A Brief Report on

Materialize

—A Turtle Egg Storage Unit

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1 Summary

TG11 is a design engineering consultant company of five members providing advices for the design of a turtle egg storage unit for Holland Heavy Industries, HHI, whose brand ethos is to create the most heavy-duty engineering products with high precision that will last a life time. Through a series of research, experiments and discussions, it was shown that a soft high density polymer foam inner matrix in tandem with a stiff boron carbide protective casing may be the best design choice for the company.

2 Introduction

During the brief session with the CEO of HHI Alexander Holland, the group was given a rough understanding to the customer's expectations on the turtle egg storage unit:

Table 1: Brief from CEO Alexander Holland

The turtle egg storage unit would be used by biological researchers collecting eggs from turtle nest on beaches, and then transported long distance to research facilities.	
Capacity	20 average sized turtle eggs
Structure	An outer shell for structure and an inner cushion
Other specifications	To be light enough so that a single researcher can carry it
	To be intuitive and simple to use (not overly engineered)
	That the cushioning layer is easily cleaned or disposable

This report briefly explores the structural design and material choices required to create a product that is suitable with both HHI's company ethos and the consumer's nature. Two groups of materials, hard and soft have been covered and advices are given based on analytical calculations and evaluation experiments.

3 Background Information

Sea turtles have existed over 220 million years ago, but are now disappearing at a dangerous rate: more than 45% of turtle species worldwide are listed as threatened and endangered, mostly due to human interventions [1]. Four crucial aspects must be considered when taking care of turtle eggs, namely the orientation of the egg; the temperature of the egg; the circulation fresh air around the egg and most importantly the protection of the egg from external excitations. [2]

The group started by investigating on the environment of natural turtle nests as it is a given condition that can most certainly give birth to baby turtles. As the following quantitative information is heavily dependent on species, the group has analyzed the most common species found in the United Kingdoms: The *Testudo graeca* [3]. Naturally, female *graeca* turtles will search for a dark and quiet beach at night between March and October scrape out a circular nest typically between forty and fifty centimeters deep [4]. They then begin laying between 50 and 350 eggs before refilling the hole with sand [3]. The temperature within the nests varies but are usually around 29 degrees Celsius [2] where there is an equal chance for both male and female turtles to be developed, a temperature lower than this will result in a predominantly male population and a higher temperature will result in the development of predominantly female turtles [5]. Furthermore, temperatures above 35 degrees Celsius will spoil the eggs [2] and it is unlikely that an embryo will survive temperatures below 20 degrees for a prolonged period of time. Another aspect worth mentioning is that due to the highly porous nature of sand, typically between 25 to 50 percent hollow [6], it allows plenty of air to diffuse in and out of the egg, keeping the embryos alive. Finally, as turtle embryo absorbs minerals from its shell [3], the shell of a turtle egg can be significantly more fragile and prone to breaking when compared to that of birds [3]. It is discovered that even minor shocks can dislodge the cell membrane that attaches the embryo to its shell, causing death similar to the effect of turning the egg [4]. Here, the natural sandy environment of turtle nests again help to protect the eggs from shocks by transforming most of the mechanical energy into heat [7], which is also due to its porous nature where when sand particles are excited they create a large amount of friction moving against each other.

Conventionally, turtle eggs are transported by professionals with ventilated boxes typically made from clear plastics, polystyrene or other polymers [8]. These boxes were to be filled with damp sand from the dig site and small indentations were made in the sand to hold the turtle eggs upright. On one hand, the sand and boxes, especially that of polystyrene creates an insulating layer that prevents heat lost and helps to absorb some shock. On the other hand, the porous sand allows sufficient diffusion of oxygen and carbon dioxide around the egg. However, although this method successfully meets all the crucial aspects of turtle egg incubation, the thin layer of sand and polystyrene container does not provide enough shock absorption [3] and the sand can also absorb much of the heat generated by the embryo [10]. The damp sand can also promote bacterial, viral and fungal growth [10], potentially threatening the life of the baby turtle. As a result, many eggs become invalid after the transportation, and have to be destroyed [3]. Considering user experience, the conventional damp sand method is also very nasty to work with: users are expected to scrape indentations in the sand with their bare hands, cover the eggs with more sand and finally removing the sand upon arrival, something that is exclusively done outdoors. Furthermore, the box of damp sand can be extremely heavy and the polystyrene container can easily change shape or even break, posing potential threats to the turtle eggs. The process also results in a lot of waste which is the number one cause in the endangerment of turtles.

Concerning the brand ethos of HHI and the nature of animal research, TG11 must design a turtle egg storage unit that is better at shock absorption than polystyrene foam; good thermal insulating capabilities to provide a service temperature of 20 to 35 degrees Celsius; enough air ventilation [A] to keep the embryo alive and enough support to the orientation of the egg. The end product must be durable, easy to use and less dense than a box of damp sand which typically weighs 1905 kilograms [11] per cubic meter. There must be a disposable cushioning layer that is not exceedingly expensive and a heavy duty case that can be easily operated. Give that the product will be operated near salty water and under direct sun light, to still “last for a life time” it must also exhibit anti corrosion and anti UV degradation abilities. Finally, the material chosen should look and feel like it’s of high standards and quality.

4 Development

4.1 Design

Since the general structure for TG11’s turtle egg storage unit has already been given by HHI CEO Mr. Alexander Holland during the initial brief session, the group focused on the strength and usability in the design, as well as tackling all the problems individually.

To start, the group redesigned the egg carton into a $2 \times 2 \times 5$ (eggs) cuboid case to give the turtle egg storing unit its structure. The material used must be stiffer than that of a pulp paper egg carton, which has a typical maximum young modulus of 8.9 GPa and a yield strength of 34 MPa [12]. This is important as it provides the structure and space where sufficient damping can take place, and is a critical aspect in matching HHI’s company ethos of heavy duty and long lasting.

To minimize transportation induced vibration, movement and shock, the turtle eggs are encased in two layers of shock absorbing material that has a better damping performance than sand and polystyrene. Edges of the stiff case are also thickened and rounded to allow even distribution of mechanical energy.

To allow sufficient diffusion of air, air holes were positioned on the stiff outer cases of the product and the use of permeable materials for the inner matrix is preferred. Another way to achieve sufficient air permeability is by using a granulated form of a non-permeable material much like sand itself.

As the turtle embryo starts to develop, it attaches to the top of the shell and a change in the egg's orientation can cause it to dislodge and die [2]. To keep the egg upright, a formable material was used for the inner matrix, maximizing its contact area with the egg and thus hold it in place like sand. This can also be done by using granulated forms of non-formable materials.

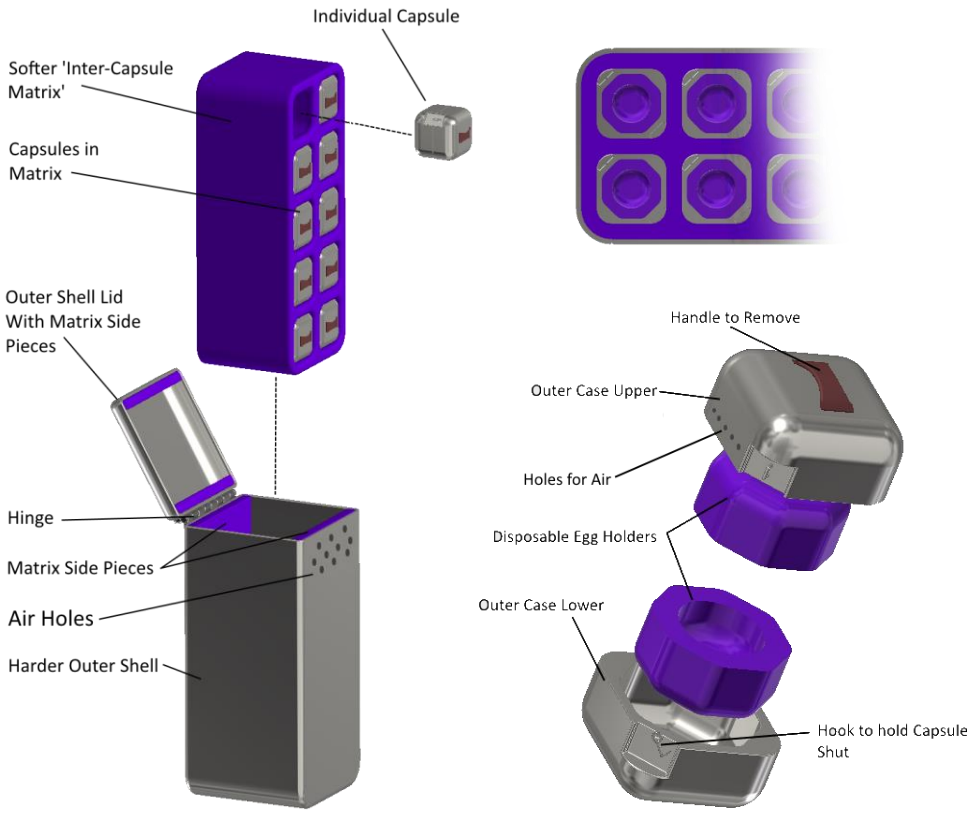

Figure 3: CAD screenshots of the product's design.

Considering user experience, the cover of the outer case is kept closed simply by friction between the cap and the inner capsules are held together by hooks on the diagonals of the capsules, allowing easy packing. Handles are also added to each individual capsule and damp sand is no longer required. Therefore, the case no longer creates a mess nor require professional employees to operate. Furthermore, the cubical design allows more units to be stacked together and the case of the product is also design to look thick and heavy duty, giving the customer a sense of quality and security.

4.2 Material Selection Process for the Hard Casing Material

The primary function of the hard material is to provide durable and long lasting structural support to the eggs. Therefore, the material must exhibit a high young's modulus and compressive strength. However, a relatively light product was also requested, so the density of the materials will also be analyzed. Other preferable properties include: shock absorbing and dispersing properties, high quality look to match HHI's company ethos; smooth surface for ease of cleaning and heat insulating properties, which has not been thoroughly analyzed but are included in the formulation process of the end decision.

4.2.1 Evaluation experiments on the hard casing material:

To start, TG11 has conducted semantic differential on three materials commonly used for structural and protection purposes.

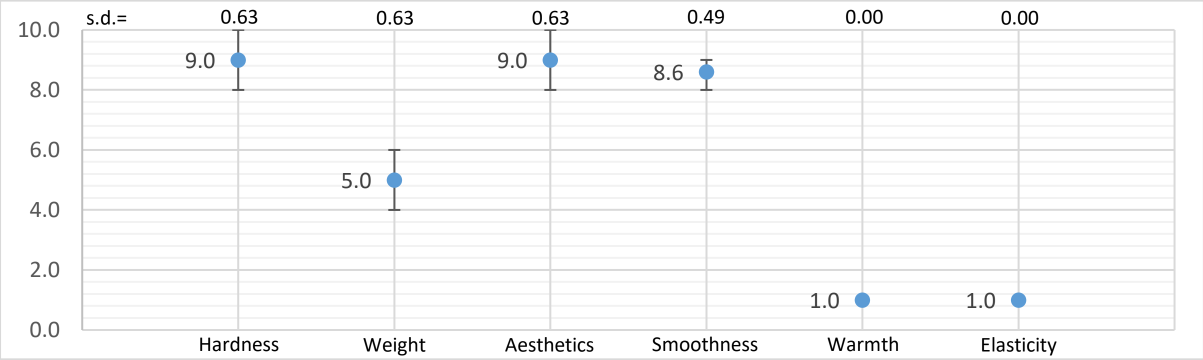

Figure 4.1: Semantic differential scale for aluminum metal, taken from five individuals

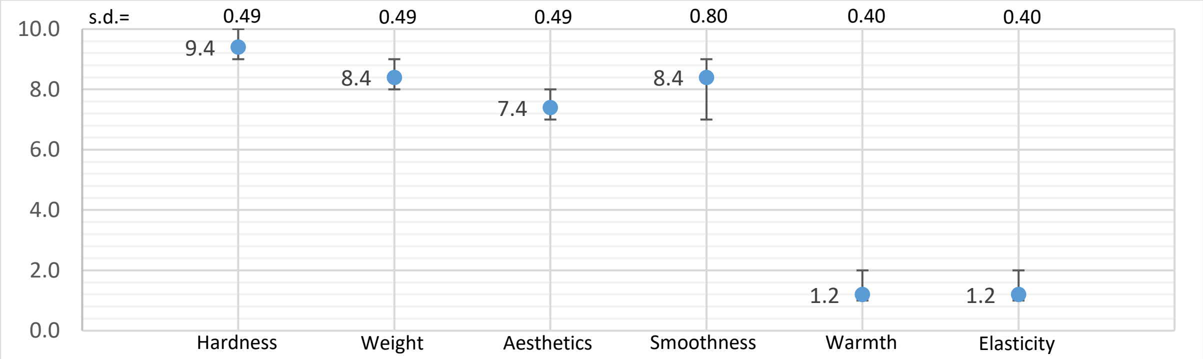

Figure 4.2: Semantic differential scale for stainless steel, taken from five individuals

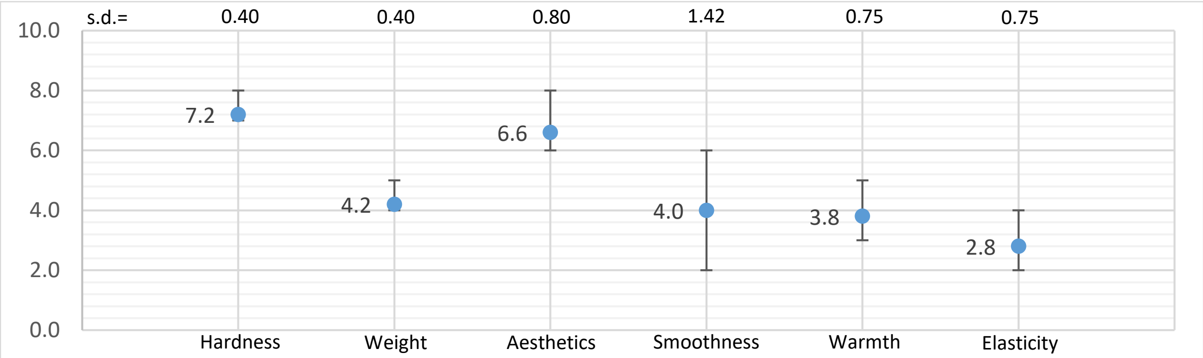

Figure 4.3: Semantic differential scale for high impact polycarbonate (phone shell), taken from five individuals

From the semantic differential results, it is apparent that the majority of consumers feel that metals are tougher and more aesthetically pleasing when compared to high density polymers. However, polycarbonate was considered to be lighter and warmer than metals.

Although only five individuals gave responses to the semantics differential, the small range and standard deviation despite being completed individually shows that the results are reasonably reliable.

4.2.2 CES Edupack Aided Material Analysis for Hard Casing Material:

Two performance indices were chosen for the analyses of the hard casing material with the aid of CES Edupack, namely the stiffness-limited material at minimum mass (P_s) and compressive strength-limited material at minimum mass (P_c). P_s is important because stiffness and structural support is the main purpose of this material. Compressive strength was analyzed instead of yield strength or other strength-limited indices as it is unlikely that the turtle egg storage unit will be put under tension.

Other requirements are assessed using boundary conditions:

Table 2: Boundary conditions for property of the hard casing material

Material Property	Limits	Reason the Limit was Chosen
Young's modulus/ GPa	>8.9	Taken from the young's modulus of a typical pulp paper egg carton: a competitor in the market at a very low price.
Compressive strength/ MPa	>55	Taken from the compressive strength of a typical pulp paper egg carton.
Density/kgm^{-3}	<7700	Taken from the density of stainless steel from the semantic differential feedbacks. The volume of the hard part of product is estimated to be around 0.005 m^3, materials that are denser will not be able to carry.
Anti-corrosion from fresh water	Excellent	Product will be used under wet conditions. Therefore, this is crucial in matching HHI's brand identity.
Anti-corrosion from salty water	Excellent	Product will be used near the sea. Corrosion must be limited.
Anti-U.V. degradation	Excellent	UV radiation can be very strong on beaches, causing discoloration or weak spots.

For optimal stiffness of a plate at minimum mass, maximize P_s where:

$$P_s = \frac{E^{\frac{1}{3}}}{\rho} \quad (1)$$ [13]

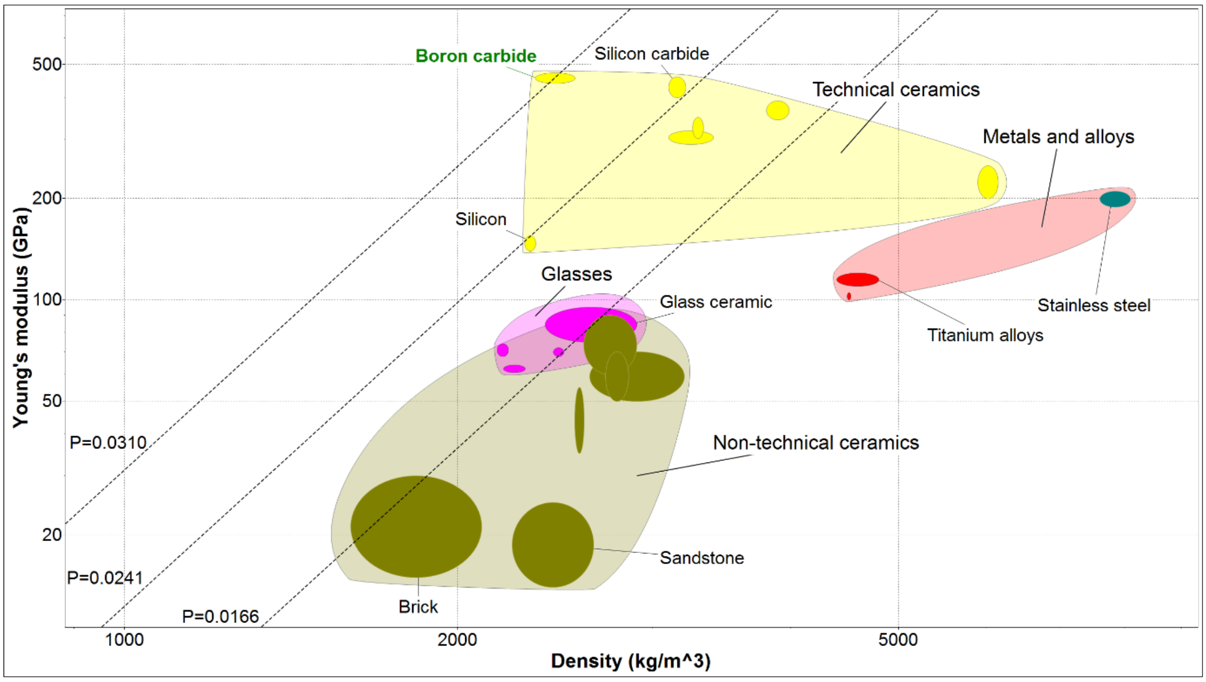

Figure 5.1: Edu level 2 Ashby plot for hard casing materials (Young's modulus/Density)

For optimal compressive strength of a plate at minimum mass, maximize P_c where:

$$P_c = \frac{\sigma_c^{\frac{1}{2}}}{\rho} \quad (2)$$ [13]

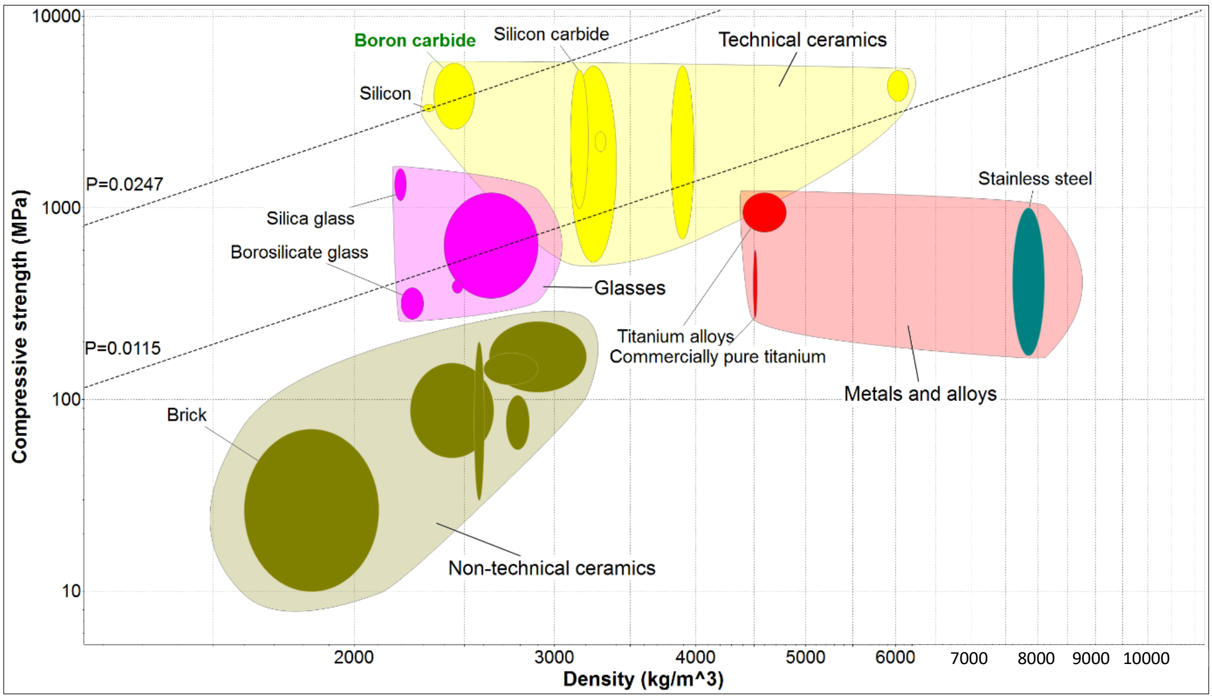

Figure 5.2: Edu level 2 Ashby plot for hard casing materials (Compressive strength/Density)

Although by volume, boron carbide is roughly six times more expensive than stainless steel and may not be as aesthetically pleasing when compared to metals and alloys, it exhibited by far the highest performance index in both Ashby plot analyses. This shows that boron carbide is extremely stiff and strong but at the same time very light when compared to other materials. Furthermore, technical ceramics like boron carbide are also less reactive and are therefore more durable against UV radiation, salt water and acidic environments when compared with metals and alloys. Given that the main concern of HHI is in the durability and performance of their products while price and aesthetics are of minor concern, boron carbide is possibly the best option and is highly recommended to be used as the hard casing material for the final product.

4.3 Material Selection Process for the Soft Matrix

The primary function of the soft matrix is to protect the turtle eggs from rupturing. Therefore, damping performance must be maximized. Furthermore, thermal insulating performance, formability and permeability of air is also indispensable, but since the problem with formability and permeability can be solved by using a granulated form of the material, they are not of crucial importance. It was also requested by Mr. Alexander Holland that the inner matrix should be disposable as to prevent bacterial growth, this means that the material should at least be downgradable and reasonably priced.

4.3.1 Evaluation experiments on the hard casing material:

To start, TG11 has conducted semantic differential on three materials commonly used for damping and insulating purposes.

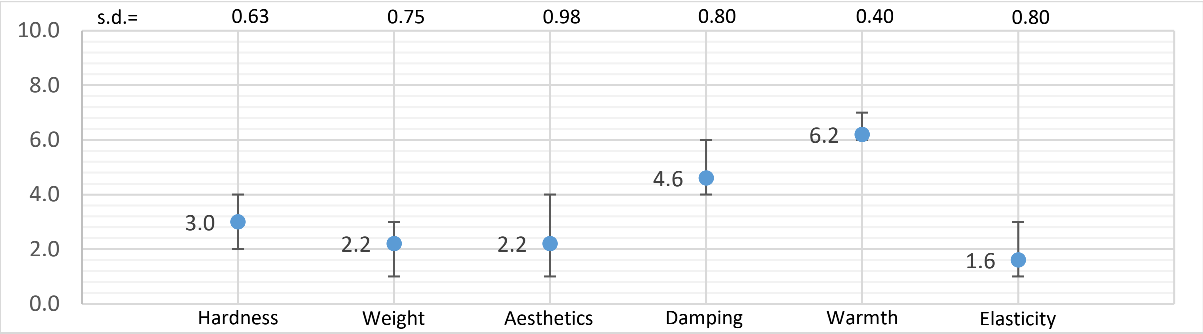

Figure 6.1: Semantic differential scale for polystyrene foam taken from five individuals

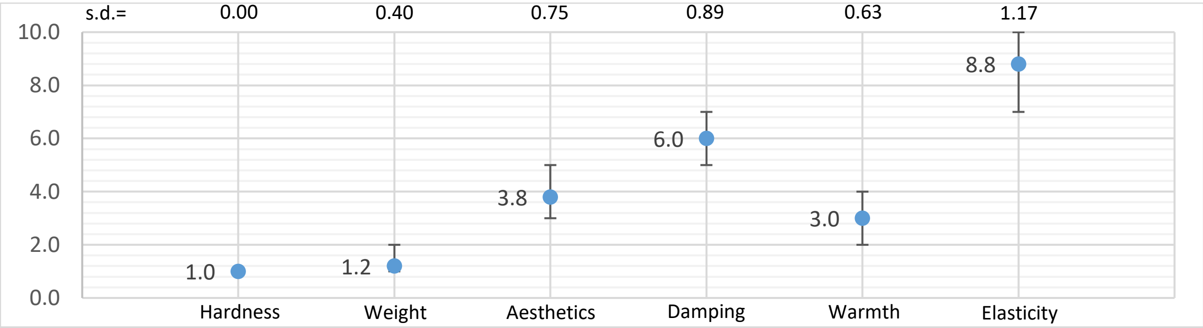

Figure 6.2: Semantic differential scale for polyurethane sound proofing foam, taken from five individuals

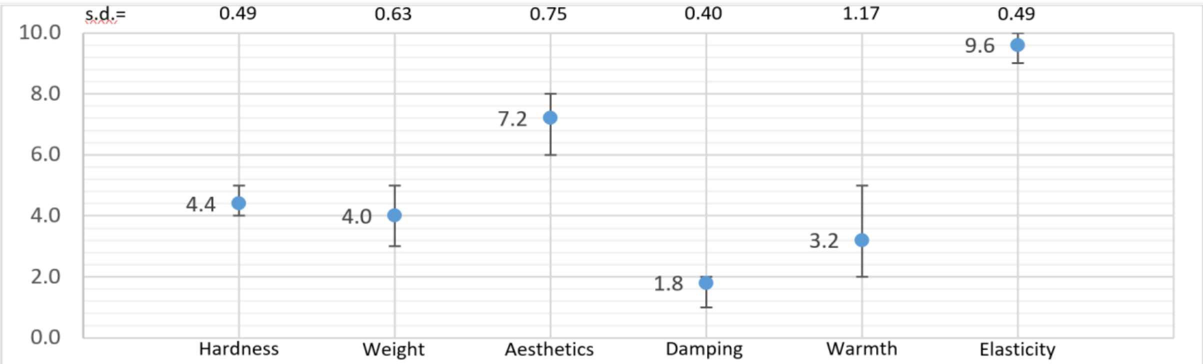

Figure 6.3: Semantic differential scale for PVC elastomer foam, taken from five individuals

From the semantic differential results, it appears that the general public found polyurethane sound proofing foam, the softest material of the three to have the best cushioning effect. In fact, from these three results there was a clear negative correlation between hardness and cushioning effect. Implying that softer materials in this case may give customers a higher sense of security.

Like the previous semantics differential scales, the results have a small range and standard deviation, and is therefore reasonably reliable.

4.3.2 CES Edupack Aided Material Analysis for Soft Cushioning Material:

Two different performance indices were required for this analysis. The damping effect of this material is assessed by the damping performance index P_d, and the insulation effect is assessed by the thermal insulation performance index P_i.

Other requirements are assessed using boundary conditions:

Table 3: Boundary conditions for property of the soft cushioning material

Material Property	Limits	Reason the Limit was Chosen
Density/kgm^{-3}	<1905	Taken from the average density of damp sand, as this product is expected to be better than conventional methods.
Mechanical loss coefficient (tan δ)	>0.02	Taken from the tan δ of polystyrene, which is used in conventional methods of turtle egg transportation, something the new product must overtake.
Price/$kg^{-1}	<20	As a disposable material, prices higher than this is unjustifiable.
Downcyclable	Yes	Waste that cannot be downcycled is a major cause in the reduction in turtle population. Therefore, it would be counterintuitive to produce more waste while saving turtles.
Toxicity	Non-toxic	Toxic materials can poison the turtle eggs.

For optimal damping performance, maximize P_d where:

$$P_d = \eta E \qquad (3)$$ [13]

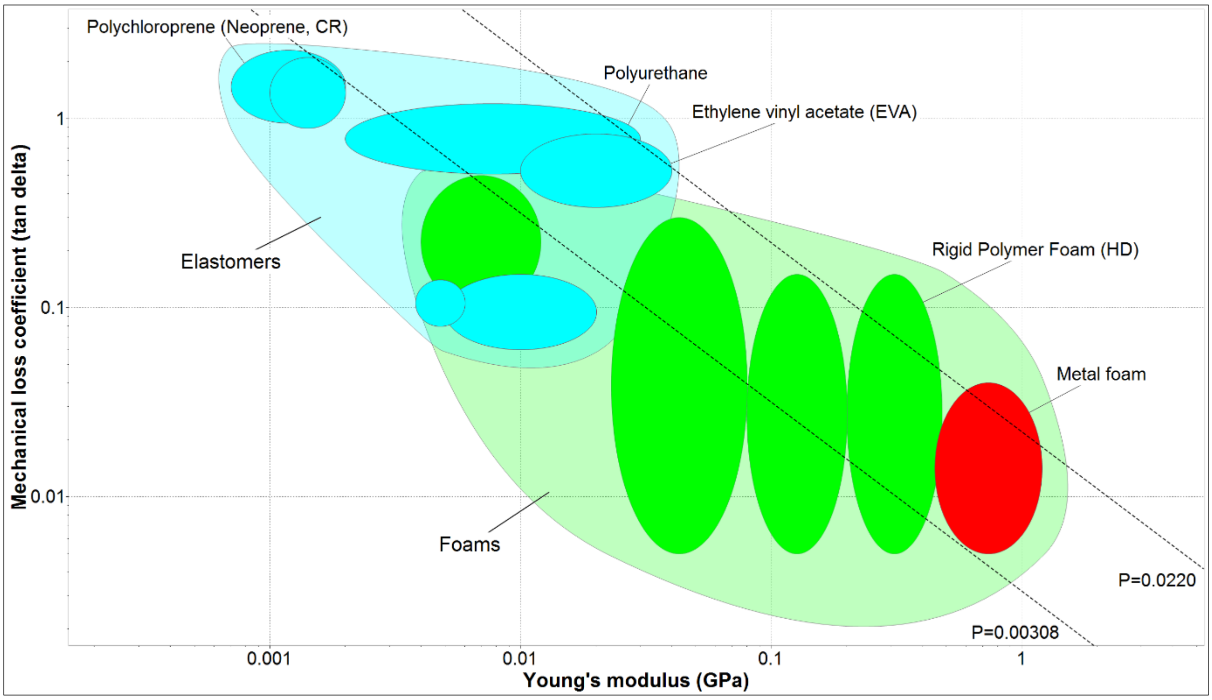

Figure 7.2: Edu level 2 Ashby plot for soft cushioning matrix (Mechanical loss coefficient/Young's modulus)

For optimal thermal insulation performance, minimize P_i where:

$$P_i = \frac{\lambda}{a^{\frac{1}{2}}} \qquad (4)$$ [13]

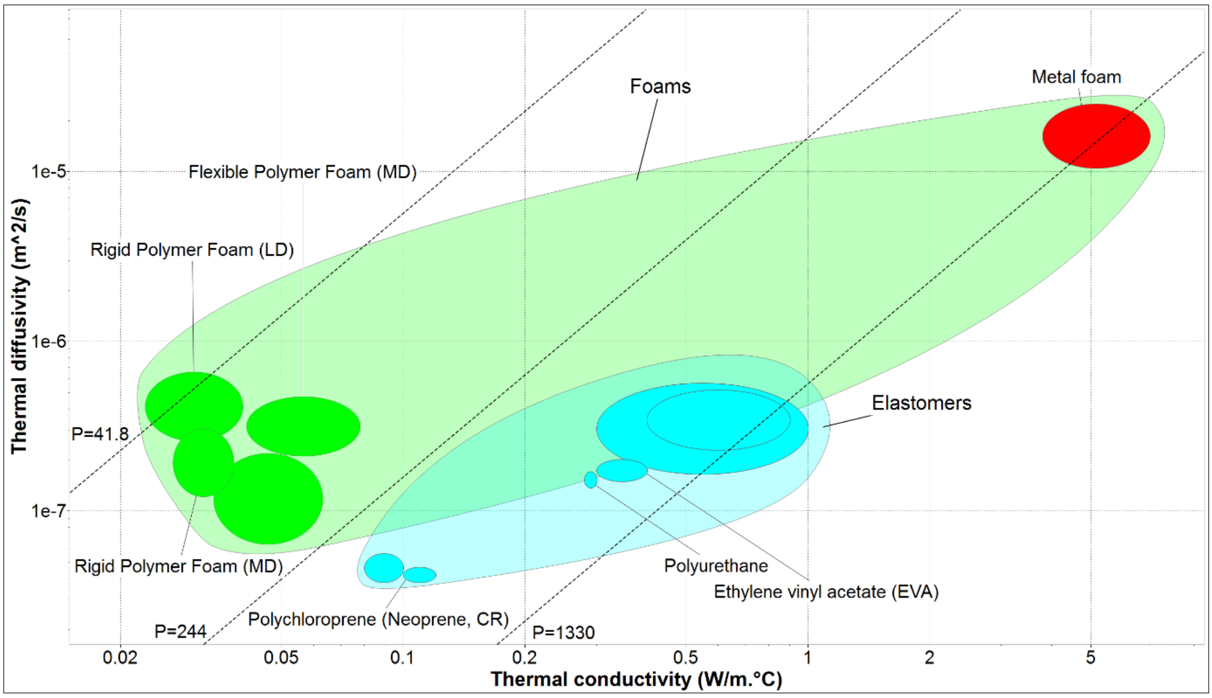

Figure 5.2: Edu level 2 Ashby plot for soft cushioning matrix (Thermal diffusivity/Thermal conductivity)

Five materials of interest were further analyzed:

Table 4.1: Individual properties of five potential soft cushioning materials

Material	Cost(c) (kgGDP^{-1})	tan δ	young's modulus (GPa)	thermal conductivity (W/m.°C)	Density (kg/m^3)
Rigid polymer foam (HD)	10.8	0.15	0.48	0.034	170
Rigid polymer foam (LD)	10.8	0.30	0.08	0.023	36
Polyurethane	3.51	1.20	0.03	0.280	1020
EVA	1.61	0.83	0.04	0.300	945
Metal foam	8.05	0.04	1.20	3.800	240

Using formulas (3) and (4) and inverting P_i and cost:

Table 4.2: performance and cost indices of five materials

Material	P_d (GPa)	P_i^{-1} (Jm^{-3}°C^{-3})	c^{-1} (kgGBP^{-1})
Rigid polymer foam (HD)	0.0720	13.2	0.093
Rigid polymer foam (LD)	0.0240	36.82	0.093
Polyurethane	0.0360	2.40	0.285
EVA	0.0332	2.66	0.621
Metal foam	0.0480	1.00	0.124

Using the weighing equation:

$$P_T = 0.45 \frac{P_d}{\max P_d} + 0.4 \frac{1/P_i}{\max 1/P_i} + 0.15 \frac{1/c}{\max 1/c} \quad (5)$$

Table 4.3: relative performance, relative cost and overall performance of five materials

Material	$\bar{P}_d$ (GPa)	$\bar{P}_i^{\ -1}$ (Jm^{-3}°C^{-3})	$\bar{c}^{\ -1}$ (kgGBP^{-1})	Overall Performance P_T
Rigid polymer foam (HD)	1.000	0.358	0.149	0.615
Rigid polymer foam (LD)	0.333	1.000	0.149	0.572
Polyurethane	0.500	0.065	0.459	0.320
EVA	0.461	0.072	1.000	0.386
Metal foam	0.666	0.027	0.200	0.341

In Table 4.1 and 4.2, it was shown that high-density rigid polymer foam (HDRPF) provides the highest damping effect. However, HDRPF is not as good of a thermal insulator when compared with its low-density counterpart. At the same time, HDRPF and low-density rigid polymer foam (LDRPF) are both the most expensive material by weight in the list while EVA is the cheapest. When considering customer experience, the results from the semantic differential scales (Figure 6.1 and 6.2) shows that polyurethane is more aesthetically pleasing than Styrofoam, a type of rigid polymer foam. Furthermore, it was also shown from the semantic differential scales that a softer material like LDRPF, polyurethane and EVA can create a stronger sense of protection.

In Table 4.3, Overall performance index P_T shows that HDRPF is most capable in both of the primary functions of the soft cushioning matrix while remaining reasonably cost-effective when considering that this layer must be disposable. Another advantage of this material is that it is easily formed into small spheres and can therefore become permeable and formable, meaning that all four crucial aspects required for keeping the turtle embryo alive are well met. Therefore, the use of HDRPF should be considered when creating the soft cushioning matrix of the final product.

5 Conclusion

The presented work has briefly explored the selection process for two materials that are related to a design concept. During the selection process, boundary conditions were taken from competing products and materials were analyzed by multiple figures of merit including the strength-weight ratio, damping capacity, thermal insulating performance and relative cost. User attitudes were examined using semantic differential scales and were included in the decision for the final suggestions. The recommended material for the product's hard protective casing and soft cushioning matrix are boron carbide and HDRPF respectively.

6 Appendices

6.1 Appendices A

Table 5: Gaseous exchange during incubation [14]

Day of incubation	Absorption of oxygen (ft^3)	Expulsion of carbon dioxide (ft^3)
1	0.50	0.29
5	1.17	0.58
10	3.79	1.92
15	22.70	11.50
18	30.00	15.40
21	45.40	23.00

7 References

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