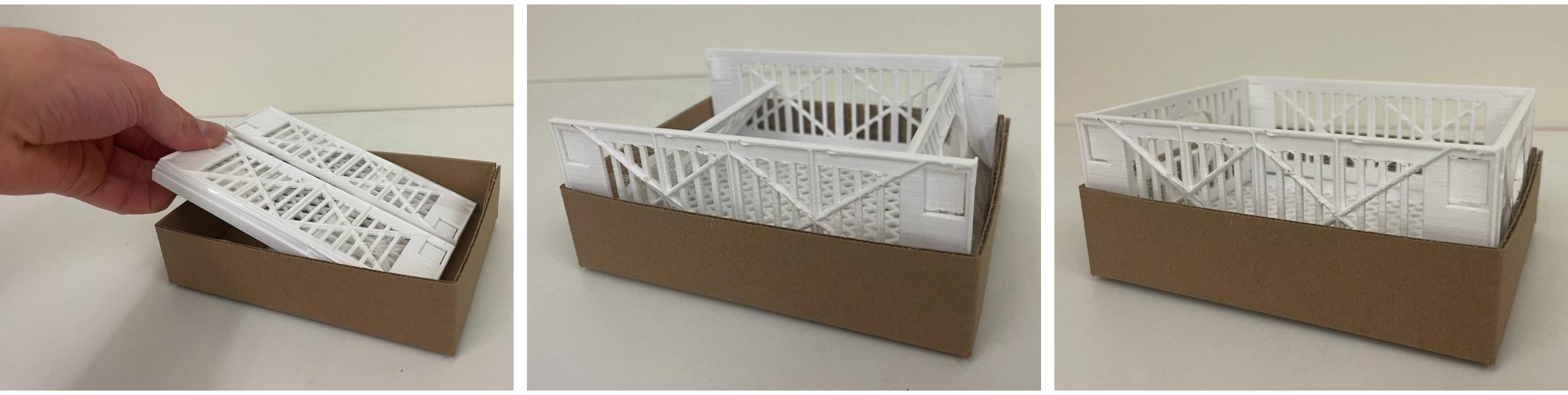


Figure 29 | First prototype of mesh crate with sleeve as support

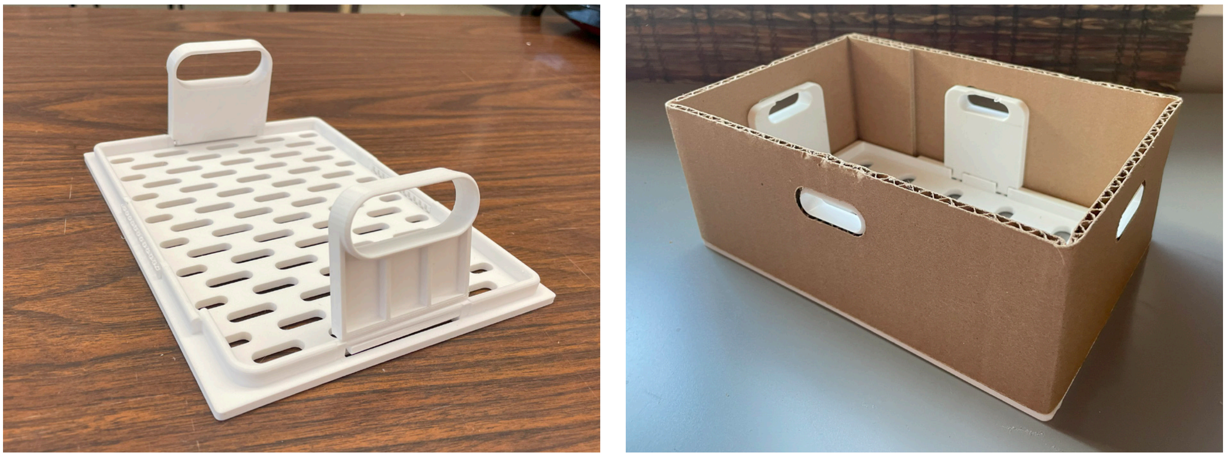


Figure 30 | Rapid prototyping of handles-only concept

3.2.3 Final 3 concept directions

In the next paragraphs, the result per concept is highlighted and the assembly and disassembly method is explained, together with the expected benefits and challenges which need to be addressed in further development. The concepts are discussed with experts in the fresh produce packaging field (Jay Singh, Jim Vangelos, Roland ten Klooster, Shoeller-Allibert, Smurfit Kappa, HB-RTS).

Snap system concept, see figure 31

How it works:

Cardboard sleeve is pushed onto bottom from top (1 movement): snap systems snap into cardboard holes

↓

Snap systems hold parts together when carrying

↓

To disassemble push bottom part through cardboard sleeve (1 movement)

Uncertainties/challenges:

- Sleeve has support only from the inside. Fresh produce will push force from inside to outside too so question is will it keep shape good enough so snap systems keep being attached to holes or will sleeve bend outside too much?
  - Also, cardboard changes in size when moisture rate variates. Could be a problem in this concept
- Will a couple of holes in cardboard sleeve be strong enough to hold the fresh produce in when box is being carried? -> **tensile test** cardboard
- Is support on the bottom of the sleeve only from the inside enough to make the box rigid enough? -> **compression test**

Benefits

- This concept is the most modular of all, because all wanted changes can be made in the cardboard sleeve, without effecting the connection method to the plastic part. Height/holes/flute type/etc.

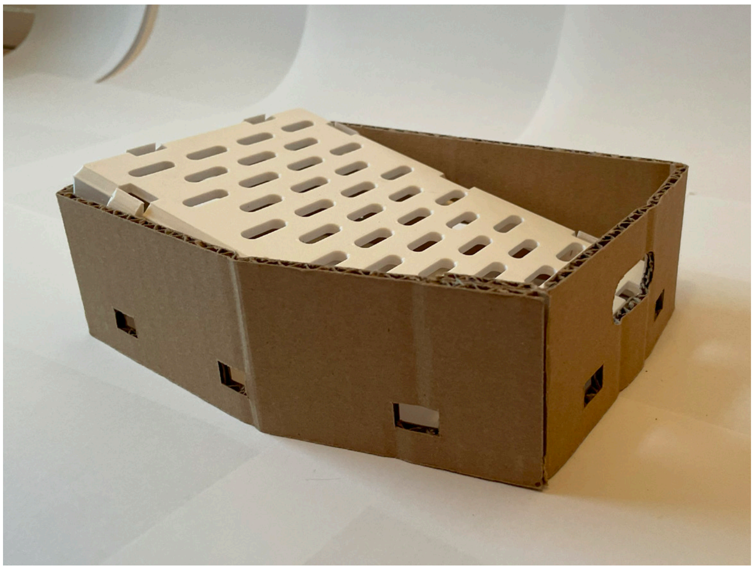


Figure 31 | Snap system concept

Handles-only concept, see figure 32

How it works:

Assembly sleeve onto plastic bottom

↓

Unfold all 2/4 plastic sides and attach them to the cardboard sleeve (2-3 movements)

↓

Plastic sides will attach to the holes of the handles of the cardboard sleeve, this makes the connection between the two materials, when the box is carried the strength comes from the connection of the plastic sides to the plastic bottom

↓

To disassemble fold the 2/4 plastic sides

↓

Take the sleeve out and discard (2/3 movements)

Uncertainties/challenges:

- The time it takes to assemble should be comparable with a current RPC, it is uncertain whether this will be the case for this concept -> assembly test
- To make the concept modular in height, which is a benefit compared to current RPCs, the handles should be easily replaceable or multiple height should be in stock, though this is the same system as with current RPCs or the height should be interchangeable while keeping the handles at the same height, but the ergonomics of the box deteriorates.

Benefits

- The expectation is that this concept will be possible to be strong enough to be carried and used in the field, because it is based on current RPCs.
- Carrying the box is done in the plastic handle holes, which is preferred towards cardboard holes

Figure 32 | Handles-only concept

Inside clamming concept, see figure 33

How it works:

Assembly sleeve into outside bottom ring

↓

Put inside plastic part into sleeve

↓

Push inside part down which crates the clamming (3 movements assembly)

↓

Clamming between inside plastic part and outside ring with cardboard sleeve in between makes the connection between the parts

↓

For disassembly push the inside part from the bottom to get it out

↓

Get the sleeve out of the outside ring and dispose (3 movements)

Uncertainties/challenges:

- How strong will the clamming connection of the plastic parts with the cardboard sleeve be? Hard to predict because of the collaboration of 2 materials. Not to test in solidworks, behavior of cardboard is not known in that program. Tried to test with a scaled model on a tensile tester, but a scaled model is not representative of a full scaled model, plus a 3D-printed part behaves way different from an injection molded part so is also not representative.
- Also, there is a fold in the middle of the bottom of the plastic part. This is already the weakest part of the bottom of current boxes. A fold will weaken it so to make it strong enough is a challenge. -> compression test
- Having 2 parts to make the connection is a drawback, according to employee of Shoeller-Allibrecht. Having the possibility to lose a part during the distribution process is a big drawback and not accepted in this stage of development. If 1 part gets lost, the hole bottom becomes unusable.

The development of this concept **stops** here, because it exists of two different parts which is a big disadvantage compared to the other two concepts.

Figure 33 | Inside clamming concept

3.3 Conclusion

The goal of this design phase was to come up with possible concepts for a design of a hybrid secondary package, using a plastic bottom and cardboard sleeve. Ideation and iteration were done using sketches and physical 3D-models using rapid prototyping. This resulted in three different concepts based on three different ways of movements for assembly. With that, three different options are given as an answer on the design questions.

The developed concepts are aimed at answering the questions about what possibilities exist for connection and assembly methods, but don't address the strength it can have. Therefor two tests will be executed. A compression test to gain knowledge about the strength of a cardboard sleeve, compared to a cardboard tray, and looking into the influence of a fixation at the bottom of the sleeve. And a tensile test, to address the tensile strength of the holes in the cardboard sleeve for the snap system concept, to get an idea of the cardboard sleeve will be strong enough to function as the connection method of the sleeve to the bottom while the box will be carried around with content in it.

4. Compression test

For all concepts the compression strength of a cardboard sleeve is an important part of the total strength of the hybrid box concepts. Compression strength plays up when the boxes get stacked on top of each other, especially when they are filled with the fresh produce. The bottom box should be able to carry all boxes that are stacked on top of it. Depending on the weight of the produce that is transported, the box should be able to withhold a different weight. This test is set up to discover the compression strength of a cardboard sleeve with a 4 mm thickness (C-flute) and will be compared to a box with an open top (a tray). The test is executed with multiple heights (100, 200, 300 mm) to see if there is a difference in strength. Next to this, the influence of a bottom support on the inside, outside, or both sides of the cardboard sleeve is tested. This information can be used into the design process of the concept, to get a feeling which support has the most influence on the strength of the hybrid box.

4.1 Compression test set-up

Research question 1: Is a sleeve strong enough to hold the load as secondary box for the fresh produce distribution?

Hypothesis 1: A cardboard sleeve is stronger than a cardboard tray which is folded on the bottom, because the folds weaken the structure of the cardboard which exists out of flutes.

Research question 2: What is the influence of a fixation on the bottom of the cardboard sleeve and does the tightness of the fixation have an influence?

Hypothesis 2: A bottom fixation will strengthen the cardboard sleeve, if the cardboard is not deformed by the fixation, so a tight clamming might have a negative influence on the strength

Method: Following ASTM D642. For all different sizes, 5 samples are used and tested separately. The test setup is shown in figure 34 & 35. The sleeve with different heights will be tested without any fixation to the bottom, with an inside fixation, outside fixation, inside and outside fixation, double height fixations and tighter fixations, to test the influence of these different options (figure 36-39). All samples are conditioned at 23 ± 1 °C and 50% relative humidity for 48 hours prior to testing in accordance with ASTM D4332.

Material: 4mm C-flute cardboard is used for this test. The reason for this type of flute is that this flute is mostly used in the fresh produce chain for cardboard boxes in the US. The cardboard is cut with a CNC-machine and is glued together using hot glue. For the inside and outside bottom fixtures, wooded planks are used and cut out with a waterjet to ensure the right dimensions. Wood is chosen as material because it is stiffer than cardboard so it will influence a force on it. Wood has different properties than plastic, the surface of the material is rougher, which will influence the force it will put on the sleeve, but for this test this influence is low enough to neglect it.

Figure 34 | Compression strength test set-up

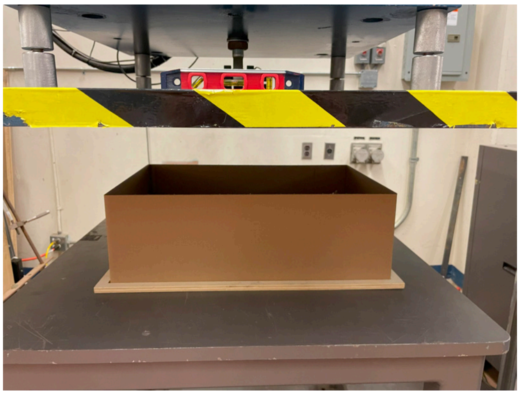


Figure 35 | Compression strength test set-up

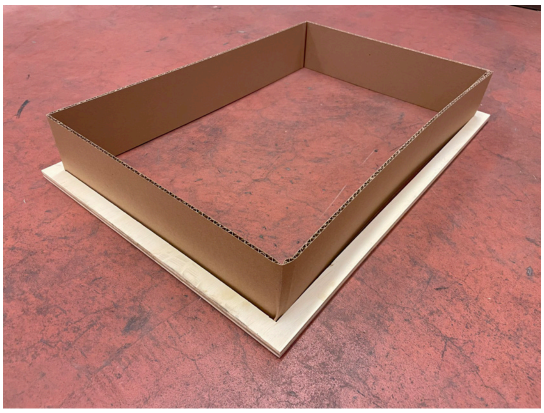


Figure 36 | Outside fixation

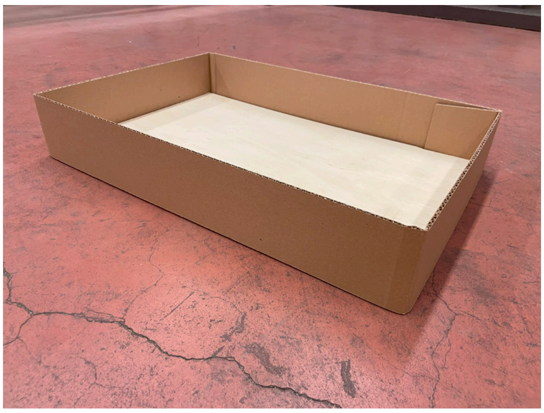


Figure 37 | Inside fixation

Figure 38 | Outside & inside

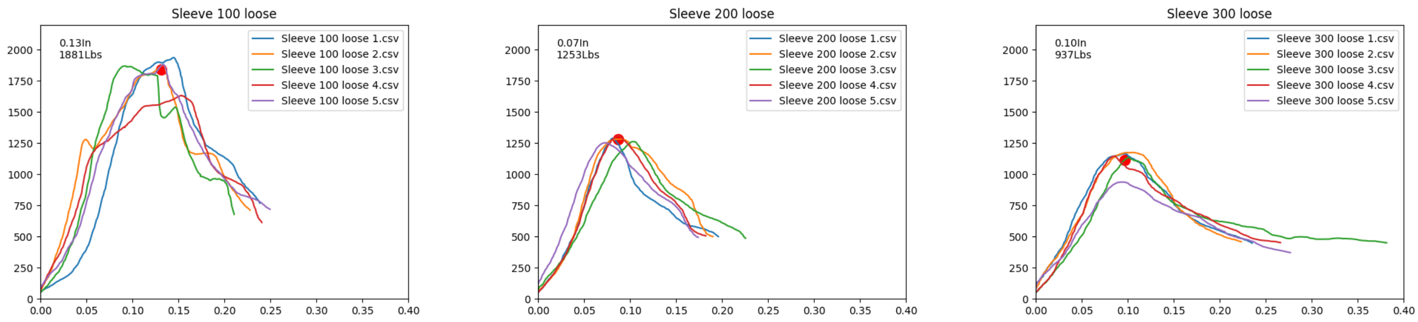


Figure 40 | Plotted results, red dot stands for average of the 5 samples

4.2 Results

For each different test, 5 samples were tested and plotted in graphs, see figure 40. The averages of these 5 samples are extracted and used for comparison. The tested boxes are shown in figure 42.

Results cardboard sleeve only

This graph shows that the numbers for the boxes are lower than the numbers for the sleeves, but they are also further to the right of the graph. This means that they failed after greater compression (0.1 inches for the sleeves vs. 0.3-0.6 inches for the boxes).

The necessary compression strength can be calculated with the following formula:

$C_w=(N-1)*G*9.81*f(n)$

In which:

- C_w = compression strength in Newton
- N = number of stacked layers = 10 layers
- G = weight of 1 box = 15 kg
- 9.81 = to Newton
- f(n) = factor that influences compression strength (see Appendix B.1)

For a box filled with 15 kg of fresh produce, and a calculated safety factor of 2.666, a compression strength of 3923 N is required, converted to 882 Lbs. Looking at the average compression strength values for the different test setups in figure 41, this value can be

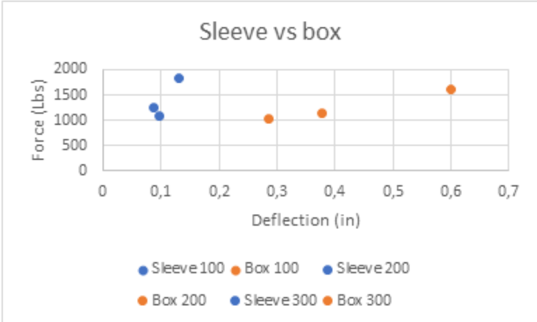
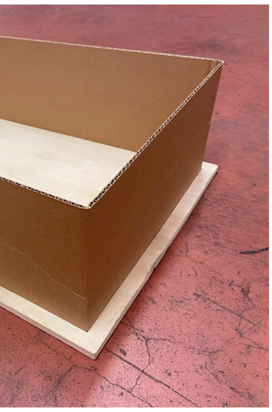


Figure 41 | Results sleeve vs box



fixation

Figure 39 | Double height fixation

Figure 42 | Impression of tested boxes

achieved with the cardboard C-flute cardboard sleeve with a height up to 300 mm high.

In Appendix B, the results of the different bottom fixations can be found in graphs, using the average points of the 5 samples which were tested per differentiation. The lower the height of the sleeve is, the higher the compressive strength. Furthermore, there is no correlation found between the different types of bottom fixation, when looking at a bottom fixture from the inside or outside or when looking at the tightness and height of the bottom fixture.

4.3 Discussion

Hand holes and ventilation holes are not included in this test. It is known that holes in the sides of a box reduce the compressive strength of the box (Singh et al., 2008). This means that for further development of the hybrid concepts, the hole design in the cardboard sleeve should be tested to see what the influence of these holes is and if the box is still strong enough.

Having a (tight) clamming at the bottom of the sleeve has no discernible effect on the compression strength of the cardboard sleeve, contradicting the 2nd hypothesis. After presenting these results at the IAPRI conference in India, Paul Singh provided an explanation for this outcome. In dynamic situations the secondary packaging will be influenced by external factors during transportation when stacked, which is likely to affect the sleeve's shape retention. Since the current test was static, the impact could not be observed. Therefore, this remains an intriguing case to evaluate further in the hybrid box's development to achieve the best strength shape and optimize the bottom fixation impact on the sleeve. Testing the hybrid secondary package as a complete assembly is of interest, as it examines the collaborative efforts of the plastic and cardboard materials.

4.4 Conclusion

The 1st hypothesis is accepted. The sleeve is stronger than the cardboard tray. Research question 1 can also be answered. The required compressive strength was calculated for a plausible weight of contents, 15 kg, and is below the tested values of the different sized sleeves, which means that the sleeve will be strong enough to hold the load as a secondary box for fresh produce distribution.

4.4.1 Consequences of results per concept

The results of the compression test have influence on the further development of the concept ideas. Although discarded, one of the uncertainties of the clamming concept was the influence of the deformation of the cardboard using a tight clamming for the connection of sleeve to bottom part. This test shows no clear negative consequence of a tight clamming at the bottom of the sleeve and with that the deformation of the flutes in the sleeve.

The compression test did not show clear consequences of having support only on the insight of the cardboard sleeve. This can be a result of the test being static, but for now no clear insights have been formed to keep into consideration for further development of this concept.

For the handles-only concept there is no decision made yet if the bottom needs to be fixated from both sides, or if a fixation on only the inside is enough. This test has not shown a significant difference, so both are still possible.

5. Tensile test

The snap system concept is dependent on the strength of the holes in the cardboard sleeve. The snap systems, attached to the plastic bottom ensure that the bottom stays attached to the sleeve while the box is carried. This test examines how holes behave in cardboard and how the shape of the holes affects the overall strength of the paperboard.

5.1 Tensile test set-up

Research question 1: How big is the tensile strength of holes in cardboard and will they be strong enough to be used for the connection of the cardboard sleeve to the plastic bottom?

Research question 2: How do holes behave in corrugated board and how does the shape of the hole affect the strength of the board?

Method: Following ASTM D828-22. For all different sizes, 5 samples are used and tested separately. All samples are conditioned at 23 ± 1 °C and 50% relative humidity for 48 hours prior to testing in accordance with ASTM D4332. See figure 43 for the test set-up.

Material: 4mm C-flute cardboard is used for this test. The reason for this type of flute is that this flute is mostly used in the fresh produce chain for cardboard boxes in the US. The cardboard is cut with a CNC-machine. Next to that, the part that is pulling on the hole is 3D-printed and can be fixed to the tensile tester.

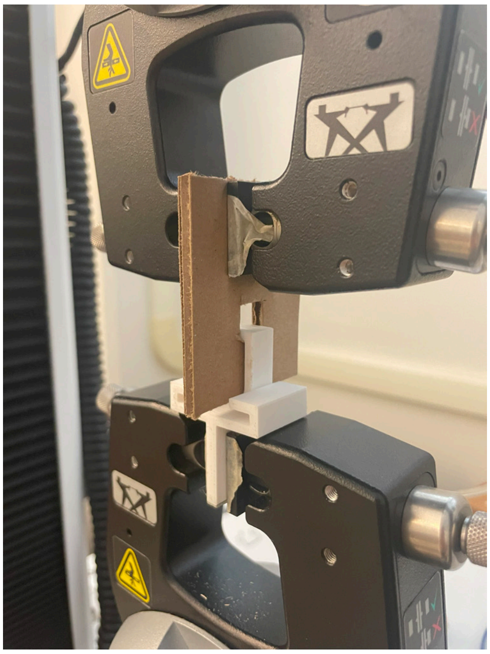


Figure 43 | Test set up tensile test

The features being tested are shown in figure 44. Two different dimensions of all the features are included in the test and the effect of these differences can be compared. The purple one is the height, the blue is the width of the hole, the yellow is the area of the cardboard next to the hole, and all features are also tested with a rounded edge at the bottom.

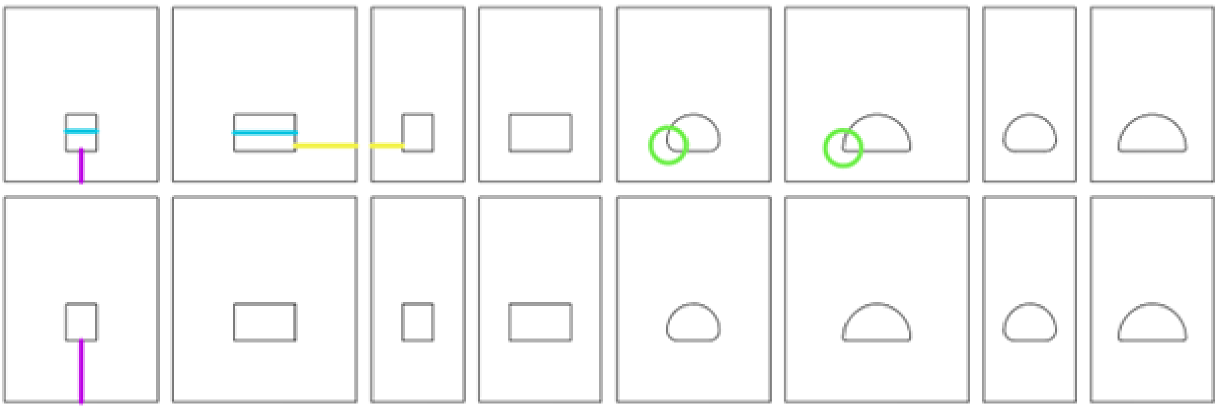


Figure 44 | Differentiation in sizes in samples (blue: width of tested hole; purple: height of hole; yellow: material to the sides of the hole; green: roundness of round

5.2 Results

For each characteristic, 5 samples were tested. The results of the tests are plotted on a graph and an average number is read from the graph. The failure point of the cardboard is not when it reaches the highest load it can bear, but it tears before it fails. This point is identified in the graph by the first negative value in the graph, visualized by the red dot in the graphs, figure 47. The pink dot is the calculated average of the points. This is the value to work with when interpreting the data.

Looking at the graph with a hole width of 20 mm, a height of 20mm and a space next to the hole of 20 mm (figure 45), all in the high/big category, the cardboard doesn't break at any point, but it tears (figure 46). Torn cardboard becomes weaker and is undesirable while the product is still in its use phase.

With a small hole width, 10 mm, the cardboard doesn't break at any point, but the plastic part tears in the

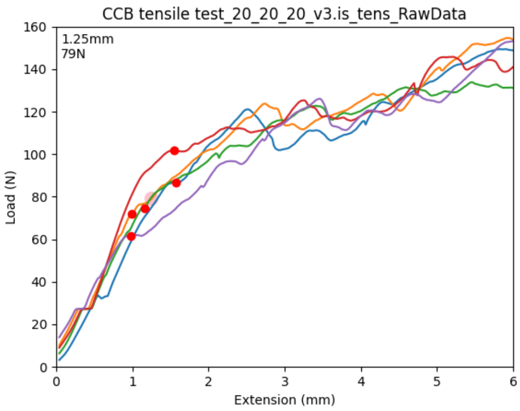


Figure 45 | Graph sample big dimensions

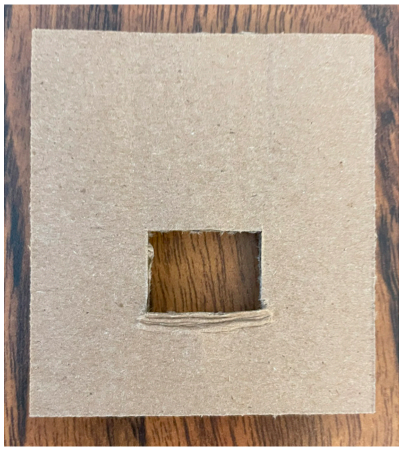


Figure 46 | Sample big dimensions

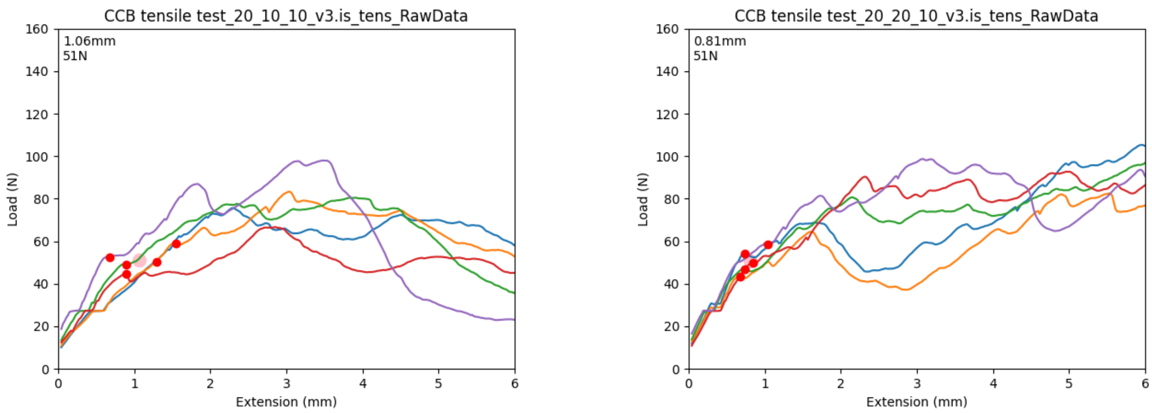


Figure 47 | Graphs results 5 samples tensile test: hole width 10 mm

Figure 48 | 10 mm hole tear

Figure 49 | 10 mm round hole tear

Figure 50 | 10 m, 10 mm side breakage

Figure 51 | 10 mm round hole, 10 mm side breakage

Figure 52 | 10 mm side breakage

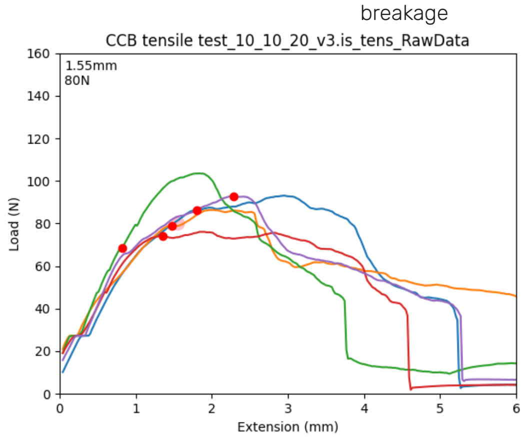


Figure 53 | Graph 10 mm side breakage

hole, very good visible in figure 48. The height of the hole doesn't matter for faster or slower failure, but with a higher hole there is a greater safety factor before real failure. Figure 49 shows a round hole and the tear in the cardboard is also very constant. The distance to the sides of the holes is an important factor in failure to breaking point. With a smaller side the sample broke more often.

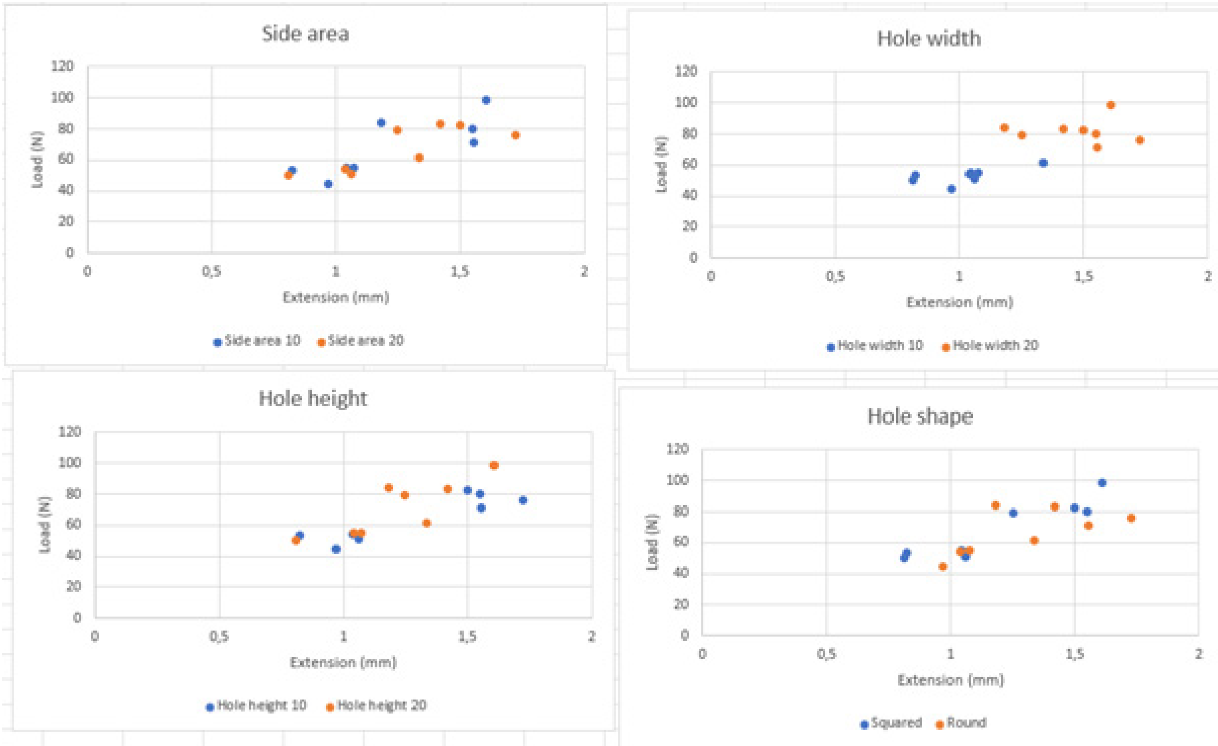


Figure 54 | Graphs of merged results

The large size of the hole, but the small size of the surrounding area, shows us that the width of the hole makes the hole itself more stable. The hole doesn't tear, but the damage is taken by another part of the cardboard, in this case the side, probably because it was the least resistant. The graph, figure 53, also shows that there is not much tearing before failure.

The merged results (figure 54) demonstrate that an increase in the diameter of the hole in the cardboard samples correlates with an increase in strength of the hole, regardless of the size of the surrounding area. For the holes with a rounded edge at the bottom

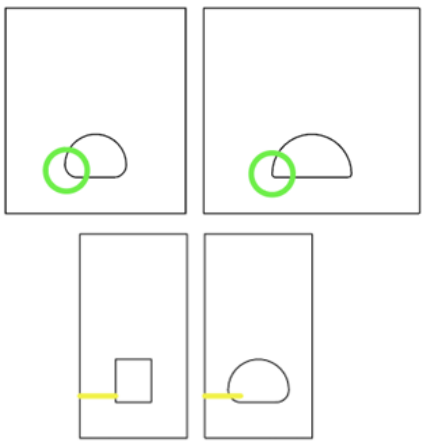


Figure 55 | Different roundness and different side size

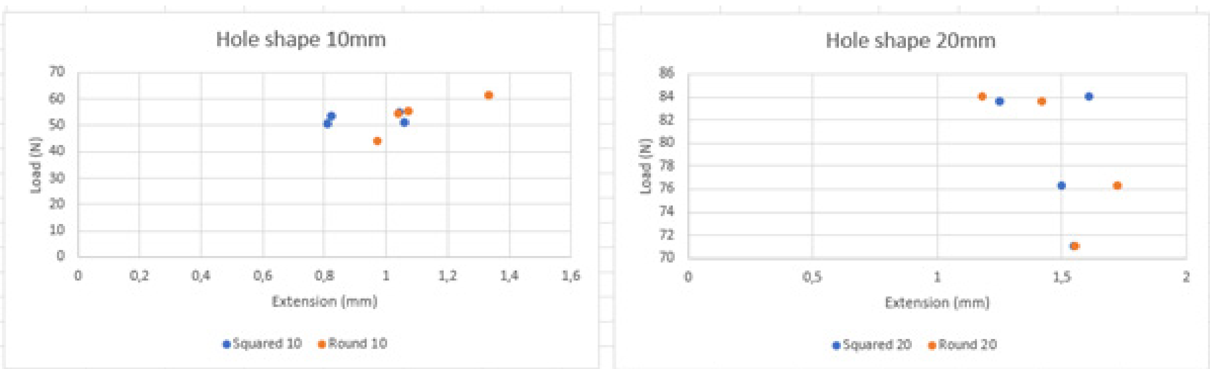


Figure 56 | Compared hole shape per hole width, 10 & 20 mm of the hole, there was a variability in roundness of the edge across different hole sizes. This was overlooked during the test execution, see figure 55.

In general, the 10 mm round hole shapes are stronger than the square ones, except for the one with 10 mm side space. In figure 55, the yellow line shows the length of the side clearance of the sample. The round hole is wider, so the plastic tensile part still has 10 mm of space to pull on a flat surface, but the side of the sample hasn't changed. This is the reason for this exception. The 20 mm wide hole only had a rounded top with a small fillet at the bottom. The graph in figure 56 shows that there is no strength difference for this shape.

No clear correlation is found in the other plots.

The average value of the strongest hole is about 80 N. To carry a box with a content of 2500 N (maximum content weight for one person to carry), the hybrid box would only need 4 snap systems to hold the content (in theory).

5.3 Discussion

This test was conducted in an isolated manner. It focused only on the behavior of a cardboard hole when pulled on its bottom surface. This was done so that the values of this test could be applied to the behavior of cardboard. To use this test for the development of the snap system concept, other factors also influence its strength. If the snap system doesn't cover the whole depth of the cardboard sleeve, the contact area is reduced, and the strength is likely to be reduced. Next to that, a snap system is flexible. This means that it can be attached to a rigid part, but I can also move when force is applied. This can reduce the overall strength of the cardboard hole working together with the snap system as well. So, for the strength test for the overall strength of the snap system concept, the strength of the cardboard hole should be tested in a more applied way, best with injection molded snap system to imitate the behavior of them working together with the cardboard sleeve. This test can still be well used to decide on the cardboard hole and make a prediction of how strong it will be.

5.4 Conclusion

Answering research question 2, the width of the hole has the greatest influence on the strength of the entire hole. This knowledge can be used in the further development of the snap system concept. Also using a big round fillet at the bottom of the hole, positively influence the strength of the hole. A round top in the hole doesn't seem to influence the strength of the hole.

The cardboard material tears before it breaks. This already damages and thereby weakens the board, so when evaluating the test results, the tear is treated as the failure point. A small area next to the holes will cause the cardboard to break, so the bigger the area next to the hole, the less likely the hole will break. The damage will only be the tearing of the cardboard. Therefore, the greater the height of the hole, the greater safety factor the product will have. The cardboard can tear further after being damaged, before it actually fails, although tearing should already be avoided.

The needed tensile strength of the holes in the cardboard sleeve for the snap system concept was calculated and with four holes the cardboard sleeve would be able to withhold the strength of the hybrid box when being carried. This estimation is applied only on the holes in the cardboard and doesn't consider the behavior of the snap systems and friction of the contact surfaces. Therefore, four cannot be taken as the fixed number of snap systems necessary. Tests with injection molded snap systems should be done to gain knowledge about the behavior of the combination of the materials.

DESIGN PHASE CONCLUSION

Three prototypes were the result of the ideation process during the design phase of this project. All three with a different point of view for the action to assemble the sleeve to the plastic bottom and the connection method to carry the hybrid by handles in the sleeve. One of these concepts existed of two different parts, which is not desired in the industry. Therefore, the development of this concept is canceled in this project. The concept idea can still be considered in the further development of a hybrid seconday box besides this master thesis.

In order to evaluate the compressive strength of a cardboard sleeve, and to discover if a sleeve is strong enough to be used in the hybrid as a supporting part while stacking, a compressive strength test is performed. The sleeve is compared to a simple cardboard tray. The sleeve was found to be stronger in this static test situation and therefore suitable to be used. Different fixations were tested for the bottom of the sleeve, in different sizes. There was no clear correlation found between the different fixation types. Also, a tight fit did not affect the strength of the sleeve negatively. This means that for further development, all types of fixtures can still be used, but they need to be evaluated in a later stage of the development, preferably in a dynamic setting with the entire developed and assembled hybrid.

The tensile test was performed to evaluate the strength of holes in cardboard. It appears that the wider the hole is, the more force it can withstand. Cardboard deforms first before it tears. If there is enough space at the sides and bottom of the hole, the tearing is postponed. Using four holes in the snap system concept seems to be sufficient. This should be further tested to include the deformation of the snap systems while carrying weight inside the hybrid. This deformation could effect the strength of the cardboard holes.

"Develop a transport box, using a combination of a single-use and reusable part, to transport fresh produce."

The actions taken in the design phase provide an answer on the first goal of this phase, which was to prove that a hybrid design can be developed, and the expectation is that it can meet the set up requirements. The scaled-down prototypes are a first step in proving that the assembly methods will function, but a full-scale proof of concept is needed to be able to assess the movements necessary for assembly and disassembly. However, the tests conducted prove that the selected materials are strong enough in a hybrid design and further evaluation of the environmental impact can proceed. Full-size prototypes will be built in a later stage of this project.

To evaluate the second goal, a Life Cycle Analysis will be performed, using the final concepts developed in this phase. Since the hybrid secondary packaging is still a conceptual idea and there is no data available on how it will be used in the industry, data of the life cycle of the RPC and CB is used as a basis for this study. This study will also be used to identify potential applications for the hybrid.

Validation phase

6. Life cycle analysis

Carbon footprint of Secondary Packaging Systems for the Fresh Produce Distribution in Europe.

6.1 Introduction and goal of the study

The goal of this project is to discover if a hybrid transport box could be another option to transport fresh produce in. One of the most important aspects of the possibility of this idea is the impact it will have on the environment. Past years, the comparison between the single use cardboard box (CB) and the reusable plastic crate (RPC) is researched to discover which one scores better regarding environmental impact, but the general conclusion of these studies is that not one of them is better in all cases. Every situation in the distribution of fresh produce is different which results in a different outcome of which secondary packaging method is preferred. One known important factor on the results is the transport distance the secondary package needs to cover during its life cycle, even as the number of rotations an RPC can survive or the number of recycled crates or boxes at the end of their lifetime (Accorsi et al., 2022). In this chapter there will be looked into these processes with impact more thoroughly, focused on the impact of the hybrid solution specifically, to discover in what area of use this solution can be beneficial compared to the secondary packaging on the market right now, and how the combination of materials influences the breakeven points within different aspects, such as kilometers of transport and the number of rotations of the plastic part.

To discover these influences on the environmental impact of the hybrid, a life cycle analyses (LCA) is executed. This is an impact assessment method in which all processes a product encounters in its full life cycle is put together in a program using a database to calculate the emissions of these processes. The whole cycle of the product is taken into account, so it is a cradle to gate analysis. This implies that a product is produced somewhere using different building materials, such as plastic granulate, electricity and water. When it is ready it will go into its use phase, for a crate it will undergo many rotations to distribute fresh produce, being cleaned and transported again for the distribution, until it breaks down and can't be repaired anymore. At that point it enters its End of Life (EoL) stage, in which it will be recycled or incinerated. This process is dependent on the type of material used and where the EoL happens. In the Netherlands for example, the numbers of intake of packaging are higher than in France (Eurostat, 2023).

According to the ISO 14040 standard (ISO 14040, 1997), there are four process steps that need to be executed in order to make a complete LCA. First the scope of the analyses needs to be defined, in which decisions are made about the technical aspects of the to be compared products, the functional unit is decided, and a system boundary is set up. Then, the Life Cycle Inventory can be discovered. This includes an overview of all the process the products undergo during their life cycle, within the system boundary, and functions as input blocks in the database. With this knowledge, the Impact Assessment can be made which gives results. These results can be divided in impact categories, which are a group of environmental impacts. In this study the ReCiPe 2016 (Huijbregts et al., 2017) method is used with Climate Change as main midpoint. The results in the Climate Change impact category are compared to each other in the interpretation phase of this analysis. During the interpretation phase, the results of the hybrid are compared against the values of the RPC and CB and the impact of the hybrid can be established. Also, the influence of different processes of the secondary boxes will be discovered, to evaluate on the viability of this research and to discover processes which have a big influence on the results and are therefore important aspects for when the hybrid will be put into the market.

Goal:

Discover the environmental impact of the hybrid solution, compared to the RPC and CB, and discover processes with great influence on the impact, to use as recommendation or requirements for further development of hybrid and implementation into the market

6.2 Scope of the study

The scope of the study states what information will be included in the study, what information is excluded and gives a detailed description of the input used.

7.2.1 Product systems

The study looks at the two most relevant packaging systems currently used in the fresh produce distribution chain (in Europe). One is a returnable system, a Reusable foldable Plastic Crate (RPC), and one is a non-returnable packaging system, namely a single-use Cardboard Box (CB). Next to these two, a new solution, a hypothetical Hybrid Box (HB) is examined in this study, consisting of a returnable plastic bottom and a single-use cardboard sleeve serving as the sides of the hybrid box.

This study assesses these packaging systems based on other studies executed which were in accordance with the requirements in the standards ISO 14040 and ISO 14044 (Castellani et al., 2022; Krieg et al., 2018).

The life cycles of the product systems used for this study are schematically presented in figure 57.

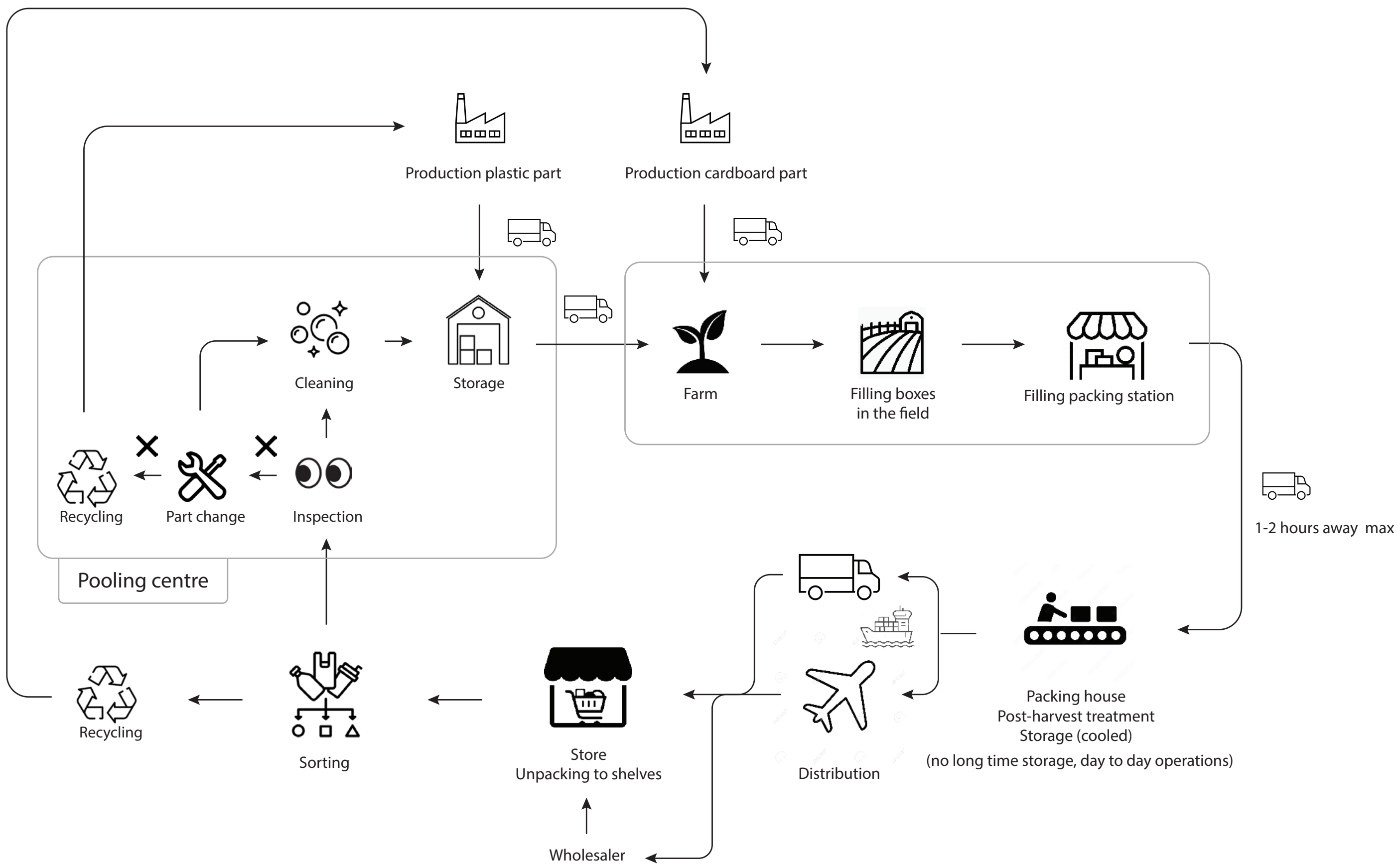


Figure 57 | General life cycle of a plastic crate (following plastic part path), cardboard box (following CB part path) and hybrid (following both paths)

After manufacture, during the use phase, the RPCs are used for several times until their technical end of life is reached, whereas the single use CBs will be directly disposed after one use. For the hybrid box the same applies for the reusable part and the single use part.

As input data, reference containers currently used in the market are used. For the RPC a fresh produce RPC of the leading brand IFCO is taken. For the CB the leading brand FEFCO is used for information about dimensions. In table 1 an overview of the technical properties of the used containers is shown. These values are used over the full study. For the plastic part of the hybrid box, an estimation of the weight is made using the 2 concept designs. The cardboard sleeve is calculated using the weight of cardboard per square meter and the estimated size of the sleeve.

The reference containers assume the same dimensions, load capacity and therefor the same transport capacity. They differ in the material they are based on, type of use (reusable or single use) and the weight of the product. This is where the difference in outcome originates from. For all packaging systems a load of 15 kg fresh produce is assumed. For in the European context, the transport is assumed to be done using trucks, which is the base assumption of this study.

The properties shown in table 1 are input values for the base line of the study. Though because this study is done in a preliminary phase of the development of the hybrid concept, all values will be changed so the effect of processes become clear.

Table 1 | Technical properties ofreference containers

Technical properties of reference containers			
	RPC	**CB**	**Hybrid**
Material	PP	Cardboard	PP & Cardboard
Type of use	Reusable system	Single-use system	Both systems
Rotations	50	1	""
Average breakage rate	0,53%	-	""
End of life	Energy recovery, material recovery		""
Weight container (kg)	1,82	0,78	1,16
Weight plastic part part (kg)			0,91
Weight cardboard part (kg)			0,25
Dimensions container(mm)	600x400x210		""
Dimenssions folded	600x400x29	1000x210x8	600x400x25
Filling load (kg)	15		""

7.2.2 Product function and functional unit

A functional unit is used for this study to ensure comparability of different packaging systems. The function of the packaging system is the reference value of how many products are needed to fulfill this functional unit. The calculated results refer to this reference value.

This study analyses the greenhouse gas emissions from fresh produce distribution, for now focusing on the European market. The functional unit is:

The distribution of 1,000 ton of fresh produce

The packaging systems to fulfil this functional unit are compared, namely a Reusable Plastic Crate (RPC), a Cardboard Box (CNB) and a Hybrid Transport Box (HTB).

The functional unit is based on a study of the comparison of an RPC and a CB, executed by the Fraunhofer Institute (Krieg et al., 2018).

To fulfill the functional unit, the reusable containers must be filled 66,667 times, when assuming a load of 15 kg per container. The base line of this study assumes about 50 rotations in an RPC life cycle with an average breakage rate of 0.53% per rotation which results in 1,687 RPCs necessary for fulfilling the functional unit in the base scenario. The breakage rate includes RPCs that need to be replaced due to stresses and strains acting on RPCs during their use phase.

For the non-returnable system, a new CB is required for each of the 66,667 fillings to fulfill the functional unit.

For the hybrid box, both systems are included. The numbers for the baseline scenario are copied from the existing systems and are later changed and tested to form a scenario more plausible for the hybrid concept.

7.2.3 System boundary

The system boundary establishes the processes that are included in the to be executed study. It defines how detailed the processes will be included. The system boundary of this study is based on the boundary of the reference study, which is shown in figure 58.

This study covers the supply of raw materials, production, and distribution of empty and filled boxes and the end-of-life situations of material recovery and energy recovery.

Properties like printability, product hygiene, product protection or ease of use are not considered in the scope of this study but will be discussed somewhere else in the general thesis.

For the baseline scenario, proper use is assumed for all packaging methods, so the products are not supposed to suffer loss or be subjected to inappropriate disposal.

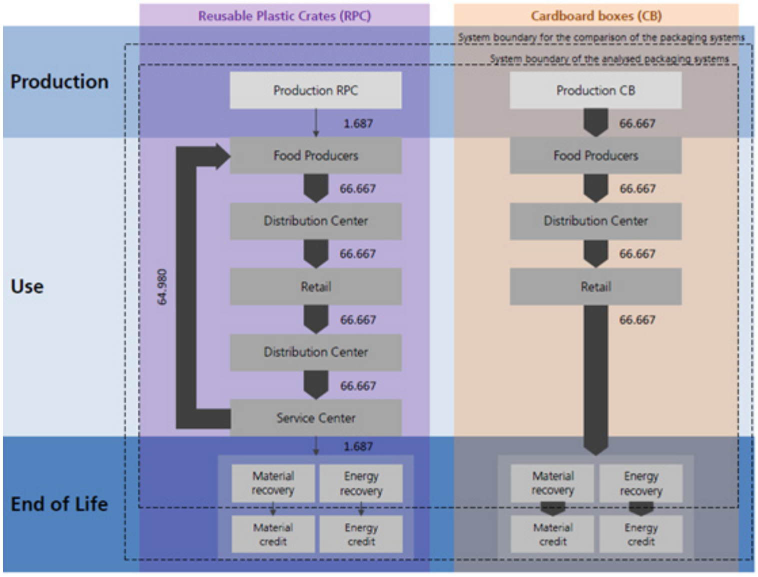


Figure 58 | System boundary of the two reference packaging systems (Krieg et al., 2018)

No general cut-off criteria have been defined for this study. All available data in the Gabi and Sphera data base are included in the processes within the system boundary, including energy and material flows. The study does not include the production of infrastructure.

7.2.4 Selection of ReCiPe as environmental impact category

The midpoint Climate Change of the ReCiPe index is chosen to be the general impact category for this assessment. The ReCiPe 2016 method is a database which has calculation factors of the emissions that come out of the assessment. These emissions all have a different impact on how much it influences for example Climate Change. So, ReCiPe 2016 is the method to make a characterized impact value. All emissions in the process are transformed to kg CO2 eq., to be able to give the impact in one unit and be able to compare the products.

7.3 Life cycle inventory analysis (LCI)

To determine the impact and emissions of the three packaging systems a life cycle inventory model is created. In figure 59 the full usage life of a crate, box or hybrid box is shown.

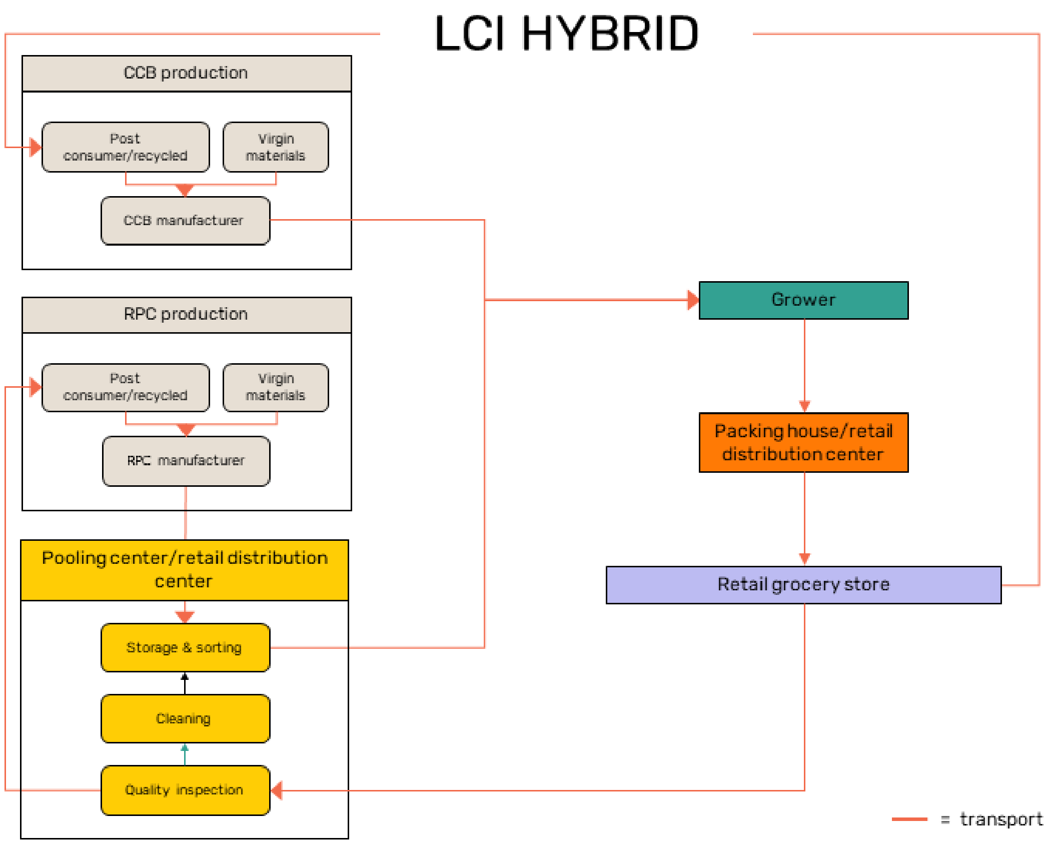


Figure 59 | Life cycle inventory

Two LCA studies of a comparison of CB with RPCs are taken as an example for this study. All data used in this study is used as input data for the LCA. This is done because the LCA for the hybrid transport box is done in an early stage of the development of the box, so there is no data available yet about the scenario it will be used in, how much transport it undergoes, and what kind of waste treatment it will have.

So, for the inventory analyses, there are two cases set up for the study. These results will be compared to the original study and if they are comparable, the study will be reliable to be used for scenario modelling.

The SIM study is executed by Fraunhofer IBP (Krieg et al., 2018), which is an institute doing research and development for innovative projects and execute LCAs for clients. In this case the client is SIM (Stiftung Initiative Mehrweg), a German company who wants to increase reusable packaging to save on used resources.

The FEFCO study is executed by Ramboll (Castellani et al., 2022), which is a company based in Denmark, helping their clients develop into a more sustainable future. The did an LCA study comparing reusable plastic crates with single use cardboard boxes for FEFCO. FEFCO is the market leader in cardboard box design and production. This LCA has the result of the single use cardboard box having a lower environmental impact in the category climate change. Compared to the study for SIM, this result is the opposite. The difference originates in the data used as input. These two studies differ a lot from each other. For example, the average breakage rate of the RPCs is 2,5% in the FEFCO case, compared to a 0,53% in the SIM case. This results in a significant different output. Following a report where these two studies are compared in, the 2,5% breakage rate in the FEFCO case is a very high amount which doesn't occur in practice (Albrecht et al., 2022).

7.4 Impact Assessment

The results of the baseline study of the SIM case are shown in figure 60. The hybrid appears to have a lower impact on climate change than the secondary packaging boxes currently in use. To address the reliability of the LCA done, a consistency check is executed, in which the results of this study of the RPC and CB are compared with the results of the study this one is based on. As a check on top of that, the input values are changed into the values of the FEFCO study, shown in figure 61. If these values are comparable as well, the study will be treated as reliable in this research and the hybrid can be compared to the RPC and CB.

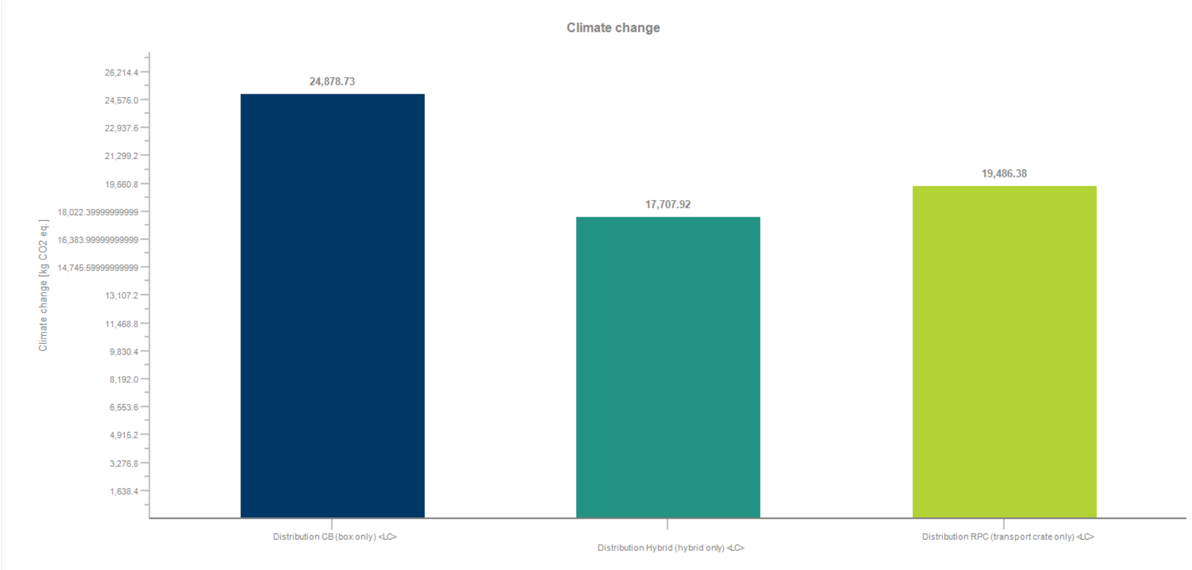


Figure 60 | Results LCA on Climate Change; based on SIM case

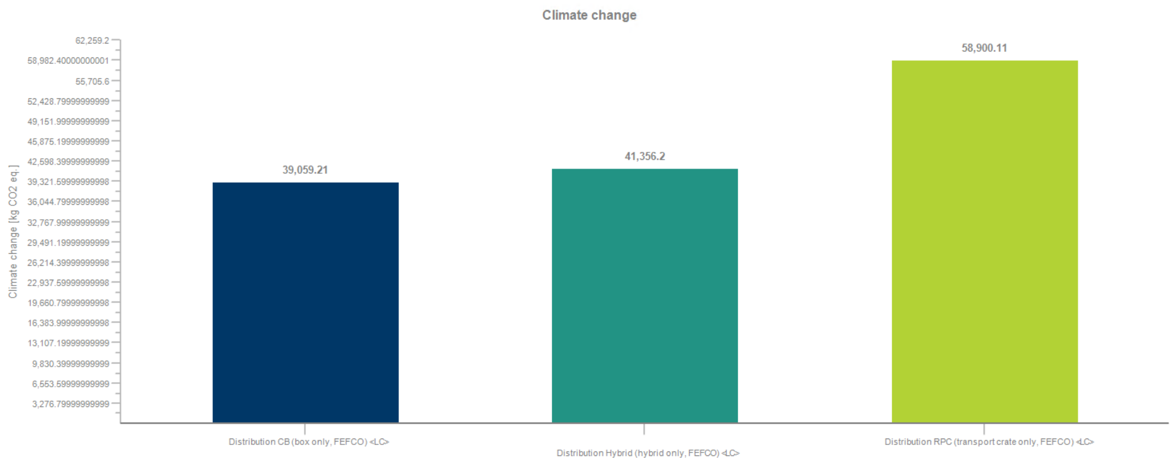


Figure 61 | Results LCA on Climate Change; based on FEFCO case

7.4.1 Consistency check

Table 2 | Climate change emissions comparison

SIM case copied			Original
CB:	24.900 kg CO2 eq.	vs.	37.700 kg CO2 eq.
RPC:	19.500 kg CO2 eq.	vs.	14.500 kg CO2 eq.
FEFCO case copied			**Original**
CB:	39.00 kg CO2 eq.	vs.	34.700 kg CO2 eq.
RPC:	58.900 kg CO2 eq.	vs.	47.9 kg CO2 eq.

The input data of the LCA with the SIM case as baseline for the input data, is changed to the known input data of the FEFCO case. Processes like transport distance, recycling rate, number of rotations and breakage rate of the RPC and percentage of maximum filling weight of the packages differed. This results in a different output of all the secondary packages. The results based on the SIM case are similar to the original study, even as the study based on the FEFCO case. In table 2 the total emissions are shown of the original studies compared to this study. For the Sim case the RPC had lower emissions, even as the results in this study. For the FEFCO case the cardboard box had lower emissions, also as the results in this study show. The exact numbers differ from the original cases. This can have multiple reasons. First, the data used in the Sphera database gets updated continuously. Doing an analysis in different periods of time result in different results. Also, the exact process blocks used in the example studies are not known. These process blocks all contain a different calculation of what impact the used processes have on the emissions. Using different blocks result in different results as well.

Climate change is chosen as the general midpoint because the SIM study only used this midpoint in their comparison. To keep it simple, this midpoint was chosen for this study as well. In the SIM study, Climate Change including biogenic carbon was used, but the results in this study resembled more with the midpoint Climate Change, excluding biogenic carbon. Because the goal of this study was to get comparable results with the studies currently done, to be able to compare the hybrid with the RPC and CB, the midpoint CC, excl. biogenic C was chosen. Multiple reasons could be the reason behind this difference, for example the way of characterization was done for the study. This study uses the Recipe 2016 method, but the SIM study uses different characterization factors.

So, the setup of the LCA seems to be consistent enough, proved by changing the input data to another example scenario, to be used for an extended analysis on the environmental impact of the hybrid compared to the CB and RPC. This study will be a rough estimation of the actual environmental impact of the hybrid but can give a general idea of the processes that play an important part in the final results.

7.5 Interpretation

With the setup of the LCA checked using a comparison of results of other assessments, the results of the LCA can for a broader investigation into the influence of the hybrid on Climate Change. First, a contribution analysis is executed to reveal the relative contribution of the main processes to the total impact. This knowledge can then be used in the breakeven analysis on Climate Change. In this breakeven analysis there is tried to discover what kind of influence all processes have on the final result, how big this influence is and how it differs with changing the parameters. This knowledge can be used in the further development of the hybrid box and for implementation of the hybrid solution into the market, to make a substantial decision of where to implement.

7.5.1 Contribution analysis

During the contribution analysis it is the goal to discover the relative contribution the main processes have to the total impact. This relative contribution is the percentage of the impact of separate processes to the total score. The higher the contribution is, the more important it is that the input data of this process is reliable. With values differing only a small amount from the real values, a big change can be noticed already in the final results.

Table 3 | Contribution analysis cardboard box; base line SIM

Cardboard box base line SIM			
Life cycle phase	**Climate change (kg CO2 eq.)**	**Relative contribution**	**Ratio Production/Service life**
Production	**42100**	**169%**	93/7
Service life	**1804**	**7%**	
End of life	**-19000**	**-76%**	
Total emissions climate change (kg CO2 eq.)	**24.904**	**100%**	

The total emissions of the cardboard box are mostly caused by the production and end of life phase (table 3). This results in a low impact of the service life and with that, transport during its life cycle has a low contribution to the final results. This explains the conclusion of multiple researches that transport distance matters less for the cardboard box than for the RPC, looking at environmental impact of the two transport systems.

Table 4 | Contribution analysis plastic crate; base line SIM

Plastic crate base line SIM			
Life cycle phase	**Climate change (kg CO2 eq.)**	**Relative contribution**	**Ratio Production/Service life**
Production	**9830**	**51%**	31/69
Service life	**13520**	**69%**	
Use phase	2650	14%	
Distribution	10870	56%	
End of life	**-3870**	**-20%**	
Total emissions climate change (kg CO2 eq.)	**19.480**	**100%**	

Distribution is the process with the biggest impact on the total impact of the RPC (table 4). This alligns with research claiming that the transport phase has a big influence on the total emmissions of plastic crates and the assumption that the higher the transport distances, the higher the environmental impact is of plastic crates and RPCs become less vavourable than cardboard boxes.

Table 5 | Contribution analysis hybrid; base line SIM

Hybrid base line SIM			
Life cycle phase	**Climate change (kg CO2 eq.)**	**Relative contribution**	**Ratio Production/Service life**
Production	**19000**	**107%**	60/40
Cardboard sleeve	13500	76%	
Plastic bottom	5500	31%	
Service life	**6984**	**39%**	
Use phase	306	2%	
Distribution	6678	38%	
End of life	**-8270**	**-47%**	
Cardboard sleeve	-6100	-34%	
Plastic bottom	-2170	-12%	
Total emissions climate change (kg CO2 eq.)	**17.714**	**100%**	

The production and end of life phase have a bigger infliuece again for the hybrid, see table 5, leaning towards the cardboard box results, but not as high that the impact of the service life becomes almost not appearant.

The production and end of life phase are about doubled compared to the RPC impact results, but the impact of the service life, mostly due to the distribution phase, is lower compared to the RPC. This makes the hybrid less vulnerable for high transport distances compared to the RPC and the way the plastic bottoms are cleaned matters less than with the RPC.

7.5.2 Breakeven analysis on Climate Change

In the breakeven analysis the influence of the different processes in the life cycle of the secondary boxes is researched. With the goal to be able to get an idea how the environmental impact of the hybrid box behaves regarding the input values and scenarios it is used in. To make a better substantiated decision which secondary box to use in which case or to discover how much design freedom there is left.

For this analysis, only the environmental impact of Climate Change is taken into consideration. This midpoint is taken because it is a general midpoint taken in other studies done before this one as most important one. It gives a general idea of the impact of the secondary boxes on climate change. It can be seen as an assumption for a first study, to discover first trendlines of the influence of different process. In a later stage of doing an LCA on the hybrid secondary box, more midpoints could be considered.

7.5.2.1 Weight differentiation

Sarting at the weight values of the hybrid design. The development of the hybrid is still in its concept phase. This means the end product is not decided yet and the design can still change a bit. With changing the design, the weight can differ from the values that are used for the LCA now.

In figure 62, two lines are plotted which represent the deviation of the plastic and cardboard share in the hybrid. The common trend is the higher the share of plastic is in the hybrid, the lower the climate change impact. The light blue line represents the hybrid box with the weight of the plastic crate (100%) and is plotted with the amount of plastic vs. cardboard in the hybrid box design. The dark blue line represents the hybrid box with a total weight of 70% of the RPC. The baseline value in this LCA is a weight differentiation of 80% plastic, 20% cardboard. Cardboard weight: 0.25kg which is the calculated weight needed to make the sleeve out of B-flute cardboard, and the plastic weight was calculated with the 3D-model made in SolidWorks.

The breakeven point for the hybrid with the RPC in this case is on 74% plastic and 26% cardboard. This means the design of the hybrid can still be modified and exist of less plastic and more cardboard to still be more environmentally beneficial than the RPC. Compared to the CB the breakeven point is higher, around 55% plastic and 45% cardboard.

The expected reason for this correlation is that the plastic crate has lower emissions than the box made from cardboard. If the share of plastic is heightened against the cardboard share, the emissions of the box then decrease.

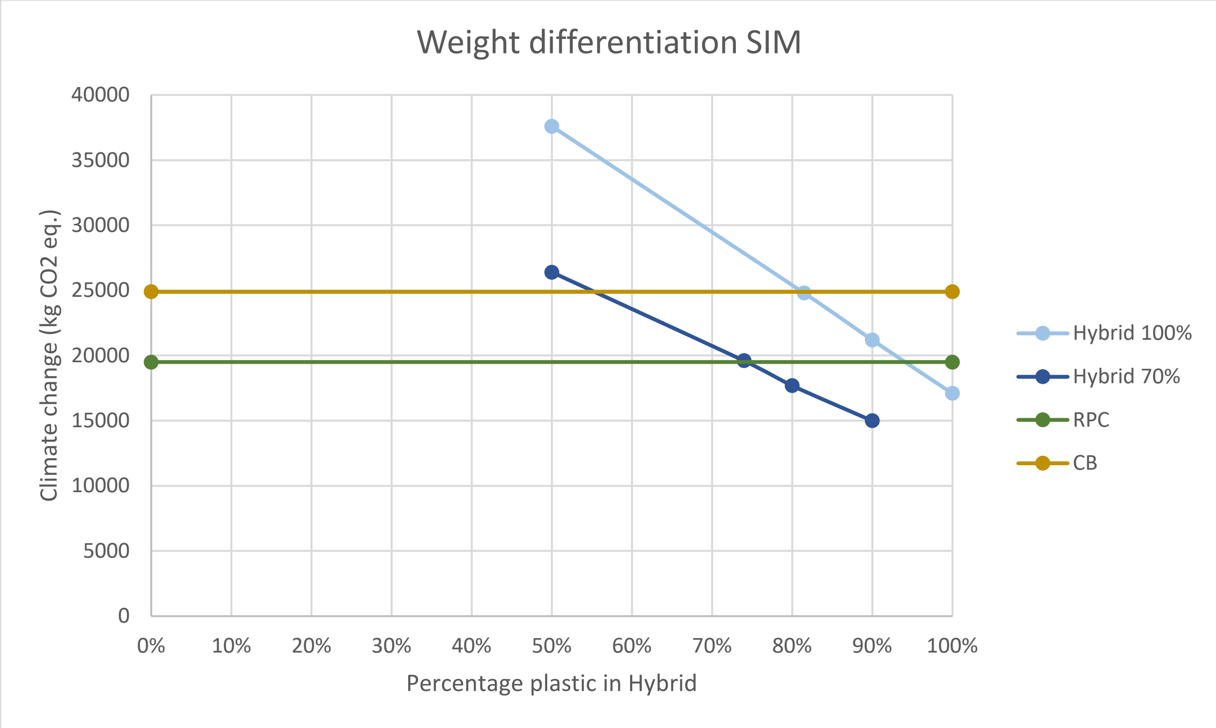


Figure 62 | Weight differentiation; SIM case

Keeping this conclusion in mind, the expectation for the FEFCO case then is the other way around. In this case the cardboard box had a lower impact compared to the RPC, so the expectation is that with lowering the plastic share and heightening the cardboard share, the impact of the hybrid box would decrease.

In figure 63 the weight differentiation graph for the FEFCO case is shown and shows that the hypothesis of

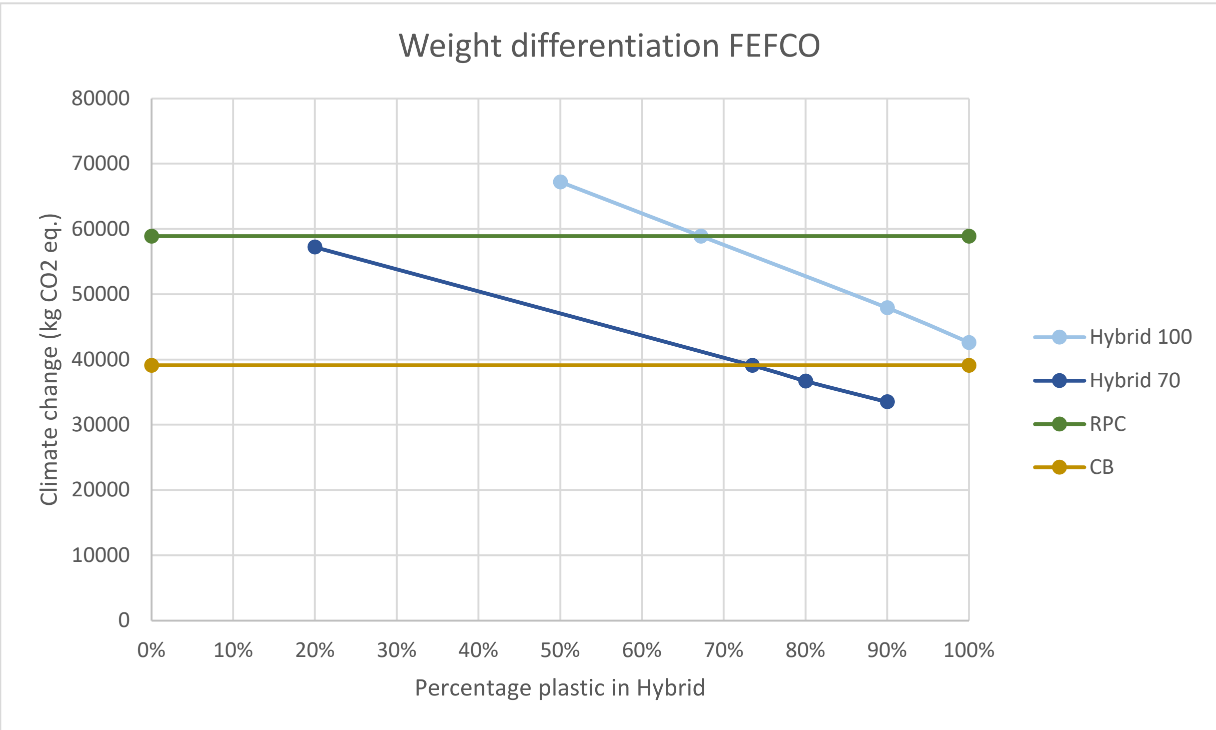


Figure 63 | Weight differentiation; FEFCO case above is not true. This graph shows the same trend as the one of the SIM case.

So, the higher the plastic share in the hybrid, the lower the emissions are of its life cycle.

7.5.2.2 Transport distance

The transport distance influence on the three packaging systems is plotted in the graph in figure 64. They have a linear relationship to each other. As input values for transport, all transport processes are set to a shared value. This value is changed to discover the relationship between the overall transport distance and the three secondary packages. The rest of the values in the LCA are based on the SIM case. The first breakeven point that is found is between the hybrid and the RPC, around 100 km per transport block. For very low transport distances the RPC would be more beneficial, but this is unlikely to happen in real life. The breakeven of the RPC and the CB is at 500 km for all transport blocks. So, the CB has less impact with high transport distances than the RPC. This is corresponding to other research done and found in literature (voorbeelden noemen). The breakeven of the hybrid with the CB is around 900 km for all transport blocks. This a big distance to cover for the distribution of fresh produce, especially because the fresh produce needs to be transported to the grocery store fast and it can't be too far. Otherwise, the produce will mature too much before it can be sold. This means that the use case of the hybrid has some space in the exact amount of distance it needs to cover in real life, to still be more environmentally friendly compared to the cardboard box. Another conclusion that can be drawn from this breakeven point, is that the cardboard box keeps being a better option, looking at less impact on climate change, when transporting the goods over very far distances. This subject is only looking at transport distances over the road. Looking at produce that needs to be transported over see or air will have different results, but another factor plays a big role in those subjects too, which is the reverse logistics of the plastic part of the hybrid. The expectation is that this RL will have a big contribution to the emissions of the transport box, so expected is that the single use cardboard box will keep being the most beneficial option for this kind of shipment.

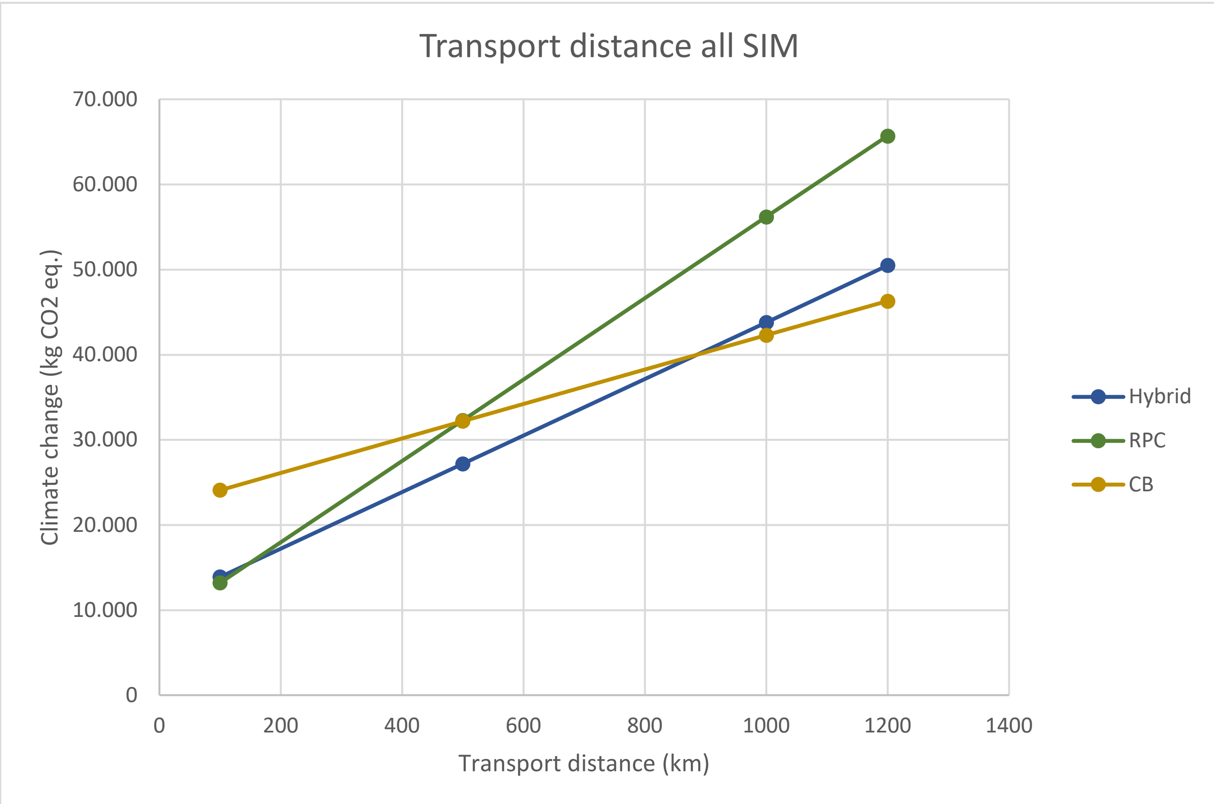


Figure 64 | Transport distance general value for all distances; SIM case

For reference of how much distance the boxes travel, the total values for each point in the graph is shown in table 6.

Table 6 | Total distance traveled per point in graph

Total km travelled	100	500	1000	1200
Hybrid (km)	1300	6500	13000	15600
RPC (km)	900	4500	9000	10800
CB (km)	600	3000	6000	7200

7.5.2.3 Recycling rate

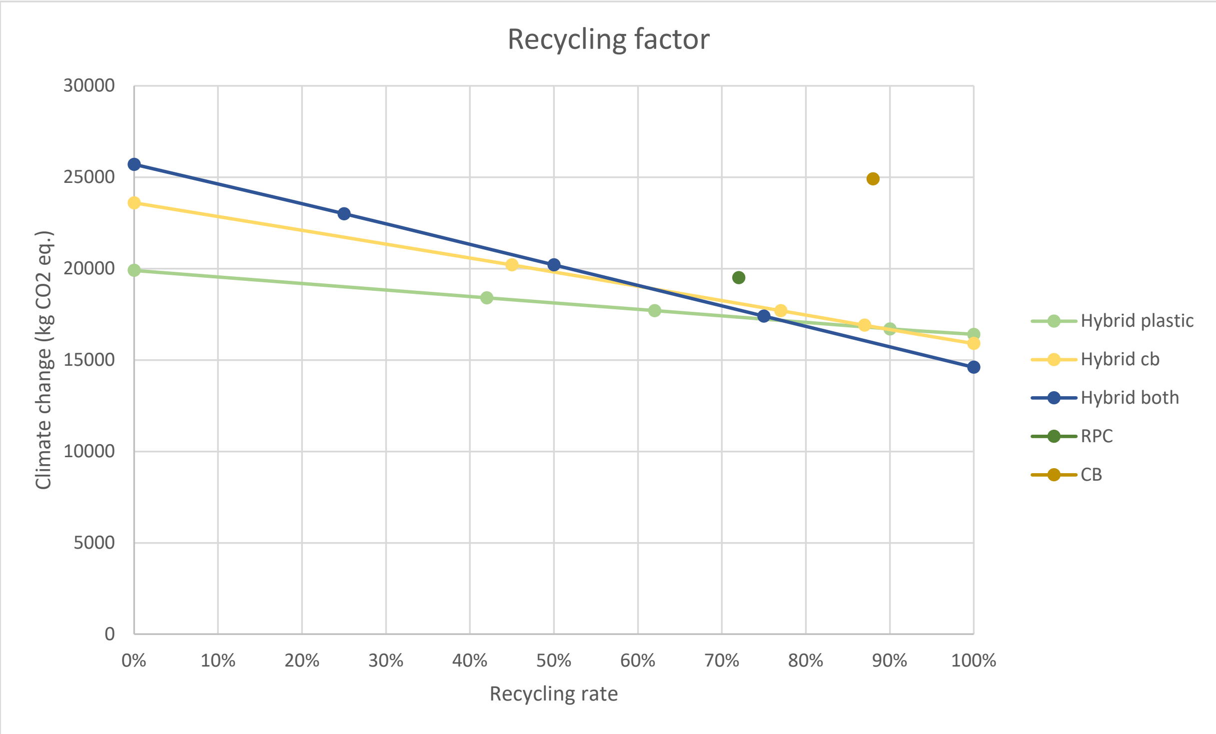


Figure 65 | Influence recycling percentage in hybrid; SIM case

At the end-of-life stage of the hybrid, so when the parts of the product don't function anymore and the materials go to waste, the materials are partly recycled, and the rest is going to be incinerated. There are two different recycling stages. Primary recycling means the recycled material will be used in the production of the same product again. With secondary recycling the material has some quality loss and will be used in another product again. These different processes are considered in the LCA, but in the graph (figure 65) the percentage of the recycling rate is about the total percentage of recycling, including quality loss, so for example, the numbers at 100%, all materials will be used in the same product again, which is an unlikely scenario.

The recycling rate has a linear impact on the output results. The line in the graph of recycling cardboard is steeper than of recycling the plastic parts in the hybrid, so it has a bigger influence on the total emissions of the hybrid box.

7.5.2.4 Rotations

The number of rotations the hybrid survives is an important number, especially in the lower values. Producing the plastic part of the hybrid has a high impact on climate change if it would be used only once or a couple of times. To make this concept environmentally friendly, it needs a fair amount of reuse before the investment of production is worth it. In this case based of the SIM study, this breakeven number is around 6 reuses to equal the cardboard box, see figure 66. To equal the RPC with 50 rotations, the hybrid needs at least 31 rotations. If the durability of the hybrid would be the same as the RPC, the breakeven point of the two is at 87 rotations. From that point onwards, the RPC has a lower impact on climate change.

From 50 reuses on of the plastic bottom, the impact stagnates, it almost stays the same for higher values. This means 50 reuses is a well-chosen value because it doesn't alternate much if the value would differ from the chosen value a bit in real life.

The number of rotations for the reusable products in the FEFCO case is set on 24. At that point the hybrid has a higher impact on climate change than the cardboard box. The breakeven point is set on 31 rotations of the plastic bottom of the hybrid. This would be within reach of the durability of the plastic bottom and the requirement of number of reuses is set on 50 for the development of the bottom design. If this is reached, the hybrid would also be more environmentally friendly in this case.

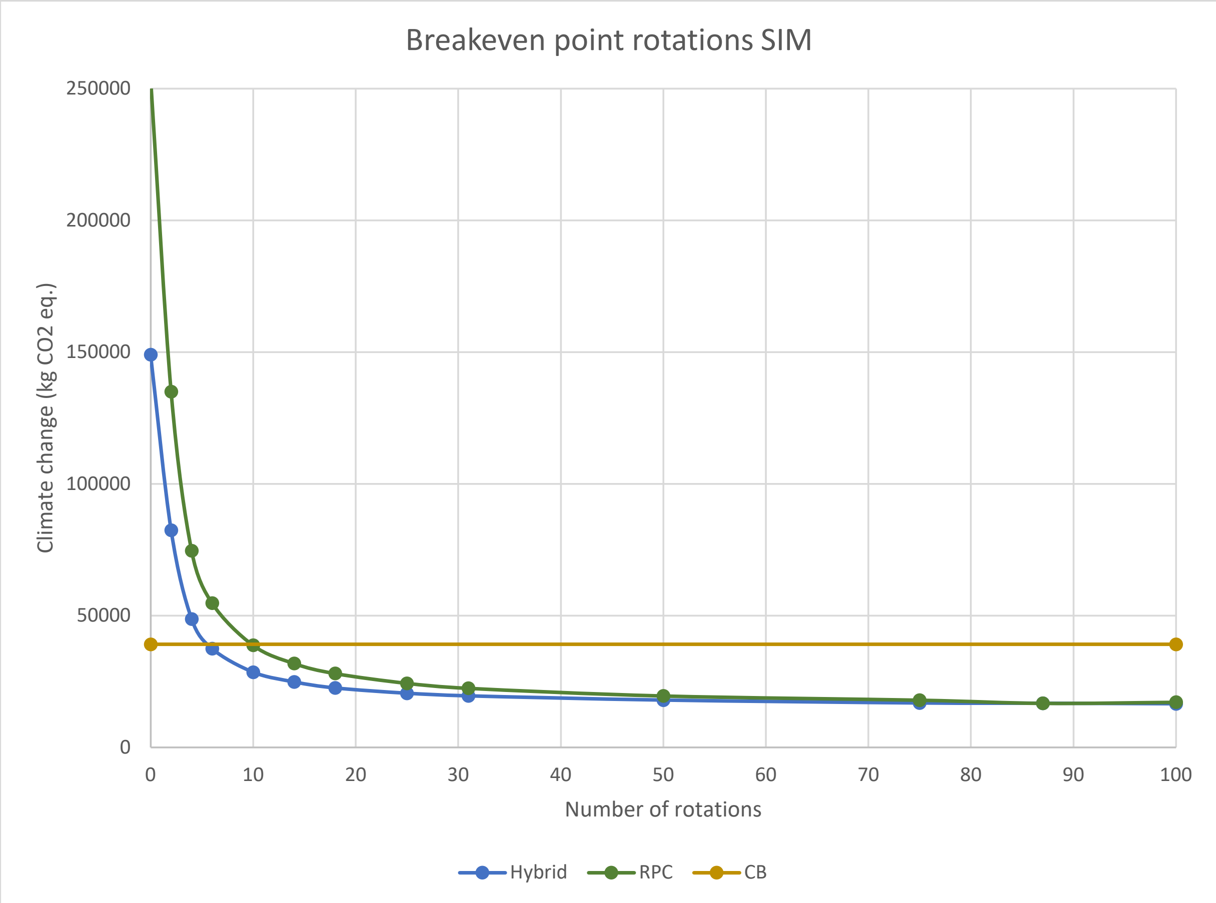


Figure 66 | Breakeven points rotations; SIM case

The breakeven point graph for rotations of the FEFCO case shows a comparable pattern with the SIM case, but with the breakeven points on different values (figure 67). Also, the difference of impact between the three packaging systems is smaller than with the SIM case. The expected reason for this is because of the low value of capacity to transport per box or the breakage rate taken in the FEFCO case. These two values have the biggest difference from the SIM case. The low filling load capacity, 70% of the maximum weight of a box in the FEFCO case, means that there are 30% more boxes needed to be able to ship the same amount of produce. This high number of boxes could result in a more comparable impact of these boxes. Another explanation could be the high breakage rate. In the FEFCO case it is 2.5% and in the SIM case 0.053%. A higher breakage rate results in more crates needed to be able to ship the same amount of produce. A higher number of crates needed heightens the impact of the RPCs or hybrid, which makes the impact closer to the cardboard box.

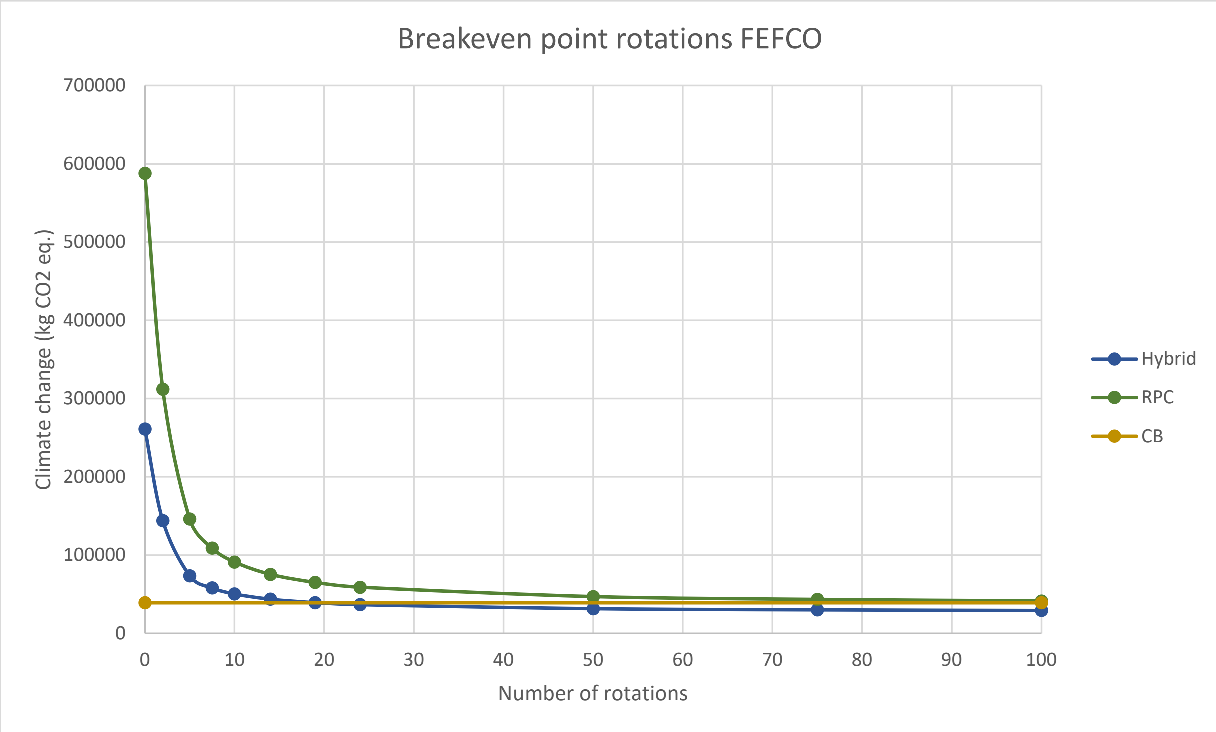


Figure 67 | Breakeven points rotations; FEFCO case

5.2.5 Capacity

The effect of the filling load of the boxes is shown in figure 68. The lines in the graph are staying at about the same distance from each other while the max capacity is changed. With changing the max capacity, the functional unit changes, so the number of secondary boxes needed to fulfil the functional unit of transporting 1000 ton of fresh produce. So, with lowering the capacity of the secondary boxes, the emissions of all secondary boxes go up.

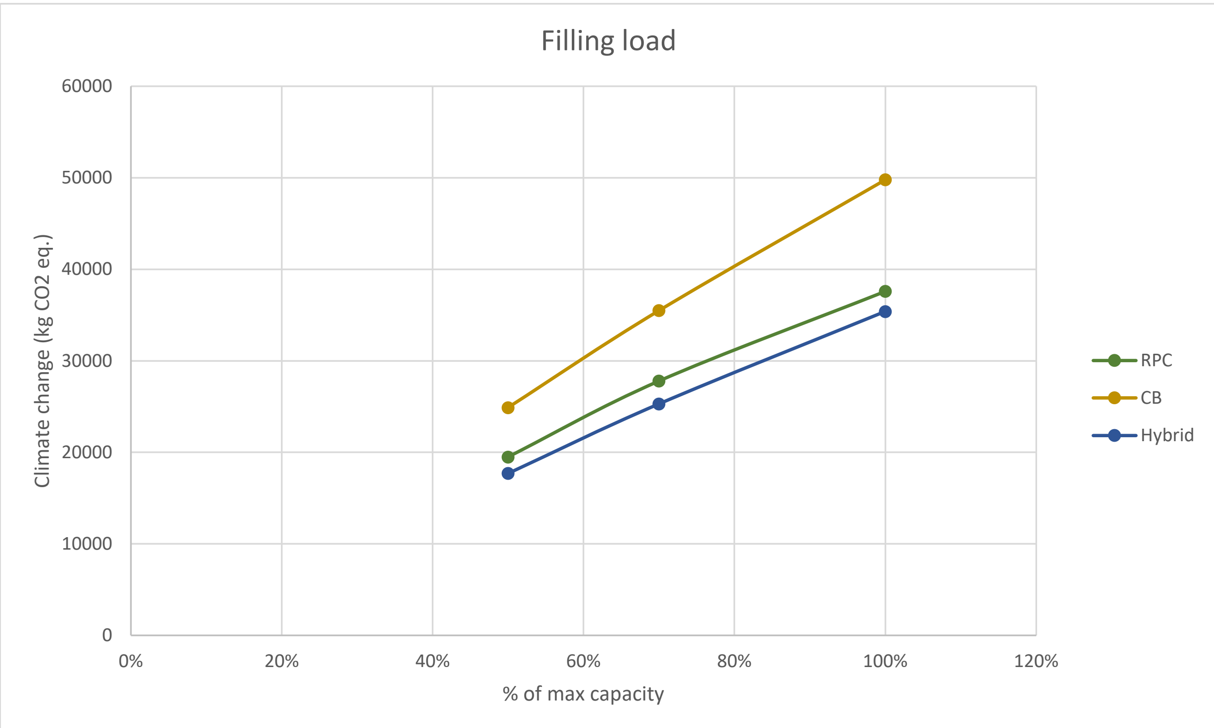


Figure 68 | Capacity/filling load boxes; SIM case

7.5.2.6 Breakage rate

The breakage rate of the RPC and plastic bottom of the hybrid has a linear effect on the emissions, as seen in figure 69. Two lines are showed for the hybrid and two for the RPC, both differing in number of rotations the parts make before being at the end of their life. The number of rotations has the effect of the height of the line, but not on the gradient.

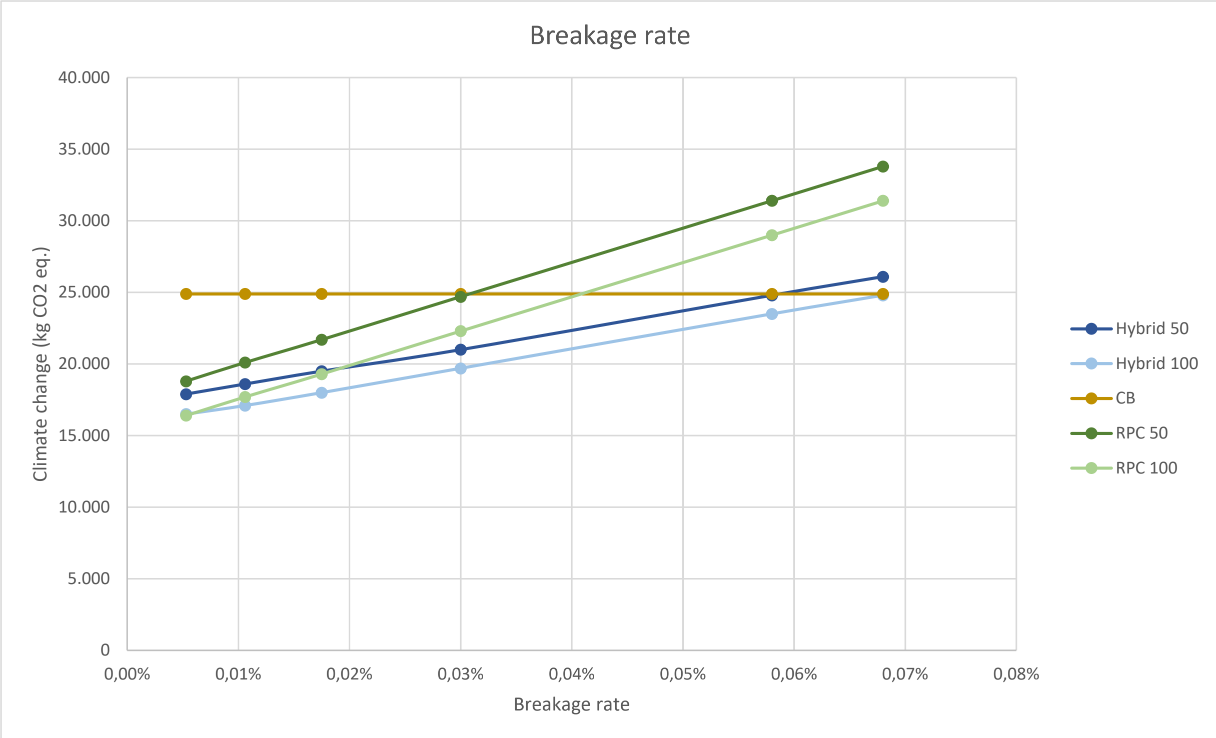


Figure 69 | Capacity/filling load boxes; SIM case

In the FEFCO case the breakage point is very high compared to the SIM case, which heightens the impact of the RPC and hybrid drastically, the RPC more than the hybrid because the RPC has a higher gradient in the graph. That could be a reason of the higher score of the RPC in the FEFCO case.

The chosen breakage rate of 0,53% is an average value following (Krieg et al., 2018). This might be on the lower side of realistic use cases, but there is space for the hybrid box for if its breakage rate would be higher. The breakeven point for the hybrid box with 50 reuses in its use life is around 5,8% breakage, so the expectation is that the plastic bottom of the hybrid will stay under this value.

7.5.2.7 FEFCO case

Looking closer into the input values of the FEFCO case, the breakage rate, filling load and number of rotations have the biggest influence on the results being different from the SIM case.

The low filling load of all secondary boxes results in higher output numbers then in the SIM case. So, changing the filling load doesn't have an influence on the comparison between the secondary boxes.

The breakage rate of 2,5% in the FEFCO case is very high, compared to the 0,053% in the SIM case. Lowering the percentage of the FEFCO scenario to the one of SIM, the hybrid turns out to have lower emissions than the cardboard box, see figure 70 & 71 & 72.

What already has been discussed in paragraph 7.5.2.4, about the influence of the number of rotations, is the chosen value by FEFCO on 24 rotations for an RPC. This seems to be a low value according to the IFCO statistics of their RPC life cycle (Thorbecke et al., 2019).

When the value of number of rotations is chosen of the SIM case, the hybrid gets under the climate change impact of the CB again.

Lowering both number of rotations and breakage rate for the FEFCO case, the hybrid and the RPC have a lower impact on climate change than the CB. This means that those 2 values are of high importance for the impact of reusable options for the distribution of fresh produce.

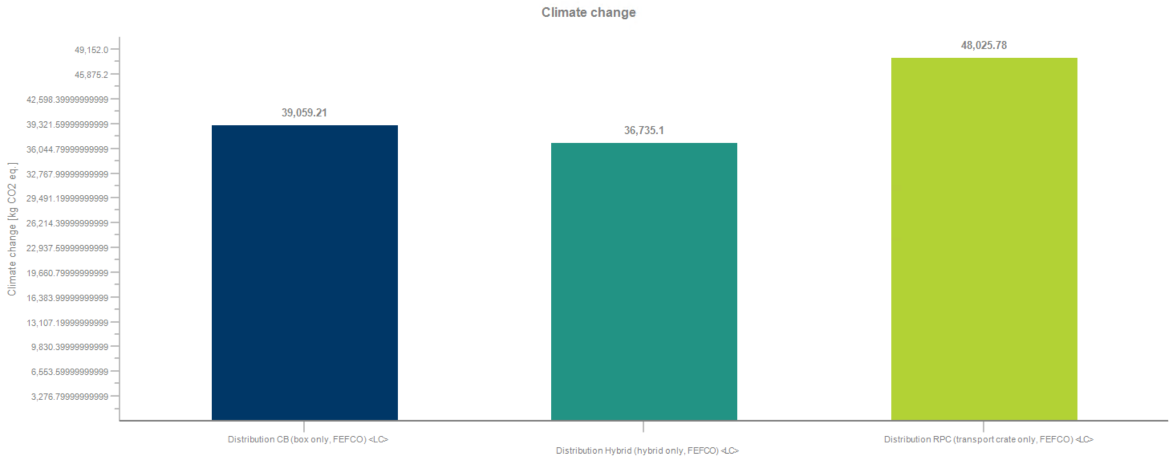


Figure 70 | LCA results all boxes FEFCO case with lowered breakage rate

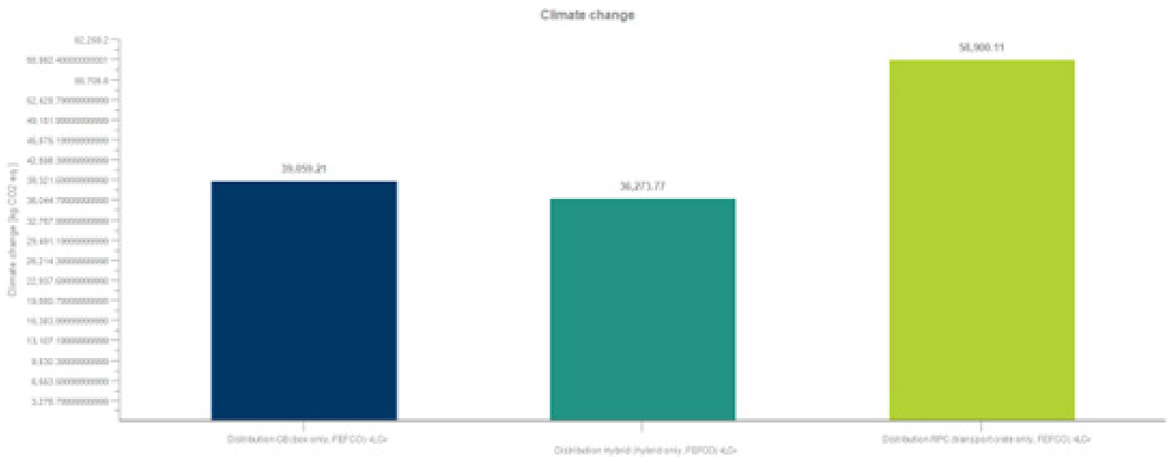


Figure 71 | LCA results all boxes FEFCO case with lowered number of rotations

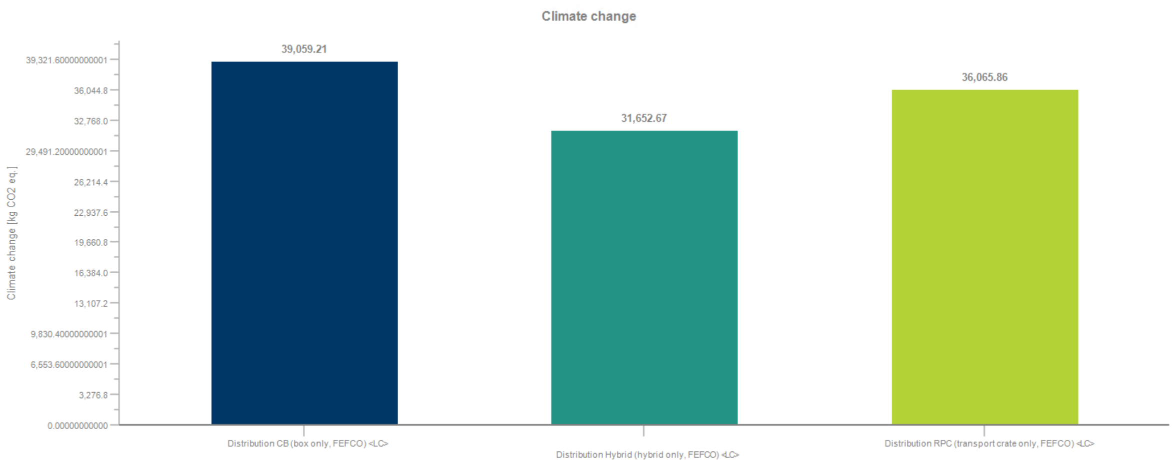


Figure 72 | LCA results all boxes FEFCO case with lowered breakage rate and number of rotations

7.5.2.8 Conclusion breakeven analysis

The breakeven analysis made the influence of different processes visible, by plotting the results in graphs. The main takeaways of this analysis are summed up below and the influence these results have on further development of the hybrid concept are stated as well.

Influence weight differentiation materials hybrid

- The higher the plastic share in the hybrid box, the lower the climate change emissions
- For the development of the hybrid this means that strength can better be extracted from adding to the plastic bottom than adding the cardboard sleeve, at a certain level
- Influence transport distance
- The higher the transport distance, the higher the climate change emissions for all three secondary packages
- Transport distance had the biggest influence on the RPC. Even bigger than on the hybrid, while the hybrid's distance travelled is higher because of it exists of two different materials.
- This means that with making a choice of which secondary package to use, the hybrid can be chosen over the RPC for high transport distances. When the distance gets even higher, the CB should probably be chosen.

Influence recycling rate

- The higher the recycling rate, the lower the impact on climate change.
- The recycling rate of the cardboard part has a bigger influence on the total impact than in the plastic part.
- This means the intake numbers and correct waste treatment of the parts of the hybrid are important during its use. This is no different from the current secondary packaging though.
- Influence number of rotations
- The higher the number of rotations the RPC and plastic bottom can make, the lower the impact on climate change is.
- This can be achieved with a durable design and making it repairable, which is important for the further development of the hybrid
- Influence filling load
- With lowering the percentage of filling load of the max capacity the impact on climate change goes up. The factor of change is comparable for all three secondary boxes, so doesn't have an influence on the results of comparison with each other. Though the percentage of filling load should be kept as high as possible, to minimize the total impact of secondary packaging in general.

Influence breakage rate

- The higher the breakage rate, the higher the impact is on climate change for the RPC and hybrid. The breakeven point for the hybrid box with 50 rotations is at a breakage rate of 5.8%. This means that the plastic bottom could be designed less durable which means there are more plastic bottoms needed to be produced to fulfil the functional unit, up to a breakage rate of 5.8% compared to the 0.053% used in this case study, before the hybrid box gets a greater impact on climate change than the CB.
- Though the breakage rate should still be tried to keep at a minimum, if this turns out to be not possible, it doesn't mean that the hybrid isn't beneficial to use anymore.

FEFCO case

- Also, the FEFCO case is included in this breakeven analysis. There were two factors with a high impact on the final results in this case which differed much from the SIM case, the breakage rate and number of rotations. With changing these values to the values of the SIM case, the hybrid has a lower impact on climate change as well for this case. This makes the conclusion that the hybrid has a lower environmental impact than the CB and the RPC more viable, as long as the breakage rate are kept low and the number of rotations high.

7.6 Conclusion

Important factors for the reusable secondary boxes are breakage rate and number of rotations can be reused in its lifecycle. These two factors are in correlation with the durability of the boxes (technical design aspect, there can be designed upon), and with the logistics during their use phase. A (reverse) logistics setup is important that it doesn't loose too many crates during the process so all crates stay in the chain as long as their technical life can handle the impact during its use (is not damaged).

Also, the total transport distance is of influence on the end results, though it has less impact on the hybrid then on the RPC, probably due to its lower weight. Though the hybrid needs two different materials for the assembly of the box, so the transport to the farm and from the use phase to the waste treatment centers is doubled, it has still less impact than the "heavy" RPC. Recycling rate is important as well. It can make or break the result of more or less emissions than the RPC or CB. So also for this, the reverse logistics process is very important.

The filling load should be as close as possible to the 100%, to reduce the general impact of all secondary packages.

7.6.1 Discussion & Limitations

In this LCA, only the impact on Climate Change is considered. This has been done to ease the process of recognizing trends in the impact of different processes for 1 impact category. For that, climate change is chosen because it is often taken as the example category for these kinds of studies, and it is an important one in Europe to lessen the climate change emissions. For in a next analysis, it is recommended to see if the changes of the different processes have the same impact on other categories or if the impact is different. For specific cases the LCA will be done for, there can be looked at the importance of these different impacts and others can be considered as well. In the scope of this thesis, there was not enough time for doing it and the project is still in an early stage, so it is okay that only one category has been chosen as for first results.

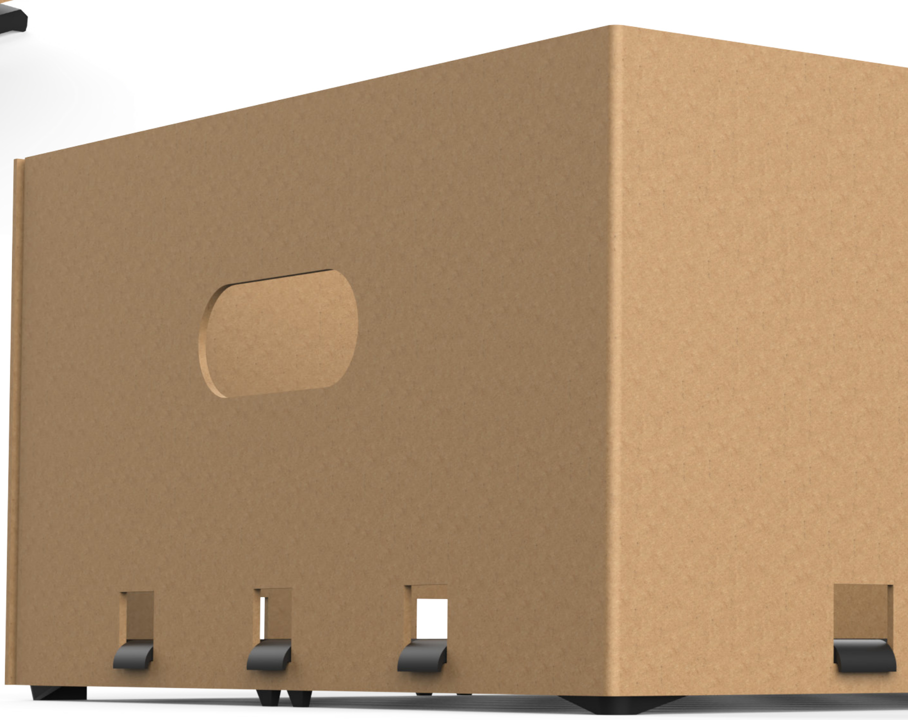
7. Final Concepts

In this chapter, the results of the developed concepts will be discussed with two real sized prototypes. Potential failures of the concepts and points of improvement are identified with the help of multiple brainstorm groups. One group of Industrial Design Engineering master students and PhD's, one group of employees of Schoeller-Allibrecht, which is a reuasble plastic crate design company, and with Remco Boer, who is a Plastic Injection Molding specialist.

An explenation of all functions of the final two concepts are visualized in figure 73 & 74.

Snap systems catch sleeve when sleeve is pulled up

Assembly by pushing sleeve onto bottom part

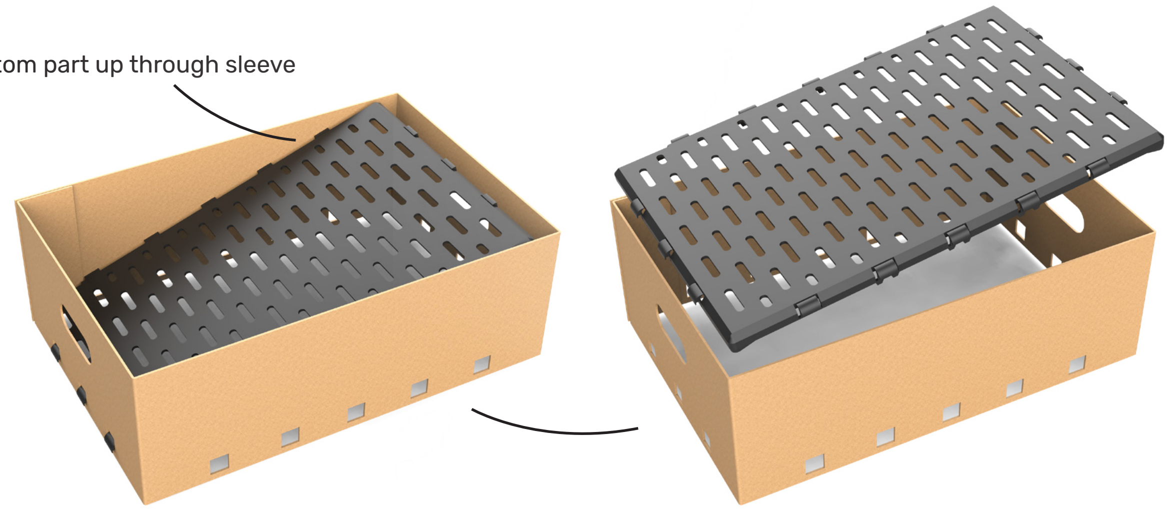


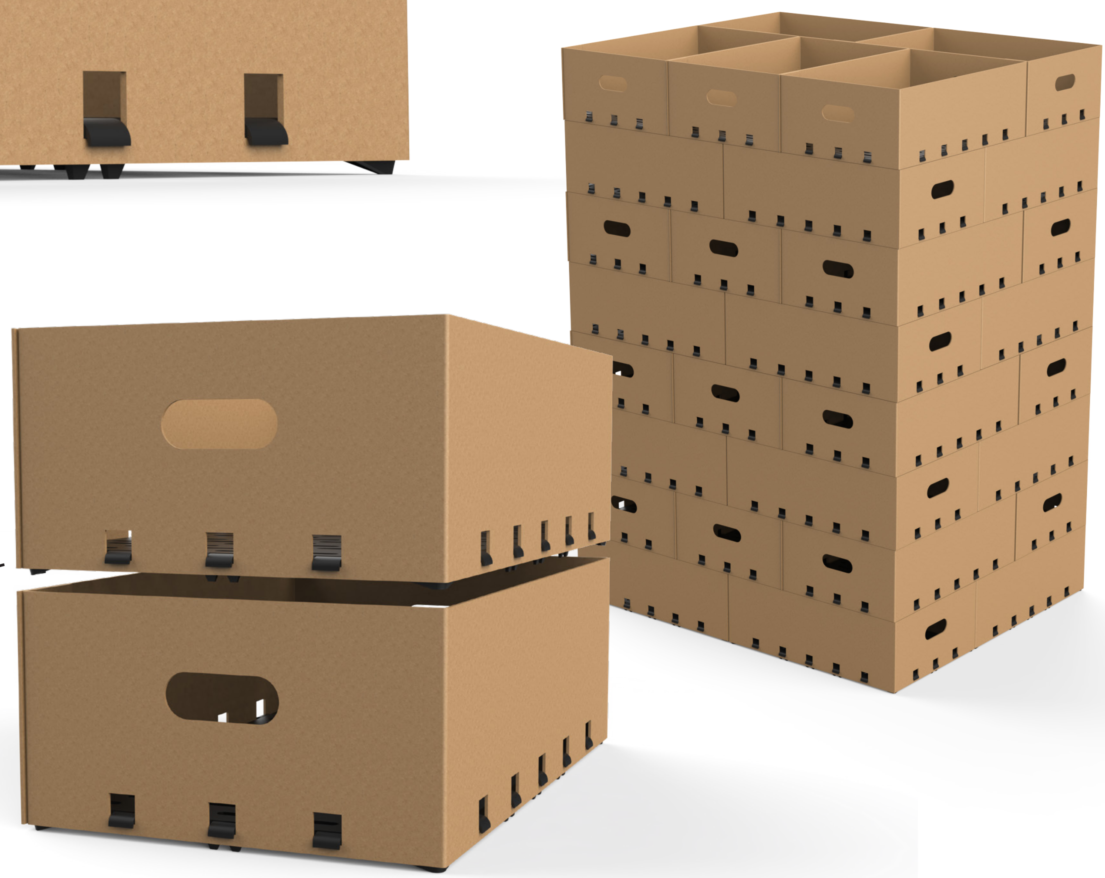
Snap system concept

Exisits of one bottom part

Figure 73 | Visualization of snap system concept

Disassembly by pushing bottom part up through sleeve





Features are added to the bottom
to make stacking easier

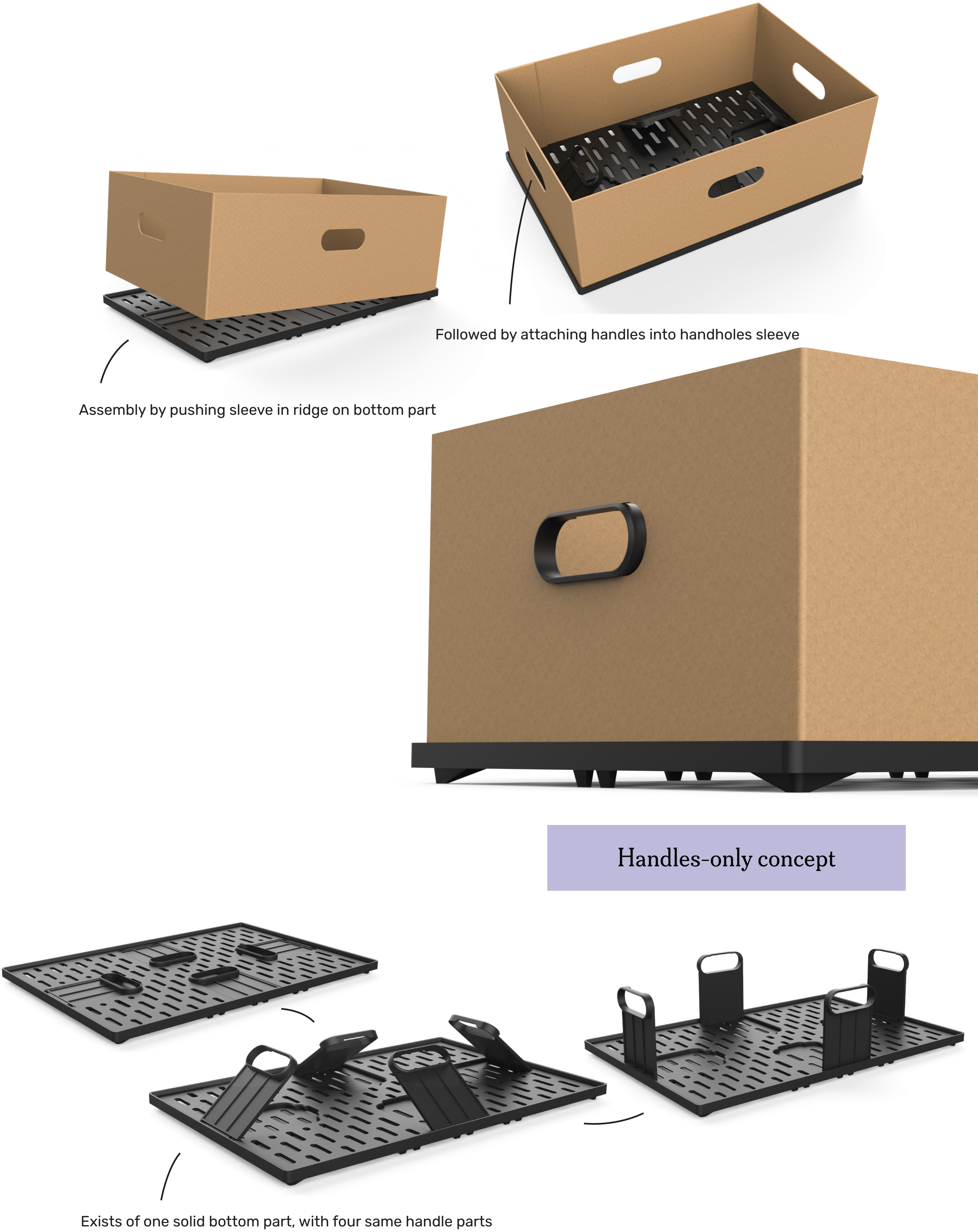
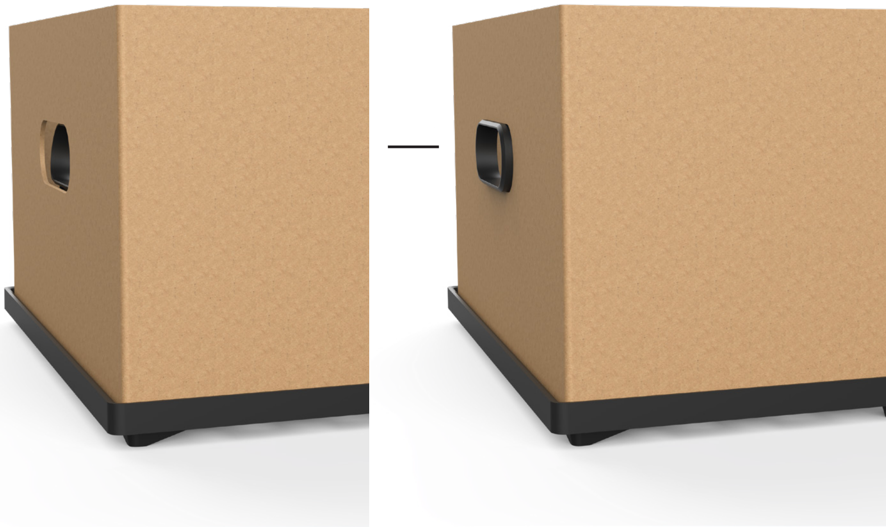


Figure 74 | Visualization of handles-only concept

Plastic handles assemble in holes sleeve



Features are added to the bottom to make stacking easier

7.1 Assessment prototypes

The packaging design phase resulted in two concepts with the potential of being developed to working principles. To be able to discover beneficial parts of the concepts and points of improvement, a real sized prototype is made for each concept (figure 75 & 76). These prototypes are assessed in an interactive brainstorm session with a group of Industrial Design Engineering master students and PhD's.

The goal of the session is to discover faults in the design things that aren't working well, or efficient, and to generate ideas for iteration options.

The same kind of session is done with Remco Boer. He is a specialist in designing for and optimizing injection molded products, so he has a lot of experience in identifying the needs of a product, how to optimize a product for implementation to the market and has knowledge about the production process injection molding and the materials which can be used, so can make a well prediction if it is possible to produce using injection molding.

Most of the results of the two sessions were similar, so the results of both sessions are presented at once in the paragraph results. On top of that, identified possibilities before the two sessions are included as well, to give a complete overview as possible of the current state of the concepts and the possibilities to improve them.

Figure 75 | Handles-only concept full-size prototype

Figure 76 | Snap system concept full-size prototype

7.1.1 Design requirements

The most important requirements the design should be working with are stated below. These requirements will be explained during the session, so the participants know where to pay attention to.

- C.011: The assembly of the box should be able to be done in less than 3 actions/steps
- C.011: The disassembly of the box should be able to be done in less than 3 actions/steps
- C.012&C.013: During the disassembly, it is accepted that the cardboard sleeve would break. During assembly this is not acceptable.
- C.051: The box should feel rigid during carrying it by the handholes. The feel of rigidness will be asked to the participants, so it is an opinioned test.
- C.050: The box should be able to be carried using the bottom as handles as well.
- C.014: The assembly of the box should be clear for the test persons, without needing too much thought going into it. The test persons will be asked to assemble the boxes by themselves without an example, but they can figure it out together.

7.1.2 Method

During the assembling and disassembling, the brainstorm session will take place, to make it interactive and get as many ideas out of them as possible about points to improve and ideas on how to approve the designs.

Also, an estimation will be asked to the participants if they think the concepts can be developed into a working principle.

7.1.3 Limitations

The prototypes are not fully done at the time of testing. Not all 3D-prints were done in time, so for the snap systems concept, three snap systems have a tolerance which is too big, so they can fall out of the hole in the laser cut part and won't support the cardboard sleeve when assembled. The handles only concept misses one handle and has one handle which only has 1 part that attaches it to the bottom instead of two.

The assembly time couldn't be assessed well. This is because he chamfer to push the sleeve onto the plastic bottom was made too small. It is a first full-sized prototype so a wrong estimation was made on the size of the needed chamfer.

7.1.4 Results

7.1.4.1 Snap system concept

The snap systems in the plastic bottom have gotten an iteration step and are U-profiled, so they can catch the sleeve. The sleeve is assembled by pushing it onto the plastic bottom. The holes align at that moment with the bottom of the U-profile. When the sleeve is being pulled on for carrying the plastic box, the holes in the sleeve are caught by the U-profiled snappers and is ready to be used. There are features at the bottom that are lower than the cardboard sleeve to make the stacking of the hybrid safer.

The assembly of this concepts is easy. It is one step, and the hybrid is ready for use. To make aiming of the sleeve easier, the chamfer on the plastic bottom should be bigger. The cardboard sleeve needs to have a tight tolerance to make the snap systems catch the edge when pulling on the sleeve. If the tolerance of the sleeve gives too much space, the sleeve is likely to bend to the outside and go outside of the snap systems.

Though, even with a tight tolerance of the sleeve, the sleeve is still likely to bend outside, especially when it would be filled with produce. The produce will be stacked on top of each other and will execute pressure on the insides of the sleeve to the outside. Now, the sleeve is not being caught by the snap systems, when the hybrid is standing on the ground and the sleeve is free to move outside which creates a gap between the sides and the plastic bottom.

For this, a solution could be to replace the middle snappers of the four sides to a moving part which pushes the sleeve up. For the snap systems to catch the sleeve, the sleeve needs to move up, so it is in the U-profile. This happens while carrying but not when it is standing on a flat surface. The part to move the sleeve up should be designed. Figure 77 shows an explanatory sketch of the idea. A warning for this idea is that the compression strength of the concept is gained from the sleeve leaning on the ground surface. If there are parts which moves the sleeve up, that means that when the hybrid is on the ground, the sleeve wouldn't touch the ground anymore, but will lean on the pushing parts. This will lessen the compression strength drastically, so should be avoided. (When the compression force gets high on the pushing parts, they should move away again so the sleeve will touch the ground surface fully. Also, it would be sick if the pushing part move into position while the sleeve is being pushed on top of the plastic bottom during assembly, so assembly stays one action. If not possible, the pushing parts can be like a suitcase closure or something)

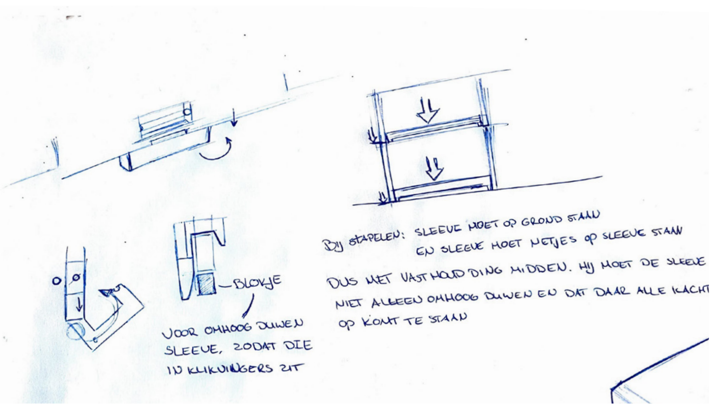


Figure 77 | Explanatory sketch snap system iteration

The design still needs a full optimalisation step to develop on the needed strength, stiffness and producibility. The bottom needs to be provided with an optimized rib and ventilation design. The chamfer for easy assembly needs to be bigger. An expectation is identified that when the snap systems would be designed bigger, they can catch the sleeve better. This could be tested before the pushing part will be developed. Lastly, it can be a challenge to make the snap systems out of injection molded PP or PE as flexible as they are printed. PP and PE are both stiff materials. This should be considered when optimizing the snap systems. The optimization of the stiffness and producibility can be done with FEM-analysis for the strength and mold flow analysis for the producibility.

The cardboard sleeve will decrease in strength in humid surroundings, which will have direct influence on the strength of the holes for the snap systems. The degree of influence should be tested with humid or wet cardboard. The holes in the sleeve can be heightened if the test results in that the holes are not strong enough now. Heightening the holes has influence on the total height of the plastic bottom and how many bottoms can be transported on a pallet for the reverse logistics.

The snap systems are prone to break during a fall of or high impact punch on the plastic bottom. The snap systems should be designed for durability, but they stay vulnerable. They could or be designer for repairability, but this complicates the production process., or a higher breakage rate should be considered. Results of the LCA show that there is room for a higher breakage rate for the hybrid, keeping the emissions still under the current secondary packaging systems, so an increased breakage rate doesn't mean the hybrid is not beneficial anymore.

7.1.4.2 Handles only concept

The handles only concept hasn't changed since the scaled down prototype during the development phase. The sleeve needs to be pushed into an edge in the plastic bottom after which the four handles can be unfolded and attached to the handholes in the cardboard sleeve.

The first thing noticed is the strength the prototype already has. The ridge in the plastic bottom assures the sleeve to stay in place, and carrying the hybrid using the handles attached to the plastic bottom assures strength and doesn't influence the attachment of the sleeve to the bottom. When executing force on the inside of the hybrid, the fixation in the bottom of the sleeve assists the sleeve in keeping its form. Also, the placement of the handles in the middle of the sides of the sleeve assist in this. This makes the prototype feel rigid by the participants and gives assurance of the believe this prototype will be strong and usable when being in use.

To make the assembly of the sleeve to the bottom easier, the ridge in the plastic bottom should have a bigger chamfer, so it can lead the sleeve better into position and the user must aim the sleeve less precisely. But the ridge in the bottom should stay tight so the connection stays firm. The ridge can be sensitive to dirt, so optimalisation for cleaning should be done for this.

The plastic handles should stay straight up when unfolded. This could be done by adding a fixation at the bottom in the hinge, of by using the flexibility of the cardboard material. The plastic part could be fixed by adding a snap system like feature or a small ridge to the bottom and top. The ridge can force the cardboard a bit, and makes the handle stay behind the cardboard.

In general, the needed iterations for this concept are minimal, so only a full optimization step is necessary. This means that this concept is working in general and only needs small adjustments for optimization.

7.1.4.3 Cardboard type choice

The sleeve of the prototypes is made using B-flute cardboard. This is the most used type of cardboard in Europe for secondary boxes. This doesn't align with the compression test done for this project. For this test C-flute was used because that is the most used flute type for secondary boxes in the US. The results of that test was that the sleeve is expected to be strong enough to be used as compression carrier for the hybrid. The B-flute is thinner than C-flute so less strong. This means that this type of cardboard still needs to be tested to be able to know what strength it can handle and if it will be strong enough to be used in the hybrid concept. If it turns out it is not strong enough, other types of flutes can be considered, for example a double B-flute, BE-flute, or C-flute. The choice of which flute to use, can be dependent on the use case the hybrid will be used in.

That is the advantage of the modularity of the hybrid packaging system. The compression strength of the flute types can be tested in an isolated situation, like the C-flute is tested, but a dynamic test in combination with the developed plastic bottom would be useful as well, as a replacement or on top of the static test. This test is necessary to get knowledge about the behavior of the assembled hybrid and what influence the connection between the sleeve and the bottom have.

The ergonomics of cardboard boxes is not always optimized (L. C. da C. B. Silva et al., 2013). There are possibilities for better ergonomics, which should be further investigated for the design of the hybrid and if possible implemented, to improve on the current shortcomings of the cardboard boxes. The handles only concept, may be more like the RPC, in ergonomic handling of the box. This could be an advantage for the implementation of the concept.

7.1.5 Conclusion

The real sized prototypes have been useful to identify the well-working features in the design ideas and identifying the limitations and points of improvement of the concepts. The handles only concepts design is identified as strong. The prototype shows the concepts potential, and the expectation is this concept will be well working. Only a few optimalisation steps are necessary for the concept to be fully functioning. Features as the producibility of the parts, the stiffness of the bottom, rib and ventilation design, strength of the connection of the handles to the plastic bottom and improving the easiness of assembling the sleeve and stacking the hybrid should be developed. The snap system concept needs another design iteration to be able to say it will be able to be used as a secondary packaging box. The snap systems in the plastic bottom don't catch the sleeve all the time, due to the flexibility of the sleeve and forming to the outside. A first idea is presented to improve this, but this idea needs to be elaborated and tested using rapid prototyping, before it is possible to say that this concept will work. If it turns out the concept is expected to work, an optimalisation process needs to be done as well, like the handles only concept.

With the results of the assessment of the two prototypes it is possible to conclude that the idea of a hybrid secondary package will be able to be designed, following the setup requirements in the package design phase of this project. The compression and tensile strength test done proves the strength of the cardboard sleeve is great enough to be used as the sides for a transport box.

7.2 Cost calculation

To get an understanding of the eventual costs of the hybrid system, compared to the RPC and CB, a breakeven analysis is made. All data is based on rough estimations, which are added in the Appendix D. The result of the cost estimation is shown in figure 78.

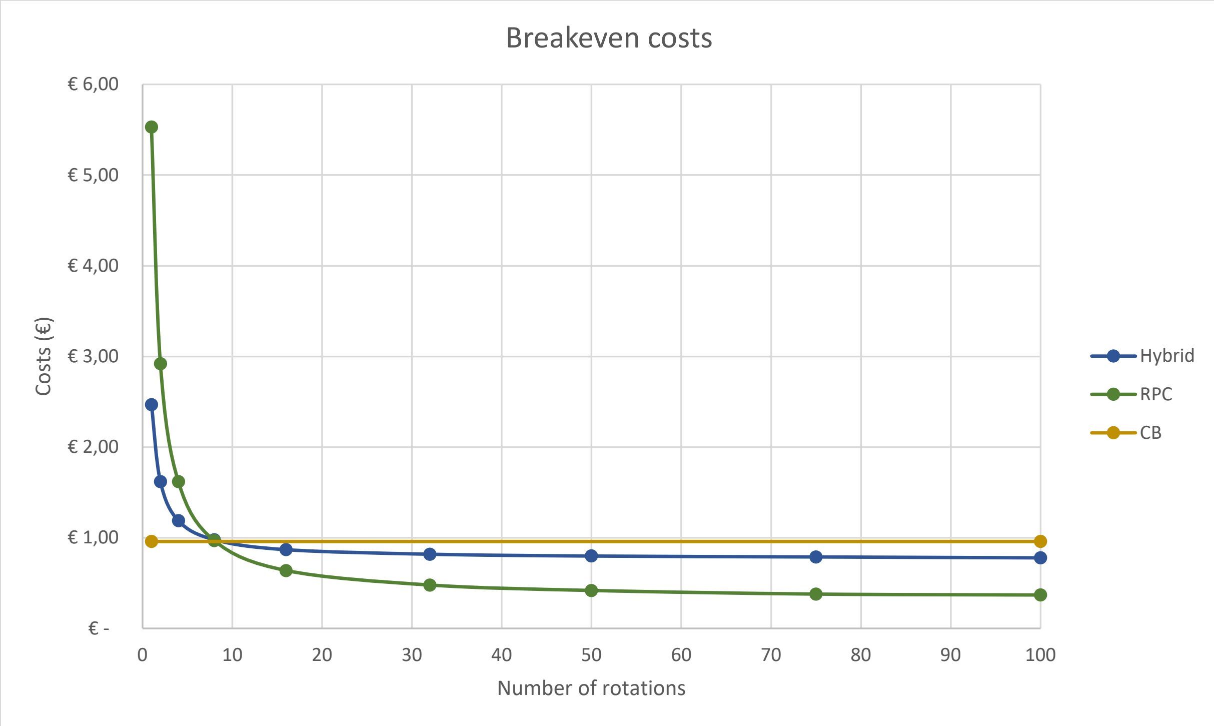


Figure 78 | Breakeven cost estimation

7.2.1 Limitations

No data was found for the costs of the cleaning process of RPCs and the storage in a service center. Therefore, a rough estimation is made. The amount of these costs is important for the final costs, especially for the hybrid. At 50 rotations of the hybrid the breakeven with the CB is at €0,79, compared to the CB of €0,96. This difference is noticeable on a big scale but doesn't give a lot of room for the hybrid to get more expensive to keep the same result of being less expensive.

Investment costs of cardboard are not considered in this calculation, because they are low compared to the ones of the RPC and hybrid plastic part. Though, if there will be many modular options for the cardboard sides, the investment costs become a bit higher.

These results are in accordance with studies done in the past, in which become clear that the RPC turns out to be economically beneficial compared to the CB (Albrecht et al., 2013). This benefit mostly comes due to the production costs can be split up between the number of rotations the RPC will have. This aligns with the results of this study. The breakeven analysis shows the influence of the number of rotations which divides the costs of production.

7.2.2 Conclusion

The hybrid secondary package system needs an investment up front, like the RPC, to be produced and implemented in market. This can be seen as a hazard compared to using a cardboard box, but the investment costs pay back already after an estimated 8 rotations of the plastic bottom, which also applies to the RPC coincidentally enough. The difference of the hybrid and the CB is not that big in this calculation, but it will be noticeable in the application on big scale.

If the hybrid turns out to be more expensive than both the RPC and CB, it can be argued that the environmental benefits of the hybrid weigh up against the cost's disadvantage. Also, a possibility in future could be that companies will get compensation for more environmental beneficial choices. The hybrid could be such a choice so companies might be possible to get such a compensation for the use of it. Though this should not be the assumption and goal of development. It is always better to try to lower the costs of the hybrid and get an advantage on the current methods.

For the investment costs, it would be a possibility that the pooling companies of RPCs would take the hybrid into their portfolio, on top of the current existing RPCs. The investment in new plastic bottoms is less than in new RPCs, at most 2 different molds are needed. The infrastructure of pooling the RPCs, so the reverse logistics process, is already in place in many locations, so the plastic bottom could make use of this. Besides that, a small investment is needed for molds the production of the cardboard sleeves, depending on the amount of modular options the company wants to have.

7.3 User interaction

Possibilities and limitations to the hybrid system when it's in use in industry are identified here. These are all expectations and were not able to be checked in the timeframe of the project.

The reverse logistics of the plastic bottom of the hybrid, could be added to the already in place pooling system of the reusable crates. The added reverse logistics can be a hazard of implementation for company, but with the pooling system this hazard is taken over by another company. The bottoms can be owned by them. This way the companies using the hybrid crates can only use them and not worrying about high investment costs, they can rent the crates from the RL company. These RL companies are already in place and the service centers exist for storing and cleaning, so adapting the plastic bottom should be possible in the current process.

The RPC appears to be damaged less during the distribution of fresh produce than a cardboard box (J. Singh et al., 2016). The expectation for the hybrid is that its damage during the distribution process will be closer to that of the CB than the RPC, because this benefit comes from the strength of the RPC, although this expectation is not tested in any way, so should be tested thoroughly in the further development of the concepts. Other factor about damage of fresh produce during the distribution were found as well. The CB could maintain a humid surrounding in the boxes, which helps in keeping the produce fresh (Albrecht et al., 2013), and the CB softness reduces surface damage of soft skinned fruits (Sasaki et al., 2022)(Sasaki et al., 2022). RPCs are favorable again when the produce is cooled for a long time in a humid room, or using melting ice (Chonhenchob et al., 2017; J. Singh et al., 2016). This shows that the different secondary packaging systems have their different strengths depending on the applications they will be used in.

The assembly time of the hybrid is an important factor for the farmers who will fill them with the harvested produce. They are paid by number of filled packages and not by hour so an increase in assembly time will cost them money. That's the reason for the goal of getting the assembly time as low as possible. This should be tested in the further development of the hybrid concepts and optimized. The increase in assembly time could be compensated by lower production costs and with that a lower price of using the hybrid. Or potentially by a subsidy for the users for the environmental benefits the hybrid brings, as explained in the cost analysis chapter.

7.3.1 Use case display ready in store

Printing the hybrid has the benefit of being able to make the brand of the produce known while the box is presented in the store, like the cardboard boxes are used for. The RPC doesn't have that option. If the hybrid will be used as display boxes in a grocery store, lots of plastic bottoms are needed to provide every store with the hybrid, because the boxes will be used in the store for some amount of time. If the hybrids are all used for a week for example, then the need for the bottom goes up fast. This means more bottoms need to be in the pool cycle. The investment costs will go up if the hybrid will be used for this application. For the environmental impact, it is a discussion if the impact will go up. More bottoms are needed to fulfill the necessary bottom in the pool, but with good management of the crate, they still have the same number of rotations they will survive, the breakage rate should stay the same and the percentage of recycling should stay the same as well. So, the environmental investment in production will go up, but in the end the use case stays the same. This is not tested for now, but should be in future, if this application would be an option.

7.4 Conclusion

The prototypes of the final concepts are used to analyze the designs and identify points of improvement. The snap system concept needs another design iteration before it can be proven the concept will work. The handles only concept is developed in such a way that the expectation is it will get strong enough. This concept needs an optimalisation step, but the idea in general works.

The hybrid is possibly cheaper than a CB, but the cost analysis is a rough estimation and should be further developed before a real statement can be made in this subject.

The hybrid could be included in the pooling system of the RPCs which is already in place. The choice of which secondary system to use should be dependent on the type of produce that will be distributed. In some cases, the RPC turned out to have less damage during the distribution process compared to a CB, and in other cases the CB had less damage, resulting from studies done in the past. The damage rate of the hybrid should be tested in further development of the idea.

The assembly time of the hybrid solution needs to be tested and developed upon as well, because it is an important aspect for the implementation of the concept by the direct users.

8. Conclusion

“Is it possible to design a packaging system to distribute fresh fruits and vegetables, combining reusable packaging systems and recyclable single use materials, to create a more sustainable product-packaging combination by using best of both worlds?”

The goal of this research was to discover design options for a new secondary box for the fresh produce distribution. This new design was aimed at combining two circular approaches into one product, using the single use recyclable material cardboard as the sides, and a reusable plastic part as the firm bottom of the secondary box. This was done to combine the best of both worlds: to create a sustainable product-packaging combination. Two concepts were proposed, both with different benefits in the design and user application.

The strength of the cardboard sleeve has been proven to be sufficient to function as the carrying part of the hybrid while stacking. A full-size prototype has been made of the two developed concepts which are assessed by different stakeholders. This with the result that the handles-only concept is feeling strong when assembled, and expected to be able to be worked out as a fully functioning product. The snap system concept is easy to assemble, only using one movement of pushing the sleeve onto the plastic bottom, but the snap systems did not catch the sleeve in all times. To improve this, another iteration on the concept idea is necessary before a decision can be made on if the concept will be suitable to function as a hybrid packaging system.

The environmental impact of the hybrid versus the current secondary packaging systems, the reusable plastic crate and single use cardboard box, was assessed in an environmental life cycle assessment. The results of this were positive regarding the hybrid box design. It was a preliminary assessment, so the assessment was done with estimated input data using other LCAs on the same topic as an example. The impact of the hybrid resulted to be lower than of the RPC and CB, for the use case that was used as example. This reflects the statement in the research question that the hybrid box uses a product-packaging combination that uses the best of both worlds in terms of the circular aspects of recycling and reuse. Combining single-use cardboard with a durable, reusable plastic part results in a lower environmental impact than using only one of the two systems for the product in other use cases than where the single-material boxes are optimal. Next to this, the input data of the LCA was alternated per specific topic, to discover the influence per topic, and a benefit of implementing the hybrid to the market has been discovered. In between the low environmental emissions of the RPC with small transport distances, and the low environmental emissions of the CB with high transport distances, the hybrid could be another solution having less impact on the environment.

Bortolini et al. (2018) have already stated it in its research, but this research proves as well, that combining the two end of life systems could be a way to a more environmentally friendly future of secondary packaging. This was a case specific research but the benefits of combining these two systems should be researched further in the future and might benefit in more (packaging) applications.

8.1 Recommendations

Life Cycle Assessment

In the time frame of this project, a basic LCA was performed to obtain initial results on the environmental impact of the hybrid compared to the RPC and CB. Several things can be done to further develop this LCA. Data based on real cases in industry could be used for building knowledge on which transport system to use in which case. Also, different impact categories should be considered. Depending on the location the secondary packaging systems will be used, important impact categories need to be assessed, apart from climate change. The LCA can be used as a design tool for the further development of the concepts and for decision making in what cases which secondary box can be used best, regarding environmental impact, to be able to make more considered choices.

One factor that could be included in the LCA is material that is "stuck" in the cycle, based on Bocken's theory (Bocken et al., 2016). This is particularly important if the hybrid is used as secondary packaging on grocery store shelves. The impact of requiring much more plastic bottoms should be evaluated before this idea is implemented. If the cardboard box appears to have a lower environmental impact for this application, then this secondary packaging system should remain and not be replaced with something that has a higher environmental impact. When implementing the hybrid, the transportation distance should always be considered, and logistics should be optimized wherever possible. This should become a standard in the industry to avoid excessive transportation and waste. Especially for reusable packaging systems, transportation distance is an important factor in environmental emissions and should be considered at every stage.

Some processes of the life cycle of the secondary packaging systems are not considered yet in the current LCA. Printing cardboard is one of them, as well as the need for different molds for stamping the cardboard sleeve to make the height modular. The cooling method that could be different with cardboard or plastic is also not considered.

In the end, choosing which secondary packaging system to use for what application, should be made considering the environmental impact of the different systems, so LCAs should be done to gain knowledge for this.

Packaging design

This study resulted in two full-size prototypes of two different assembly methods of the cardboard sleeve to the plastic bottom. The handles-only concept is in a development stage that it seems to be working well, and is ready for optimization of all features. The snap system needs an extra iteration before it can fully function. A design engineer should work on this. Another possibility is that a new concept can be developed by a design engineer, using this report as a base.

An important aspect that still needs to be assessed is the time it will take to assemble the hybrid. This will differ for the different concepts. It couldn't be assessed with the made prototypes, because the assembly was still too hard, the sleeve wasn't led good enough into the right position. This should first be improved before the assembly time can be assessed.

An important step for development of a working concept is to test the developed hybrid in the field, for the assembly method and the rigidness of the hybrid for use during harvest, and the use in the distribution center and grocery store, including the easiness of disassembly. For the technical part of the hybrid, the compression strength in a static and dynamic environment should be tested, including the whole assembly. The strength in compression can be improved by using thicker or double layered flutes for the cardboard sleeve, but this will affect the environmental impact of the hybrid, which needs to be considered when changing the flute type. The advantage of the sleeve is that the flute type can be alternated between different use cases, without big investments in costs or environmental impact.

The easiness of stacking and of pushing the sleeve into the plastic bottom should be improved by making a bigger and longer chamfer, to lead the way of the sleeve. The plastic bottoms need to be optimized for injection molding, to design rib placement and material thickness to develop strength of the bottom, and ventilation pattern should be optimized. A material should be chosen for the plastic bottom, probably PP or PE, which are rigid and often used plastics for in RPCs. This optimization can be done using FEM analyses. The use of recycled content in the production of the bottoms should be considered and tried to be as much as possible, with the goal to use 100% recycled content, to improve its circularity. This also applies to the cardboard sleeve.

The strength of the connection between the plastic handles and the bottom should be optimized, as well as the flexibility and rigidness of the snap systems, if they will be used in the final design. Also, the height of the snap systems should be researched, regarding the height of the holes in the cardboard sleeve. With this, humid conditions and weakening of the cardboard should be taken into account.

A useful application of the hybrid secondary packaging box lies in use cases where an RPC isn't environmental beneficial anymore because of high transport distances, but the return of reusable parts is still easy enough. Compared to using cardboard boxes which need a lot of material to produce every single time, less material is needed every time, and with the reusable plastic bottom, material is saved.

Also, when the cardboard gets humid, it is not known yet if it remains its form well enough for the concept to keep working

Recommendations on the technical development of the hybrid secondary package is one thing, but the advantage of combining the two end of life systems should be further researched as well. The exact origin of this advantage should be elaborated on and published so this combination can be used in more fields.

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Combining the strength of reusable and one-way systems into a secondary packaging design

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APPENDICES

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Table of Contents Appendices

A. Design phase

A.1 Requirements list

Number	A. Originate (develop, produce, ...) Discription requirement or wish
A.010	The parts of the hybrid box should be able to be produced with (an amount) of recycled content

Number	B. Distribution (storage, transport, ...) Discription requirement or wish
B.010	The hybrid box should withstand humid circumstances
B.020	The hybrid box should protect the content (fresh produce) from outside factors, such as vibration, sl pressure forces

Number	C. Use (function, circumstances, actions, ...) Discription requirement or wish
C.010	The attachment of the sleeve to the plastic bottom needs to be able to withhold a tensile strength c load it will be designed for
C.011	The attachement of the sleeve to the plastic bottom and the disassembly of it should be possible to in less then 3 (easy) steps
C.012	The plastic part of the attachment system of the sleeve to the plastic bottom needs to be able to be disassembled and assembled >50 times
C.013	The assembly of the hybrid should be clear without any explenation necessary
C.014	The sleeve may break during the disassembly of the sleeve to the plastic bottom
C.020	The plastic bottom should withstand >50 cycles
C.021	The plastic bottom should survive a fall of 1m high
C.030	The assembled hybrid box should be able to withstand a compression strength of the load it will be filled with, times the amount the hybrid box can be stacked on a pallet
C.040	The hybrid box should have a locking machanism when being stacked

	Reason/Explanation	Test method	Source
	To highen the recycling circle and strive to a circular economy	Strength tests material production	Future scenario

	Reason/Explanation	Test method	Source
	During distribution the climate outside can be humid or the produce can be cooled in a humid room	Cardboard tests	Chonhenchob et al., 2017)
hock,	Function as secondary package	Full-sized prototypes	Analysis phase

	Reason/Explanation	Test method	Source
f the	The box can be designed for different weights to carry. The attachment needs to be able to carry that weight	FEM-analysis, cardboard tests	Design challenge
do	The assembly and disassmble of the box should be easy and fast	Prototype	Jay Singh conversation
	The box will be reused >50 times	FEM-analysis, repeated tests	Future scenario
	So every user can handle the product in the intended way, to prevent breakage	Assembly test	Design challenge
	The sleeve is single-use, which can be used as advantage for the design of the hybrid	Design	Future scenario
	The plastic bottom must be durable and able to be reused to lowen the environmental impact	FEM-analysis, repeated tests	LCA study
	To lengthen the lifetime of the bottom	FEM- analysis, repeated tests	Future scenario
	The bottom box needs to carry the weight stacked on top of it, but it is dependent the type of produce it will distribute	Compression tests	Future scenario
	To ensure stability on a pallet	CAD-model, prototypes	Current designs
	To ensure a stable pile of bottoms and		Future scenario, current

C.041	The empty bottoms of the hybrid box should be able to be stacked and locked into eachother
C.042	The empty plastic bottoms should be as low as possible when stacked
C.050	The plastic bottom should be designed for stiffness
C.051	The assembled hybrid needs to be stiff enough to carry the content in it while being carried
C.052	The hybrid should be able to keep the contents inside and protect them from forces from outside
C.060	The plastic bottom must be cleanable
C.061	The plastic bottom should have no loose parts
C.070	The hybrid box should have ventilation possibilities
C.080	The cardboard should be printable

Number	D. Discard (reuse, recycle, ...) Discription requirement or wish
D.010	The cardboard used must be recyclable
D.020	The plastic used must be recyclable

Figure 79 | Requirements list

make the stacking height lower	CAD-model, prototypes	designs
To be able to transport as much bottoms as possible during the reverse logistics	CAD-model, prototypes	Future scenario
The hybrid box must keep its form when being used	FEM-analysis	Design chalenge
Function of secondary package	Prototype	Design chalenge
Function of secondary package	Prototype	Design chalenge
The design of the plastic bottom must be designed for easy cleaning	CAD-model	Future scenario
So parts can't be lost during the reverse logistics of the bottom	Design	Schoeller-Allibrecht meeting
Different fresh produce requires different amount of ventilation to keep freshness	Air flow analysis	Current designs
To make branding possible	Material choice	Analysis phase

Reason/Explanation	Test method	Source
To lowen environmental impact and strive to a circular economy	Material choice	Future scenario
To lowen environmental impact and strive to a circular economy	Material choice	Future scenario

B. Compression test

B.1 Results

C_W = (N-1) x G x 9.81 x f1 x f2 x f3 … x f_n etc.				
In which:				
• C_W = compression strength	3923,042	N	881,9349	Lbs
• N = number of stacked layers	10	layers		
• G = weight of one box	15	kg		
• 9.81 = to Newton	9,81	N		
• f(n) = factor that influences compression strength	2,666016	Total f		
	1,3	1 week of stacking		
	1,05	Column stacked		
	1,25	Open deck pallet		
	1,25	75% RH		
	1,25	Normal transport		
	1	Contents not carrying		

Value of factor f(n)

Aspect	Value	Factor	Aspect	Value	Factor
Time of stacking	1 day	1	Climate	50 % RH	1
	1 week	1.3		75 % RH	1.25
	1-2 months	1.5		90 % RH (tropical circumstances)	2
	3 months	1.8		95 % RH	3-4
	1 year	2	Transport	Light	1.1
Pallet pattern	Column (aligned)	1.05		Normal	1.25
	Column + outside pallet	1.1-1.7		Heavy	1.4
	In pattern (staggered)	1.82		Extreme	1.7
	In pattern + outside pallet	2-2.5	Contents	Not carrying	1
Kind of pallet	Closed deck pallet	1		Partly carrying	0.9
	Open deck pallet	1.25		Carrying	0.8

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Figure 80 | Calculation of needed compression strength transport box with a weight of 15 kg, including estimated safety factor

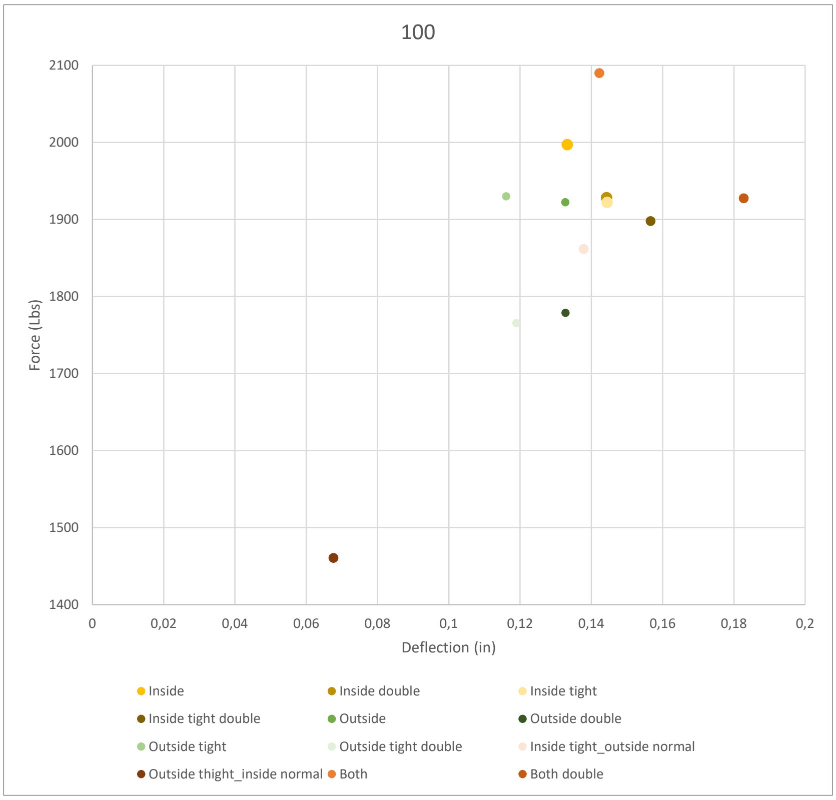


Figure 81 | All results for height of 100 mm in one graph

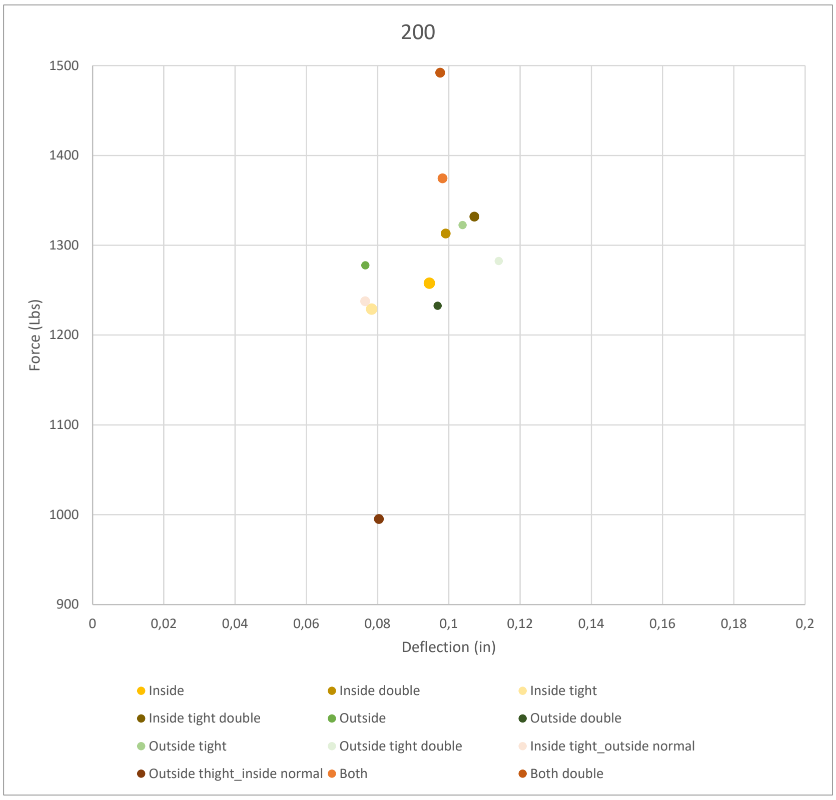


Figure 82 | All results for height of 200 mm in one graph

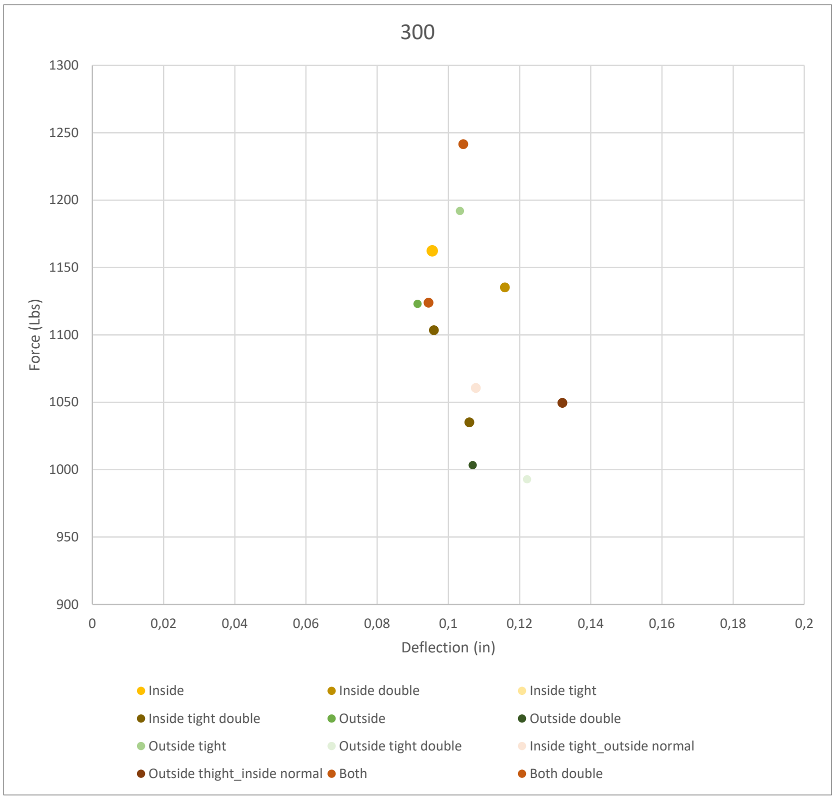
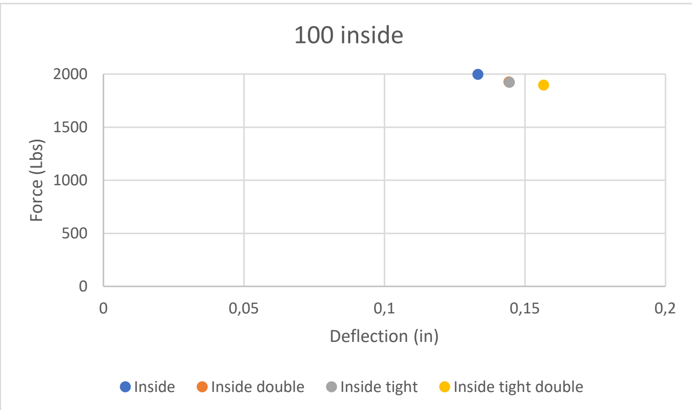
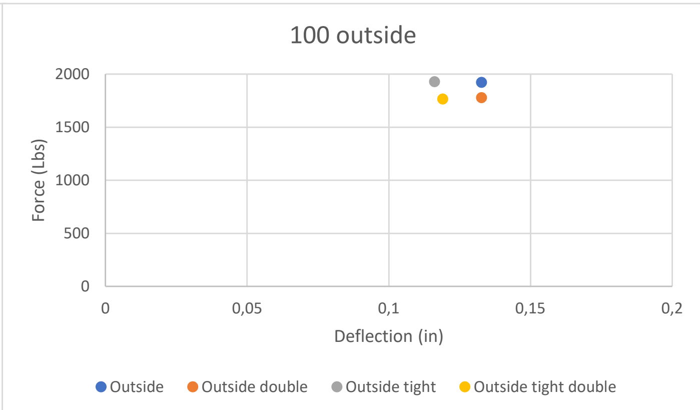
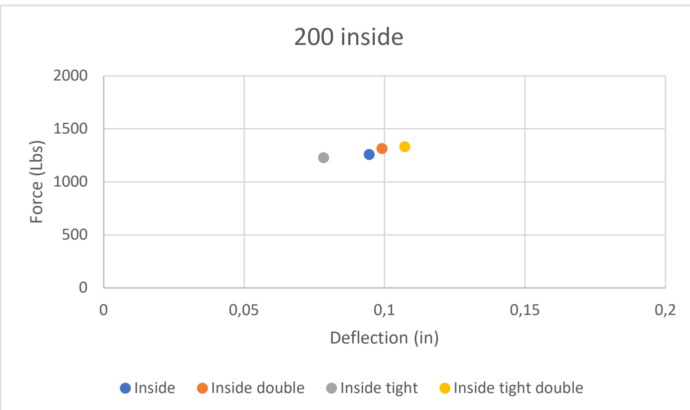
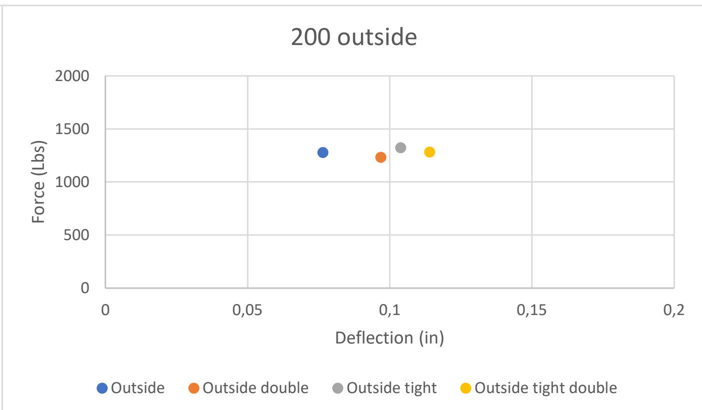


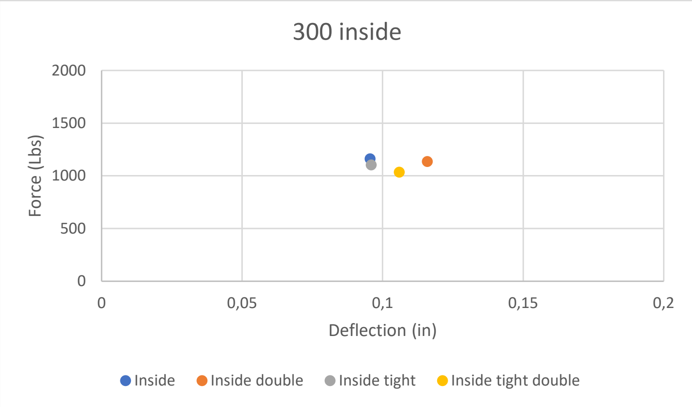
Figure 83 | All results for height of 300 mm in one graph

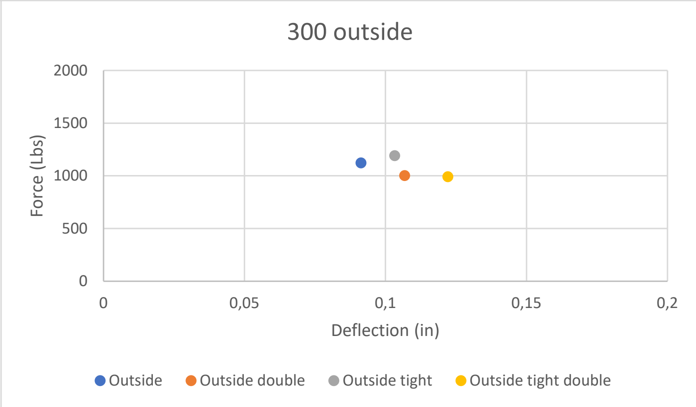


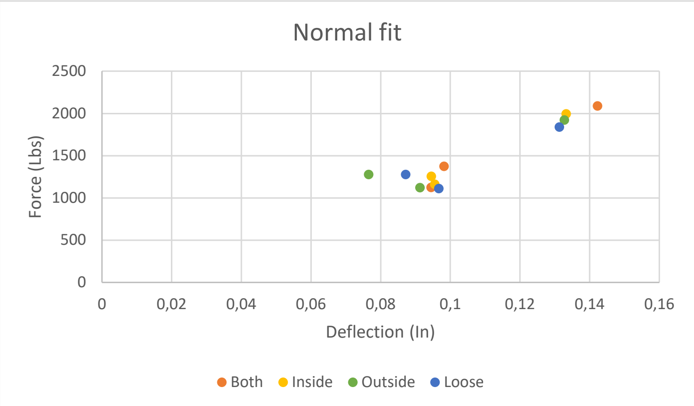


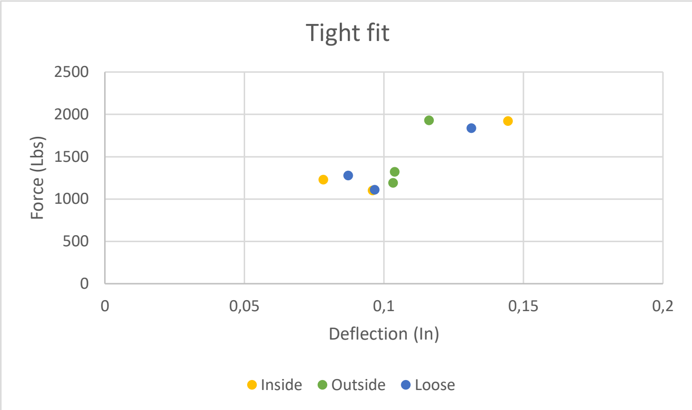


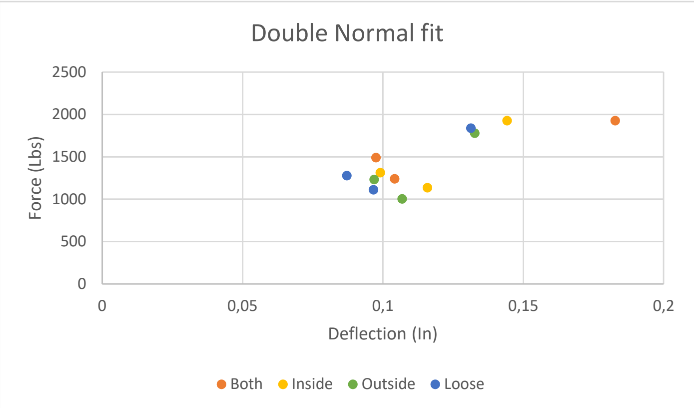


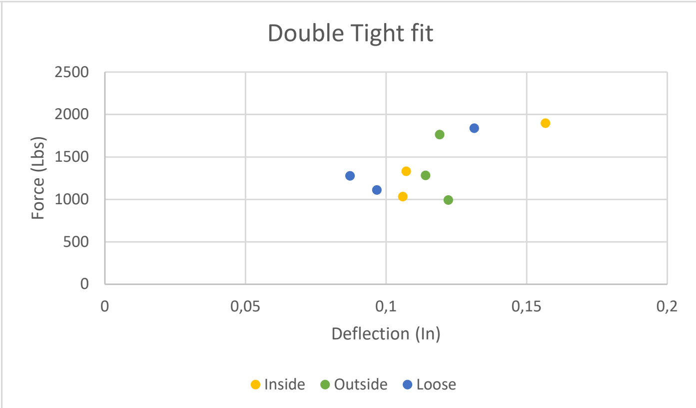

300 inside
Force (Lbs)
Deflection (in)
Inside
Inside double
Inside tight
Inside tight double

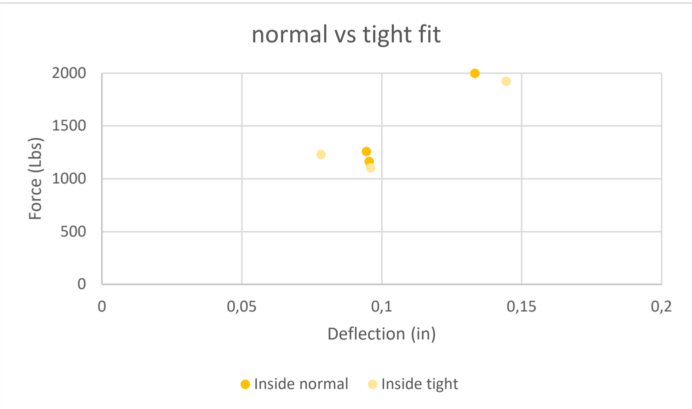

300 outside
Force (Lbs)
Deflection (in)
Outside
Outside double
Outside tight
Outside tight double

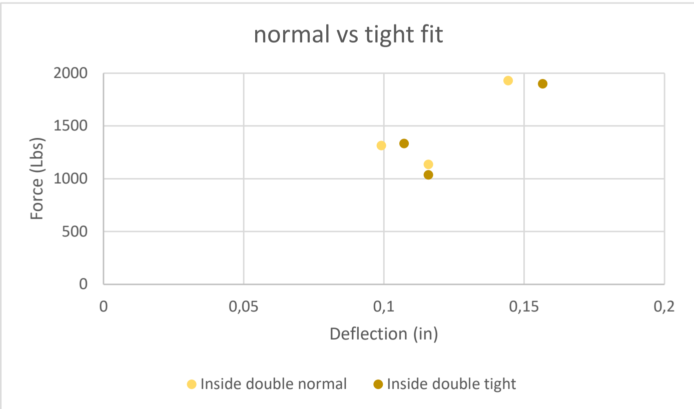

Normal fit
Force (Lbs)
Deflection (In)
Both
Inside
Outside
Loose

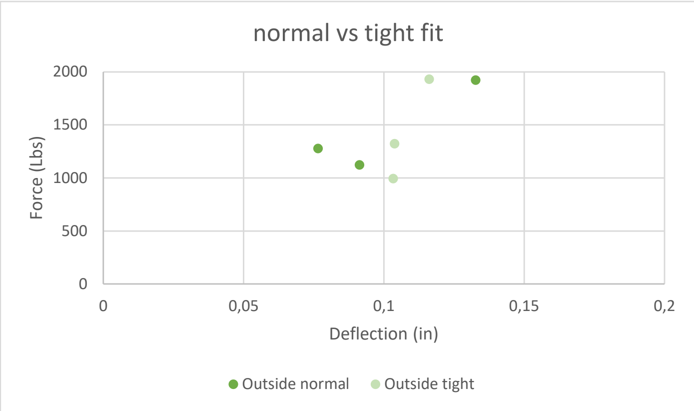

Tight fit
Force (Lbs)
Deflection (In)
Inside
Outside
Loose

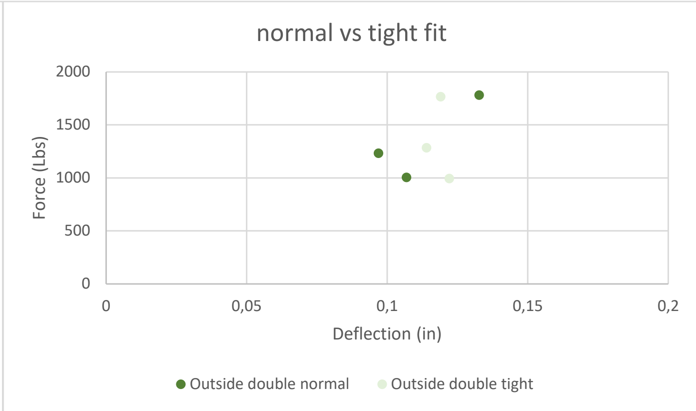

Double Normal fit
Force (Lbs)
Deflection (In)
Both
Inside
Outside
Loose

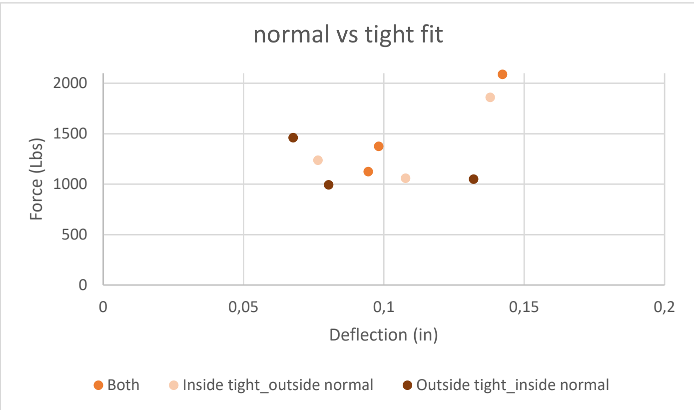

Double Tight fit
Force (Lbs)
Deflection (In)
Inside
Outside
Loose

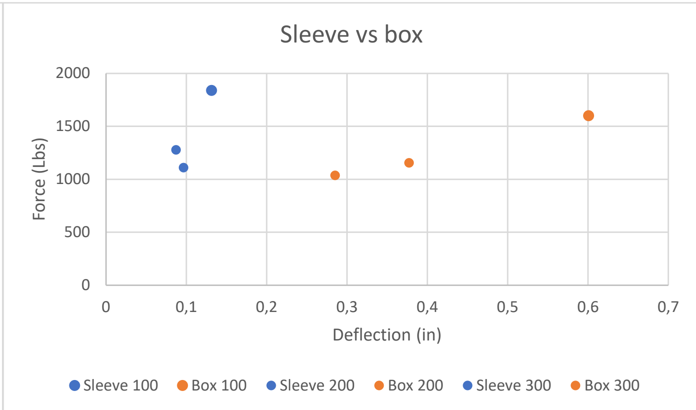

normal vs tight fit
Force (Lbs)
Deflection (in)
Inside normal
Inside tight

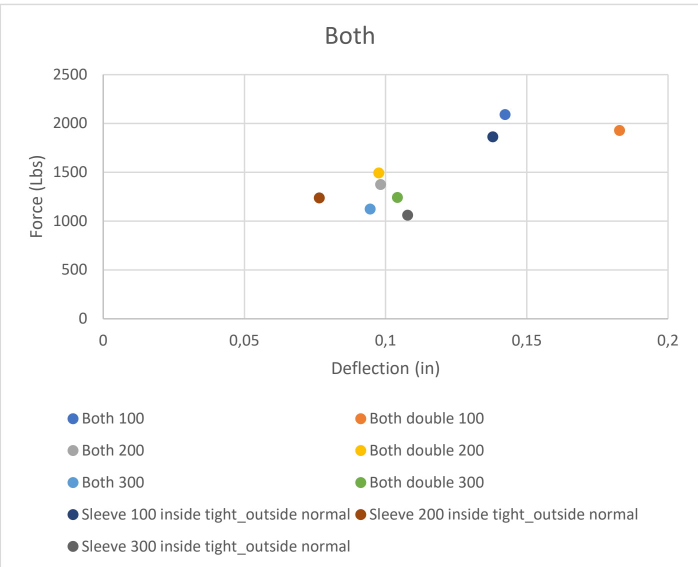

normal vs tight fit
Force (Lbs)
Deflection (in)
Inside double normal
Inside double tight











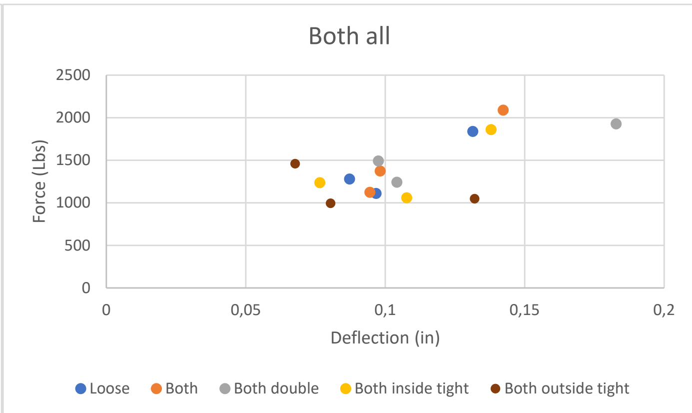
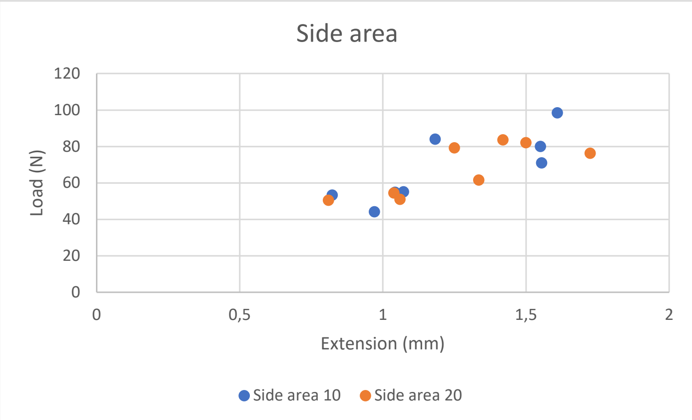
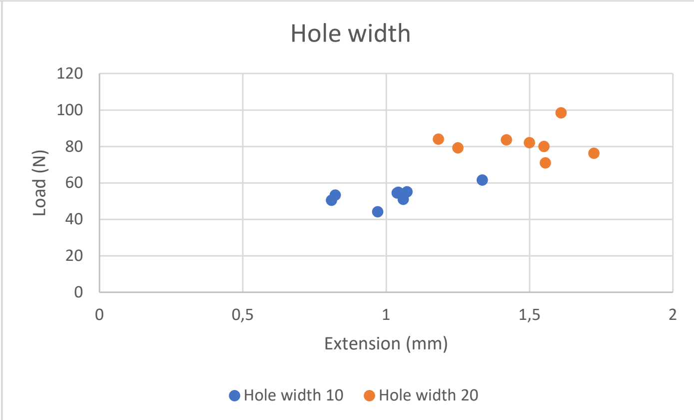


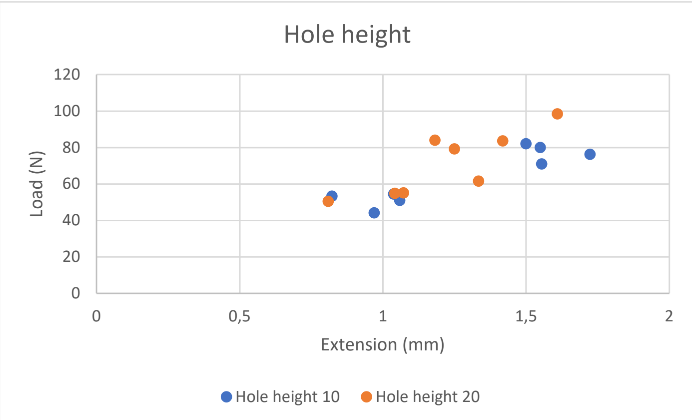
Figure 84 | All plotted graphs compression test

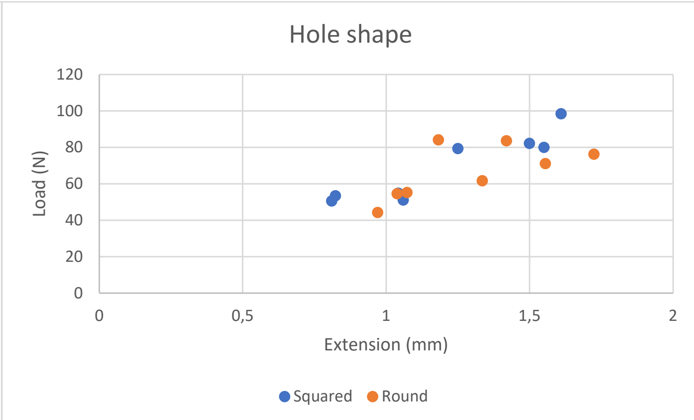
C. Tensile test

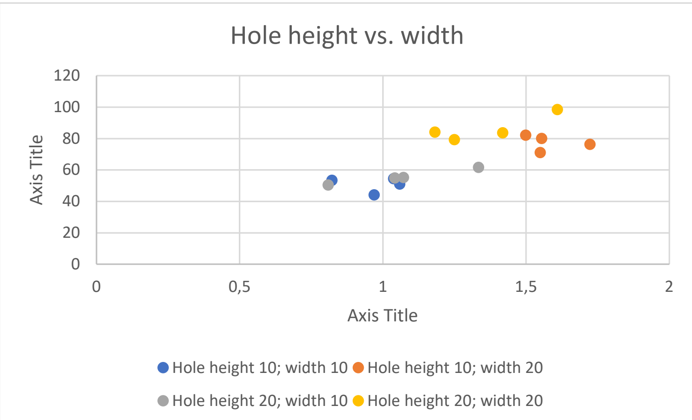
C.1 Results

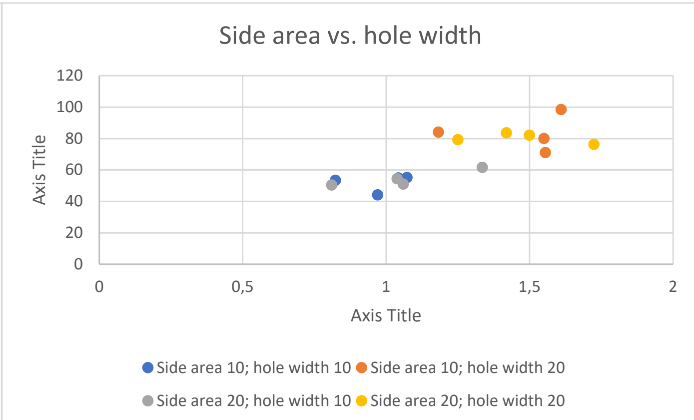












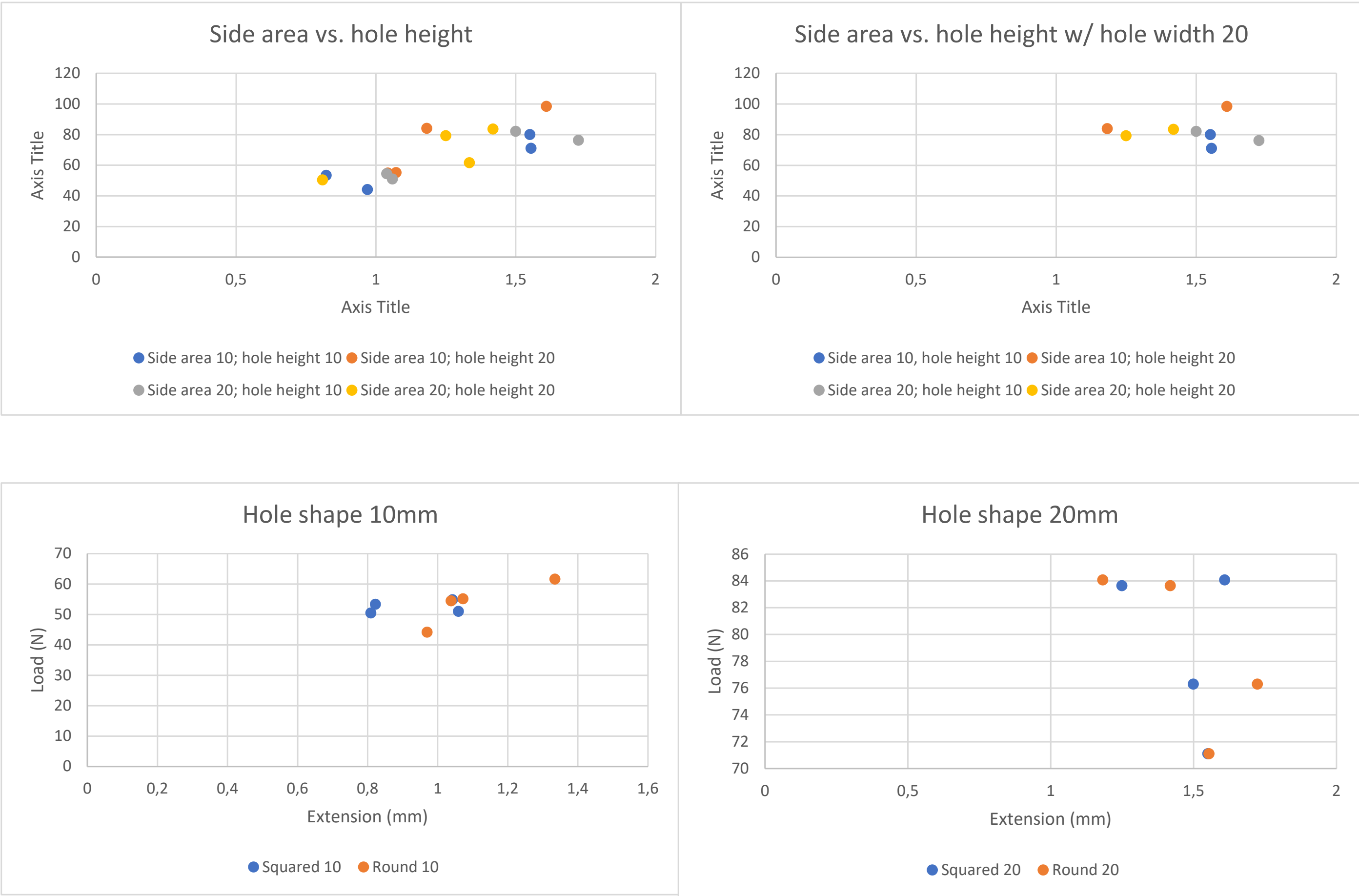


Figure 85 | All plotted graphs tensile test

D. Life Cycle Analysis

D.1 Gabi processes

Hybrid

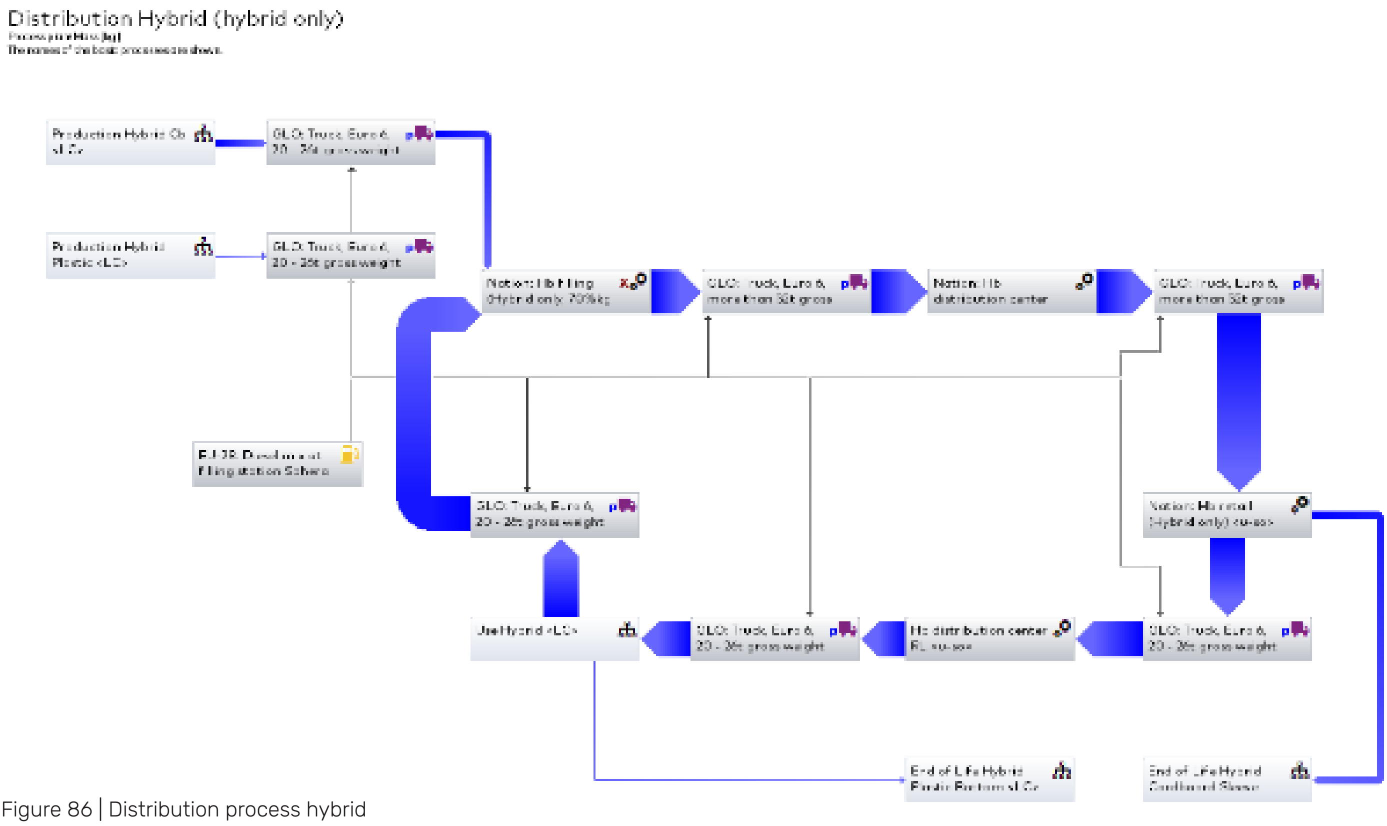


Figure 86 | Distribution process hybrid

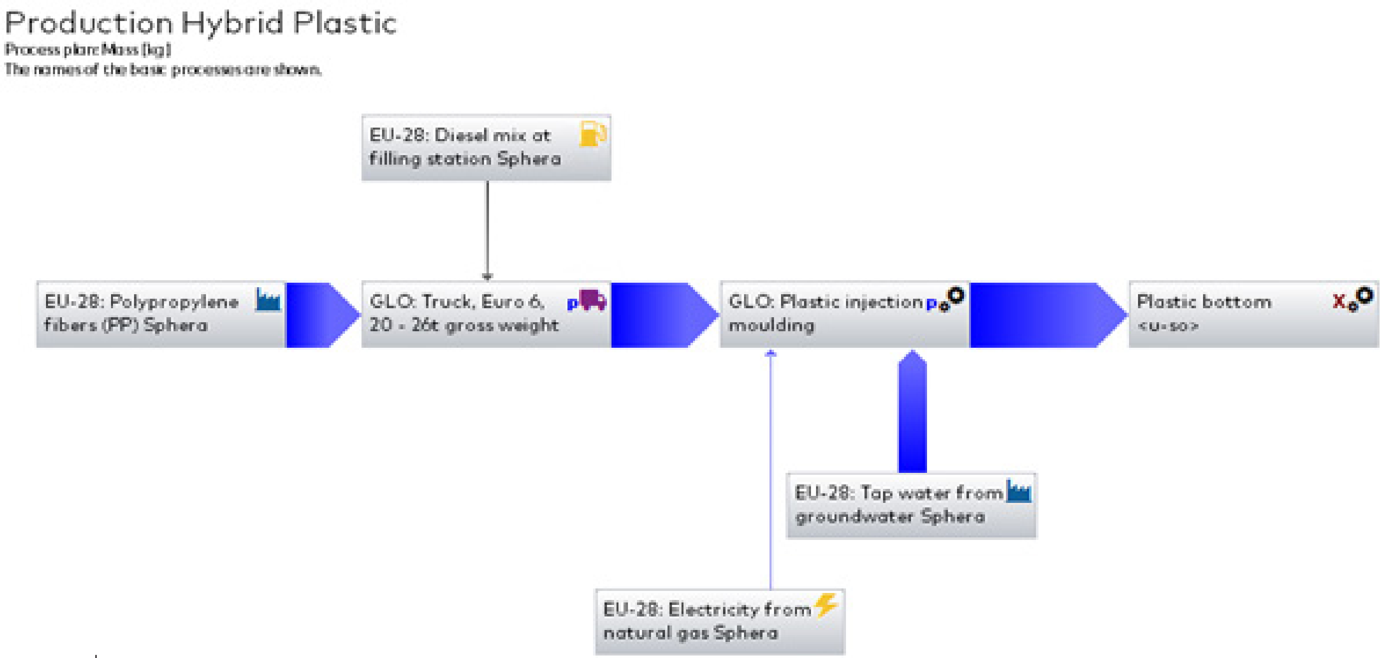


Figure 87 | Production process hybrid plastic part

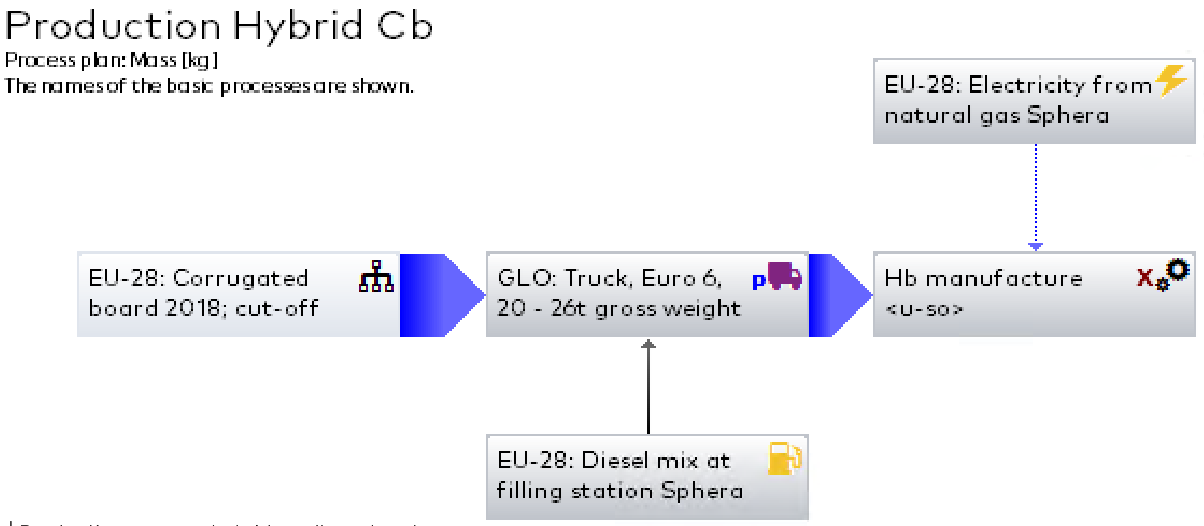


Figure 88 | Production process hybrid cardboard part

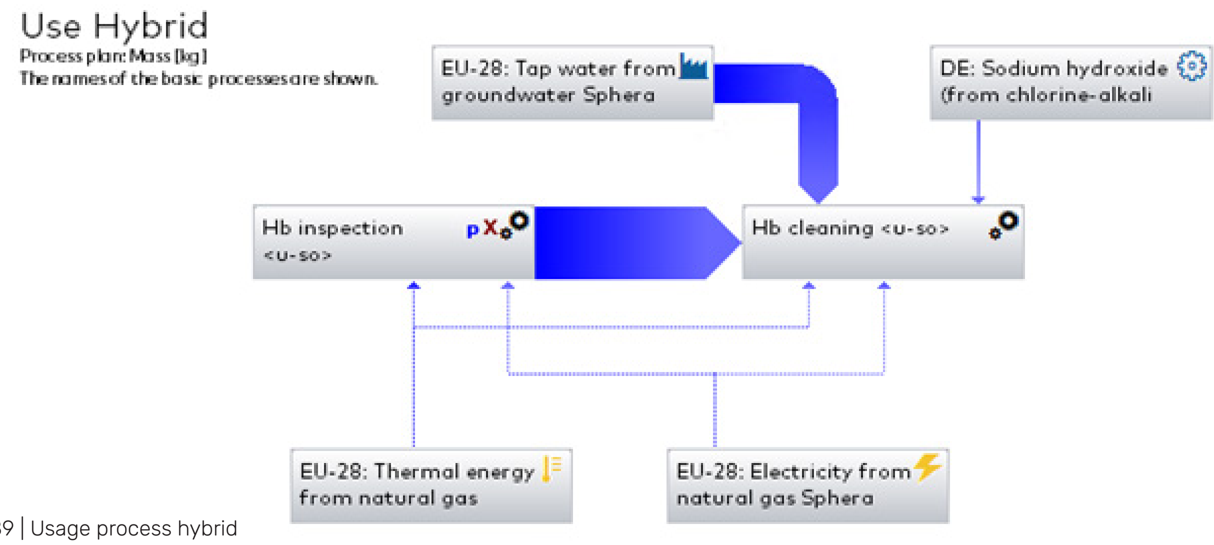


Figure 89 | Usage process hybrid

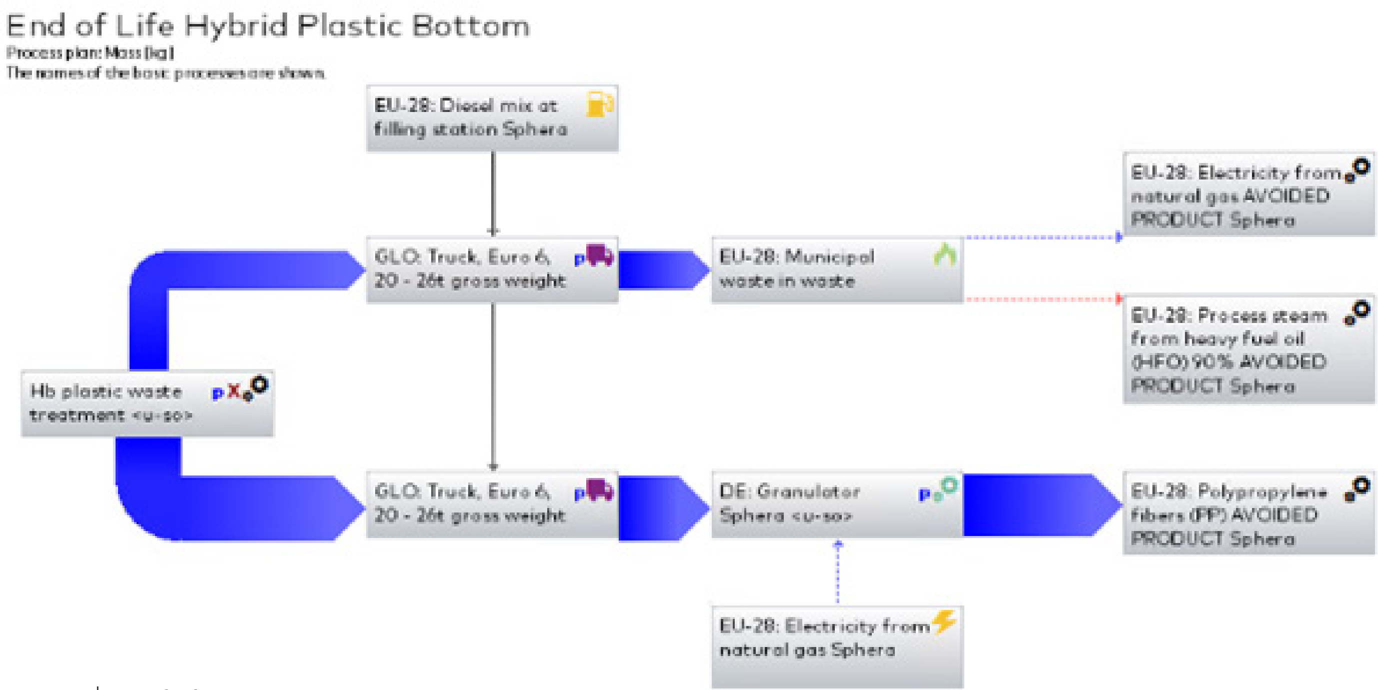


Figure 90 | End of Life process hybrid plastic part

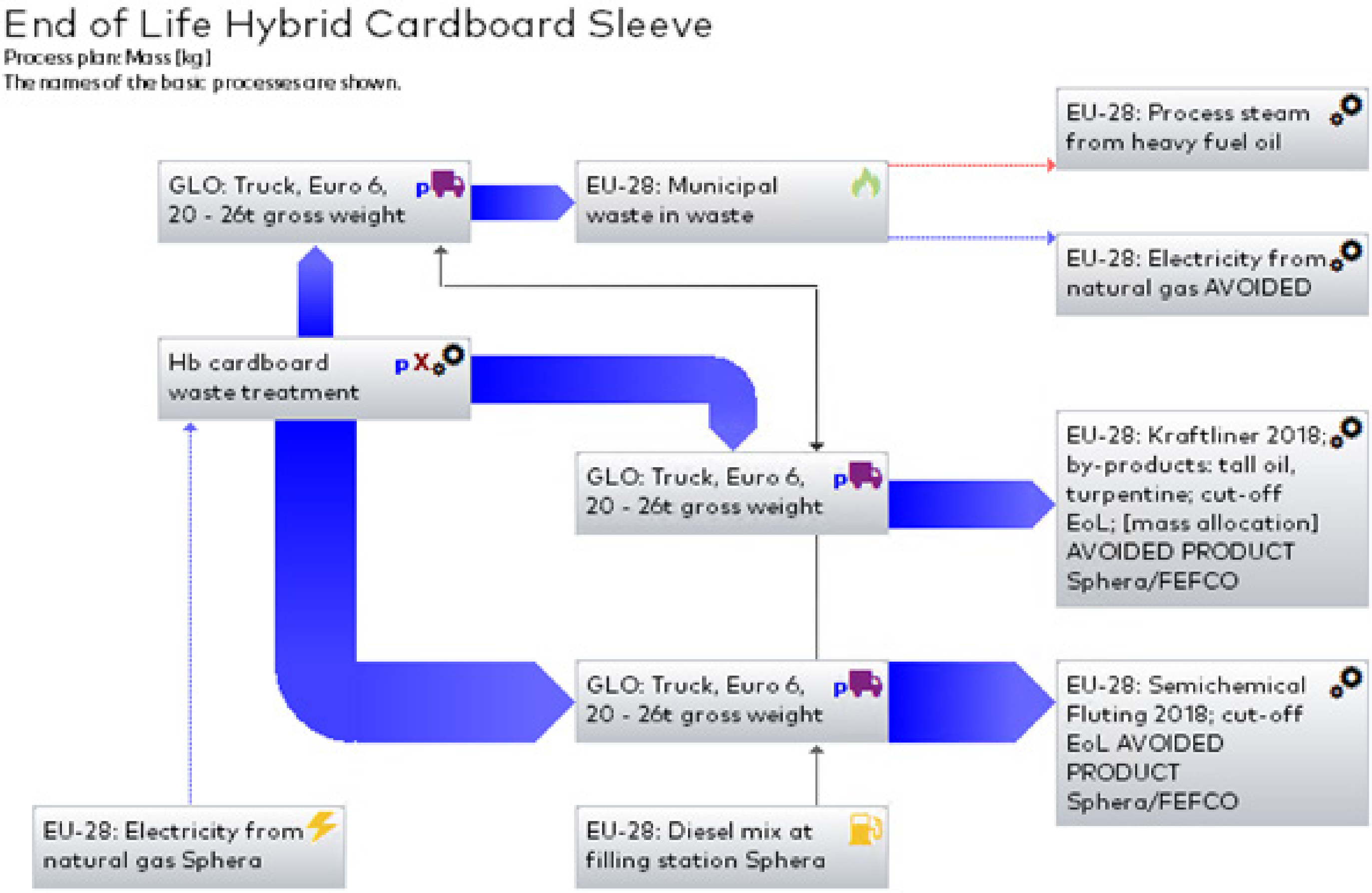


Figure 91 | End of Life process hybrid cardboard part

RPC

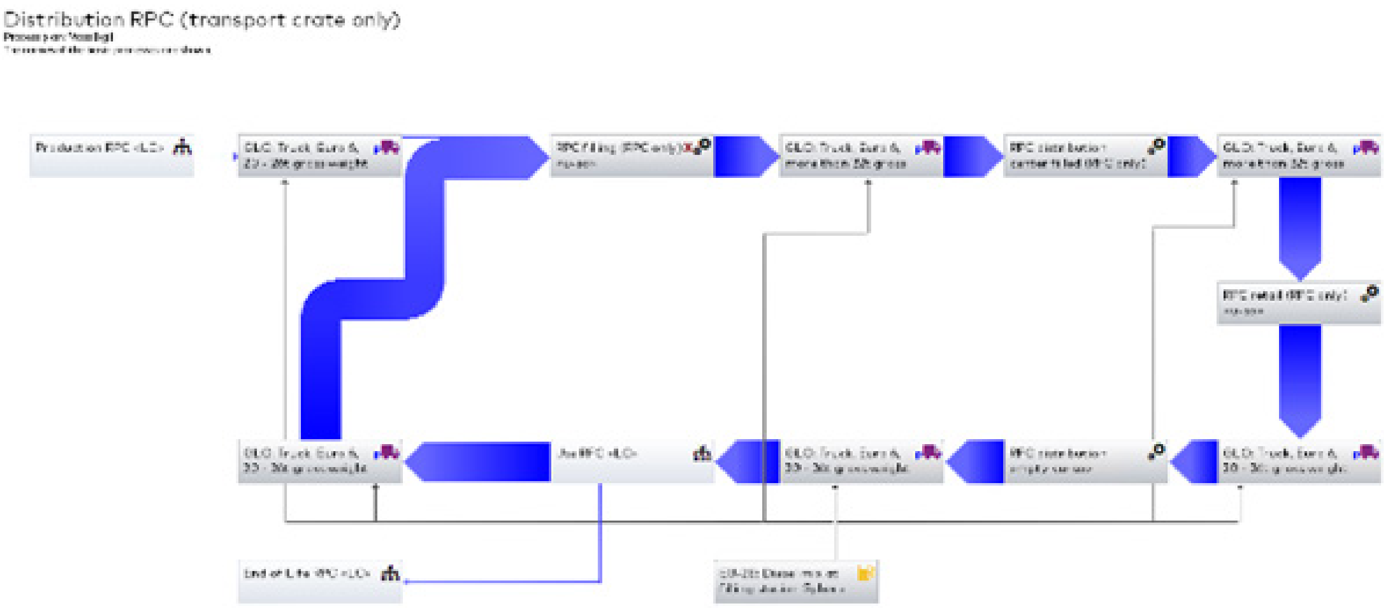


Figure 92 | Distribution process RPC

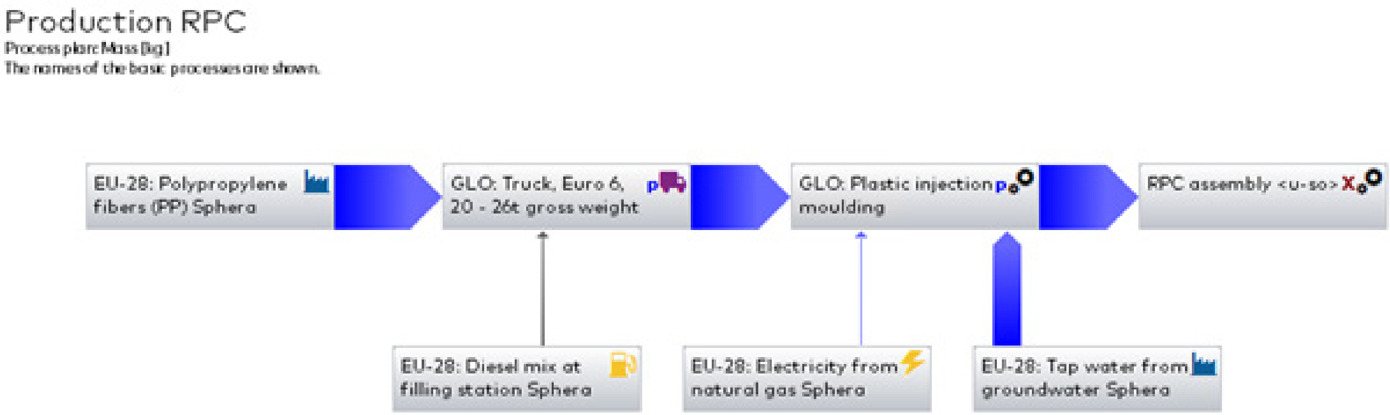


Figure 93 | Production process RPC

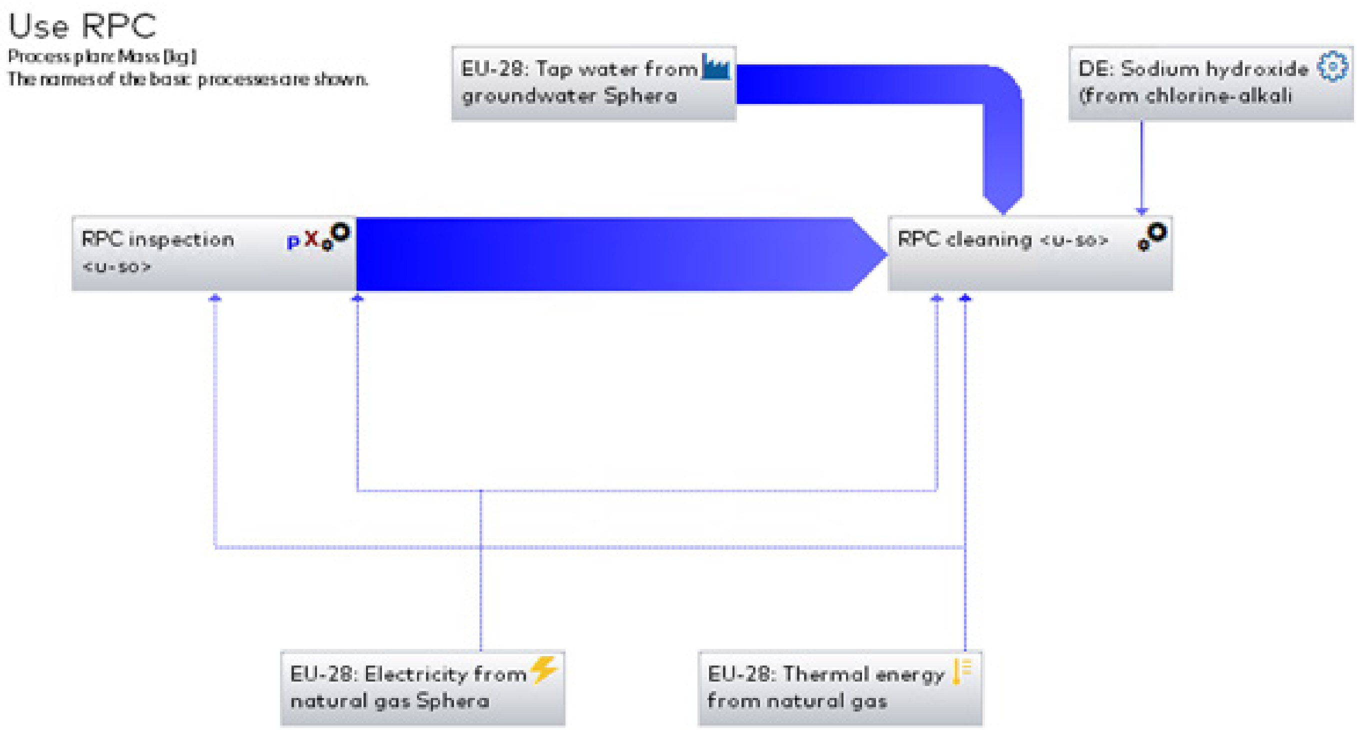


Figure 94 | Usage process RPC

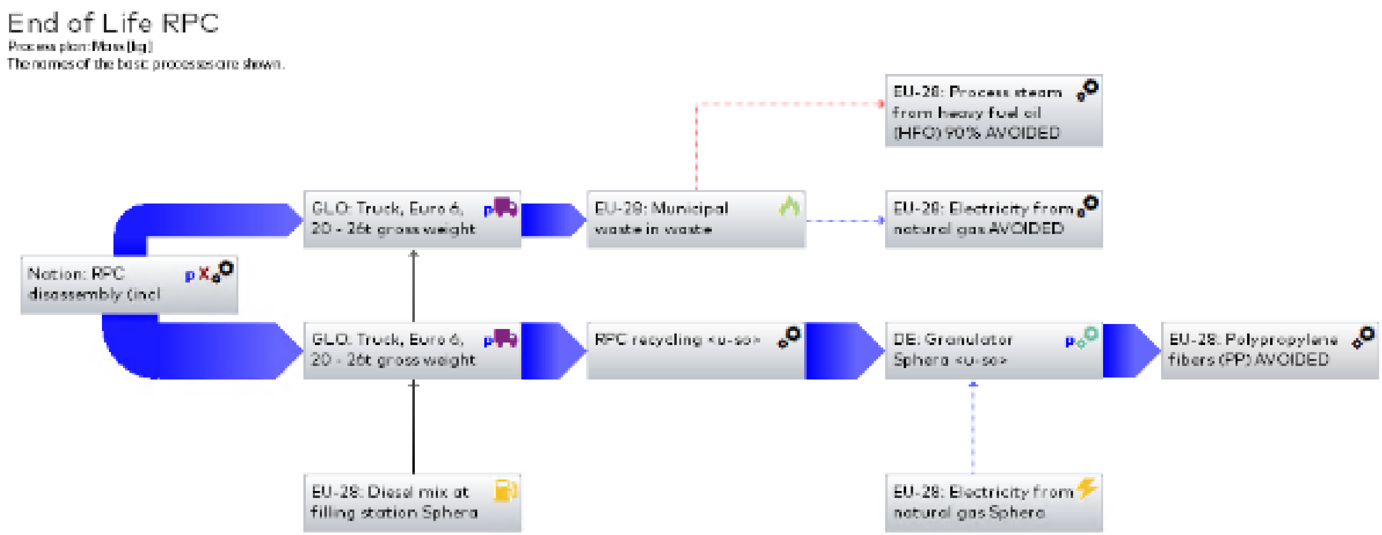


Figure 95 | End of Life process RPC

CB

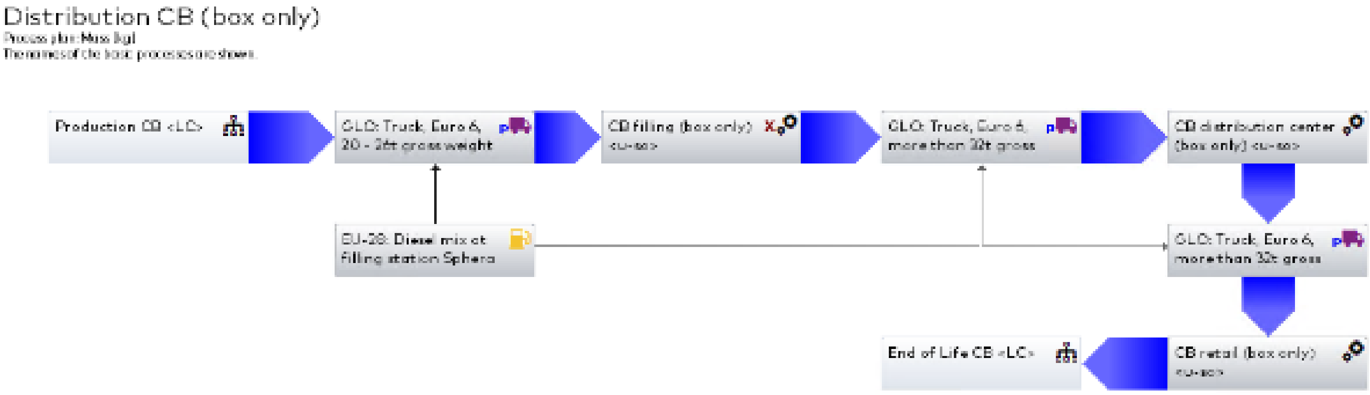


Figure 96 | Distribution process CB

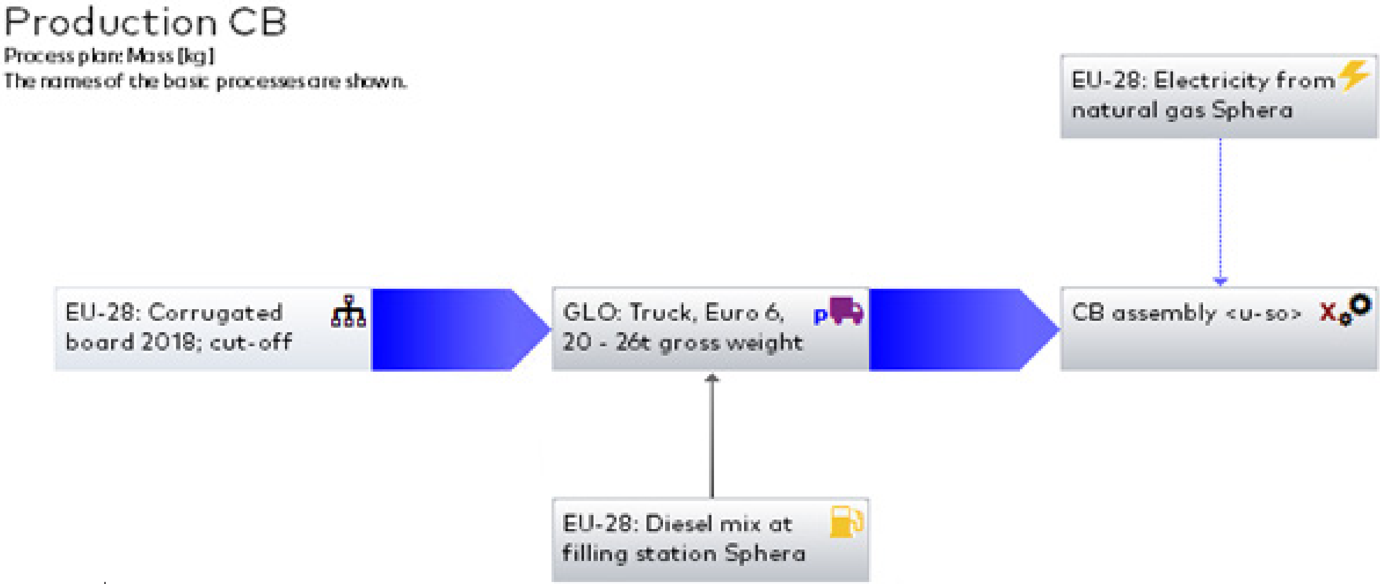


Figure 97 | Production process CB

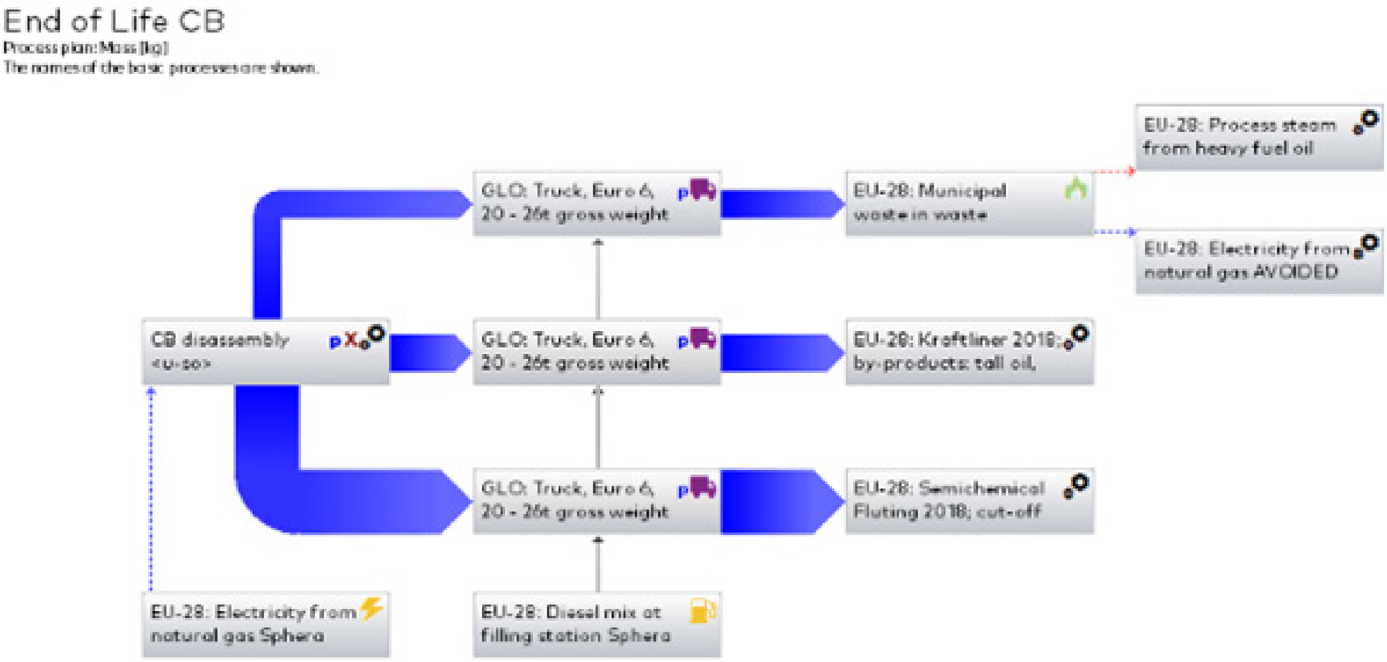


Figure 98 | End of Life process CB

D.2 Input data processes Gabi SIM case

Functional unit (FU)				
The distribution of 1000 t of fruit or vegetables in reusable plastic containers (RPC or single-use cardboard boxes (CB)				
To fulfill functional unit, containers must be filled 66,667 times, assuming a given load capacity of 15 kg per container				
66666,66667				
Functional unit (FU)				
	RPC	**CB**	**Hybrid**	
Functional unit (t)	1000			
Containers needed for FU	66667			
Average rotations RPC life	50	1	""	
Rotations per year	5		""	
RPC service life (year)	10		""	
Average breakage rate	0,53%		""	
RPC demand FU	1333		""	
RPC breakage	353		""	
Total container demand fulfilling FU	1687	66667	""	
Total weight	3070	52000	17630	
Technical properties of reference containers				
	RPC	**CB**	**Hybrid**	
Material	PP	Cardboard	PP & Cardboard	
Type of use	Reusable system	Single-use system	Both systems	
Rotations	50	1	""	
Average breakage rate	0,53%	-	""	
End of life	Energy recovery, material recovery		""	
Weight container (kg)	1,82	0,78	1,16	
Weight plastic part part (kg)			0,91	
Weight cardboard part (kg)			0,25	
Dimensions container(mm)	600x400x210		""	
Dimenssions folded	600x400x29	1000x210x8	600x400x25	
Filling load (kg)	15		""	
Transport loads				
Containers per layer per pallet	4		""	
Height on a pallet (mm)	2200			
Layers per pallet assembled	10		""	
Containers per pallet	40		""	
Pallets per truck (27 t capacity)	33		""	
Weight of pallet (kg)	12		""	
Containers filled per truck	1320		""	
Weight filled per truck (kg)	2402	1030	1531	
RPC folded layers per pallet	76	-	88	
RPC folded per pallet	304	-	352	
Pallets per truck (17,3 t capacity)	18		""	
RPC folded per truck (17.3t capacity)	5472	-	6336	
Weight RPC folded per truck (kg)	9959	-	5982	
CB assembled per truck (17.3 t capacity)	-	720	-	
Weight CB assembled per truck (kg)	-	562	-	
CbS per layer per pallet			4	
Layers per pallet CbS			275	
CbS folded per pallet			1100	
CbS folded per truck (17.3 t capacity)			19800	
Weight CbS truck (kg)	-		4950	
Transport distances			**Plastic part**	**Cadboard sleeve**
Production plant to (km)	100	100		
Food producers (fp) to (km)	921	50	*Take same numbers*	*Take same numbers*
Distribution center to (km)	406	406	""	""
Retail to (km)	50	50	""	""
Distribution center to (km)	50		""	""
Service center to (km)	223		""	""
Food producers to fp (km)	409		""	""
Material recovery (km)	867	150	""	""
Energy recovery (km)	50	50	""	""
Transport weights full truck				
Raw material to				
Production plant to (kg)	17300		17300	
Food producers (fp) to (kg)	9959	561,6	5982	4950
Distribution center to (kg)	2402	1030	1531	
Retail to (kg)	2402	1030	1531	
406	9959		5982	
Service center to (kg)	9959		5982	
Food producers to (kg)	9959		5982	
Material recovery (kg)	15570	15570	""	""
Energy recovery (kg)	15570	15570	""	""

Figure 99 | Input data SIM case, part 1

Gabi processes		
Transport		
GLO: Euro 6. Lorry truck < 27 t payload		
GLO: Euro 6. Lorry truck < 17,3 t payload		
EU-28: Diesel mix at filling station		
Production processes & materials		
Polypropyleen		
GLO: plastic injection molding		
Weight plastic part	1	
material usage	weight+waste	
waste	0,02*weight	
CW (water usage)	88,2*material*0,006	
power	6,305*weight+0,3372	
EU-28: Electricity from natural gas		
EU-28: Thermal energy from natural gas		
EU-28: Tap water from groundwater		
EU-28: Corrugated board 2018 (kg)	1	
EU-28: Kraftliner (kg)	0,4	
EU-28: Semichemical fluting (kg)	0,7	
Paper for corrugated board (kg)	1,1	
CB punching electricity usage (MJ)	0,0012	
Machine electricity usage per year (kWh)	499,2	
Boxes cut per minute	12	
Boxes cut per year	1497600	
CB assembly electricity usage (MJ)	0,0012	
Use RPC		
Inspection energy usage (MJ)	0,13	
Inspection thermal energy usage (MJ)	0,065	
Cleaning water usage (L)	0,97	
Detergent (L)	0,003	
DE: Sodium hydroxide (from chlorine-alkali electrolysis, diaphragm)		
RPC damage	0,53%	
RPC lifetime (cycles)	50	
End of life RPC		
Waste incineration	54,00%	
Primary material recycling	20%	
Secondary material recycling quality	50,00%	
Secondary recycling rate	52%	
Secondary material recycled	26,00%	
Recycled material incl quality loss	46%	
EU-28: Polypropylene in waste incineration plant		
Output: EU-28: electricity from natural gas AVOIDED PRODUCT		
Output: EU-28: Process steam from heavy fuel oil AVOIDED PRODUCT		
EU-28: PP fibers AVOIDED PRODUCT		
EU-28: Electricity from natural gas		
End of life CB		
Primary material recycling kraftliner	24,49%	
Primary material recycling semi chemical	8,65%	
Percentage of quality loss & energy recov	15%	85,1%
Recycling rate at retail	88%	
Secondary recycling kraftliner	63,41%	9,46%
Secondary recycling semi chemical flutin	79,25%	11,83%
Percentage waste incineration of quality loss		21,29%
Percentage total recycling kraftliner	78,44%	78,44%
Percentage total recycling semi chemical	76,07%	73,37%
	aantal	factor
cb (kg)	0,78	
kraft	0,283636364	0,363636364
smf	0,496363636	0,636363636
CHECK	0,78	1
kraft primary recycling	0,069462545	24,49%
smf primary recycling	0,042935455	8,65%
kraft secondary recycling	0,153009965	53,95%
smf secondary recycling	0,334656513	67,42%
Recycling rate at retail		88%
Percentage of quality loss		85,1%
Total recyclend content	0,600064478	
Inineration	0,179935522	
EU-28: Electricity from natural gas	0,00432	

Figure 100 | Input data SIM case, part 2

D.3 Input data processes Gabi FEFCO case

Functional unit (FU)				
The distribution of 1000 t of fruit or vegetables in reusable plastic containers (RPC or single-use cardboard boxes (CB)				
To fulfill functional unit, containers must be filled 66,667 times, assuming a given load capacity of 15 kg per container				
95238,09524	95,23809524			
Functional unit (FU)				
	RPC	**CB**	**Hybrid**	
Functional unit (t)		1000		
Containers needed for FU		95238		
Average rotations RPC life	24	1	""	
Rotations per year	5		""	
RPC service life (year)	5		""	
Average breakage rate	2,5%		""	
RPC demand FU	3968		""	
RPC breakage	2381		""	
Total container demand fulfilling FU	6349	95238	""	
Total weight	11556	73333	32089	
Technical properties of reference containers				
	RPC	**CB**	**Hybrid**	
Material	PP	Cardboard	PP & Cardboard	
Type of use	Reusable system	Single-use system	Both systems	
Rotations	50	1	""	
Average breakage rate	0,53%	-	""	
End of life	Energy recovery, material recovery		""	
Weight container (kg)	1,82	0,77	1,16	
Weight plastic part part (kg)			0,91	
Weight cardboard part (kg)			0,25	
Dimensions container(mm)	600x400x210		""	
Dimenssions folded RPC	600x400x29	1000x210x8	600x400x25	
Filling load (kg)	10,5		""	
Transport loads				
Containers per layer per pallet	4		""	
Height on a pallet (mm)	2200			
Layers per pallet assembled	10		""	
Containers per pallet	40		""	
Pallets per truck (27 t capacity)	33		""	
Weight of pallet (kg)	12		""	
Containers filled per truck	1320		""	
Weight filled per truck (kg)	16658	15272	15787	
RPC folded layers per pallet	76	-	88	
RPC folded per pallet	304	-	352	
Pallets per truck (17,3 t capacity)	18		""	
RPC folded per truck (17.3 t capacity)	5472	-	6336	
Weight RPC folded per truck (kg)	10175	-	5982	
CB assembled per truck (17.3 t capacity)	-	720	-	
Weight CB assembled per truck (kg)	-	554	-	
CbS per layer per pallet			4	
Layers per pallet CbS			275	
CbS folded per pallet			1100	
CbS folded per truck (17.3 t capacity)			19800	
Weight CbS truck (kg)	-		4950	
Transport distances			**Plastic part**	**Cadboard sleeve**
Production plant to (km)				
Food producers (fp) to (km)	370	55	*Take same numbers*	*Take same numbers*
Distribution center to (km)	840	840	""	""
Retail to (km)	50	50	""	""
Distribution center to (km)	50		""	""
Service center to (km)	165		""	""
Food producers to fp (km)	380		""	""
Material recovery (km)	840	150	""	""
Energy recovery (km)	50	50	""	""
Transport weights full truck				
Raw material to				
Production plant to (kg)	17300		17300	
Food producers (fp) to (kg)	10175	554,4	5982	4950
Distribution center to (kg)	16658	15272	15787	
Retail to (kg)	16658	15272	15787	
Distribution center to (kg)	10175		5982	
Service center to (kg)	10175		5982	
Food producers to (kg)	10175		5982	
Material recovery (kg)	15570	15570	""	""
Energy recovery (kg)	15570	15570	""	""

Figure 101 | Input data FEFCO case, part 1

Gabi processes		
Transport		
GLO: Euro 6. Lorry truck < 27 t payload		
GLO: Euro 6. Lorry truck < 17,3 t payload		
EU-28: Diesel mix at filling station		
Production processes & materials		
Polypropyleen		
GLO: plastic injection molding		
Weight plastic part	1	
material usage	weight+waste	
waste	0,02*weight	
CW (water usage)	88,2*material*0,006	
power	6,305*weight+0,3372	
EU-28: Electricity from natural gas		
EU-28: Thermal energy from natural gas		
EU-28: Tap water from groundwater		
EU-28: Corrugated board 2018 (kg)	1	
EU-28: Kraftliner (kg)	0,4	
EU-28: Semichemical fluting (kg)	0,7	
Paper for corrugated board (kg)	1,1	
CB punching electricity usage (MJ)	0,0012	
Machine electricity usage per year (kWh)	499,2	
Boxes cut per minute	12	
Boxes cut per year	1497600	
CB assembly electricity usage (MJ)	0,0012	
Use RPC		
Inspection energy usage (MJ)	0,13464	
Inspection thermal energy usage (MJ)	0	
Cleaning water usage (L)	0,3011	
Detergent (L)	0,0044	
DE: Sodium hydroxide (from chlorine-alkali electrolysis, diaphragm)		
RPC damage	0,53%	
RPC life time (cycles)	50	
End of life RPC		
Waste incineration	58,20%	
Primary material recycling	20%	
Secondary material recycling quality	80,00%	
Secondary material recycled	21,80%	
Recycled material total	41,8%	
EU-28: Polypropylene in waste incineration plant		
Output: EU-28: electricity from natural gas AVOIDED PRODUCT		
Output: EU-28: Process steam from heavy fuel oil AVOIDED PRODUCT		
EU-28: PP fibers AVOIDED PRODUCT		
EU-28: Electricity from natural gas		
End of life CB		
Primary material recycling kraftliner	24,49%	
Primary material recycling semi chemical fluting	8,65%	
Percentage of quality loss & energy recovery	15%	82,9%
Recycling rate at retail	88%	
Secondary recycling kraftliner	63,41%	9,46%
Secondary recycling semi chemical fluting	79,25%	11,83%
Percentage waste incineration of quality loss		21,29%
Percentage total recycling kraftliner	78,44%	77,06%
Percentage total recycling semi chemical fluting	76,07%	71,71%
	aantal	factor
cb (kg)	0,78	
kraft	0,283636364	0,363636364
smf	0,496363636	0,636363636
CHECK	0,78	1
kraft primary recycling	0,069462545	24,49%
smf primary recycling	0,042935455	8,65%
kraft secondary recycling	0,149098815	52,57%
smf secondary recycling	0,326102223	65,70%
Recycling rate at retail		88%
Percentage of quality loss		82,9%
Total recyclend content	0,587599038	
Inineration	0,192400962	
EU-28: Electricity from natural gas	0,00432	

Figure 102 | Input data FEFCO case, part 2

E. Cost estimation

E.1 All input data and calculations

What?	*Price per crate*	*Price per box*	*Price per hybrid*	*Explenation*
Production costs				
Cardboard		€ 0,75	€ 0,46	
Injection moulded plastic part	€ 0,10		€ 0,03	
Transport costs				
Transport costs empty box/crate	€ 0,30	€ 0,18	€ 0,39	*The hybrid has higher transport costs because the parts have to be transported seperately to the farm and at its end of life to the recycling or incineration plants*
Transport costs filled box/crate (15kg)	€ 1,49	€ 1,49	€ 1,49	*All boxes are the same size (for now) and all above a certain weight that the prize estimation turns out to be the same*
Filling boxes in field				
Assembly time	€ 0,04	€ 0,04	€ 0,05	
Filling with fresh produce	-	-	-	*Same for all boxes/crates so not taken into consideration*
Cleaning	€ 0,05		€ 0,04	Heeft nog geen volledige onderbouwing.... Hybrid minder want kleiner oppervlakte schoon te maken
Storage	€ 0,05		€ 0,03	Heeft nog geen onderbouwing.... Hybrid minder want kunnen meer hybrids opgestapeld worden op 1 pallet
Waste				
TOTAL	€ 2,03	€ 2,45	€ 2,50	

Figure 103 | Total costs calculation

What?	*Value*	*Unit*	*Explenation*
Costs cleaning machine	10000	€	*https://www.alibaba.com/showroom/plastic-crate-cleaning-machine.html*
Amount of crates	400	crates/hour	
Life time machine	10	years	
Days of working machine	260	days/year	
Hours of working machine	8	hours/day	
Crates cleaned with 1 mach	8320000	crates	
Cost cleaning machine per (	0,001202	€	
Costs water			
Costs detergents			
Costs energy			
Costs company employees	€ 0,04		15/h
Costs company building?			

Figure 104 | Cleaning process costs calculation

What?	*Value*	*Unit*	*Explenation*	
Costs worker in field at farm				
	18	€/h		
	0,30	€/min		
Assembly 1 crate	7	sec		
Crates assembled per min	8,571429	crates		
Assembly costs per crate	0,035	€		
Assembly 1 box	7	sec		
Boxes assembled per min	8,571429	crates		
Assembly costs per box	0,035	€		
Assembly 1 hybrid box	10	sec		
Hybrid boxes assembled per min	6	crates		
Assembly costs per hybrid box	0,05	€		

Figure 105 | Assembly in field costs calculation

Materiaalkosten karton (Roland)				
C-flute=	€ 0,72	/m2		
Snijd en lijm kosten schatting				*https://www.packagingdiscounter.nl/products/kartonnen-doos-300x200x200mm-4mm-c-golf-bruin-1-2-dagen-levertijd*
Inkoopkoste	€ 0,39			*(kleinere doos, maar veel stuks = 39 cent)*
Surface (m2)	0,318	300*200*200		
Materiaalkos	€ 0,23			
Snijd en lijm	€ 0,16			
Box	Surface (n	*Toelichting*		
FEFCO 200	0,824	*Oppervlakte uitsnijden doos (600*400*200)*		
Price	€ 0,59			
Total	€ 0,75			
Sleeve				
FEFCO 501	0,412	*Oppervlakte uitsnijden sleeve (600*400*200)*		
Price	€ 0,30			
Total	€ 0,46			

Figure 106 | Cardboard parts costs calculation

Crate	Costs mould:	Per part:	Material c	Labor costs (/part):		Krat heeft ... cyclussen	
Bottom:	€ 20.000,00	€ 0,20	€ 0,50	€ 1,00		50	
Long side:	€ 14.000,00	€ 0,28	€ 0,50	€ 1,00			
Short side:	€ 12.000,00	€ 0,24	€ 0,50	€ 1,00			
Total:		€ 0,72	€ 1,50	€ 3,00	€ 5,22	€ 0,10	
Hybrid bottom	Costs mould:	Per part:	Material c	Labor costs (/part):		Krat heeft ... cyclussen	
Bottom:	€ 20.000,00	€ 0,20	€ 0,50	€ 1,00		50	
Total:		€ 0,20	€ 0,50	€ 1,00	€ 1,70	€ 0,03	

Figure 107 | Plastic parts costs calculation

What?	*Value*	*Unit*	*Explenation*					
Cardboard box values								
C-flute	0,56	kg/m2						
Surface box	0,93	m2	*FEFCO 200 (600*400*200)*				0,824	
Weight box	0,5208	kg		1,39	0,78		0,44	0,25
Pallet values								
Surface pallet	0,96	m2	*1200*800*					
Height of pallet	1,8	m						
Number of pallets in truck	33	pallets						
Weight of pallet	25	kg						
Transport distances								
Transport cardboard plant -> farm (empty)	1000	km						
Transport plastic plant -> farm (empty)	1000	km						
Transport pooler -> farm (empty)	1000	km						
Transport farm -> grocery store (filled)	1000	km						
Transport grocery store -> pooler (empty)	1000	km						
Transport grocery store -> recycler (empty)	1000	km						
Weight of content in box	15	kg						
Transport empty boxes price calculation								
Surface folded box	0,3	m2	*(600+400)*300*					
Height folded box	0,01	m						
Rows of boxes on pallet	3	rows	*3,2*	*3 rijen dozen naast elkaar kan met 10 cm overhang (*				
Number of stacked folded boxes on pallet	540	boxes						
Number of folded boxes in truck	17820	boxes						
Weight of box material per pallet	281,232	kg						
Total weight in truck	**10105,66**	kg	*Rounded up 7 ton*					
Lichte vrachtwagen < 12 ton	1,56	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*					
Price of transport per folded box to farm	0,087542	€						
Price of transport per folded box to recycler	0,087542	€						
Total transport price folded box	0,175084	€						
Transport filled boxes price calculation								
Surface filled box	0,24	m2	*(600*400)*					
Height filled box	0,2	m						
Number of boxes in 1 layer on pallet	4	boxes						
Number of stacked filled boxes on pallet	36	boxes						
Number of filled boxes in truck	1188	boxes						
Total weight in truck	**19263,71**	kg						
Vrachtwagen, 16 ton en meer	1,77	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*					
Price of transport to grocery store per filled box	1,489899	€						
Plastic crate values								
Weight empty crate	1,5	kg						
Transport empty crates								
Surface folded crate	0,24	m2	*(600*400)*					
Height folded crate	0,02	m						
Number of folded crates in 1 layer on pallet	4	crates						
Number of stacked folded crates on pallet	360	crates						
Number of folded crates in truck	11880	crates						
Weight of folded crate per pallet	540	kg						
Total weight in truck	18645	kg	*Rounded up 18 ton*					
Vrachtwagen, 16 ton en meer	1,77	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*					
Price of transport per folded crate to farm	0,14899	€						
Price of transport per folded crate to pooler	0,14899	€						
Total transport price folded crate	0,29798	€						

Figure 108 | Transport costs calculation, part 1

Transport filled crates				
Surface filled crate	0,24	m2	*(600*400)*	
Height filled crate	0,2	m		
Number of filled crates in 1 layer on pallet	4	crates		
Number of stacked folded crates on pallet	36	crates		
Number of filled crates in truck	1188	crates		
Total weight in truck	20427	kg	*Rounded up 24 ton*	
Vrachtwagen, 16 ton en meer	1,77	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*	
Price of transport to grocery store per filled crate	1,489899	€		
Hybrid box values				
Weight plastic bottom	0,8	kg		
Surface cardboard sleeve	0,412	m2		
Weight cardboard sleeve	0,23072	kg		
Transport empty hybrid box: bottom				
Surface plastic bottom	0,24	m2	*(600*400)*	
Height plastic bottom	0,02	m		
Number of bottoms in 1 layer on pallet	4	crates		
Number of stacked bottoms on pallet	360	crates		
Number of bottoms in truck	11880	crates		
Total weight in truck	10329	kg	*Rounded up 10 ton*	
Lichte vrachtwagen < 12 ton	1,56	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*	
Price of transport per bottom to farm	0,131313	€		
Price of transport per bottom to pooler	0,131313	€		
Transport empty hybrid box: sleeve				
Surface folded sleeve	0,2	m2	*(600+400)*200*	
Height folded sleeve	0,01	m		
Number of sleeves in 1 layer on pallet	4	sleeves	*4,8*	*4 rijen van 200 passen in 800*
Number of stacked sleeves on pallet	720	sleeves		
Number of sleeves in truck	23760	sleeves		
Total weight in truck	6306,907	kg	*Rounded up 6 ton*	
Lichte vrachtwagen < 12 ton	1,56	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*	
Price of transport per folded sleeve to farm	0,065657	€		
Price of transport per folded sleeve to recycler	0,065657	€		
Total transport empty hybrid box	0,393939	€		
Transport filled hybrid box: bottom				
Surface hybrid box	0,24	m2	*(600*400)*	
Height hybrid box	0,2	m		
Number of hybird boxes in 1 layer on pallet	4	boxes		
Number of stacked hybrid boxes on pallet	36	boxes		
Number of hybrid boxes in truck	1188	boxes		
Total weight in truck	19869,5	kg		
Vrachtwagen, 16 ton en meer	1,77	€/km	*Source: Panteia.n;, Zoetermeer, juli 2018*	
Price of transport to grocery store per filled hybrid box	1,489899	€		

Figure 109 | Transport costs calculation, part 2