

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**MODELING PLASTIC CELLULOSIC BASED PACKAGING AND  
COMPARISON OF THEIR PERFORMANCES**

**M.Sc. THESIS**

**Eren BARUTÇUOĞLU**

**Faculty of Textile Technologies and Design**

**Innovative Technical Textiles Programme**

**FEBRUARY 2025**



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**Eren BARUTÇUOĞLU  
(503211862)**

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**Thesis Advisor: Prof. Dr. Hale Karakaş**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**PLASTİK SELÜLOZİK ESASLI AMBALAJLARIN MODELLENMESİ VE  
PERFORMANSLARININ KARŞILAŞTIRILMASI**

**YÜKSEK LİSANS TEZİ**

**Eren BARUTÇUOĞLU  
(503211862)**

**Tekstil Teknolojileri ve Tasarımı Fakültesi**

**Yenilikçi Teknik Tekstiller Programı**

**Tez Danışmanı: Prof. Dr. Hale Karakaş**

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Eren Barutçuođlu, a M.Sc. student of ITU Graduate School student ID503211862, successfully defended the thesis/dissertation entitled “Modeling Plastic, Cellulosic Based Packaging and Comparison of Their Performances”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor: Prof. Dr. Hale Karakaş .....

İstanbul Technical University

Jury Members: Prof. Dr. Selin Hanife Eryürük .....

İstanbul Technical University

Prof. Dr. Emine Dilara Koçak .....

Marmara University

Date of Submission: 10/01/2025

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*To my family and grandfather,*



## **FOREWORD**

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Eren Barutçuoğlu  
(Mechanical Engineer)



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## **ABBREVIATIONS**

<b>°C</b>	: Degree Centigrade
<b>BOM</b>	: Bill of Materials
<b>Cm</b>	: Centimeter
<b>F</b>	: Force
<b>FEA</b>	: Finite Element Analysis
<b>H</b>	: Height
<b>Hz</b>	: Hertz
<b>ISO</b>	: International Organization for Standardization
<b>kW</b>	: Kilowatt
<b>Mm</b>	: Millimeter
<b>MPa</b>	: Mega Pascal
<b>m/s</b>	: Meter/second
<b>N</b>	: Newton
<b>R.H</b>	: Relative Humidity
<b>t</b>	: Temperature



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## **MODELING PLASTIC CELLULOSIC BASED PACKAGING AND COMPARISON OF THEIR PERFORMANCES**

### **SUMMARY**

Packaging of a product has an important place in reaching the end user. In addition, with the increasing population and consumption, packaging is becoming a sector where the concepts of sustainability and recycling gain importance every single day. Moreover, many countries are working to make their waste management more environmentally by detailing their current packaging content regulations. In terms of reducing the use of plastic, serious bans have begun to be imposed on polystyrene group plastics in particular. This study seeks an answer to the question of whether non-woven plastozoid (LDPE-4) and EPS (PS-6) raw materials based packaging design, molded cellulosic raw material (PAP21) based packaging design, honeycomb (PAP21) based packaging design, including PS6, LDPE4, PP, PAP20, PAP21 raw materials, are suitable by using them in the packaging of cooking devices.

To achieve the goal, the designs have been created by researching the mechanical behavior of different raw materials, their compatibility with environmental conditions, and their integration with the product and design integrity. Then, the model designs were first printed by machining the honeycomb-based designs with CNC machines and creating molds for cellulose-based designs and cardboard. The results of the mechanical tests conducted with the first prints have been evaluated against the data obtained from the literature, and recommendations have been made for the improvement and use of the design. According to packaging test standards, stacking tests using a static load, vertical impact test by dropping, compression and stacking tests using a compression tester, vibration tests at fixed low frequency, horizontal impact tests, conditioning for testing, different designs were evaluated. Non-woven fabric (PP), plastozoid (LDPE-4) and EPS (PS-6) raw materials based packaging design, molded cellulosic raw material (PAP21) based packaging design, honeycomb (PAP21) based packaging design have significant positive and negative sides. Maximum deviation, drop heights, impact surface, vibration effects, water condensation, cost effect, container loadings, cosmetic damage to the product etc. on the designs have been carried out and the results have been analyzed.



## PLASTİK SELÜLOZİK ESASLI AMBALAJLARIN MODELLENMESİ VE PERFORMANSLARININ KARŞILAŞTIRILMASI

### ÖZET

Bir ürünün son kullanıcıya ulaşmasında önemli bir yere sahip olan ambalaj, artan nüfus ve tüketimle birlikte sürdürülebilirlik ve geri dönüşüm kavramlarının her geçen gün önem kazandığı bir sektör haline gelmektedir. Üstelik birçok ülke mevcut ambalaj içerik yönetmeliklerini detaylandırarak atık yönetimlerini daha çevreci hale getirmek için çalışmaktadır. Plastik kullanımının azaltılması açısından özellikle polistiren grubu plastiklere ciddi yasaklar getirilmeye başlanmıştır. Bu çalışma, nonwoven plaztozoid (LDPE-4) ve EPS (PS-6) hammadde tabanlı ambalaj tasarımı, kalıplı selülozik hammadde (PAP21) tabanlı ambalaj tasarımı, bal peteği (PAP21) tabanlı ambalaj tasarımı, PS6, LDPE4, PP, PAP20, PAP21 hammaddeleri içeren ambalaj tasarımlarının, pişirme cihazlarının ambalajında kullanıldığında performans açısından uygunluk sorusuna yanıt aramaktadır.

Bu amacı gerçekleştirmek için, farklı hammaddelerin mekanik davranışları, çevre şartlarına uyumluluğu ve ürün ile tasarımsal bütünlükleri araştırılarak tasarımlar oluşturuldu. Tasarımlar oluşturulurken referans model üzerinden detaylandırmalara gidilmiş olup, konteyner yükleme adetlerinde herhangi bir azalmaya sebep olmaması adına limit değer paket ölçüleri belirlendi. Referans modelin üzerinden akan istif yükünün, aktarılma şekline göre yeni tasarımlarda yük taşıma bölgeleri modellendi. Ürünün kablo, fiş, ızgara, kitapçık, cezvelik, wok adaptörü gibi ek parçalarının sabitlenmesi veya hareketlerinin güvenli olacak şekilde kısıtlanması sağlandı. Ardından, model tasarımları bal peteği tabanlı tasarımlar CNC makineleri ile işlenerek ve selülozik tabanlı tasarımlar ile karton kalıpları yapılmak suretiyle ilk baskıları alındı. İlk baskılar ile yapılan mekanik testlerin sonuçları, literatürden elde edilen veriler ile değerlendirilmiş olup tasarımın geliştirilmesi ve kullanımı için önerilerde bulunulmuştur. Ambalaj test standartlarına göre, statik yük kullanılarak istifleme testleri, düşürme yoluyla dikey darbe testi, sıkıştırma test cihazı kullanılarak sıkıştırma testleri, sabit düşük frekansta titreşim testleri, yatay darbe testleri, test için koşullandırma, farklı tasarımlar üzerinde değerlendirildi. Ürünlerin ağırlık verilerine göre istif yükünün hesaplanmasıyla test sonrasında çökme değerleri hesaplandı. Yine ürün ağırlıklarına göre düşürme yükseklikleri belirlenerek test gerçekleştirildi. Nakliye esnasında karşılaşılabilecek hareketlilik için titreşim testi gerçekleştirildi. Eğik düzlem çarpma testleri ile belirli hızlardaki yanal darbe dayanımları gözlemlendi. Değişken ortam koşullarının tropikal, normal, kutup bölgelerine göre ambalajın kozmetik ve mekanik davranışı gözlemlendi. Dokumasız kumaş (PP), plaztozoid (LDPE-4) ve EPS (PS-6) hammadde bazlı ambalaj tasarımı, kalıplanmış selülozik hammadde (PAP21) bazlı ambalaj tasarımı, bal peteği (PAP21) bazlı ambalaj tasarımının önemli olumlu ve olumsuz yanları olup, tasarımlar üzerinde maksimum çökme, düşme yükseklikleri, darbe yüzeyi, titreşim etkileri, su yoğuşması, maliyet etkisi, konteyner yüklemeleri, üründe kozmetik hasar vb. deneyler ve hesaplamalar

gerçekleştirilmiş ve sonuçlar analiz edilmiştir. Delinmeye karşı mekanik direnç, dokunmamış PP kumaşın seri üretimde kullanılmasının denenebilir olduğunu gösterdi. Kalıplanmış selülozik esaslı tasarım, mekanik testlerde özellikle çökme testi ve iklimlendirme performansında referans modelden ortalama %30 daha iyi performans gösterdi. Artan yüzey alanı ile yükün yayılarak taşınması ambalajın performansını iyileştirmiştir. Düşme yüksekliği ve artan darbe hızına göre ambalajın absorbe ettiği enerjinin artması ve yükün ürünle temas yüzeyinden aktarıldığı duvarlarda çatlakların oluşması bu çalışmada da benzer şekilde gözlemlenmiştir. Ayrıca yükün dengeli bir şekilde taşınması ve ambalajın çatlamasının en aza indirilmesi için desteklenen yüzey sayısı artırılıp ve kademeli bir tasarım yapılarak ürüne sarılır gibi yakın çalışıldı. Petek panel bazlı tasarım performanslarında, ızgaralı ocak modellerine kıyasla ürünlerin düz yüzeyli olması ve katmanlı düz yüzey alanları yükün yarattığı basıncı yaklaşık %50 oranında azaltmıştır. Kalıplı selülozik viyol tasarımda yan duvar sayısının artırılması yük taşımayı artırırken, petek panelde yüzey alanının artırılması fayda sağlamaktadır. Literatür araştırmasında olduğu gibi çekirdek yapının taşıdığı yük fazla olduğunda yanal darbelerde akordeon etkisi yaparak petek panelin yastıklaması azalmaktadır. Ayrıca çok katmanlı ve tek katmanlı yapıların taşıma kapasitesi hakkında genelleme yapılamayacağı örnek çalışmalarda doğrulanmıştır. Kontrollü çökme durumlarında özellikle düşük yüksekliğe sahip petek panellerin performansı beklendiği gibi yüksek çıkmıştır.

Ürün ve numune testlerinden elde edilen sonuçlar ile petek panelin örgü çapları arttığında, artan örgü çapları özellikle kenar bölgelerde patlayan hücre bütünlüğü nedeniyle tasarım boşlukları oluşturmuştur. Bu da ambalajın yanal testlerdeki performansını olumsuz etkilemiştir. Ayrıca yanal boşluklar ambalajda kozmetik kırışmalara sebep olmuştur. Referans model tasarım 3 farklı temel tasarımda yeterli performansı ile öne çıkarken, kozmetik hasarın önlenmesinde nonwoven PP kumaşların kullanımı etkili olmuştur. Petek panel temelli tasarım ürün montajı sırasında çoklu parça içermesi sebebiyle fazla uğraş gerektirmiş ve montaj karmaşası yaratmıştır. Düşürme testinde yükü yüzey alanına yayan ağ yapısı sebebiyle çoklu tekrarlar daha güvenilir bir seçenektir. Büyük petek panel parçalarının düzgün istifleme ile saklanabilmesi kolay iken küçük parçalarda fire oranı artmıştır. İstif yükü altında nem koşulları ile birlikte ürün yüzeyinde kozmetik çizik önleme için ek tedbir gerektirmiştir. Kalıplı selülozik viyol ambalajın montaj parçası azlığı ve ürün üzerine benzeyen özel şekli sebebiyle montajı petek panel temelli ambalaj tasarımına göre oldukça rahat gerçekleştirilmiştir. Düşürme testinde çoklu tekrarlar yük taşıyıcı parçaların kök diplerinin yırtılması ve görece fazla hasarlandığı gözlemlenmiştir. Viyol ambalaj parçalarının istiflenme ile saklanması içerdiği istif dudakları ile oldukça rijit olup birim hacimde daha fazla ürün için ambalaj içermektedir. Benzer şekilde istif şartları altında nem koşullarının değişkenliği ile ürün yüzeyinde ek koruma kullanımını gerektirmiştir. Sonuç olarak, plastik temelli tasarım, petek panel temelli tasarım ve kalıplı selülozik temelli tasarımın çıktılarında kullanılan ürün çeşidine, ağırlığına, ek parçaları vb. etkenlere göre farklı öne çıkan çıktılar elde edilmiştir.

## **1. INTRODUCTION**

Packaging is an important material that protects the product placed inside it in a clean and safe manner until its end use, and provides information about the product inside. According to the changing needs, packaging today appeal to a wide range of uses, including materials varies natural fiber to polypropylene. With the increasing importance of concepts related to nature such as sustainability, environmental pollution, clean air, FSC, Reach etc. , the importance of innovative and environmentalist approaches has increased in the field of packaging. It has three types: primary packaging, referred to as sales packaging; secondary packaging, referred to as grouping packaging; and tertiary packaging, referred to as shipping packaging. This study includes the design and comparison of primary packaging, defined as sales packaging.

### **1.1 History of Packaging**

The use of packaging is estimated to have been facilitating human life for over five thousand years. Packaging initially started with fibrous natural materials such as leaves, and with the advancement of manufacturing methods and material knowledge, the use of materials such as wood and glass increased. In more recent times, the use of the 'canister,' patented by the Englishman Peter Durand, became common. In the 1900s, paper and cardboard, along with metal packaging, became materials with significant usage.[1]

Today, there are packaging materials available in different capacities and features, serving various purposes. Examples of commonly encountered material types include glass, metal, plastic, paper and cardboard. The use of plastic, in particular, has steadily increased since the 1950s, when the material began to be technically recognized.



Figure 1.1: Examples of historical pottery and tin packaging.

## 1.2 Packaging Textiles

Packaging textiles have started to enter our lives, especially in sectors where durability is a priority. Many examples can be given, starting from cotton sacks used in agriculture to container airbags. Examples about Products of Packtech listed below.



Figure 1.2: Cotton sacks and container airbag.

## 100% COMPOSTABLE PLANT-BASED PYRAMID TEA BAGS



Figure 1.3: Plant based tea bag.

Polyolefin (HDPE/PP) woven sacks are versatile packing materials used extensively in the packing of cement, fertilizers, thermo plastic raw materials, food grains, sugar etc. The list of user-industries where they are used is; Cement, Fertilizers, Chemicals, Food Grains, Cattle Feed, Salt, Sugar, Polymers, Sacks - Export.

### **1.2.1 FIBC (Jumbo Bags)**

Flexible Intermediate Bulk Containers (FIBC), popularly known as —Jumbo Bags, is similar to the HDPE/PP bags but that of a larger size. FIBC's are one of the most cost effective and ideal types of packaging for shipping and storing dry bulk products. They can be produced from either tubular or flat polypropylene (PP) woven fabrics. These fabrics can be coated or uncoated and vary in terms of weights depending upon the requirements of the Safe Working Load (SWL), or Safety Factor (SF).

Panel Type

Circular woven

Baffle type (Square bags) [2]

### **1.2.2 Leno bags ( PP )**

Leno bags are excellent for packing and preserving vegetables like potato, onion, ginger, garlic, cabbage etc. and fruits like pineapple, citrus fruits, raw mango, coconut etc. The Leno Bag is made of netted fabric of virgin Polypropylene (PP) with color Master batch.

### **1.2.3 Wrapping fabric**

Wrapping fabric is made out of HDPE/PP, cotton canvas, etc. Unlaminated PP/HDPE Woven Fabric is mainly used for wrapping of paper rolls, paper bundles, steel coils, tyres, yarn cones etc. Wrapping fabric weighs 50 to 200 gsm and its size varies from 20 to 210 cms. The fabric is generally packed in roll form and can be run on automatic cutting and stitching machines. Clear Woven Sheets (Natural Woven Laminated Sheets) are used for packing of used clothes etc.

### **1.2.4 Jute hessian and sacks (including food grade jute bags )**

Jute Hessian also termed as Burlap is a finer quality jute fabric that has been long used as the most preferred packaging material for all kinds of goods. Hessian is used

for bags and many other coarse fabric uses, such as wrappers, wall coverings, etc. Presently, shopping bags are being made out of hessian fabrics. It is also used in the upholstery and home furniture. Also available in “dyed” or “bleached” form and treated with vegetable oil, Burlap meets the latest international standards for food safety.

### **1.2.5 Tea-bags (filter paper)**

Tea bags are sold by organized tea producers to the high-end consumers. Tea bags consist of a filter paper pouch with a thread, which holds the tea powder and a tag. The tea bag is dipped in hot water / milk to produce the beverage. [2]

### **1.2.6 Soft luggage products ( TT component )**

The luggage industry is classified into hard and soft luggage. Hard luggages are mainly the large travel bags made from molded plastic. Soft luggage is made out of woven fabrics like nylon and polyester. It comprises of uprights, totes, duffle and sky bags which can be with or without wheels and handles. The soft luggage today is becoming very popular due to the ease of carry as it is light and flexible. It includes handbags, military backpacks, athletic backpacks, wallets, briefcases and other soft sided luggage items. [2]

## **1.3 The Evolution of Hybridization in Packaging**

Low cost, light weight, high performance and ease of processing are more charming features to use of plastics and their related products in packaging industry by this time. [3] However, the rapidly increasing production of disposable and non-biodegradable plastics ( $3.80 \times 10^8$  t per year) have a huge negative impacts on environment especially on aquatic animals and even human’s health. [4]

Therefore, there are many encouragement concerning use of clean, strong, renewable, recyclable/biodegradable products by using lignocellulose as the raw materials [5] in packaging industry substituted for plastics and their related products in new ecologist era. Molded fiber/pulp products which are mainly produced by raw materials (plant based and/or recycled fibers) grab companies’ attention due to their sustainable advantages. In this context, this study dwells on the general concept of molded pulp products on packaging industries. Moreover, different types of molded

pulp products are also examined in terms of manufacturing processes, natural fiber sources, current applications as well as environmental sustainability of molded products. To sum up, the increasing population and consumption, packaging is becoming a sector where the concepts of sustainability and recycling gain importance every single day. Moreover, many countries are working to make their waste management more environmentally by detailing their current packaging content regulations. In terms of reducing the use of plastic, especially serious bans have begun to be imposed on polystyrene group plastics in particular.

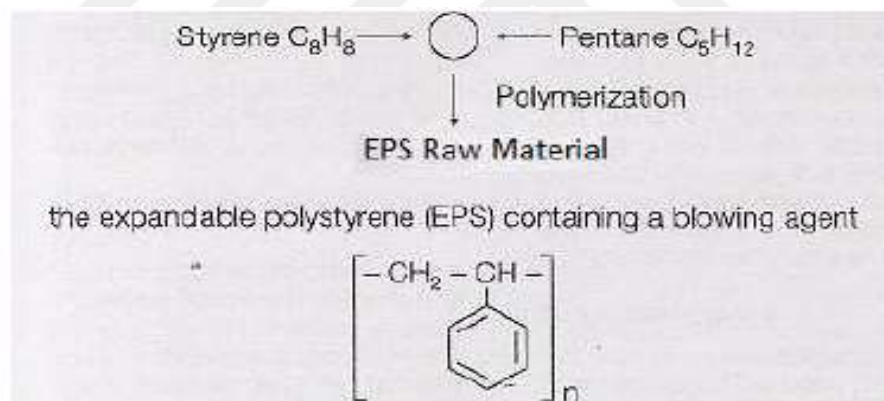




## 2. LITERATURE RESEARCH FOR DESIGN

### 2.1 Plastics Based Packaging Design

EPS is a thermoplastic, closed-cell foam plastic whose mechanical properties are largely influenced by the foam material bulk density. The mechanical properties of EPS are non-reversible and in accordance with DIN 53 421, the compressive stress is measured at a strain of 10%. For main packaging parts, lightweight compound, good compression strength, short time cooling and molding, good insulating, shock absorbency, low density and moisture resistance are the primary criteria's. EPS make the criteria's achievable. [6]



**Figure 2.1:** Polimerization of EPS raw material.

EPS production process consists of 3 main processes;

#### 2.1.1 Pre-expansion process

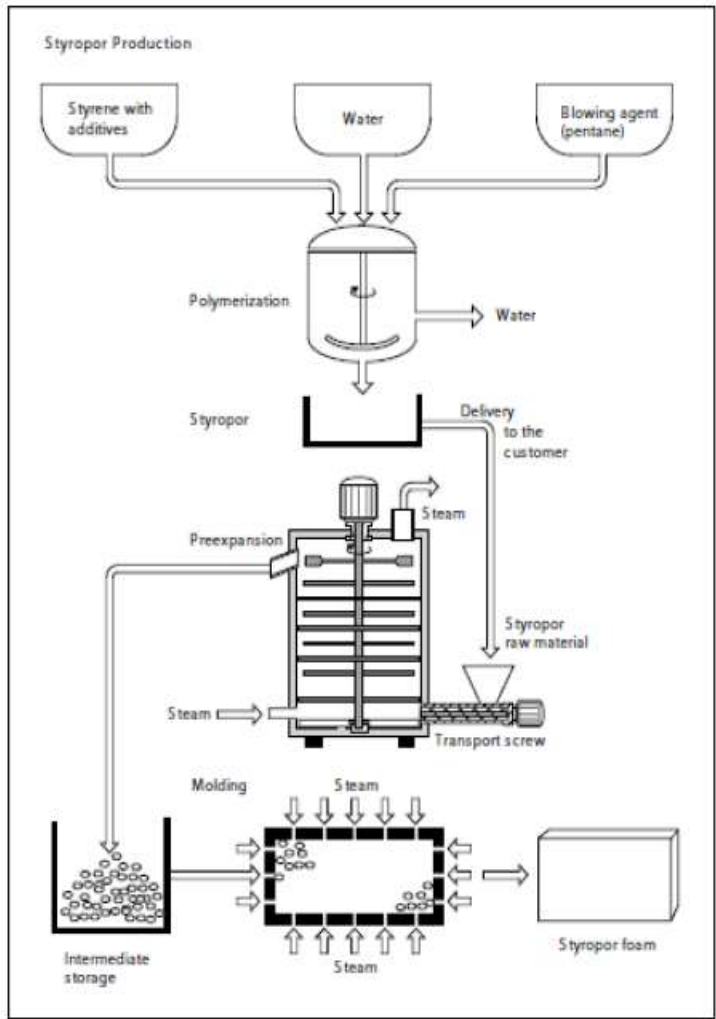
Dry saturated steam energy is used for pre-expansion of EPS particles. The inflation process stops when the pushing effect of the pentane, the atmospheric pressure that prevents inflation from outside the particle and the resistance of the polymer membrane come into equilibrium. Final product density is adjusted by the pre-inflation process.

**2.1.2 Maturation process**

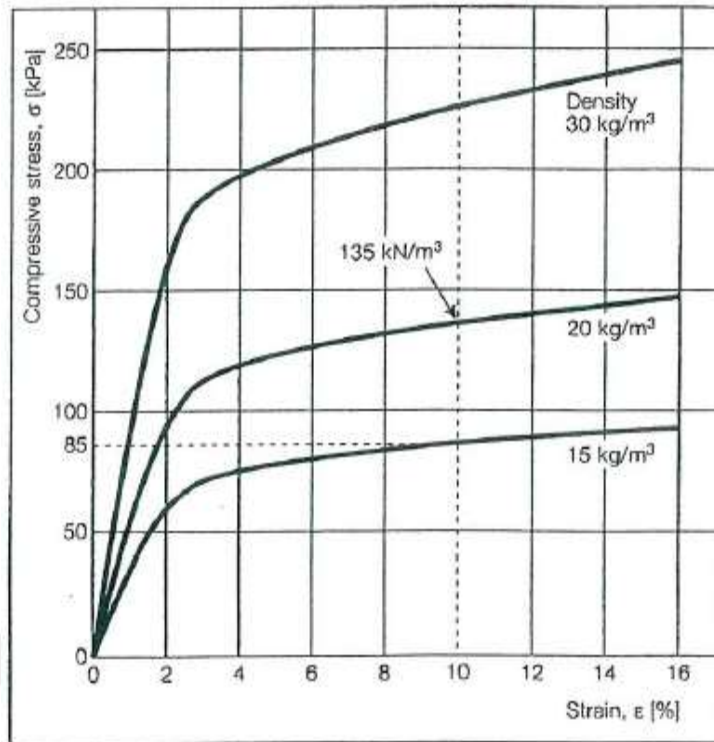
After the pre-inflation, the temporary vacuum effect that occurs inside the particle with the cooling of the pentane and water vapor inside the particles that cool down to room temperature continues until the ambient air penetrates into the particle and equalizes the internal and external pressure.

**2.1.3 Molding and cutting process**

EPS inflated with steam pressure and temperature takes the shape of the mold and becomes the final output. Alternatively EPS, which is produced by expanding in block form, is kept for a certain period of time according to the sector to be used and then shaped and cut with hot wire.[7]



**Figure 2.2:** Production of EPS blocks.



**Figure 2.3:** EPS stress-strain curve according to density. [8]

In the values to be seen in the stress-strain figure of EPS according to density, it is seen that increasing density increases the carrying capacity. In addition to the increased carrier properties of EPS packaging, dense packaging can transmit damage directly to the product instead of packaging that absorbs energy by taking damage.

**Tablo 2.1:** Moisture and oxygen barrier properties of the packaging plastics.

Material	MVTR	OTR
LDPE/LLDPE	15-25	7000-8000
HDPE	5-12	1500-2000
PP	3-7	1800-2500
PVC(U)	20-60	50-80
PS	70-160	4000-6000
PET	16-20	60-120

MVTR: Moisture vapour transmission rate for 25 μ film in g/m<sup>2</sup>/day; test conditions 38°C, 90% relative humidity.

OTR: Oxygen transmission rate for 25 μ film in cm<sup>3</sup>/m<sup>2</sup>/day; test conditions 25°C, 50% relative humidity, 1 atmosphere.

**Tablo 2.2:** Chemical resistance of the packaging plastics. [9]

Matariol	Dilute acid	Dilute alkali	Oils and greases	Alphatic hydro carbons	Aromatic hydro carbons	Halogenated hydrocarbons	Alcohols
LDPE/LLDPE	****	****	**vanable	*	*	*	****
HDPE	****	****	**vanable	*	*	*	****
PP	****	****	**vanable	*	*	*	****
PVC	****	****	**vanable	****	*	**vanable	**vanable
PS	**	****	**	****	*	*	*vanable
PET	****	**	****	****	**	**	****

For additional packaging parts LDPE based plastozoid and nonwoven PP have lightweight compound and good moisture resistance also chemical resistance properties are enough for usage. These properties make them selectable in the plastics.

## 2.2 Molded Cellulosic Based Packaging Design

It is a type of packaging produced by shaping natural fiber-based materials by molding method and has environmentally friendly properties. Cellulose is a natural polymer found in plants and is biodegradable. This type of packaging stands out as an alternative to plastic and other traditional packaging materials, especially today, when environmental awareness is increasing.[10]

Molded cellulosic production process consists of 9 main processes:

### 2.2.1 Raw material supply

Cellulose is usually derived from pulp, wood cellulose or recycled paper materials. The raw material is processed through various chemical treatments (e.g. bleaching, cleaning) to make it usable.

### 2.2.2 Liquidation of cellulose

Cellulose is mixed with water and other auxiliary chemicals to form a suspension (cellulose pulp).By increasing the solubility of cellulose, it can be poured into molds or shaped.

### **2.2.3 Formulation and mixture preparation**

Binding agents, preservatives or other additives are added to increase durability and impart properties such as waterproofing. The cellulose suspension and chemical additives are mixed to form a homogeneous mixture.

### **2.2.4 Molding (shaping)**

Mold suitable for the shape of the desired packaging are selected. Cellulose suspension is dipped on the mold surface. The mold absorbs the liquid mixture and a layer forms on the surface. Liquid cellulose is shaped in the mold under a certain pressure.

### **2.2.5 Drying**

The formed molded product is allowed to dry in steam, air or temperature controlled environment. The water in the cellulose is allowed to evaporate and the product is solidified.

### **2.2.6 Compression and shaping**

The product is shaped with a compression press and excess water is removed. This process increases the durability of the product. If necessary, additional shaping operations are performed on the mold.[11]

### **2.2.7 Cooling**

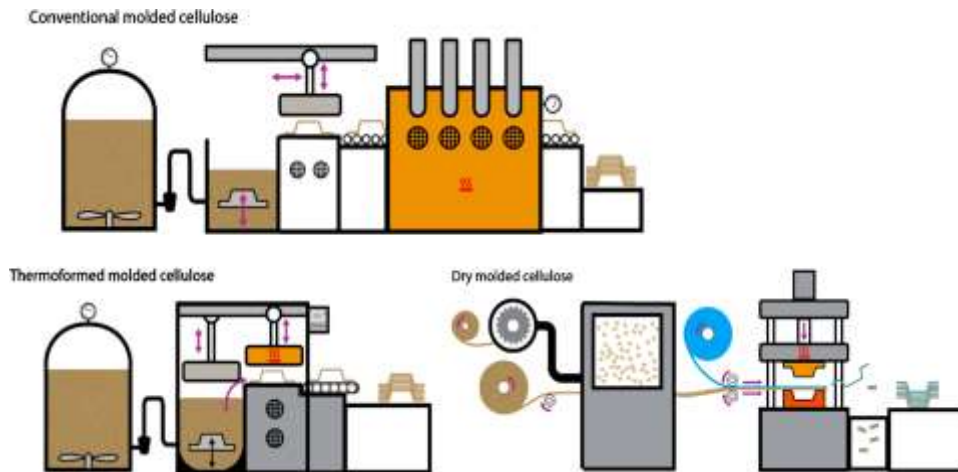
After drying and shaping, the product is subjected to a cooling process. The cooling process makes the product more robust and stable.

### **2.2.8 Surface finishing and quick check**

If properties such as smoothness, gloss or mattness are desired on the surface, some finishing processes can be applied to the product surface. Products are checked to ensure that they are free from defects. Tests such as size, thickness and durability are performed.

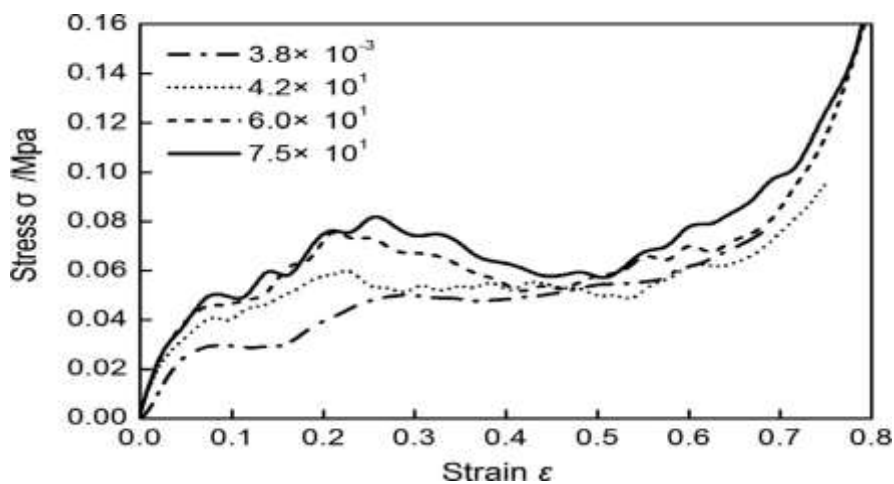
### **2.2.9 Packaging and storage**

The finished cellulosic packages are packaged in various sizes and are ready for storage. Products are routed through logistics channels to reach the end user.



**Figure 2.4:** Schematic representation of conventional molded cellulose, thermoformed molded cellulose process and dry molded cellulose process (Tridas, 2020; Larsson & Larsson, 2019). [12]

In the study investigating the behavior of the molded cellulosic-based design in the face of static and dynamic loads, compression was performed at a speed of 12 mm/min and a velocity of  $3.8 \times 10^{-3} \text{ s}^{-1}$  and the drop from heights of 25, 50, 80 cm was performed corresponding to velocities of  $4.2 \times 10^1 \text{ s}^{-1}$ ,  $6.0 \times 10^1 \text{ s}^{-1}$  and  $7.5 \times 10^1 \text{ s}^{-1}$ . In the research, FEA and experimental work were carried out together and gave similar results. In the results, deformation started locally and continued with buckling. It was observed that the yield stress of the material increased with increasing deformation rate. The rate of deformation, reduced heights and structural deformation starting with localized damage support the usability of the product in packaging design.

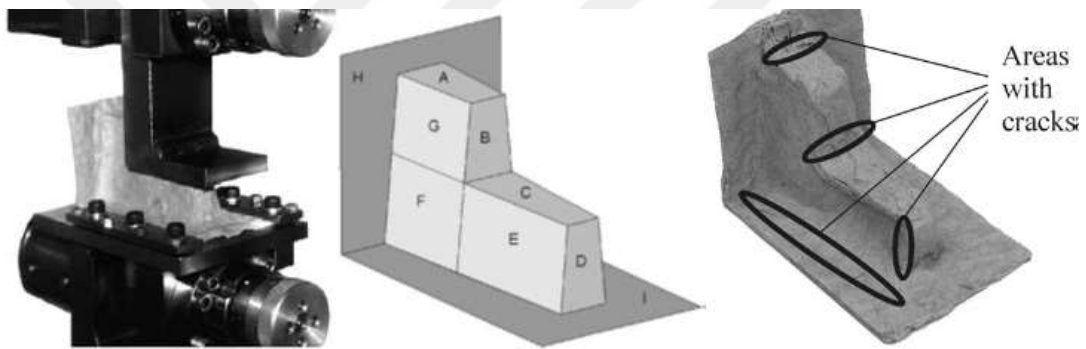


**Figure 2.5:** Stress–strain curves of molded pulp products with different nominal strain rate. [13]



**Figure 2.6:** Items of the reference packaging for the vertical cooker hood (left) and the prototype of the interior base in the molded pulp (right)

As seen in the figure above, molded cellulosic packaging design was realized in different types of white goods and it was mentioned that the study would have a positive impact on environmentalism.[14]



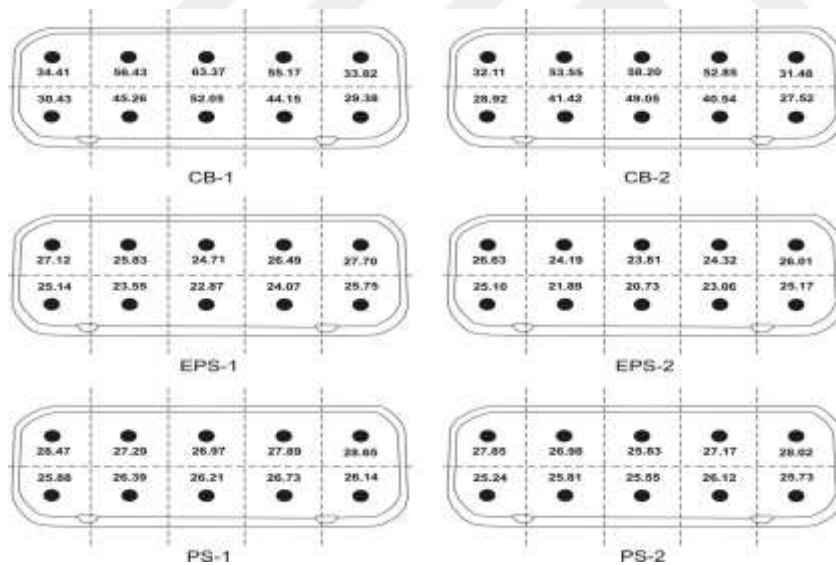
**Figure 2.7:** Compression specimen and testing result.

Another study made calculations about the load carrying of the walls of molded cellulosic packaging by compression test. There is guidance in determining the number of load carrying walls.[15] In another study, it was calculated that the draft angles of load bearing walls should be between 3-4 degrees in order to carry the maximum load.[16]

**Table 2.3:** Forces required to deforming complete ten-egg boxes with a moving plate (N).

Egg box	Mean	Max	Min.	$S_d$
CB-1	489.71 <sup>a</sup>	563.17	404.34	67.24
CB-2	428.89 <sup>b</sup>	526.39	344.22	70.01
EPS-1	160.88 <sup>c</sup>	192.46	135.59	22.95
EPS-2	156.37 <sup>c</sup>	184.63	129.46	24.38
PS-1	251.87 <sup>d</sup>	300.71	219.07	33.28
PS-2	248.33 <sup>d</sup>	291.83	214.22	30.87

In another study, the use of molded cellulosic, EPS and PS raw materials and their carriage in 2 different designs were investigated. In this study, the carriage of molded cellulosic packaging was measured approximately 3 times more than EPS.



**Figure 2.8:** Average forces required to deforming ten-egg boxes on particular egg place (N).

The distribution of the load they carry is shown in the image above and has a guiding role in the design of load carrying structures. Its preservativeness in egg protection was mentioned and it was emphasized that the mechanical behavior may change according to the moisture intensity.[17] In addition, the load coming vertically spreads from the load-bearing walls to the interior structure, making the distribution balanced.[18]

## **2.3 Honeycomb Based Packaging Design**

Honeycomb panel paper packaging production is a method used to provide durable and lightweight packaging materials. It is generally preferred for cushioning and protection in the transportation of large and sensitive products. The honeycomb panel consists of layers of paper with uniformly cut, spaced cells. While its shock and vibration absorbing feature prevents damage to the product it is used in, it creates solutions for many different sectors including transportation, automotive, construction, home appliances, furniture, advertising with its structure that offers hardness and flexibility together. [19] Honeycomb production process consists of 10 main processes;

### **2.3.1 Raw material supply and preparation**

Kraft paper or corrugated paper is usually used for the production of honeycomb panels. The raw material paper is prepared by various processes (e.g. moisturizing).

### **2.3.2 Adhesive preparation**

Water-based adhesives or special resins are generally used for bonding the honeycomb panel. Glue is applied evenly between the layers of paper.

### **2.3.3 Creating the honeycomb template**

The honeycomb shape for production is prepared with a template with a specific density and cell size. The stencil creates the grid (honeycomb) pattern, allowing the paper to take shape.

### **2.3.4 Applying adhesive on paper layers**

Apply glue on the prepared paper layers in the areas where the honeycomb structure will be formed. The paper layers on which glue is applied are joined so that they overlap.

### **2.3.5 Creating the honeycomb form**

The paper layers are placed on the template to form the desired honeycomb shape. The template is compressed under the press so that the paper is properly shaped. This ensures the formation of the honeycomb structure. [20]

### 2.3.6 Drying and curing

After applying the adhesive, the honeycomb panel is allowed to dry properly. This process ensures that the adhesive forms a strong bond. During the drying process, the durability of the honeycomb panel increases.

### 2.3.7 Cutting and shaping

The resulting honeycomb panel is cut to the specified dimensions. These cuts are necessary for the packaging to take its final shape.

### 2.3.8 Quality control and tests

The carrying capacity and durability of the honeycomb panels produced are tested. The dimensions and shape of the product are checked.

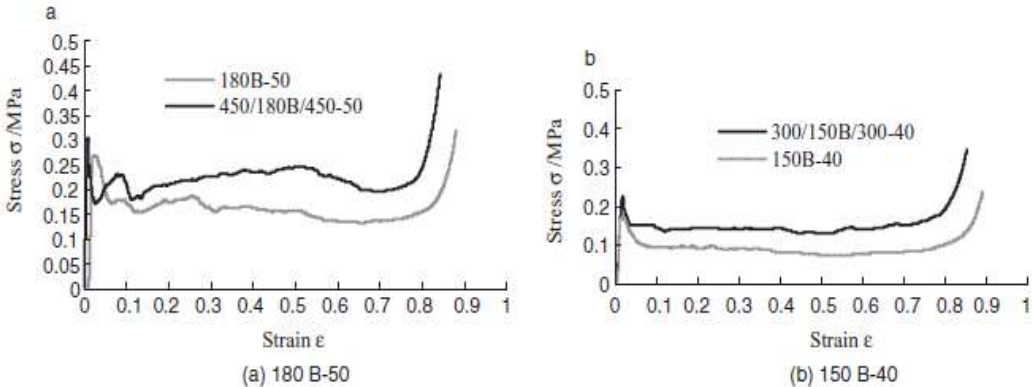
### 2.3.9 Packaging and storage

The honeycomb panel paper packages produced are neatly packed. The final product is stored in a suitable environment to store and prepare it for shipment.

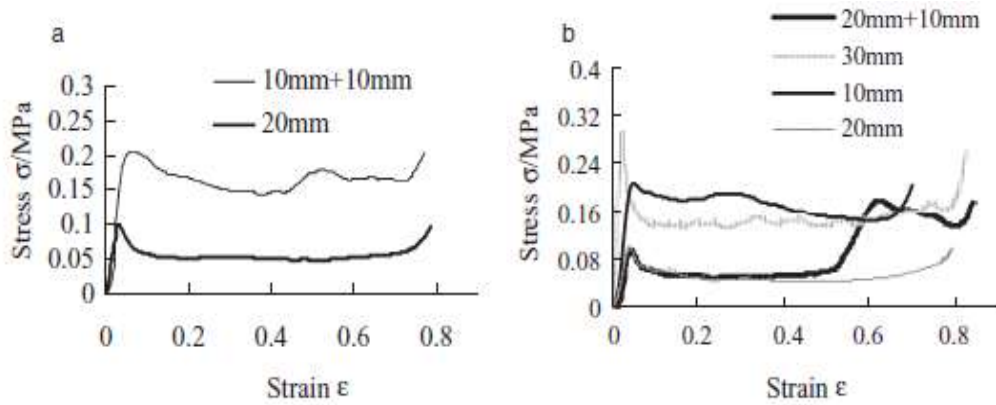
### 2.3.10 Shipment

Packages are shipped to the end user or distribution chain.

In this study, it was found that the cushioning capacity of the honeycomb panel with liner on both sides was higher than that with liner on one side, and that the effect of core material on paper quality was high while the effect of liner material was low.[21]

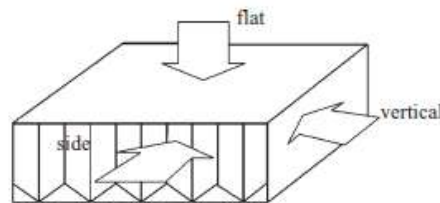


**Figure 2.9:** Comparison of paper honeycombs with and without liners.

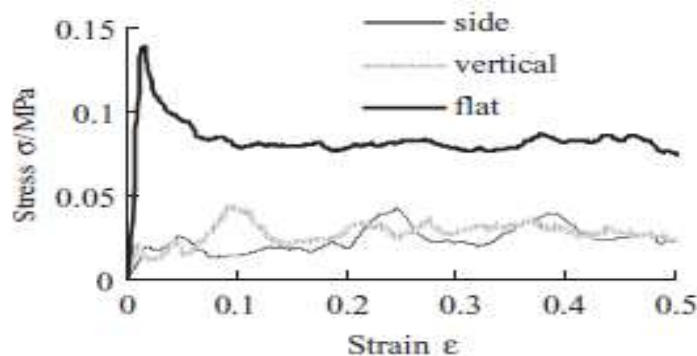


**Figure 2.10:** Comparison of multilayer and monolayer honeycomb paperboard. (a)  $10 \pm 10$  mm stack; (b)  $10 \pm 20$  mm stack.

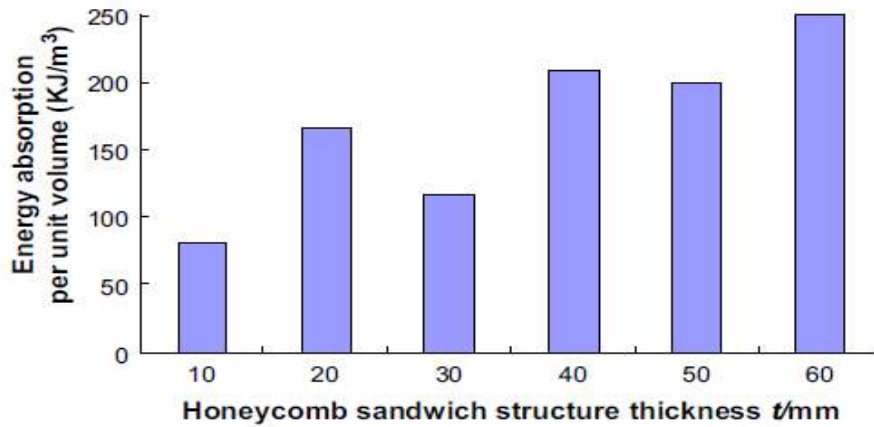
In the multi-layer and single-layer load-carrying measurement, the cushioning behaviors differed for layers of different heights, indicating that what makes multi-layer designs stand out is that they always remain more resistant to secondary damage. It is also stated that having a double-sided liner increases the buckling resistance. In another study, it is mentioned that the absorbed energy increases gradually in the higher initial volume of the honeycomb panel structure and that the multilayer structure gives better results than the single layer. [22]



**Figure 2.11:** Load direction.

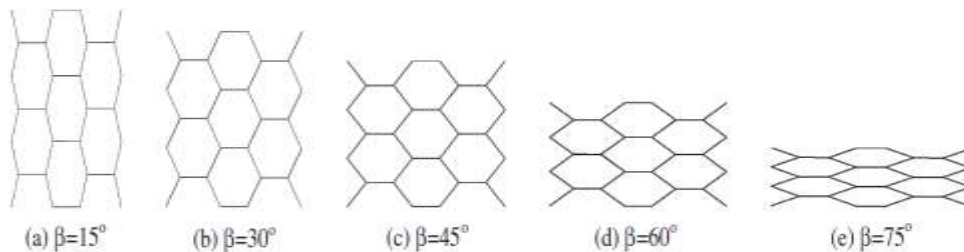


**Figure 2.12:** Three orientation compressions of 50 mm honeycomb paperboard. It was also mentioned that the carriage in the vertical and side directions is less than in the flat direction. [23]

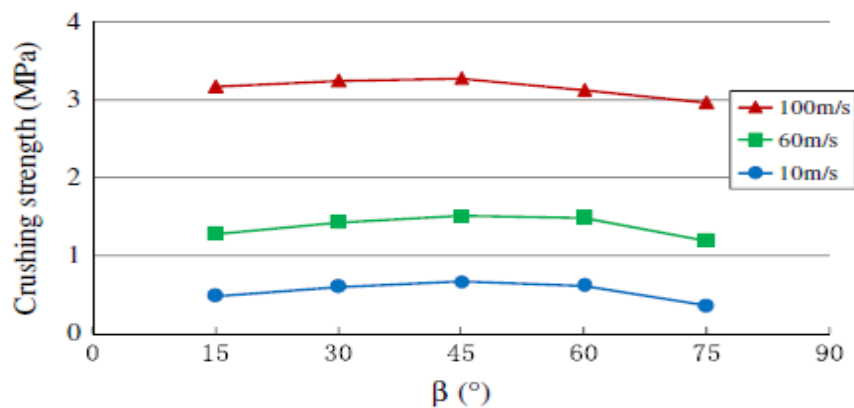


**Figure 2.13:** Energy absorption per unit volume of the sandwich structures with different thicknesses.

In another study, it was mentioned that energy absorption values decrease with increasing thickness, while core paper thickness increases the absorption value. [24] It was also mentioned that the characteristics of the honeycomb panel, such as the angle values in the honeycomb panel core structure, affect the yield strength in the bearing direction, and it was also stated that the stress value in the cushioning zone increases with increasing thickness. [25]

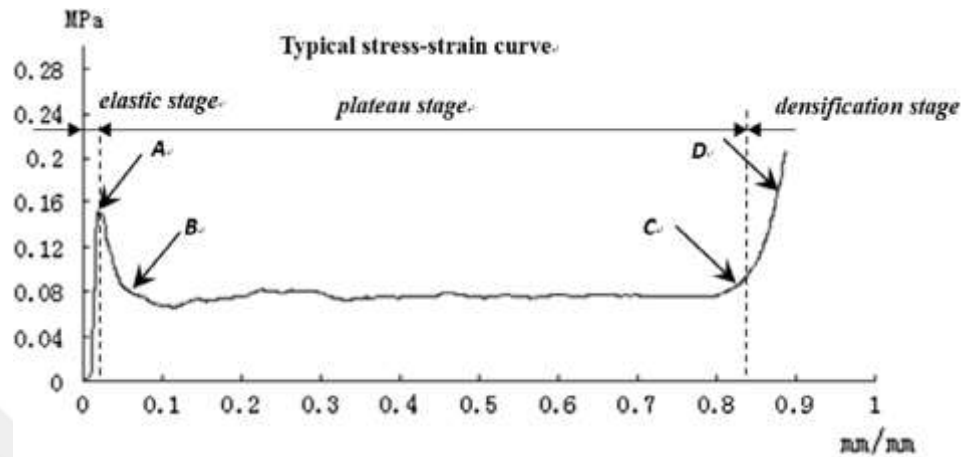


**Figure 2.14:** Honeycombs with various cell shapes.



**Figure 2.15:** Dependence of the crushing strength on the cell-wall angle of honeycombs.

In the study on the core angle, which is one of the characteristic dimensions of the honeycomb panel board, it is seen that 30 degrees is mostly used by the sector and the best strength values are obtained between 30 and 60 degrees depending on the application area. [26]



**Figure 2.16:** Static compressive stress-strain curve of paper honeycomb.

The graph above shows the yield strength of the honeycomb panel at point A, followed by the B-C region where energy is absorbed in the plastic deformation region, and finally the D point with increasing stress of the honeycomb panel that has lost shock absorption. It also shows that the cushioning energy of the honeycomb panel increases as the conditions of static loading and dynamic drop heights become heavier. [27]



### **3. DESIGN AND PRODUCTION**

#### **3.1 Purpose of Design**

The project aims to improve the design of plastic based reference packaging and to design and prepare for mass production paper-based packaging that aims to reduce the use of plastic. In order for the models to be designed to be delivered to the end user, they must meet the packaging test conditions passed by the reference products.

#### **3.2 Design Steps**

There are seven steps to consider. These are[28]

- a) Identifying the problem
- b) Researching it in-depth
- c) Ideating possible solutions
- d) Evaluating and selecting a promising solution
- e) Creating a prototype
- f) Testing and troubleshooting
- g) Making improvements to and releasing the final product

With the first three items in place so far, it was decided to design an alternative to the reference model based on paper-based packaging material.

##### **3.2.1 Reference model optimization**

The image below shows the parts in the plastic based packaging design. In our reference model, the cooker grills are mounted on the cardboard number 2 and assembled to the product so that the plastozoid and nylon bag remain at the bottom. Especially in single grid models, 1 mm thick and 20 g/m<sup>2</sup> density plastozoid (LDPE-4) used under the protection carton can be adversely affected under field conditions. In order to prevent this situation, the on the product was investigated by increasing the number of plastozoids and using nonwoven PP fabric that has not been

used before. In the improvement works on the reference base product, there are designs using 2 types of plastozoids and 1 type of nonwoven as the final model.



Figure 3.1: Reference model parts.

**3.2.2 Molded cellulosic based design**

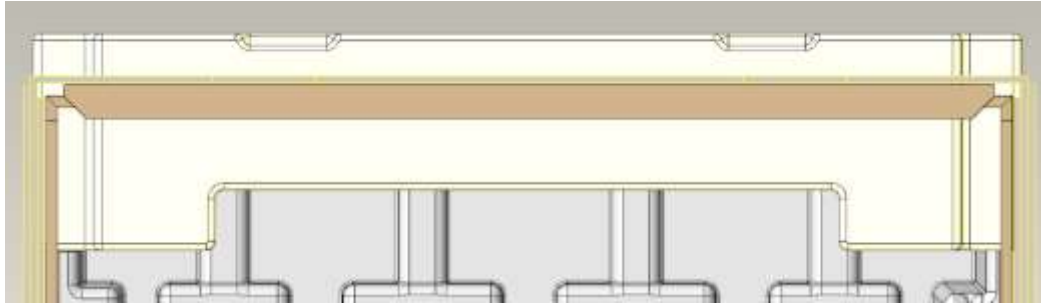
Gas hobs products are included in the product range where molded celulosic packaging design will be integrated. The stove grill and burner group in gas hobs increases the nominal thickness of the product. In addition, since it contains additional parts, the packaging should also prevent interaction between the parts. With the contribution of literature research, field research and different types of product packaging, molded cellulosic packaging design was progressed.

The path followed when starting a design;

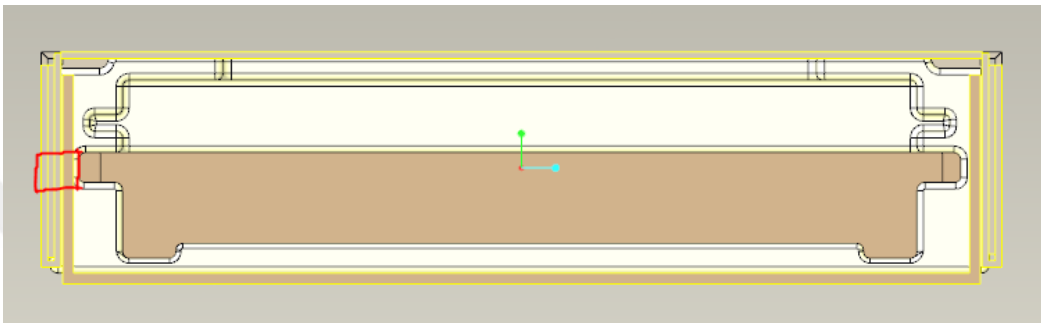
Loading quantities are important for the transportation of products. When starting the design, the priority was not to exceed the packaged exterior dimensions offered on the base model.



Figure 3.2: Side EPS 3D model 1.



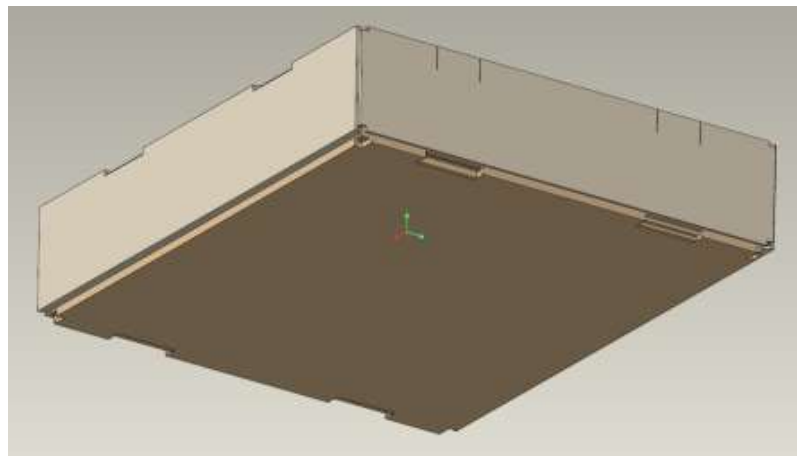
**Figure 3.3:** Assembling the designs together and checking their dimensions 1.



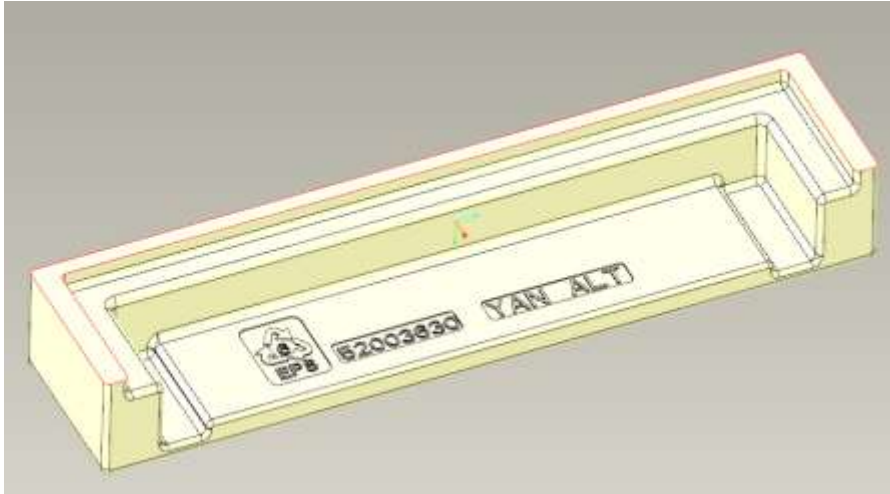
**Figure 3.4:** Load carrying walls.

Since the load carrying wall areas of the side EPS materials used in the base model are outside the product, they are surrounded by a telescopic cardboard design that increases vertical load carrying.

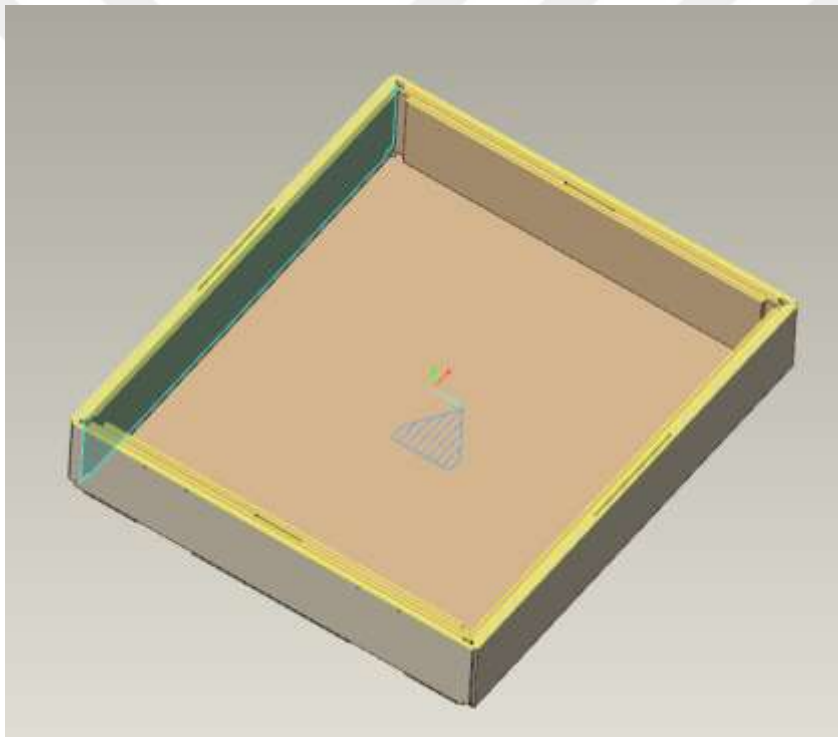
Unlike EPS material, the elastic limit of molded paper-based packaging is very low, so a design close to the product it will protect is required. For this reason, before the molded paper-based design, it was aimed to make the four vertical edges as rigid as possible and the locking areas of the upper and lower cartons were made with staggered.



**Figure 3.5:** Outer Box 3D Model 1.

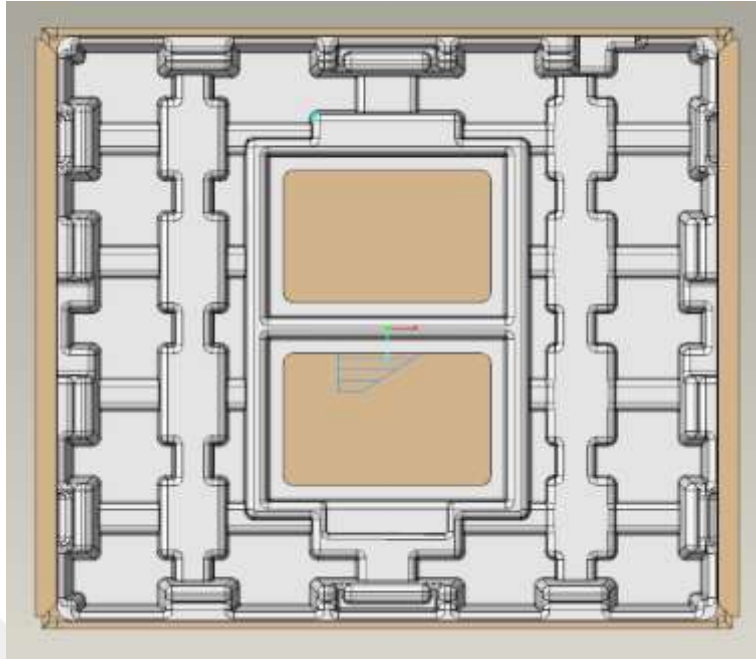


**Figure 3.6:** Critical area of side EPS model 1.

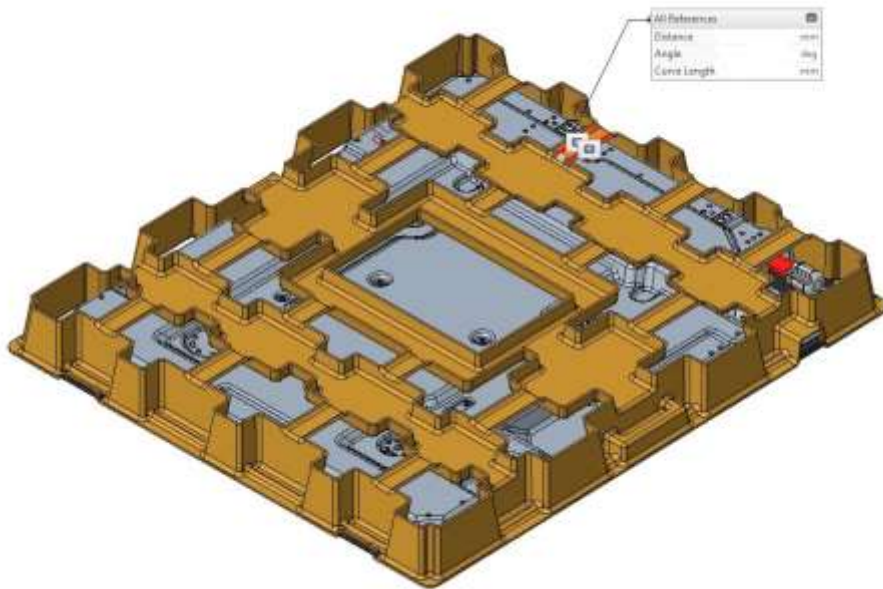


**Figure 3.7:** Section load carrying walls for outer box design 1.

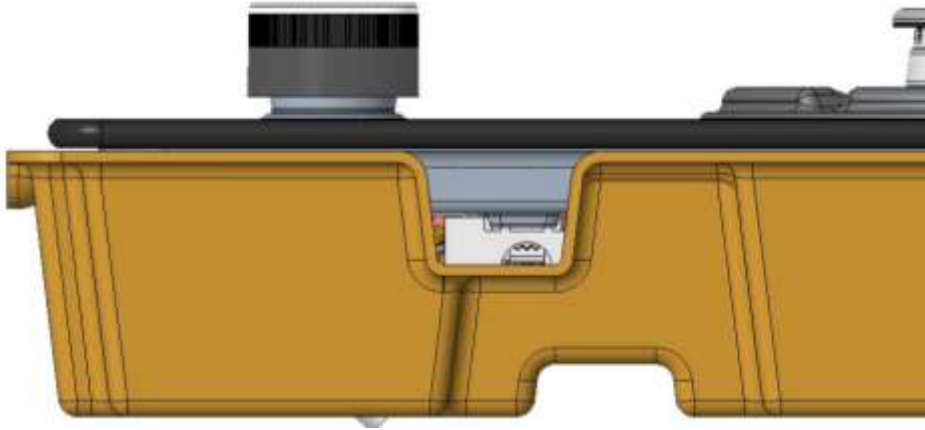
When designing molded cellulosic packaging for the bottom of the product, especially the rounded areas where the load can be carried in the form of the bottom cover of the product have been the support zones.



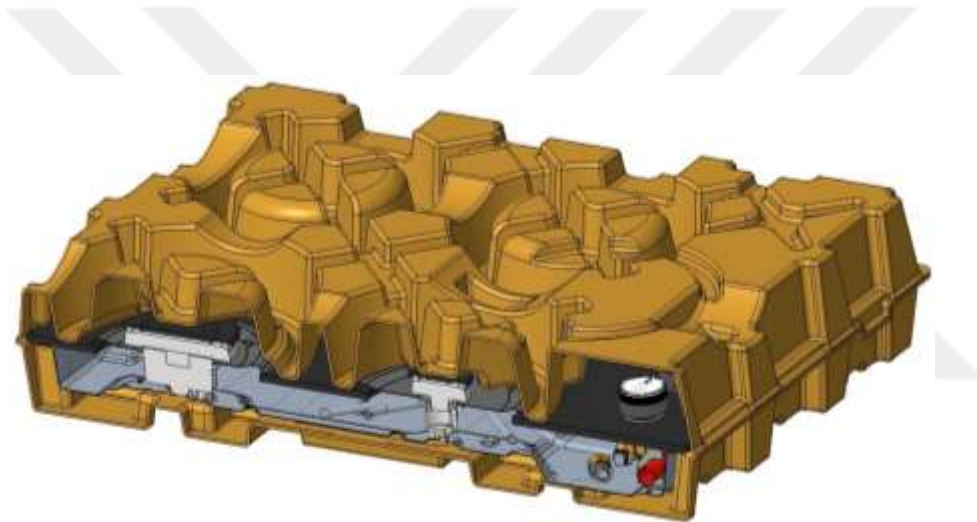
**Figure 3.8:** Bottom molded 3D design.



**Figure 3.9:** Sectional view of the product assembly with bottom cover.



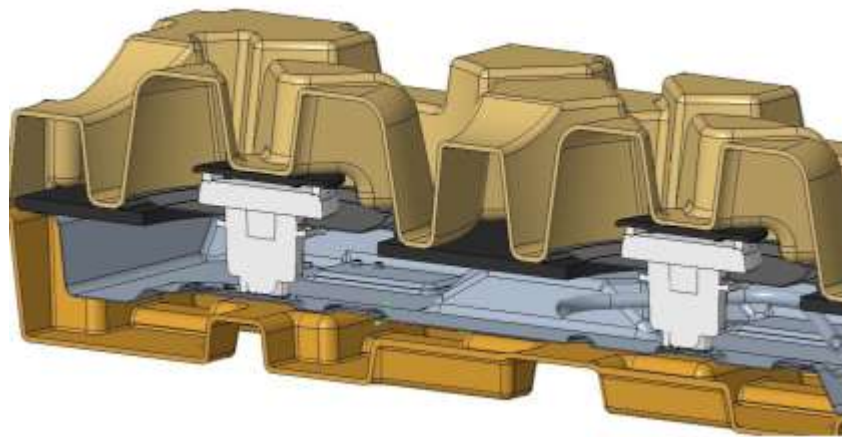
**Figure 3.10:** Detailed cross-section of the cable outlet.



**Figure 3.11:** Cross-section of the assembly of the top and bottom parts with the model.

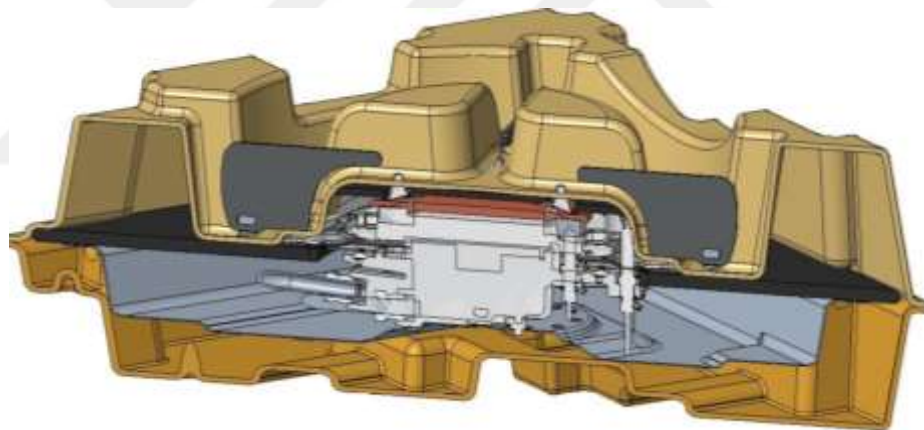
In order to prevent or minimize the damage that may be caused by falling during transportation, the load carrying areas are prioritized in such a way that there is a gradual springing in the lower cover area.

When designing the top molded cellulosic packaging part, we focused on the areas that can carry the load with the same design logic as for the bottom. In order to prevent the burners from moving during transportation and damaging the surface of the product, the integrity of the product is preserved with a shape bond as follows.

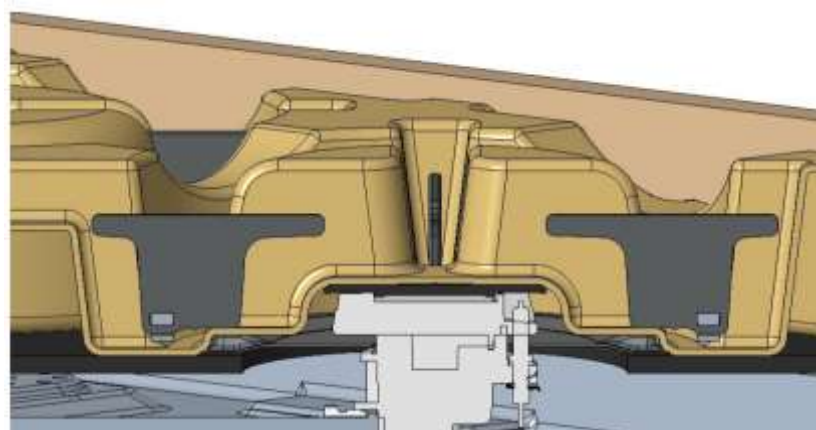


**Figure 3.12:** Cross section view of burner covering.

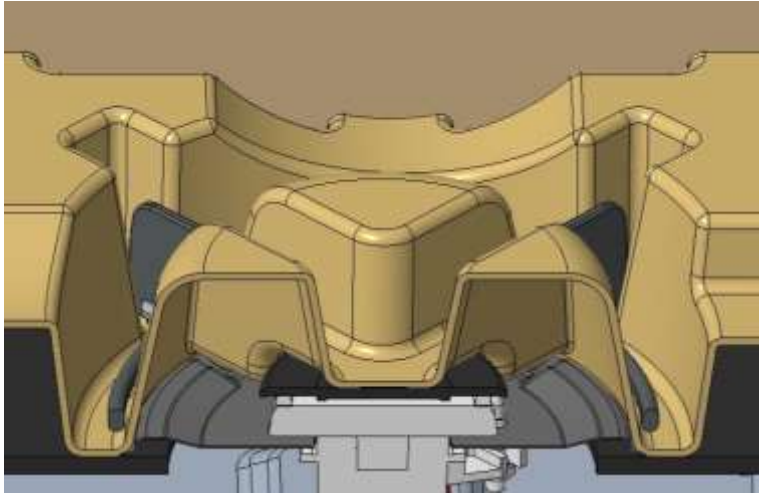
The moving parts of the product, such as the stove grill, coffee pot and plug, which can damage the product, are positioned on the upper side with the packaging material in between. In this way, the surface is protected against possible damage and ease of packaging is provided.



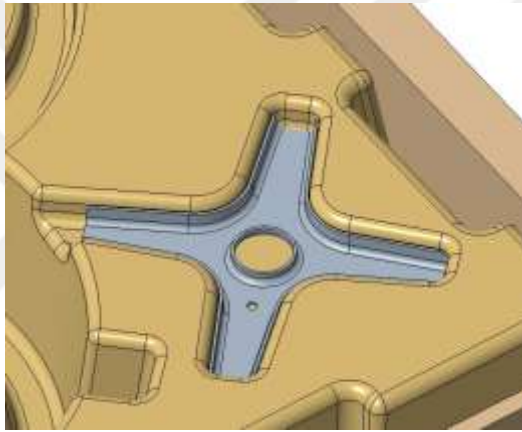
**Figure 3.13:** Cross-section-1 view of grill and top molded part.



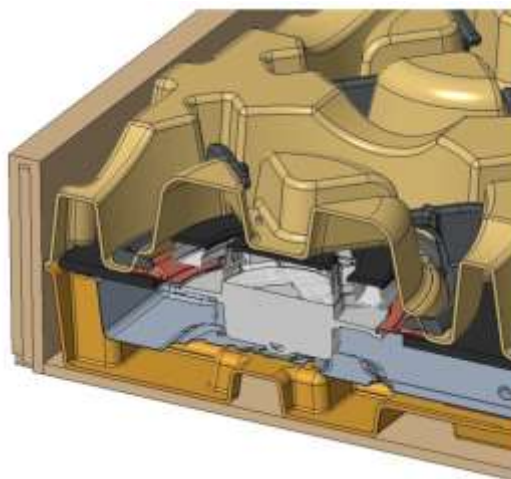
**Figure 3.14:** Cross-section-2 view of grill and top molded part.



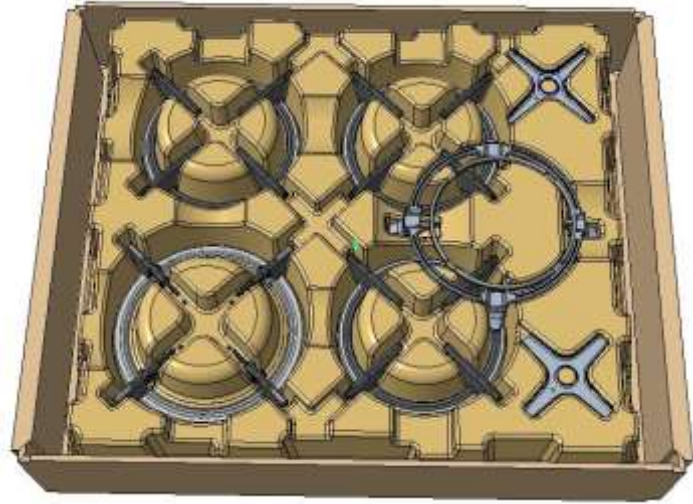
**Figure 3.15:** Cross-section-3 view of grill and top molded part.



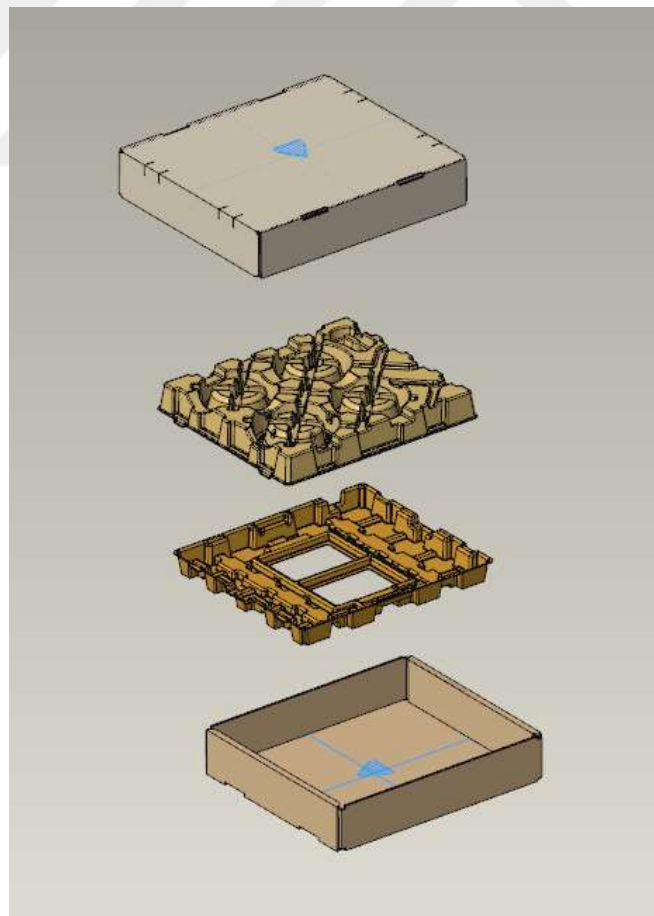
**Figure 3.16:** Detailed view of coffee pot.



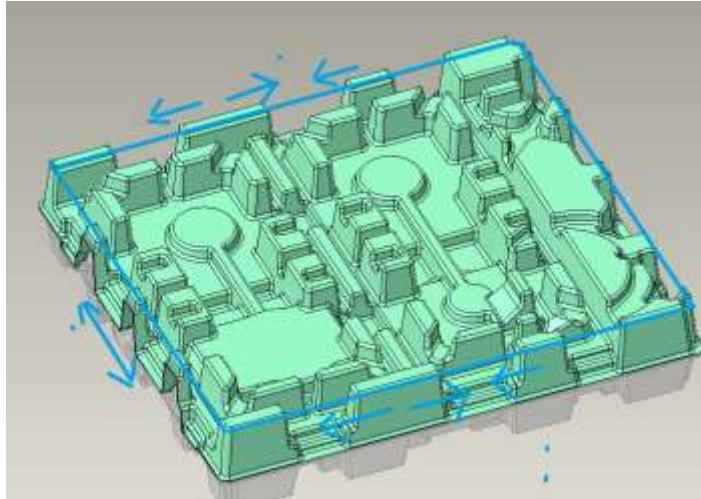
**Figure 3.17:** Assembly of molded parts and outer box.



**Figure 3.18:** Top view of assembly.



**Figure 3.19:** Exploded view of assembly parts 1.



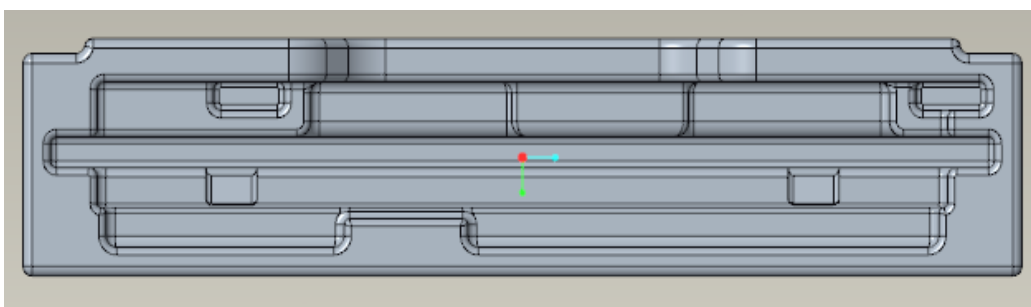
**Figure 3.20:** Peripheral load carrying walls for metal type of gas hobs.

### 3.2.3 Honeycomb based design

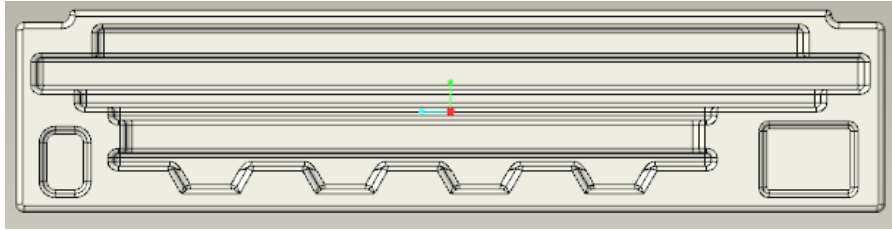
The fact that vitroc ceramic and induction hobs, unlike gas hobs, contain cooking compartments, have no moving parts other than the plug and user manual, and that the model form of the product has straight lines compared to gas hobs necessitated the development of alternative designs.

The path followed when starting a design:

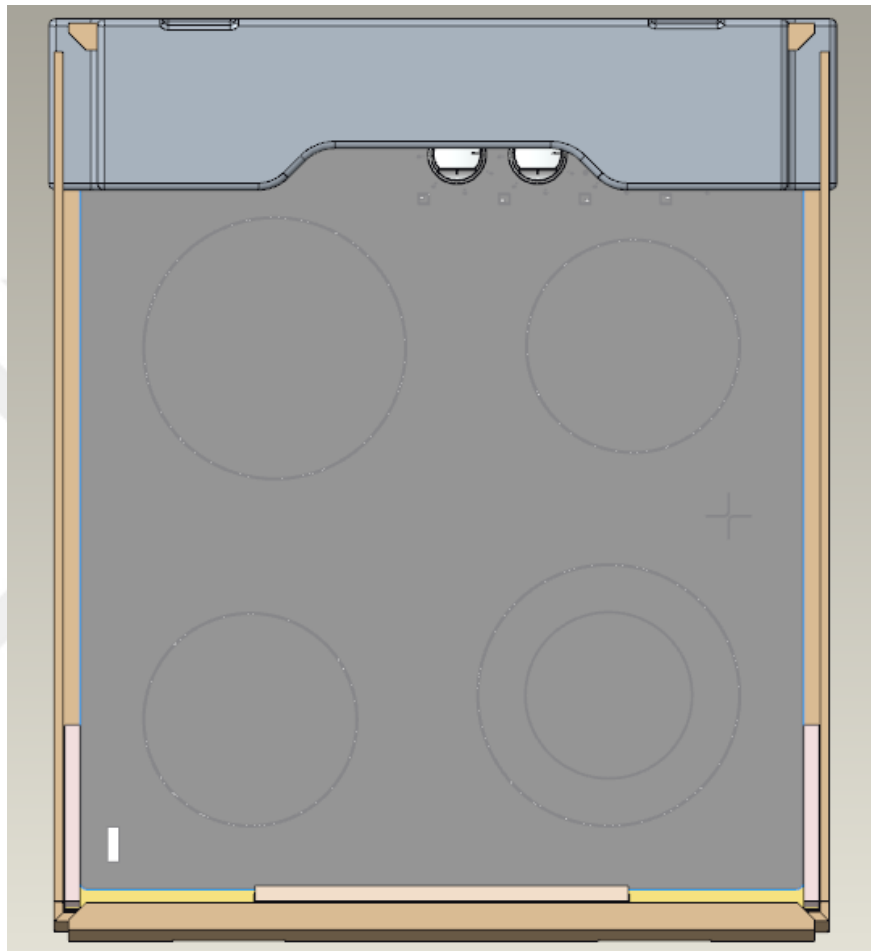
Loading quantities are important for the transportation of products. When starting the design, the priority was not to exceed the packaged exterior dimensions offered on the base model.



**Figure 3.21:** Side EPS 3D model 2.



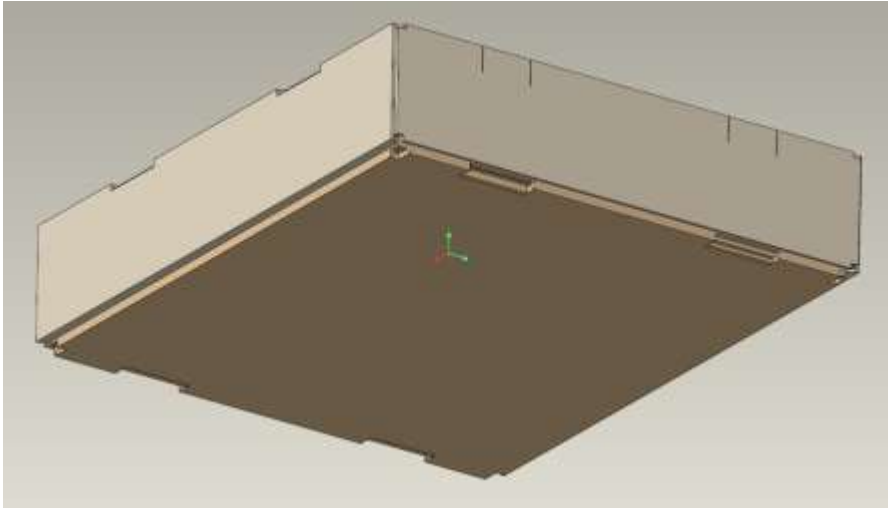
**Figure 3.22:** Side EPS 3D model 3.



**Figure 3.23:** Assembling the designs together and checking their dimensions 2.

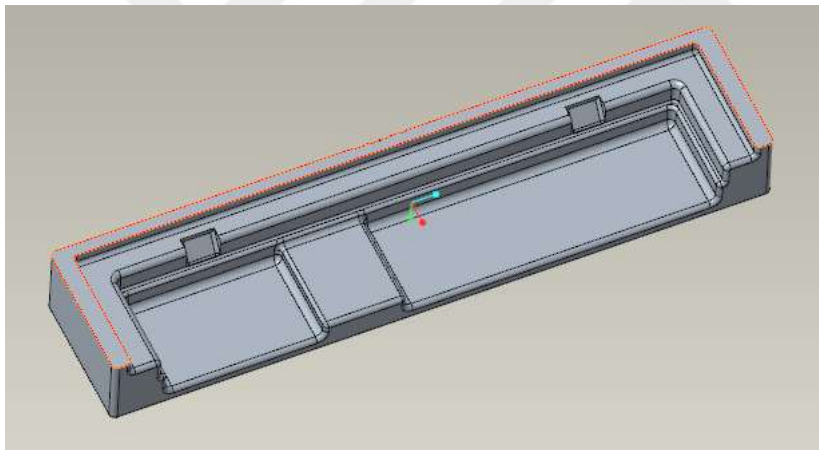
Since the load carrying wall areas of the side EPS materials used in the base model are outside the product, they are surrounded by a telescopic cardboard design that increases vertical load-bearing.

Unlike EPS material, the elastic limit of honeycomb-based packaging is limited, so a design close to the product it will protect is required. For this reason, before the honeycomb-based design, it was aimed to make the four vertical edges as rigid as possible and the locking areas of the upper and lower cartons were made with staggered.

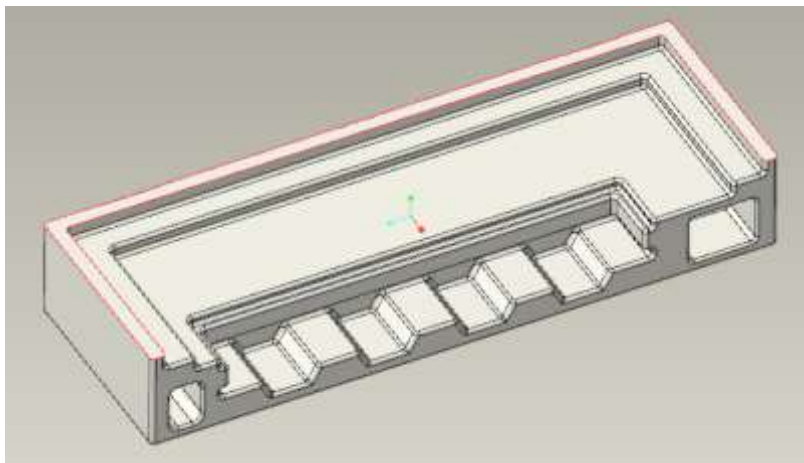


**Figure 3.24:** Outer Box 3D Model 2.

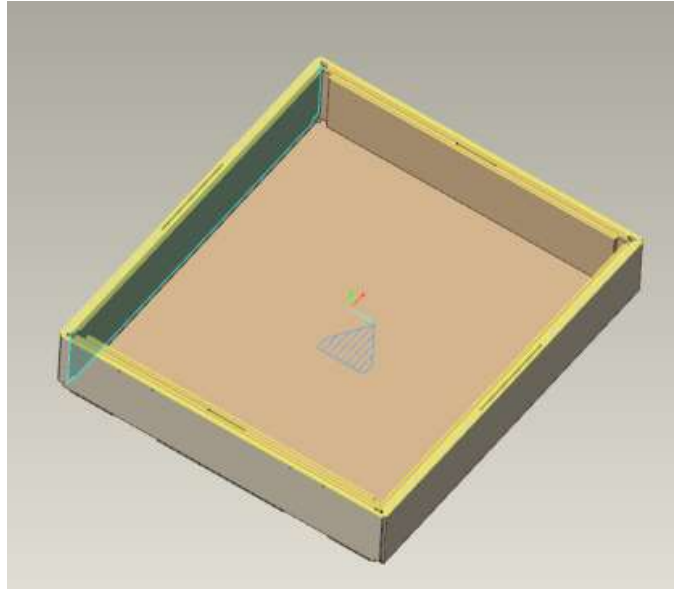
It was aimed to increase the environmental load carrying capacity of the product with an area approximately 2 times larger than the load carrying critical area in the side EPS.



**Figure 3.25:** Critical area of side EPS model 2.



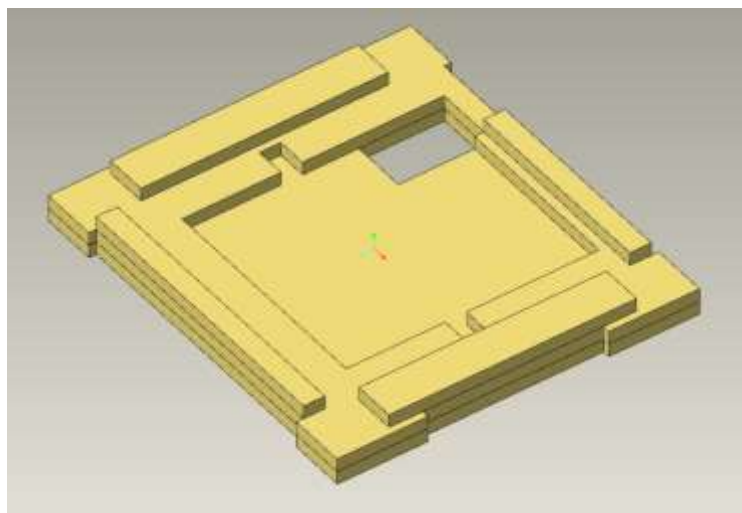
**Figure 3.26:** Critical area of side EPS model 3.



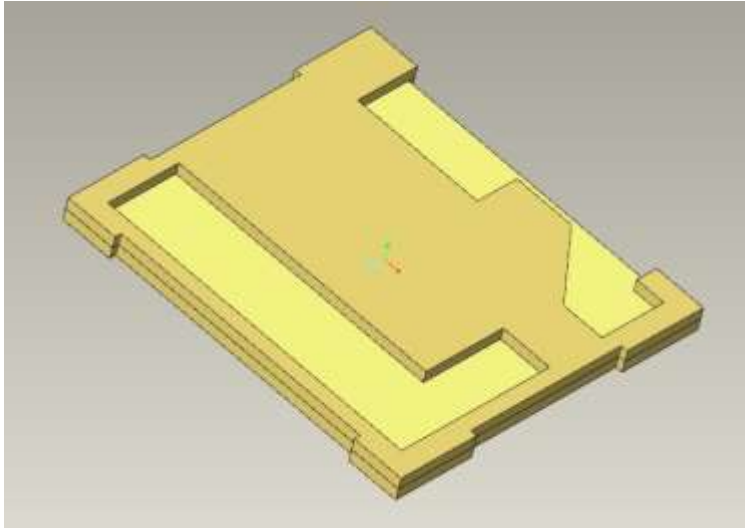
**Figure 3.27:** Section load carrying walls for outer box design 2.

While designing the bottom honeycomb panel, it was considered to unify the bottom cover differences of vitroc ceramic and induction product types in the same package. In this way, a single type of base design was made for induction products and a single type of base design was made for vitroc ceramic products.

As in the molded cellulosic packaging design, a layered honeycomb panel design was used to spread the pressure sequentially to prevent or minimize damage to the bottom of the product, thus providing resistance to multiple drops and the single-layer honeycomb panel is prevented from transmitting the impact.

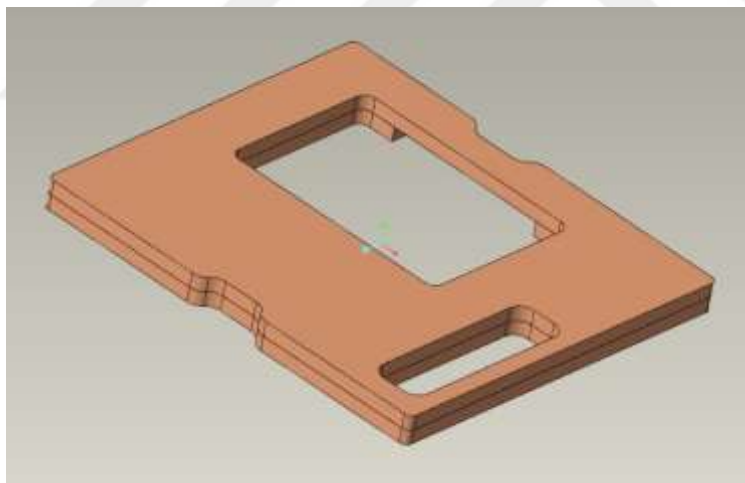


**Figure 3.28:** Honeycomb bottom part for induction hob model.



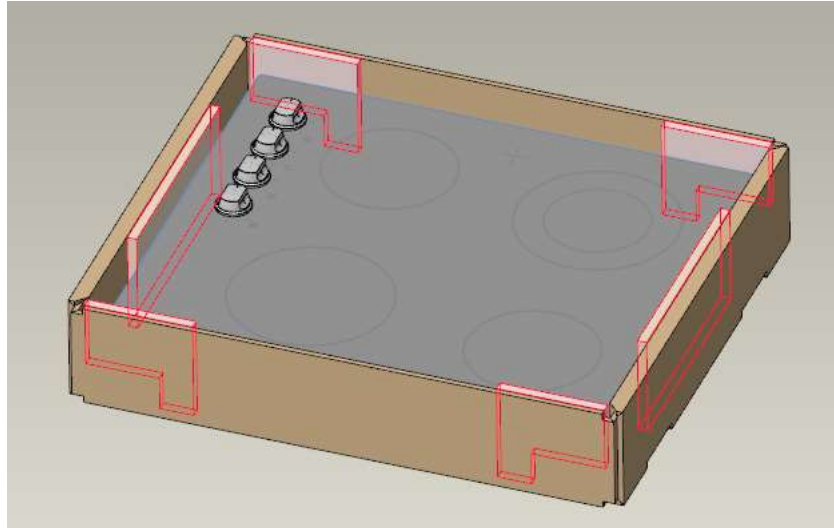
**Figure 3.29:** Honeycomb bottom part for vitroceramic hob model.

As I mentioned above, since the plug and user manual are movable parts of the vitroceramic and induction product groups, a discharge has been created in the middle of the raised upper honeycomb panel part to keep the button-controlled models safe.

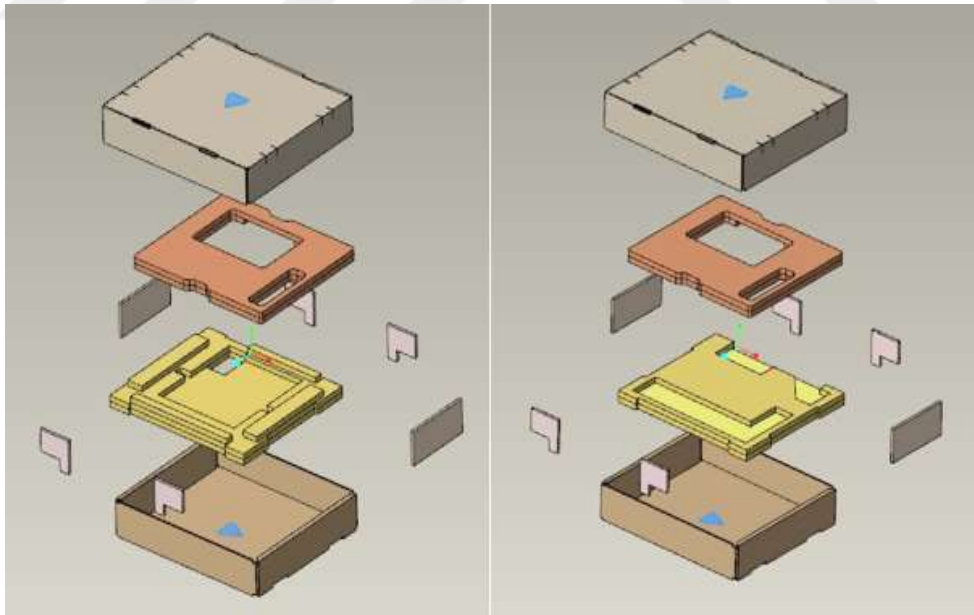


**Figure 3.30:** Honeycomb top part for both induction and vitro-ceramic hob models.

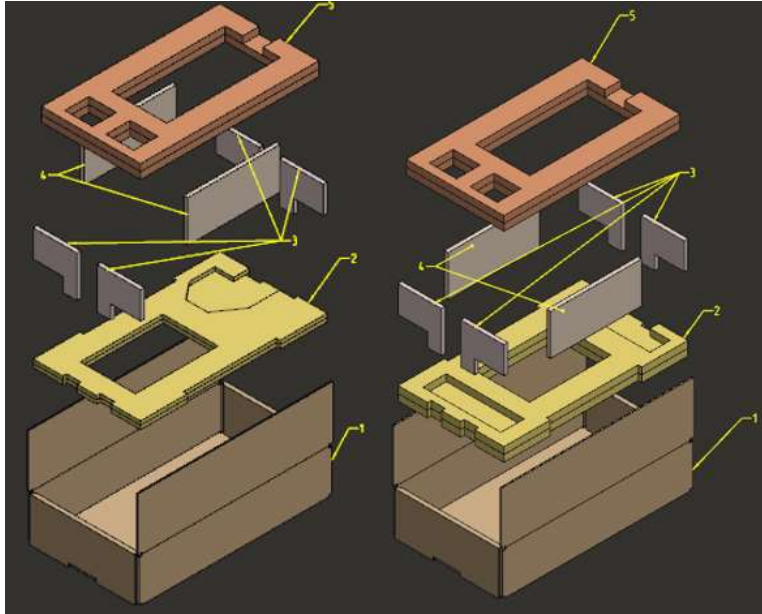
Unlike the design of molded cellulosic packaging, additional protective honeycomb panels have been designed to provide protection at the corners and sides, so that the product is not damaged by the clamping forces at the robot transfer stations, especially during the production and stacking process.



**Figure 3.31:** Honeycomb side and corner parts for both induction and vitro-ceramic hob models.



**Figure 3.32:** Exploded view of assembly parts 2.



**Figure 3.33:** Exploded view of assembly parts 3.

### **3.3 Production Steps**

In the production stages of the designs, the molded cellulosic packaging design, honeycomb panel packaging design and outer telescopic carton design will be explained.

#### **3.3.1 Molded cellulosic packaging design production**

A common bottom molded packaging design was made for the glass and metal surface models in the varieties of gas hobs, and the upper molded packaging design was two different designs due to the differences in the parts used and design.

Since the cost of the molds of the designs made of aluminum raw material was high, both the inner and outer surfaces of each of the models were produced from EPS raw material on CNC machines in order to test the suitability of the packaging on the products.



**Figure 3.34:** EPS model of molded cellulosic top part outer for metal gas hobs.



**Figure 3.35:** EPS model of molded cellulosic part both parts inner.



**Figure 3.36:** EPS model of molded cellulosic top part outer for glass gas hobs.

During the conformity check, the dimensional tolerance of the EPS raw material in the model output and the dimensional stability of the final molded cellulosic product

were taken into consideration and the mold making stage was started with regional interventions.



**Figure 3.37:** Molded cellulose top parts for both gas hob models.



**Figure 3.38:** Molded cellulose bottom part for both gas hob models.

**3.3.2 Honeycomb packaging design production**

The fact that the honeycomb panel is a material produced as a sheet and then cut with a mold consisting of special blades saves a significant amount of time in the initial sampling and control process compared to molded cellulose material.



**Figure 3.39:** Honeycomb panel initial samples.

### 3.3.3 Outer Telescopic Box Design Production

The BCT (Box Compression Test) value of the bottom telescopic cardboard was selected at 1000 kPa against moisture damage that may be encountered in mass production transportation processes. The upper telescopic cardboard was selected as 500 kPa, which is also used in the reference product.



**Figure 3.40:** Outer box size control samples.

After the measurement sample control was carried out, mold production was made and the first prints suitable for mass production were taken as follows.



**Figure 3.41:** Outer box initial mass production samples.



## **4. EXPERIMENTAL STUDY**

### **4.1 Packaging Testing**

#### **4.1.1 Purpose of packaging testing**

The purpose of the packaging test is to ensure the stability of the packaging during transportation, handling and storage for products whose packaging is completely finished. These test ensure that the impacts and stresses that may occur during transportation, storage and handling are foreseen. Both functional and aesthetic requirements must be met before and after packaging tests are carried out.[29]

#### **4.1.2 Test standards**

##### **4.1.2.1 Vertical impact test by dropping**

The drop test is carried out to determine the resistance of the packaged product to falls during manual intervention and mechanical transportation such as loading, unloading, stacking, arrangement, loading on pallets.[30]

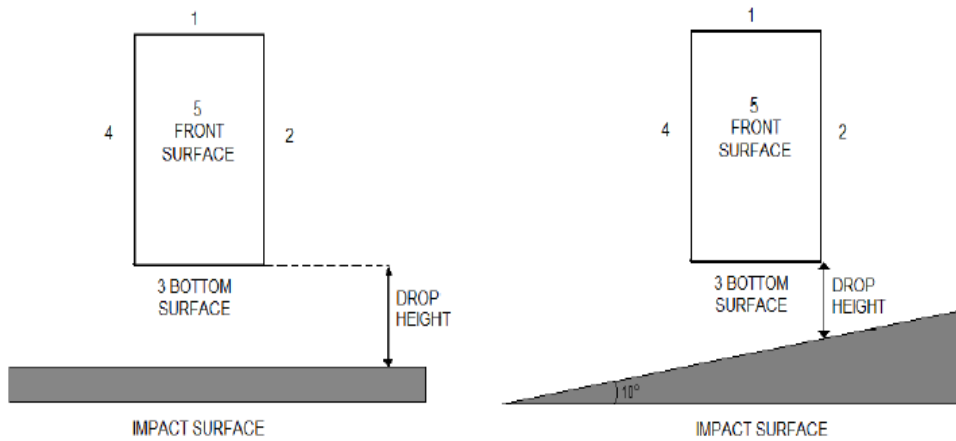
Drop Height:

The distance between the floor and the lowest point of the packaged product. The tolerance of the drop height is 2 percent.

$$\text{Drop Height (DH)} = 70 - X_p \text{ (cm)} \quad (4.1)$$

$X_p$ : It is the definition of the weight of the packaged product (kg) expressed as a number (cm).

DH: Drop height must be minimum 25 cm.



**Figure 4.1:** Drop test scenario demonstration.

During Drop Testing:

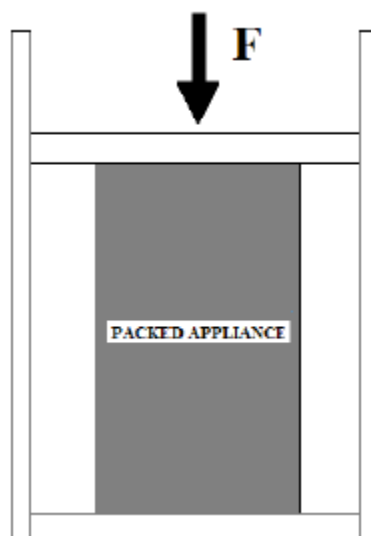
Plane (bottom face)

Front and right edges (bottom edges)

Rear and left edges (bottom edges)

#### 4.1.2.2 Compression and stacking tests using a compression tester

The compression test is carried out to test the resistance of the packaged product to stacking pressure, which is determined by increasing the test load pressure by a safety factor.[31]



**Figure 4.2:** Compression test scenario demonstration.

During Compression Testing:

The force is applied for 8 hours to the center of gravity, based on the formula below,

$$F = 1,5 \times mP \times [(H - h)/h] \times 9,81 \quad (4.2)$$

F: Force (N)

H: Stacking height in the warehouse

h: Overall height of packaged appliance

mP: Gross weight of packaged appliance, packaged mass (kg)

1,5: Safety factor

Test Duration: 8 hours

#### 4.1.2.3 Vibration tests at fixed low frequency

The vibration test is carried out to test the conditions encountered during the transportation of packaged products. Loaded and unloaded tests are performed against dynamic loads.[32]

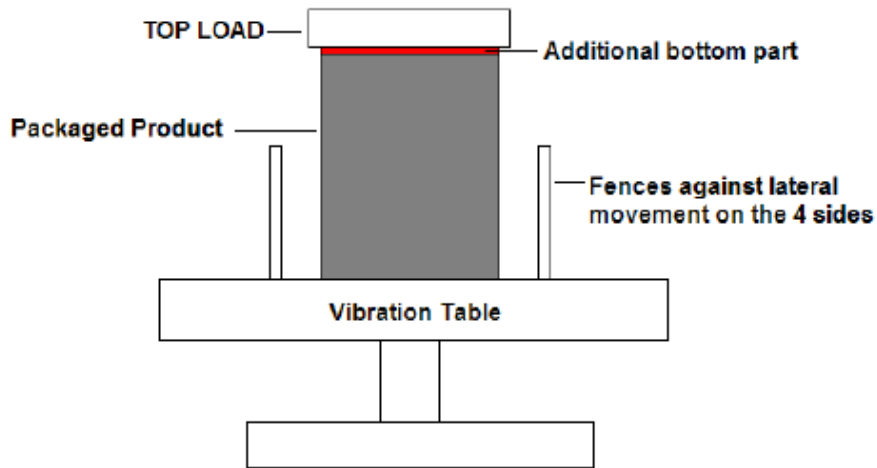
During Vibration Testing:

According to the natural stacking position, the packaged product is tested with its movement across the width and depth of the test table restricted by ropes. The test has to be completed at fixed frequency through vertical direction.

**Table 4.1:** Parameters of vibration testing.

Frequency	4.5 Hz
Waveform	Sinusoidal
Acceleration	1 g
Amplitude	±12.5 mm
Vibration Time	1 hour

The vibration test can be performed by means of the product's own weight and, if desired, the addition of a top load.



**Figure 4.3:** Vibration test scenario demonstration.

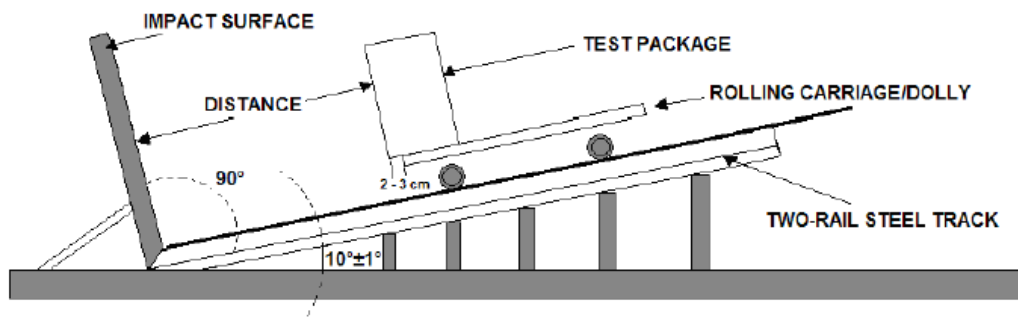
An optional vibration profile can also be made as follows.

**Table 4.2:** Optional vibration profile.

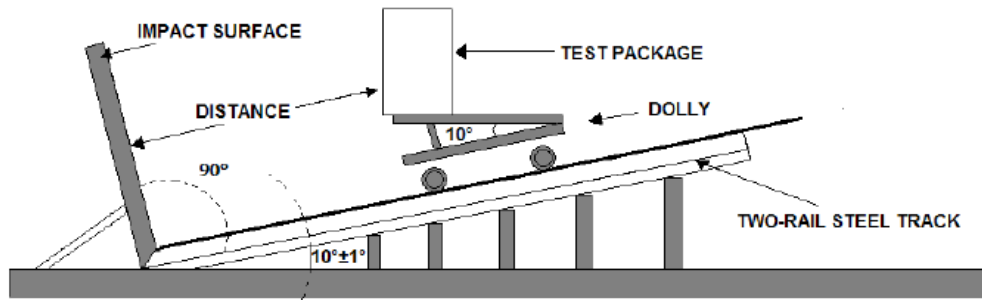
Frequency Hz	Power density $G^2/Hz$	Pitch dB/Octave
1	0.00010	9.97
4	0.01000	0
16	0.01000	-7.54
40	0.00100	0
80	0.00100	-15.08
200	0.00001	(<0)

#### 4.1.2.4 Horizontal impact tests-inclined impact test

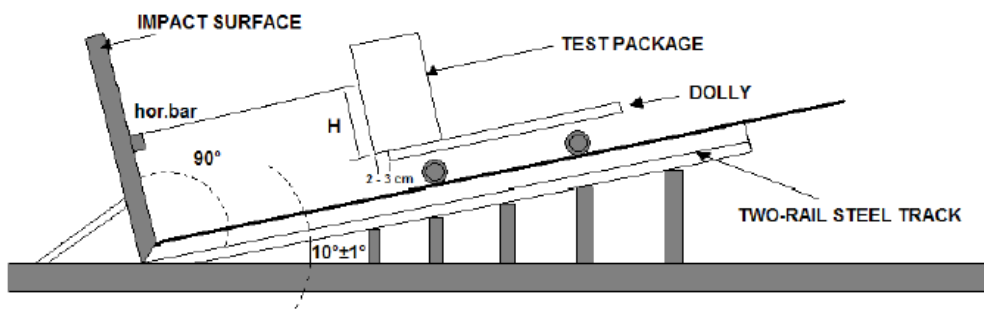
In the inclined plane impact test, all perpendicular surfaces and base edges are tested. The packaged product is placed in the test rig so that the impact surface protrudes 2-3 cm from the rig. The impact speed or impact distance of the packaged product shall be 2.1 m/s or 1,5 m, respectively.[33]



**Figure 4.4:** Testing for perpendicular surfaces.



**Figure 4.5:** Testing for perpendicular base edges.



**Figure 4.6:** Testing for local stresses.

#### 4.1.2.5 Conditioning for testing

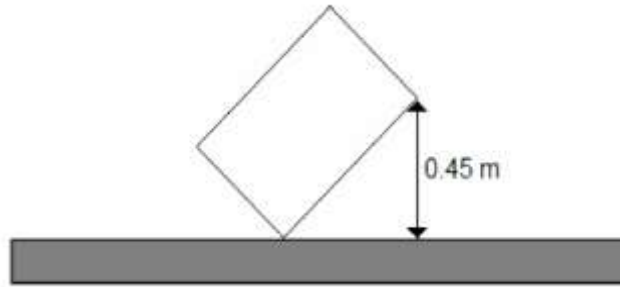
A range of climatic conditions are applied to the packaged product to reflect the climatic conditions encountered by the packaged product during production, storage and transportation. These conditions are referred to as arctic, normal and tropical. In these climatic conditions, temperature values as well as relative humidity values are variably applied on the packaged product. This test, which is carried out in a climate chamber isolated from the environment, fulfills 3 conditions for a total of 24 hours.[34]

**Table 4.3:** Parameters for conditioning.

Area	Temperture	Relative Humidity
Area of Application	$-25^{\circ}\text{C} < t < 70^{\circ}\text{C}$	$\text{H} < 90$
Test Condition	Normal	$23 \pm 5^{\circ}\text{C}$
	Tropical	$37 \pm 3^{\circ}\text{C}$
	Arctic	$-17 \pm 3^{\circ}\text{C}$

#### 4.1.2.6 Upsetting test

Upsetting test visualizes the shocks encountered by the products being transported in a load-unload scenario.



**Figure 4.7:** Upsetting test scenario demonstration.

## 4.2 Materials and Methods

### 4.2.1 Materials

#### 4.2.1.1 Reference models materials

There are side EPSs, base and top EPSs used in the reference model. In addition, integrity is created with plastic bag and grid cardboard. Since the side parts in EPS material are the main parts that protect the product, their density is different from the support parts and is  $24 \text{ kg/m}^3$ . The densities of the upper and lower support parts are  $20 \text{ kg/m}^3$ . The grid cardboard, which is used except for the EPS materials of the product, is used to prevent the grids from moving freely in the package and damaging the product.

#### 4.2.1.2 Molded cellulosic based design materials

Recycled cardboard packaging used in the waste paper industry, recycled cardboard packaging, newspaper waste can be used in high quality kraft trimmings according to changing demand. Since sustainability is important in this design, the mold was printed with raw materials produced entirely from recycled materials. This choice is also relatively competitive in terms of unit price. The plastered thickness of the molded material varies between 2.5-3 mm. When the raw material used in two different designs is molded and then printed, the lesser thickness of the material will

cause tears. Increasing the thickness of the raw material will also cause clumping and change the dimensional accuracy of the model.

#### **4.2.1.3 Honeycomb based design materials**

In this design, which is in the PAP 21 class, there are testliner and kraftliner in the raw material options. Since the desired material behavior varies in different types of product groups such as built-in ovens, panel choices vary. Paper weight options were 135 g/m<sup>2</sup> for testliner and 275 g/m<sup>2</sup> for kraftliner. After the experience of the supplier industry and literature research, it was decided to start the designs of the furnace products with a cell diameter of 16 mm. Also it was decided to choose 10 mm cell diameter for honeycomb panels to be used in other heavy products.

In the designs that can be made from single-layer honeycomb panels in the form of crushing by making multi-layer honeycomb panels and molds, the unpredictability of the mechanical behavior of the crushing method and the explosion of the carrier cell structures led us to make our design in multi-layer form. Instead of using honeycomb panels of different thicknesses that may behave scattered in layer thicknesses, the total thicknesses to be worked with were made by gluing layers in equal steps.

Due to the fact that liner paper is not very effective in carriage and the concept of sustainability, recycled paper with a density of 135 g/m<sup>2</sup> was the raw material used for the majority of the design. Honeycomb panel layer thicknesses are concentrated on using 20 mm considering concepts such as strength, shock absorption, buckling, load transmission and labor.

The graph above shows the types of honeycomb panel parts abbreviated as P.P. In this graph, the samples are differentiated according to the number of layers, thickness and honeycomb diameter information.

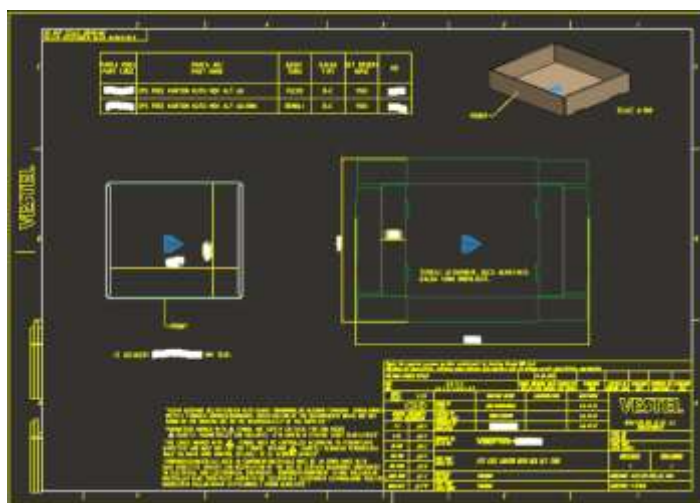
**Table 4.4:** Types of honeycomb panel parts.

<b>Specimen Name</b>	<b>Specimen Dimensions (WxDxH)(mm)</b>	<b>Specimen Types (Mesh diameter mm)</b>
1. Honeycomb Panel Comer Piece	[(127x120)-(87x41)]x11[x1 layer]	<b>16</b>
2. Honeycomb Panel Ind. Bottom Plastic Base Support	200x200x20[20x1 layers]	<b>16</b>
3. Honeycomb Panel Ind. Bottom Cable Gap	<b>200x65x40</b> [20x2 layers]	<b>16</b>
4. Honeycomb Panel Ind. Bottom Al. Cover Support	<b>250x65x60</b> [20x3 layers]	<b>16</b>
5. Outer Box		
6. Honeycomb Panel Top Support	[20x2 layers]	<b>16</b>
7. Honeycomb Panel Domino Ind. Bottom	<b>250x65x22</b> [11x2 layers]	<b>16</b>
8. Honeycomb Panel Domino Vit.Bottom	<b>200x65x40</b> [20x2 layers]	<b>16</b>
9. Honeycomb Panel Domino Vit./Ind.Top	[20x2 layers]	<b>16</b>
10. Honeycomb Panel Handle Protection	<b>500x60x50</b> [50x1 layer]	<b>16</b>
11. Honeycomb Panel (Y66,D61, Bottom)	<b>210x210x30</b> [30x1 layer]	<b>10</b>
12. Honeycomb Panel Oven Front Support	<b>240x45x11</b> [11x1 layer]	<b>10</b>
13. Honeycomb Panel Rear Support	<b>75x70x41</b> [15+11+15 3 layers]	<b>10</b>
14. Honeycomb Panel Front Support	<b>150x60x41</b> [25+16 2 layers]	<b>10</b>

#### 4.2.1.4 Outer telescopic box design materials

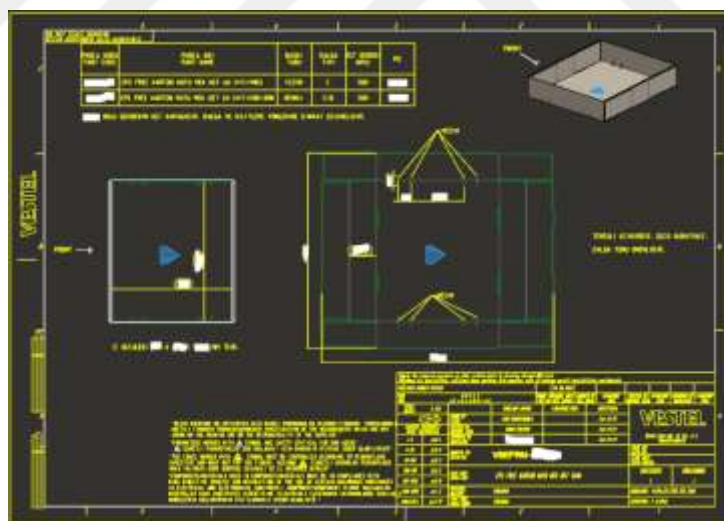
As mentioned earlier in the design of the outer carton box, the bottom cardboard was selected with an average BCT of 1100 kPa in order to withstand the variability of humidity conditions and other harsh conditions.

Testliner was chosen as a raw material paper, 150 g/m<sup>2</sup> for the inside and outside 165 g/m<sup>2</sup> for the flutes. The fact that the base cardboard has a structure containing B+C wave double flute contributes to the load bearing support as well as environmental protection.



**Figure 4.8:** Outer box bottom technical drawing.

In the top carton material selection, 500 kPa was calculated as the minimum value to support the bottom carton to withstand the load conditions. C wave cardboard with a single flute for the upper cardboard is intended to provide support for the lower cardboard. In addition, the fact that it is C wave adds flexibility to the loading, as the dimensions are taken into consideration in terms of loading quantities.



**Figure 4.9:** Outer box top technical drawing.

## 4.2.2 Methods

### 4.2.2.1 Devices

The devices on which the tests of products and samples are carried out are as follows. All tests of the products were conducted at the accredited Vestel Packaging Test Laboratory.



**Figure 4.10:** Drop testing machine.

The height adjustment mechanism sets the height at which the test is performed. This height is usually determined by the type of packaging, weight and transportation conditions. The drop systems work with a system (spring system, electric mechanism) that allows the package to fall freely. The height at which the test is performed is determined by the physical characteristics of the packaging and the transportation conditions. This height can usually range from 0.3 meters to 1.8 meters. The package may need to be dropped from different angles. This is important to see the product's resistance to all types of drop scenarios. The drop can be tested at horizontal, vertical or oblique angles. The package is released and allowed to impact with the impact from the ground.



**Figure 4.11:** Compression testing machine.

The packaging compression tester is used to test the resistance of packaging, in particular boxes, pallets and other types of packaging, to compression loads during transportation, storage and handling. This test simulates the compression of the packaging by other superimposed loads during transportation. Compression testing is particularly important for evaluating packaging design in industries where large quantities of products are transported and stored (e.g. logistics, retail, food packaging). The packaging selected for testing (e.g. cardboard box, plastic box, etc.) is placed on the instrument's test platform. The compression tester includes a control panel or mechanism to set the force or pressure to be applied to the packaging, which is adjusted to simulate the actual amount of stress the packaging will be subjected to during transportation and storage. For example, the loads on boxes on a pallet can be tested in this way. This pressure is applied by a hydraulic press and a heavy pressure plate. The pressure can be applied incrementally at a constant rate throughout the test, or it can increase continuously over a period of time. During the test, an increasing force is applied to the packaging, usually until the pressure reaches a certain value. During the compression test, the package may change shape, crush or damage the products inside. Distortions in the shape of the packaging, breaks, tears or deformations in the interior of the products are examined. [36]



**Figure 4.12:** Vibration testing machine.

The packaging vibration tester is a test device used to determine how well the packaging of products withstands dynamic loads, especially shock and vibration, during transportation and storage. The vibration test simulates the effects of vehicle

movement during transportation, road vibrations or other moving factors that products may encounter during packaging. This test evaluates the durability of products and packaging by modeling the vibrations that products and packaging will be exposed to, especially in transport vehicles (trucks, trains, ships, airplanes). First, the packaging to be tested is placed on the instrument's platform or vibration table. There may be labels or sensors on the packaging; this is used to monitor the changes that occur during the test. The vibration test instrument can be set with various parameters according to the purpose of the test. The vibration frequency is usually expressed as the number of vibrations per second (Hz). The purpose of the test is to simulate the vibration effect at a given frequency (e.g. 5-100 Hz).

The intensity or amplitude of the vibration refers to the magnitude of the force exerted on the packaging. The duration of the test is usually measured in millimeters (mm) or inches. The duration of the test is usually determined in minutes or hours, and it is decided how long to apply the vibration. The vibration can be applied in different directions, usually linear (unidirectional) and in three axes (x, y, z). This allows an assessment of how the packaging performs in different directions. The packaging vibration test instrument applies a continuous or cyclic vibration motion according to a specified frequency, amplitude and duration.[37]



**Figure 4.13:** Horizontal impact testing machine.

The packaging inclined plane impact tester is a test device used to simulate the effects of drops and impacts to which packaging is subjected during transportation, storage and other operational processes. This test tests the durability of the packaging by causing it to impact a surface on an inclined plane from a specified height to

determine whether the product can be properly protected. The packaging selected for the test, together with the product, is placed in the inclined plane tester and the inclined angle of the plane to be tested is set. The inclined plane is set at an angle, but this angle may vary depending on the standards used and the requirements of the test. This angle is related to the angle at which the package will fall. The height to be used in the test is determined to simulate the effect of the package falling. The height should be consistent with the possible heights in transportation and storage conditions.

The inclination on the inclined plane causes the package to hit the ground at an oblique angle instead of in free fall. The package slides from the apex of the test platform and moves downward along the inclined plane, striking a hard surface at the end of the plane at a designated point. The impact surface is usually made of a hard material (e.g., steel, concrete or hard plastic). This more accurately simulates the impact effects that the package would experience under real-world conditions.[38]

The shape of the packaging after a fall, damage to the outer surface, deformations, cracks and tears are observed. The purpose of the test is to determine how well the packaging protects the product and to identify potential weak points. The product is assessed for any damage, deformation or deterioration.



**Figure 4.14:** Conditioning testing machine.

The packaging acclimatization tester is a test device used to test the durability of packaging against different environmental conditions. It simulates how packaging performs against changes in temperature, humidity and other atmospheric factors.

Climatic testing is essential to ensure the durability of packaging and product protection during transportation, storage and logistics processes. The package to be tested is placed in the instrument's climate chamber.

This is necessary to assess whether the package can properly protect the product inside. Prior to testing, temperature and humidity conditions are determined. These conditions are chosen to be similar to real-world conditions that the package may encounter during transportation and storage. For example: Typically, the temperature during testing can range from -20°C to 60°C. This is necessary to simulate conditions in cold environments in winter or hot tropical climates.

Humidity can be set between 10% and 95%. The response of packaging, especially sensitive products such as food and pharmaceuticals, to humid environments is evaluated. The resistance of the packaging to rapid changes in temperature and humidity can also be tested. For example, sudden changes in temperature or increases in humidity. During the test, the instrument creates the specified temperature conditions indoors. When the temperature rises, the device uses heaters, and when it cools, it cools the environment with cooling systems. Humidity is controlled by a humidifier or vapor device placed inside the device.

For example, the package is held at a certain temperature and humidity level, then suddenly switched to another temperature and humidity level to assess the effect of temperature changes on the package. This is referred to as “thermal shock” or “humidity shock” tests. The test can usually last from a few hours to several weeks.[39]

## 5. RESULTS AND DISCUSSION

The designs were tested according to the packaging test procedure. To simplify the test results and visualizations, they are numbered as models. The test were carried out according to the information on the use of nonwoven PP and plastozoid in the numbered models.

**Tablo 5.1:** Model numbers according to design type.

Model	Design Type	Nonwoven PP/Plastozoid LDPE-4
1	Reference Model	20 g/m <sup>2</sup> Plastozoid
2	Reference Model	40 g/m <sup>2</sup> Plastozoid
3	Reference Model	70 g/m <sup>2</sup> Plastozoid PP
4	Molded Cellulosic Based Design/Metal	x
5	Molded Cellulosic Based Design/Metal	20 g/m <sup>2</sup> Plastozoid
6	Molded Cellulosic Based Design/Metal	70 g/m <sup>2</sup> Plastozoid PP
7	Molded Cellulosic Based Design/Glass	x
8	Molded Cellulosic Based Design/Glass	20 g/m <sup>2</sup> Plastozoid
9	Molded Cellulosic Based Design/Glass	70 g/m <sup>2</sup> NonwovenPP
10	Honeycomb Based Design/Vitrocera- mic-Knob	x
11	Honeycomb Based Design/Vitrocera- mic-Touch	x
12	Honeycomb Based Design/Vitrocera- mic-Knob	20 g/m <sup>2</sup> Plastozoid
13	Honeycomb Based Design/Vitrocera- mic-Touch	20 g/m <sup>2</sup> Plastozoid
14	Honeycomb Based Design/Induction	x
15	Honeycomb Based Design/Induction	20 g/m <sup>2</sup> Plastozoid
16	Honeycomb Based Design/Vitrocera- mic-Domino	x
17	Honeycomb Based Design/Induction- Domino	x

In accordance with the packaging test standards, the test conditions of the products have been determined and the compression forces and drop heights have been determined according the types.

For products with glass surfaces, the test was carried out both according to the product weight and by following the minimum drop height rule. The first outputs of the models that can be used in mass production were taken from the honeycomb panel design.

The outputs of the molded cellulosic packaging were left to the last due to the mold making process. In the test process that started with the honeycomb panel, firstly, in order to observe the variability in the drop height, the minimum drop height was performed with models 10, 11 and 14 in accordance with the 70-product weight rule as in the standard. In order to observe the impact dampening by increasing the drop height, the drop was repeated on the smaller products, models 16 and 17. No damage was observed on the products.

In addition, while similar performance was observed in the base parts of the honeycomb panels in both drop conditions, it was found that the impact on the parts became more pronounced with the increase in height in the edge guards. This supports the energy absorption data with increasing speed and height in the literature research. After determining the mechanical behavior of the honeycomb panel in multiple tests and making minor improvements on the designs, we focused on the cosmetic dusting caused by the core structure of the paper on the product.

Tests were carried out on models 12, 13 and 15 for the cosmetic protection of the product surfaces with the LDPE-4 Plastrozoid material with a density of  $20 \text{ g/m}^2$ , which is currently used in this regard. The test results showed that the surface was protected by the plastrozoid as expected.

**Tablo 5.2:** Compression force, maximum deviation and drop height according to models.

<b>Model</b>	<b>Design Type</b>	<b>Compression Force (N)</b>	<b>Maximum Deviation(m)</b>	<b>Drop Height(cm)</b>	<b>Vibration Effect</b>
1	Reference Model	2213	16	25	x
2	Reference Model	2213	13	25	x
3	Reference Model	2213	15	25	x
4	Molded Cellulosic Based Design/Metal	2200	11	60	Yes
5	Molded Cellulosic Based Design/Metal	2200	13	60	x
6	Molded Cellulosic Based Design/Metal	2200	12	60	x
7	Molded Cellulosic Based Design/Glass	2420	10	59	Yes
8	Molded Cellulosic Based Design/Glass	2420	9	59	Yes
9	Molded Cellulosic Based Design/Glass	2420	10	59	x
10	Honeycomb Based Design/Vitroceraamic-Knob	2200	7	25	x
11	Honeycomb Based Design/Vitroceraamic-Touch	2200	6	25	Yes
12	Honeycomb Based Design/Vitroceraamic-Knob	2200	6	25	x
13	Honeycomb Based Design/Vitroceraamic-Touch	2200	7	25	x
14	Honeycomb Based Design/Induction	2200	7	60	Yes
15	Honeycomb Based Design/Induction	2200	8	60	x
16	Honeycomb Based Design/Vitroceraamic-Domino	1325	6	64	Yes
17	Honeycomb Based Design/Induction-Domino	1325	7	25	Yes



**Figure 5.1:** Model 1 testing.

Model 1 was tested with a compression force of 2213 N and showed a collapse of 16 mm. The drop height was 25 cm.



**Figure 5.2:** Model 2 testing.



**Figure 5.3:** Model 3 testing.

Model 3 was tested with a compression force of 2213 N and showed a collapse of 15 mm. The drop height was 25 cm. As a result of the compression test applied on the reference model types, the collapse values were measured as 16, 13, 15 mm, respectively. Contact and waste damage was found on the product surface in the first two models using plastooids.

In the model using nonwoven PP, no damage was found on the product surface, although point holes were formed on the inner parts of the grid. In the reference model design, the spikes in the inner regions of the gratings are getting closer to the surface with the transmission of the stack load with safety coefficient, although the grating buffers are supportive here, it triggers damage formation by slipping the centering during transportation.

The spikes of the slightly off-center grating caused hole formation in the sequential tests of 3 different materials, but the hole formed on the nonwoven PP fabric did not cause any damage on the underside.



**Figure 5.4:** Model 4 testing.

Model 4 was tested with a compression force of 2200 N and showed a collapse of 11 mm. The drop height was 60 (70-Gross weight) cm.



**Figure 5.5:** Model 5 testing.

Model 5 was tested with a compression force of 2200 N and showed a collapse of 13 mm. The drop height was 60 (70-Gross weight) cm.



**Figure 5.6:** Model 6 testing.

Model 6 was tested with a compression force of 2200 N and showed a collapse of 12 mm. The drop height was 60 (70-Gross weight) cm. As a result of the compression test applied on the molded cellulosic based design/metal types, the collapse values were measured as 11, 13, 12 mm, respectively. Although the test gave good results due to the improvement of the outer cardboard used in the design compared to the reference model and the contribution of the pressure spreading in the molded cellulosic model, dusting and capillary scratches were observed on the product surface for the first model (model 4) in the vibration test. In Models 5 and 6, no damage was observed on the product surface by placing plastozoid and nonwoven PP under the overmolded material. When the mechanical collapse levels of the molded

cellulosic material and the honeycomb panel material are compared, it is seen that the pressures generated in the molded cellulosic material design are regionally concentrated. These areas left marks on the plastozoid but did not damage the surface of the hob. In order to provide more stable results of this test, models 6 and 9 containing nonwoven PP fabric were tested as an alternative and no compressive effect was observed.



**Figure 5.7:** Model 7 testing.

Model 7 was tested with a compression force of 2420 N and showed a collapse of 10 mm. The drop height was 59 (70-Gross weight) cm.



**Figure 5.8:** Model 8 testing.

Model 8 was tested with a compression force of 2420 N and showed a collapse of 9 mm. The drop height was 59 (70-Gross weight) cm.



**Figure 5.9:** Model 9 testing.

Model 9 was tested with a compression force of 2420 N and showed a collapse of 10 mm. The drop height was 59 (70-Gross weight) cm. As a result of the compression test applied on the molded cellulosic based design/metal types, the collapse values were measured as 11, 13, 12 mm, respectively.

In Model 7, dusting on the metal table surface is observed. No scratches were observed on the glass surface. Like models 5 and 6, no capillary damage was observed in models 8 and 9.



**Figure 5.10:** Model 10 testing.

Model 10 was tested with a compression force of 2200 N and showed a collapse of 7 mm. The drop height was 25 cm.



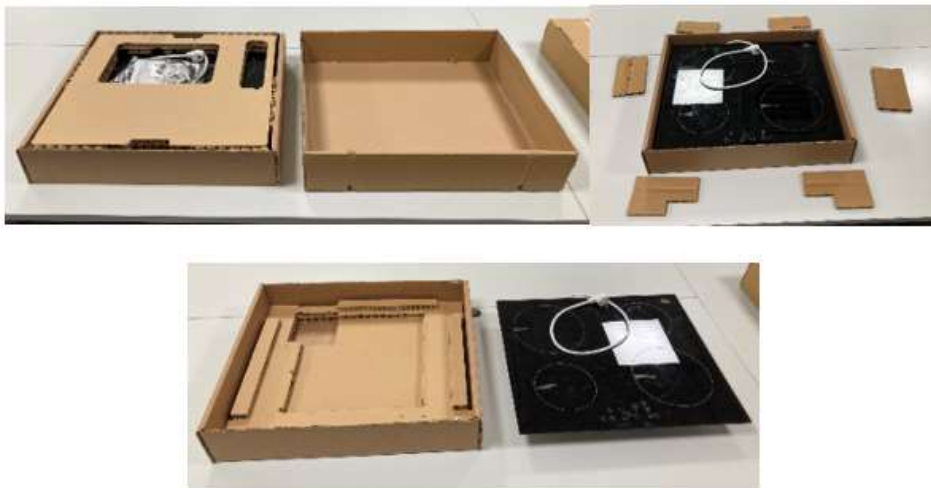
**Figure 5.11:** Model 11 testing.

Model 11 was tested with a compression force of 2200 N and showed a collapse of 6 mm. The drop height was 25 cm.



**Figure 5.12:** Model 12 testing.

Model 12 was tested with a compression force of 2200 N and showed a collapse of 7 mm. The drop height was 25 cm.



**Figure 5.13:** Model 13 testing.

Model 13 was tested with a compression force of 2200 N and showed a collapse of 7 mm. The drop height was 60 (70-Gross weight) cm.



**Figure 5.14:** Model 14 testing.

Model 14 was tested with a compression force of 2200 N and showed a collapse of 8 mm. The drop height was 60 (70-Gross weight) cm. In designs using honeycomb panels, capillary marks were observed similar to molded cellulosic designs, but the reason here is a mark created by the compression force of the mesh structure of the core section.



**Figure 5.15:** Model 15 testing.

Model 15 was tested with a compression force of 1325 N and showed a collapse of 6 mm. The drop height was 64 (70-Gross weight) cm.



**Figure 5.16:** Model 16 testing.

Model 16 was tested with a compression force of 1325 N and showed a collapse of 7 mm. The drop height was 25 cm. Apart from the packaged tests of the products, the local carrying capacity of the parts used was tested by giving controlled deviation values in a compression test machine. The specimens classified according to the part differences before the test were cut in the specified dimensions and entered the test. After the test, calculations were made according to each specimen area and stress values were calculated.

**Tablo 5.3:** Pressure and deviation values.

Specimen Name	Controlled Deviation (mm)	Carried Load at Controlled Deviation	Specimen Area(mm <sup>2</sup> )	Specimen Pressure(N/mm <sup>2</sup> ) (MPa)
1- Honeycomb Panel Comer Piece	3	3178	11673	0,272
2- Honeycomb Panel Ind. Bottom Plastic Base Support	4	2000	40000	0,050
3- Honeycomb Panel Ind. Bottom Cable Gap	7	1100	13000	0,085
4- Honeycomb Panel Ind. Bottom Al. Cover Support	6	1364	16250	0,084
5- Outer Box	8 ve 13	1001 ve 1727		
6- Honeycomb Panel Top Support	Same as Specimen 3	1100		
7- Honeycomb Panel Domino Ind. Bottom	3	1059	13000	0,081
8- Honeycomb Panel Domino Vit. Bottom	4	1218	13000	0,094
9- Honeycomb Domino Vit./ Ind. Top	Same as Specimen 3	1100		
10-Honeycomb Panel Handle Protection	3	2227	30000	0,074
11-Honeycomb Panel(Y66,D61, Bottom)	3	1325	44100	0,030
12-Honeycomb Panel Oven Front Support	3	2021	10800	0,187
13-Honeycomb Panel Rear Support	4	540	5250	0,103
14-Honeycomb Panel Front Support	4	1400	9000	0,156

**Tablo 5.4:** Weight information by specimens.

Specimen Name	Specimen Dimensions(WxDxH) (mm)	Specimen Types(Mesh diameter mm)	Specimen Weight(g)	g/m <sup>2</sup>
1- Honeycomb Panel Corner Piece	[(127x120)-(87x41)]x11[11x1 layer]	16	9,5	813,8
2- Honeycomb Panel Ind. Bottom Plastic Base Support	200x200x20 [20x1 layers]	16	40,4	1010,0
3- Honeycomb Panel Ind. Bottom Cable Gap	200x65x40 [20x2 layers]	16	22	1692,3
4- Honeycomb Panel Ind. Bottom Al. Cover Support	250x65x60 [20x3 layers]	16	35,3	2172,3
5- Outer Box				0,0
6- Honeycomb Panel Top Support	[20x2 layers]	16		0,0
7- Honeycomb Panel Domino Ind. Bottom	200x65x22 [11x2 layers]	16	13,7	1053,8
8- Honeycomb Panel Domino Vit. Bottom	200x65x40 [20x2 layers]	16	18,3	1407,7
9- Honeycomb Domino Vit./ Ind. Top	[20x2 layers]	16		0,0
10- Honeycomb Panel Handle Protection	500x60x50[50x1 layer]	16	40,3	1343,3
11- Honeycomb Panel(Y66,D 61, Bottom)	210x210x30[30x1 layer]	10	51,7	1172,3
12- Honeycomb Panel Oven Front Support	240x45x11 [11x1 layer]	10	7,4	685,2
13- Honeycomb Panel Rear Support	75x70x41[15+11+15 3 layers]	10	12,4	2361,9
14- Honeycomb Panel Oven Front Support	150x60x41[25+16 2 layers]	10	19,4	2155,6

In order to compare the data of the literature research in honeycomb panel design, controlled collapse tests were performed on samples taken from different parts used and the data are as above. In these tests, similar to the literature, it was once again seen that the effect of the weight of the liner paper on the load bearing is limited, while the effect of the characteristics of the honeycomb panel such as core structure, angle, mesh diameter, thickness is direct. For example, while the  $m^2$  weight of specimen 2 was about 25% higher than specimen 1, specimen 1 achieved a much higher value than specimen 2 in the pressures they carried. Similarly, specimens 3 and 4 had one additional layer, but the value remained the same. The support here is that the number of layers in multiple pulses can always be advantageous. While specimen 4 was 50% more than the  $m^2$  weight of specimen 10, specimen pressure values were similar at 2 times the controlled deviation.



**Figure 5.17:** Honeycomb panel specimens.

## 6. CONCLUSIONS AND RECOMMENDATIONS

In this study, the performances of packaging design versions, which are basically divided into 3, were compared. The performance of the nonwoven PP fabric as well as the LDPE-4 plastozoid material used in the packaging containing EPS, which is the reference model, was observed. The mechanical resistance to puncture showed that the use of nonwoven PP fabric in mass production could be logical. The molded cellulosic-based design outperforms the reference model by an average of 30% in mechanical tests, especially in the collapse test and air conditioning performance. The spread transportation of the load with increased surface area has improved the performance of the packaging.

The increase in the energy absorbed by the packaging according to the drop height and increasing impact velocity and the formation of cracks on the walls where the load is transferred from the contact surface with the product were similarly observed in this study. In addition, in order to carry the load in a balanced manner and to minimize the cracking of the packaging, the number of supported surfaces should be increased and the product should be worked close to the product as if hugging it if a staggered design is to be made. In the honeycomb panel-based design performances, the flat surface of the products compared to the grid models and the layered flat surface areas reduced the pressure created by the load by approximately 50%. While increasing the number of side walls in the molded design increases the load bearing, increasing the surface area in the honeycomb panel is beneficial.

As in the literature research, when the load carried by the core structure is high, the cushioning of the honeycomb panel decreases by making an accordion effect in lateral impacts. In addition, it was confirmed in the sample studies that no generalization can be made about the bearing capacity of multi-layer and single-layer structures. In controlled collapse situations, the performance of the honeycomb panels, especially those with low height, was high as expected. With the results obtained from the product and sample tests, the mesh diameters of the honeycomb

panel can be increased, but the increased mesh diameters may create design gaps due to the exploded cell integrity, especially in the edge regions. This may adversely affect the performance of the packaging in lateral tests. In summary, while the reference model design stands out with its sufficient performance in 3 different basic designs, the use of nonwoven PP fabrics in the prevention of cosmetic damage can be tried in mass production. In our world where sustainability and environmental concerns are increasing day by day, molded cellulosic-based and honeycomb panel-based designs should be developed and taken into mass production. We hope to get more efficient outputs with increasing studies and the outputs of this study.



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## **APPENDICES**

### **APPENDIX A : Formulas**





## APPENDIX A

A.4.1 Drop Height (DH) = 70 – Xp (cm)

Xp: It is the definition of the weight of the packaged product (kg) expressed as a number (cm).

DH: Drop height must be minimum 25 cm.

A.4.2  $F = 1,5 \times mP \times [(H - h)/h] \times 9,81$

F: Force (N)

H: Stacking height in the warehouse

h: Overall height of packaged appliance

mP: Gross weight of packaged appliance, packaged mass (kg)

1,5: Safety factor

Test Duration:8 hours



## **CURRICULUM VITAE**

Name Surname : Eren BARUTÇUOĞLU

### **EDUCATION :**

- B.Sc. :

2021, Istanbul Technical University/Istanbul-TURKEY, Mechanical Engineering Department

### **PROFESSIONAL EXPERIENCE:**

- 2024-..... MANISA, Vestel Cooking Appliances Plant, Senior Mechanical Design Specialist, Packaging Design Team
- 2023-2024 MANISA, Vestel Cooking Appliances Plant, Mechanical Design Specialist, Packaging Design Team
- 2023-2023 MANISA, Vestel Cooking Appliances Plant, Mechanical Design Engineer, Packaging Design Team
- 2022-2023 ISTANBUL, Vestel, 13. MT Programme
- 2022-2022 KOCAELI, Arçelik Washing Machine Plant, Production-Plastic Production Team

### **PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS :**

‘Hybridity of Non-Woven, Polystyrene Plastics and Cellulosic Based Packaging and Comparison of Their Performances’ AUTEX 2025 WORLD CONFERENCE.