DESIGN OF A HELMET

by

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Abstract

Starting from engineering analysis, a model for engineering optimization is developed. Then, we use the survey data collected from the class to develop a microeconomics (demand) model to predict the sales when our products hit the market. At the meantime, we also conduct a deep literature survey to address how we couple customers' demand with our design and manufacturing processes so that our cost estimation model is refined. Finally, by solving the optimization coupled with the engineering and marketing model, we propose a product family featuring 3 different products targeting commuters, amateurs, and professional racers. Each product specification is stated and the compromise arose from sharing components to achieve maximum profit is also discussed.

Please note that all intermediate results are left out on purpose for integrality since our ultimate goal is using the developed models to analyze and introduce 3 different products on the market. Hence, a future business plan is also included in our appendix.

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1. Summary on Helmet Design Considerations

1.1 The Product Design Problem and Challenge

Helmet can protect vehicle riders from severe injuries during traffic accidents. Traffic injuries have only quite recently been recognized as a major public health problem in developing countries. Also, serious bicycle accidents have increased in the last two decades. Traffic injuries often involve severe cases and require critical care that eventually causes high medical costs and economic losses. Such burdens would be prolonged if the victims consequently sustain disabilities. In order to reduce deaths and traumas of traffic accident, the helmet act for motorcyclists and bicyclists was enacted in many countries. Some countries even enforced the helmet use to be nationwide.

The global share market of helmet is difficult to estimate. However, due to some helmet acts and enforcements, also it is believed that consumers usually replace helmets periodically. The market is assumed to be large enough to run a new series of products. And the product levels should be determined. For example, it is not easy to get into the high performance helmet market which is shared by several specific brands.

To design a functional helmet, it is important to analyze the structure of helmets. The main helmet components are the foam linear (EPS, PU, PP, PE, Pb, PVDC or integral skin) and the shell (Thermoplastic or Composite). Basically, the function of the foam is to absorb most of the impact energy, while the function of the shell is to resist penetration of any foreign object from touching the head and resulting in direct skull damage, and to distribute the impact load on a wider foam area thus increasing the foam linear energy absorption capacity.

Usually manufacturers design their helmet based on experimental verification. During the experimental verification, the helmet must absorb the energy of the impact such that the headform acceleration shall exceed certain predetermined values (300g). The shell must resist penetration of a falling 60° conical anvil with specific dimension. The criterion is that the spike does not touch the headform on the helmeted-headform test setup. This penetration test is the main criteria for shell thickness determination and, in fact, resulting in a helmet with a thicker shell and consequently a weight of about 6-8 times as compared to the foam liner.

If a thicker shell is chosen, the strength will increase, unfortunately, as well as cost and weight. Or an alternative material should be considered.

It is very important to check out all of the local regulations of the target market. Violations of laws and standards may result in re-design and unexpected delay and cost.

1.2 Design Consideration: Ideas at the Initial Stage

The helmet must be designed to provide the user with the most lightweight, form fitting system, while meeting other system performance requirements. This can be achieved through a complete analysis of the system requirements. The advanced helmet development process for developing aircrew helmets includes the utilization of several emerging technologies such as laser scanning, computer aided design (CAD), computer generated patterns from 3-D surfaces, laser cutting of patterns and components, and rapid prototyping (stereolithography). Advanced anthropometry methods for helmet development are also available for use. The use of these advanced technologies will minimize errors in the development cycle of the helmet and molds, and should enhance system performance while reducing development time and cost.

A new helmet design with an exterior elastic skin, capable of moving independently from the hard layers underneath, could decrease brain injuries from motorcycle accidents when the rider's head hits the road or a vehicle with a glancing blow.

1.3 Design Criteria

1.3.1 Reduce the risk of mild traumatic brain injury (MTBI)

Three key features designed with the intent of reducing the risk of MTBI.

I. Side and facial protection— of the impacts that were analyzed, over 70% of those that resulted in MTBI were from a blow to the side of the head, face, or mandible area.
II. Increased Shell Offset – the distance from the helmet shell to the wearer’s head gives the helmet to manage the types of impacts that cause MTBI without compromising its response at higher energy levels.
III. Carefully-designed Shell Shape –the shell extends into the mandible area, and it has been computer designed around the head’s anatomical center of gravity.

1.3.2 Stability and Fit

I. The stability of the helmet on the wearer’s head is critical to keeping the protective system in its intended place, where it can best protect the athlete.
II. A properly fit helmet is key to player protection.

1.3.3 Comfort

I. Ventilation
II. Ear Channel — allowing for much easier donning and doffing than traditional football helmet designs.
III. Lightweight — producing a lightweight product without compromising protection

2. Engineering Models

2.1 Structure of Helmet

A good design starts from a throughout understanding about the concept of a new product. Fig. 1 shows the common parts of a helmet. A brief description for the function of each part is also given to highlight their importance in the design process.

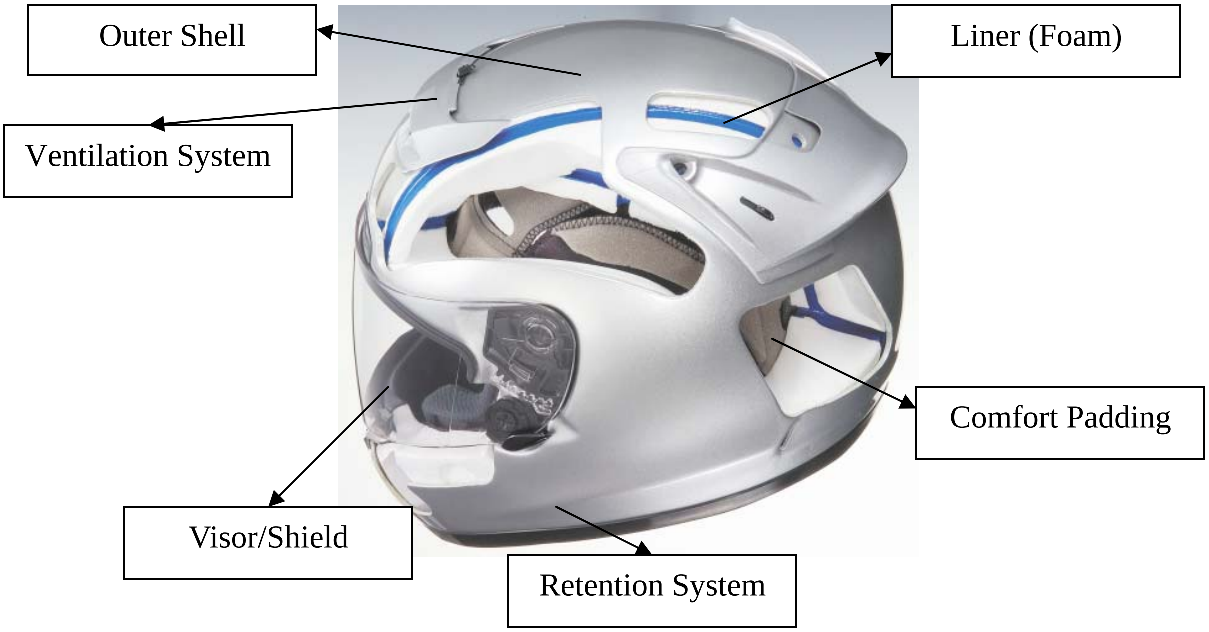


Fig.1 Components of a helmet

2.1.1 Visor

The visor is made of a strong and transparent material, e.g. polycarbonate, and is designed to protect the face of the rider from wind, dust and insects. In addition, the visor is equipped with a water- and scratch-proof coating.

Manufacturing a distortion-free visor including a reliable opening mechanism not only calls in a manufacturer's development strength, but is equally dependent on the right production technology.

2.1.2 Outer Shell

During an accident, the hard outer shell has to both absorb and disperse the impact. At present, outer shells are generally made of thermoplastics or fibre-reinforced polymer (FRP), a composite material consisting of a synthetic resin reinforced with, for instance, fibreglass.

2.1.3 Comfort Padding

Despite its rounded shape, an EPS liner is much too hard to guarantee a good fit. The comfort padding, which consists of a sufficiently firm synthetic foam pad covered with a skin-friendly fabric, is thus all the more important.

2.1.4 Ventilation System

The system ensures fresh air is ducted into the helmet and exhaled air and humidity are vented out.

2.1.5 Retention System

A special synthetic-fibre chin strap that fulfils the strict breaking- and tensile-strength requirements serves to secure the helmet firmly on the head of the rider. The retention system is attached to the helmet with strong metal rivets.

2.1.6 Liner(Foam)

The liner protects the wearer's head by absorbing the remaining force of the impact that was already partially absorbed and dispersed by the outer shell. The liner located on the inside of the shell is made of lightweight and highly impact-absorbing EPS (expanded polystyrene).

2.2 Standard for Helmet Strength

Different countries have their own standards for helmet tests, and the ASTM F1446-95a [1] helmet standard had been the most-used standard in the world. All of the standards require helmets to pass lab tests where they are placed on an instrumented head form, turned upside down and dropped for a measured distance onto flat or hemispherical anvils. Drop distances vary but are generally between one and two meters. For the helmet to pass, the instruments inside the head form must register less than 300 g's during the impact, or in some cases less than 250 or even 200 g's. The most-used three helmet testing standards, CPSC, ASTM F1447 and Snell B-95, are compared in table 1. It is obviously that Snell uses more severe criterion for helmet test.

Table 1

Helmet test criteria for CSPC, ASTM F1447 and Snell B-95 [2]

	CPSC	ASTM F1447	Snell B-95
Drop height on flat anvil	2.0 m	2.0 m	2.2 m
Drop height on hemispherical anvil	1.2 m	1.2 m	1.5 m
Head form weight	5 kg	5 kg	5 kg
Failure threshold	300 g	300 g	300g

2.3 Standard for Head Protection

Criterion used to measure the performance of the helmet for head injury prevention is not only the head acceleration. Another criterion is the Head Injury Criterion (HIC). HIC is a measure of the severity of an impact and takes into account its duration as well as its intensity. The criterion is based on the results of research into the effects of impacts on the human head. HIC is defined by the following integral formula

$$HIC = \max\left\{\left[\frac{\int_{t_1}^{t_2} a(t)dt}{t_2 - t_1}\right]^{2.5} (t_2 - t_1)\right\}$$

Where a is the head form center of gravity acceleration and t_1 and t_2 are chosen so that the HIC is a maximum. The requirement for helmet protection is that HIC should less than 1000.

2.4 Nomenclature

Parameter	*Units*	*Description*
σ_m	**N/m^2**	**Maximum stress**
σ_y	**N/m^2**	**Impact stress**
ν		**Poisson's ratio**
E	**N/m^2**	**Young's modulus**
E_f	**J**	**Foam energy absorption**
F	**N**	**Impact force**
G	**m/t^2**	**Head center acceleration**
h	**m**	**Mass block drop height**
M	**kg**	**Helmet total mass**
M_f	**kg**	**Helmet foam mass**
M_h	**kg**	**Head mass**
M_s	**kg**	**Helmet shell mass**
Pc	N	**Acting load**
q_f	**Kg/m^3**	**Helmet foam density**
q_s	**Kg/m^3**	**Helmet shell density**
t_f	**m**	**Helmet foam thickness**
t_s	**m**	**Helmet shell thickness**
V_f	**m^3**	**Helmet foam volume**
V_s	**m^3**	**Helmet shell volume**
U	**J/ m^3**	**Energy density**
X	**m**	**Helmet impact deformation distance**

2.5 Establishment of Engineering Model

From the engineering viewpoint of helmet design, the most important is the final design should pass the requirement of test standard and head injury criterion as mentioned before. These standards and criteria are based on the idea of impact forces acting on the human heads. In order to reduce the impact forces, choice of helmet shell and foam materials are the most important for our engineering viewpoint of design. The total mass of helmets can be described as following equation

$$M = M_f + M_s \qquad (1)$$

where M is the total mass of helmet, M_f is the mass of foam and M_s is the mass of shell.

Mass of foam material can be changed by its density and the design of thickness as

$$M_f = q_f V_f (t_f) \qquad (2)$$

$M_s = q_s V_s(t_s)$ (3)

where q_f, q_s are the densities of foam and shell and V_f, V_s are volumes where V_f , V_s are the function of thickness t_f and t_s.

From Eq (1), (2) and (3) we can get that helmet total mass is the function of density and thickness of shell and foam. Otherwise, from ASTM [1] that the total mass of helmet should less than 1 kg and maximum head center acceleration during drop test should less than 300g. The functions are described in following equations:

minimize $M = f(q_f, q_s, t_f, t_s)$ (4)

$M \leq 1kg$ (5)

$G \leq 300g$ (6)

In the following sections, energy method is used to define the relationship between head impact force, F_h , and foam thickness or foam density.

2.5.1 Design of Foam Density

In an attempt to simplify the helmet basic analysis and design, Mills [3] carried out a simple mathematical approach based on the energy method. The model is assumed that the section of human skull and helmet are spherical, as in fig. 2. Because helmet shell takes up less impact energy, it could be ignored and the mathematical solution could be simplified.

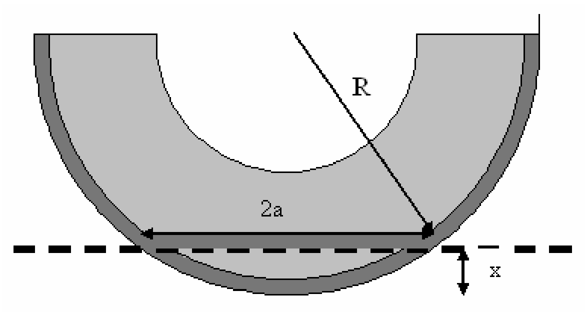


Fig. 2. The geometry of the contact between helmet and rigid flat [3].

The foam is assumed to crash at a constant stress σ_y when compressed. The compress area is a circle of diameter 2a when the maximum deflection of the foam is x. The relationship between R, a and x is:

$R^2 = (R - X)^2 + a^2$ (7)

If the amount of linear crash x is much less that the radius of curvature R of the spherical outer surface, then x^2 term can be ignored. The contact area A is given by

$A = 2\pi RX$ (8)

The force transmitted by the foam is given by

$F = 2\pi R \sigma_y X$ (9)

Using the radius of the helmet at the impact site, the foam the foam yield stress is chosen to give loading curve that pass design point (90% of foam thickness, 15 kN) of the force-deflection theoretical graph as shown in Fig. 3 [4]. It is shown in the graph that the impact energy must be absorbed without crossing the injury force limit.

Four types of foam material with different densities are chosen by Shuaeib [4] as shown in table 2. The foam thickness due to other criteria is chosen to be 25 mm. The input energy for material helmet application is estimated from the drop weight impact velocity and is equal to 100J. Using Eq. (9) we can plot the relation between deflection and striker force as shown in Fig. 4. From this method, we can see that the foam with 68kg/m^3 is closer to the energy requirement. Furthermore, from Fig. 3 and 4 we can assume foam density and absorbed energy have the relationship as:

$$E_f = C_1 \frac{1}{q_f} \tag{10}$$

Table 2
Foam material properties of different densities [4]

Foam Type	EPS (68)	EPS (54)	EPS (60)	EPS (50)
Density (kg/m^3)	68	54	60	50
Yield Stress (MN/m^2)	1.08	0.7	0.65	0.35

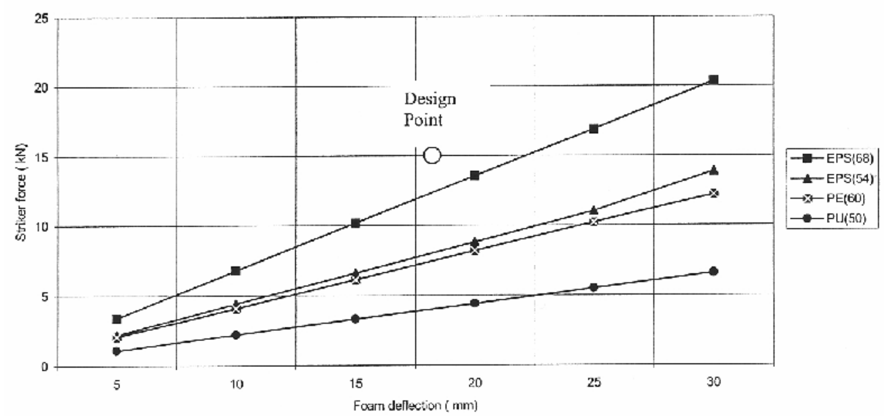


Fig. 4 The force –deflection curve for different foam densities [4].

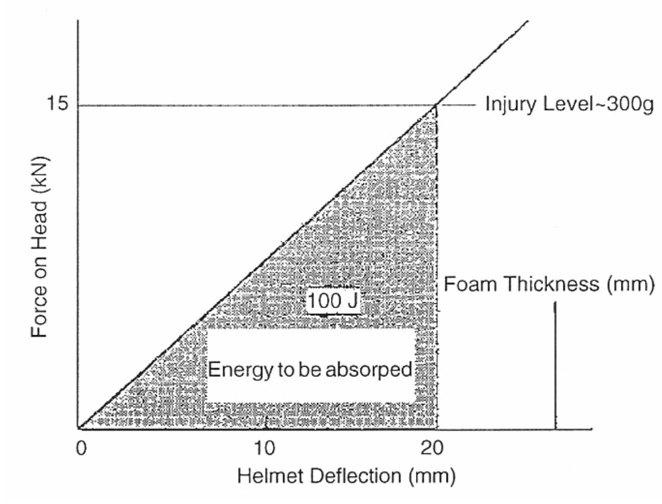


Fig. 3 The force-deflection graph for a helmet impact [4]

2.5.2 Design of Foam Thickness

Energy method is used for foam thickness design which is based on the cushioning curve principle by Mills [3]. The cushioning curve of foam material is shown in Fig. 5. From this method, a rectangular object of mass, m, falling a distance, h, onto a block of thickness, t. The peak acceleration G of the falling mass measured in g's is recorded. The static stress is experienced by the foam when the mass is resting on it. A is the contact area between the mass and the foam.

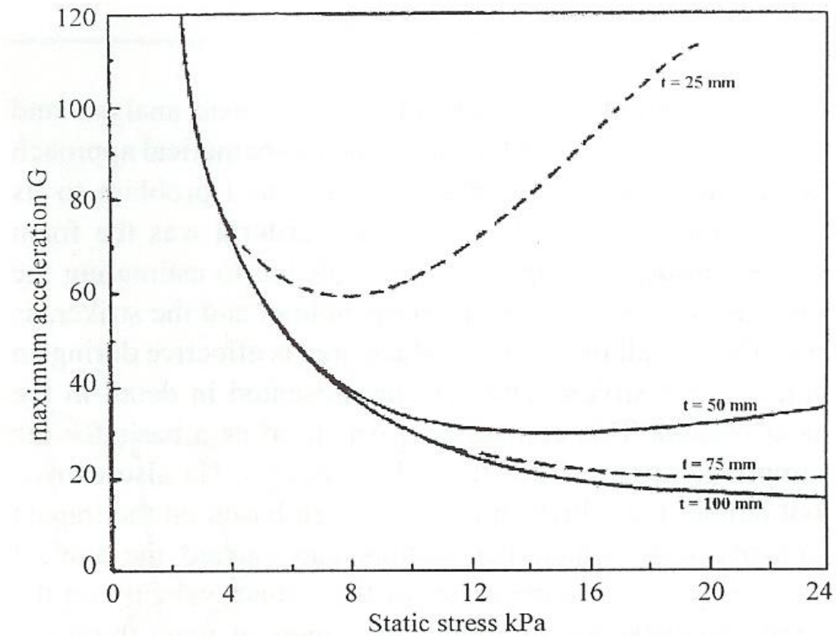


Fig. 5 Experimental cushion curve for foam density 70 kg/m3 and different thickness, t, for drop height of 0.6 m [4]

The energy density U, input to the foam is given by:

$$U = \frac{mgh}{At} = \int_0^{\sigma_m} \sigma d\varepsilon \qquad (11)$$

The integral which is up to the maximum stress σ_m represents the area under the stress-strain curve and the result is a function of $U(\sigma_m)$ at the maximum stress.

The static state stress σ_{st} is given as a function of U as

$$\sigma_{st} = \frac{t_f}{h} U(\sigma_m) \qquad (12)$$

The maximum acceleration in the impact G occurs when the compressive stress is at maximum value σ_m. Since the unit acceleration, when the static stress σ_s is applied via the foam to the mass is 1g, the ratio of the acceleration gives.

$$G = \frac{\sigma_m}{\sigma_s} = \frac{h}{t_f} \frac{\sigma_m}{U(\sigma_m)} \qquad (13)$$

From Eq. (13), if the drop height and the stress-strain curve (get σ_m) are given, it is easy to get the relation between acceleration G and foam thickness:

$$G = C_2 \frac{1}{t_f} \tag{14}$$

It means the increase of foam thickness can reduce head impact acceleration. However the design of foam thickness is limited by the size standard and helmet mass requirement.

2.5.3 Foam Material Choice

Helmet mass design depends on the choice of foam density and thickness. Combining Eq. (2), (10), (14) and transferring head acceleration G into function of head impact force F, it can be seen that helmet mass has the relationship with head impact force as shown in Eq. (15) and Fig. 6. Even the design goal is to minimize the impact force, it will increase the mass and make the helmet less comfortable and also increase the cost. According to Mills [3], the final foam material choice will close to 200g, but it depends on the multiple choices of shell material that the total helmet mass should less than 1 kg.

$$M_f = C_3 \frac{1}{F^2} \tag{15}$$

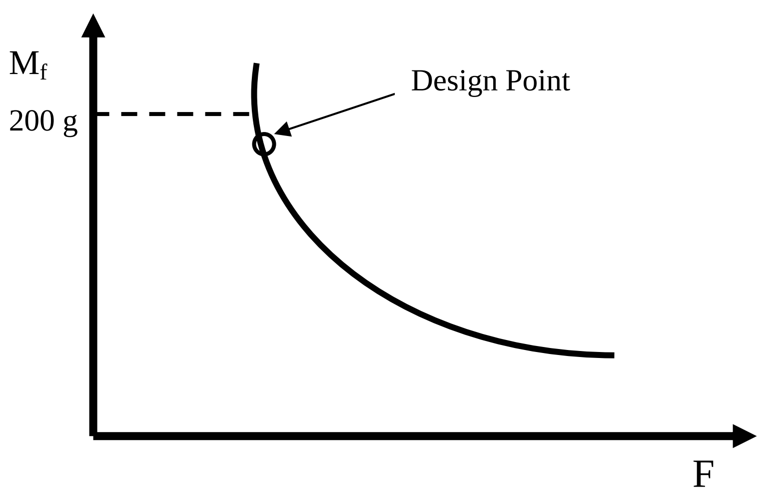


Fig. 6 Design choice in helmet foam mass and head impact force curve.

2.5.4 Design of Shell Thickness and Material Choices

Mills [3] introduced Kollar & Duluska's theoretical analysis (1984) for the buckling of a spherical cap under a central point P. The critical load Pc is given by

$$P_C = \frac{2\pi E t^3 Q}{12(1-\nu^2)R} \tag{16}$$

where E is Young's modulus, ν is poisson's ratio, R is the shell radius and Q is a dimensionless parameter.

Eq. (18) shows the relationship between load Pc and shell thickness that

$$Pc = C_3 t_s^{\ 3} \tag{17}$$

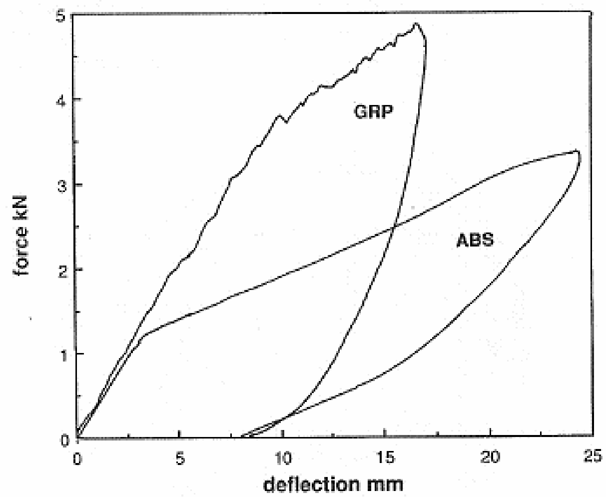


Fig. 7 Force-deflection relationship for GRP and ABS [3]

However, shell can have a mass of 800 g, about 80% of helmet, in a helmet. As the same consideration of the design of helmet foam material, even the thicker shell can provide better protection; the thickness is limited by its total mass.

The widest used helmet shell materials in market are GRP and ABS. The GRP provides high strength and low weight, but its price is much higher than ABS. Force deflection relationship for a hemispherical impact onto the top of spherical caps cut from ABS and GRP helmet shell is shown in Fig. 7. Generally, the helmet shell made from ABS is 4.2 to 4.6 mm thick and from GRP is 2.5-3.5 mm thick.

It can be seen from Fig. 7 that the strength of GRP are stronger than ABS. In another world, GPR helmet shell can provide better protection than ABS helmet shell. However, the costs of GPR shell helmets are much more than ABS shell helmets. The choice of helmet shell material in this project will be considered later with the market accept abilities analysis.

2.6 Helmet Design Optimization

As can be seen in Fig. 7, GRP helmet shells have better stiffness than ABS shell. Otherwise, GRP weight is much less than ABS. Thus, GRP is chosen to be our motorcycle helmet shell material that we can have more flexible design choice for foam material and other helmet device design. From Eq. (17), critical load P_c increases when thickness t increases, so thicker shell could have better protection. According to the helmet penetration test determined in ASTM 1446 [1] and shell material property test by Mills [3], GRP shell helmets thickness must be more than 2.5 mm. Density of GRP shell material is not various in the market. Thus, 690 kg/m^3 GRP density shell is chosen in our model as the most common in the market that manufacture cost can be less than using the particular material. Based on the choice of shell density and the limitation of helmet total mass in Eq. (1), the thickness of helmet must be less than 3.2 mm.

From Eq. (5), if foam density is set to be 68 kg/m^3 and total mass of foam and shell mass are design to be 1 kg, the relationship of helmet shell thickness and foam thickness are shown in Fig. 8. As can be seen, foam thickness is decreased when shell thickness is increased. However, from

Fig. 3, foam thickness should be larger than 20mm, so from fig. 13, it is obviously that shell thickness should less than 2.8 mm.

$$2.5mm \le t_s \le 2.8mm \quad (18)$$

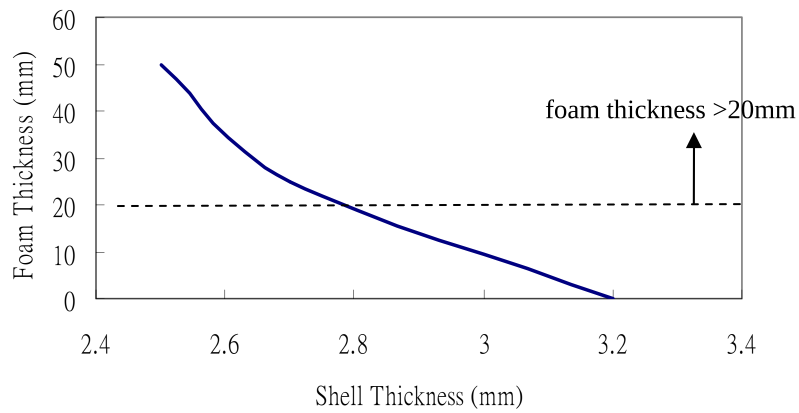


Fig. 8 Relationship of 1kg helmet shell thickness and foam thickness combination

After the shell material is determined, the choice of foam thickness and density can be bounded by its total mass. Assume that helmet shell with 2.5mm thickness and 690 kg/m^3 is chosen, and the most common foam density in the market of 68 kg/m^3, 60 kg/m^3, 54 kg/m^3, and 50 kg/m^3 are selected. The relationship between maximum foam thickness and foam density are shown in Fig. 9. From Fig. 9 that we can set the foam density and thickness boundaries as:

$$50kg/m^3 \le q_f \le 68kg/m^3 \quad (19)$$

$$t_f \le -0.322q_f + 54.31 \quad (20)$$

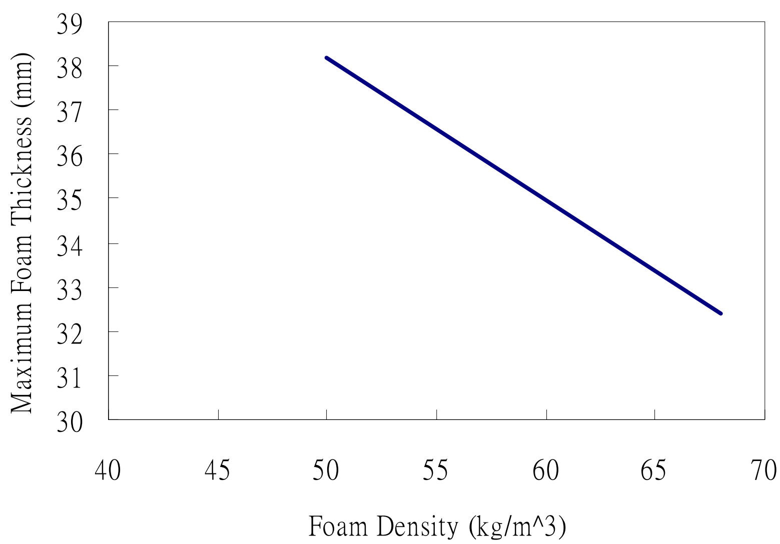


Fig. 9 Design choice of foam thickness and density

From Mills [3] mathematical model in Eq. (10) and Eq. (14) that head center acceleration during head impact is decreased by the increase of foam thickness and density as $G = C_1 \frac{1}{q_f}$ and $G = C_2 \frac{1}{t_f}$. In order to minimize the head center acceleration to reduce HIC value, increase of foam density and thickness is necessary. LS-DYNA3D finite element code is used to estimate parameter C_1 and C_2 of Eq. (10) and Eq. (14). Fig. 10 and Fig. 11 show the effect of foam thickness and density with head center acceleration. It can be seen that head acceleration G in the boundary of foam density $50kg/m^3 \le q_f \le 68kg/m^3$ and foam thickness $20mm \le t_f \le 38.11mm$ are all almost under the safety criterion 300g.

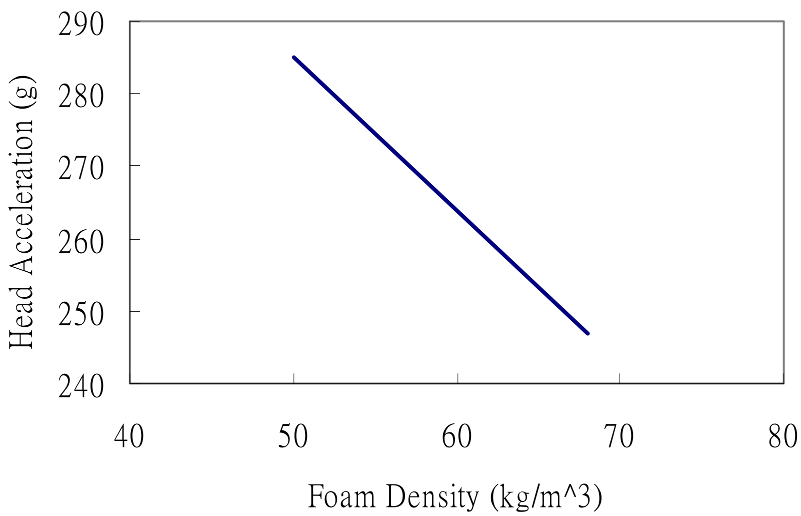


Fig. 10 Relationship of foam density choice and head impact acceleration

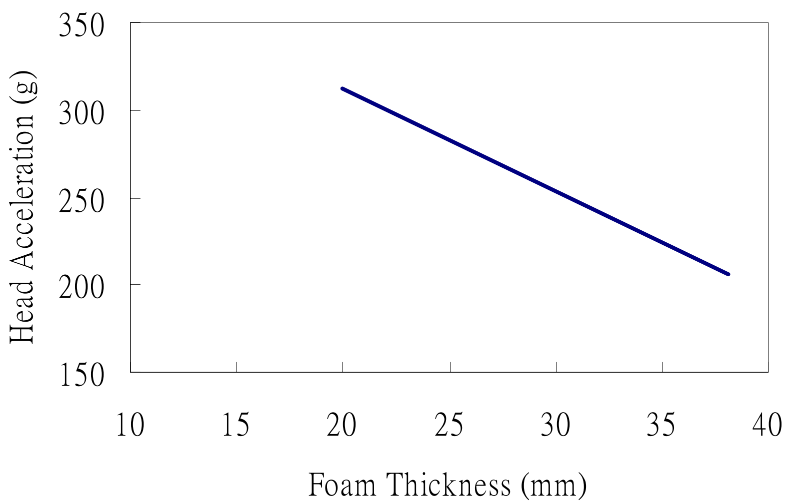


Fig. 11 Relationship of foam thickness choice and head impact acceleration

From the discussion above, we can conclude our helmet design optimizations as following equations:

$\min G = f(q_f, t_f)$

$\min M = f(q_f, t_f, t_s)$

subject to

$$M = q_f V_f(t_f) + q_s V_s(t_s)$$
$$= 126.6296 t_f^{\,3} q_f + 25338.05 t_s^{\,3} q_s$$
$$G = -211.136 t_f - 3.2673 q_f + 3.53264 v + 226.9584$$
$$0kg \le M \le 1kg$$
$$0g \le G \le 300g$$
$$50kg/m^3 \le q_f \le 68kg/m^3$$
$$650kg/m^3 \le q_s \le 750kg/m^3$$
$$2.5mm \le t_s \le 2.8mm$$
$$0mph \le v$$

2.7 Solution for Optimization

The solution of the above optimization problem is given as a Pareto set in Fig. 12. However, the optimal design set i.e. the Pareto curve remains arbitrary. Hereby, we will make some assumptions and some engineering sacrifices to meet our design requirements. The detailed is given in the following paragraph.

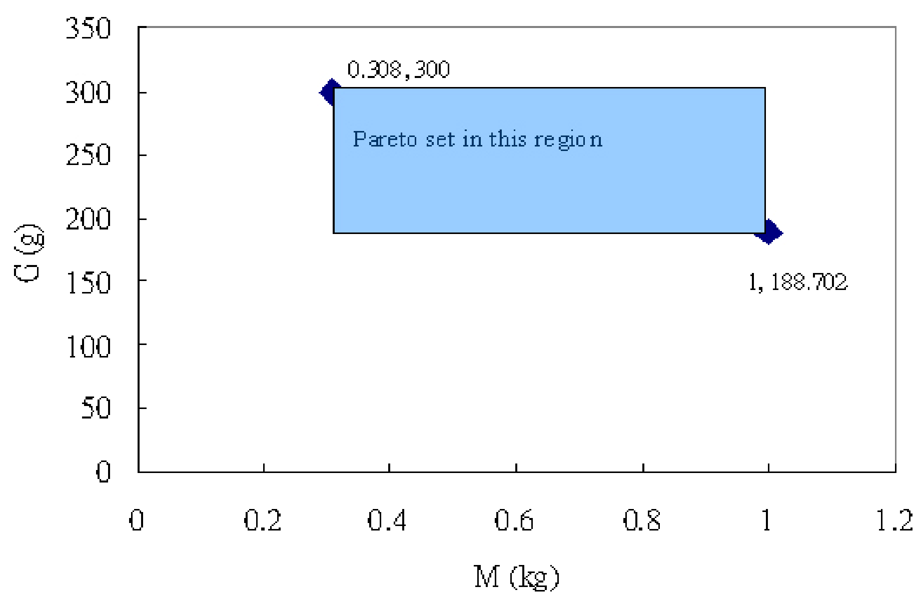


Fig. 12 Design space of helmet total mass and head acceleration

Because the mass of helmet shell occupied about 80% of total helmet mass, in order to reduce the helmet weight, a GRP helmet shell of density 690 kg/m^3 and thickness of 2.5mm is chosen. Varied foam thickness (20mm, 25mm, 30mm), with 68 kg/m^3 density is input into LS-DYNA3D finite element code to analysis the relationship between helmet total mass and head center impact acceleration as shown in Fig. 13. As can be seen, head center acceleration decreases when total mass decreases. Because our helmet with GRP shell has reduced a lot helmet weight, we might choose foam with 30 mm foam to get better protection and total mass of 0.74 kg still much less than the criterion 1 kg.

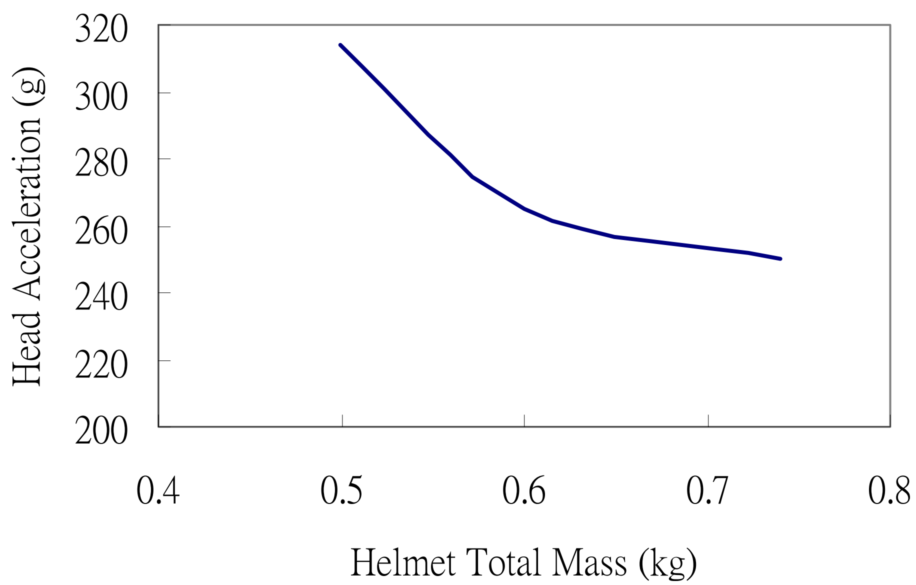


Fig. 13 Design choice of helmet total mass and head acceleration

3. Microeconomics Models via Market Survey

3.1 Quality Function Deployment (QFD)

Value to the customer is the ratio of the benefits the customer receives divided by the price paid. When products are designed using customer needs, value and sales go up. When start-up problems are reduced and cycle times shortened, costs go down. Increased sales and lower costs means greater profits.

QFD translates customer requirements into design requirements. QFD has helped organizations like 3M, Ford Motor Co. and AT&T improve customer satisfaction, reduce product development time, and reduce start-up problems.

3.1.1 Key Benefits

With a QFD analysis we can do the above, and are able to identify:

- What modules of a solution are the most important to solving a problem
- What pieces of the solution gives the desired benefits
- What dependencies exist for specific features of the solution
- What portions should be developed and installed first to achieve management's desires
- What our customers will receive

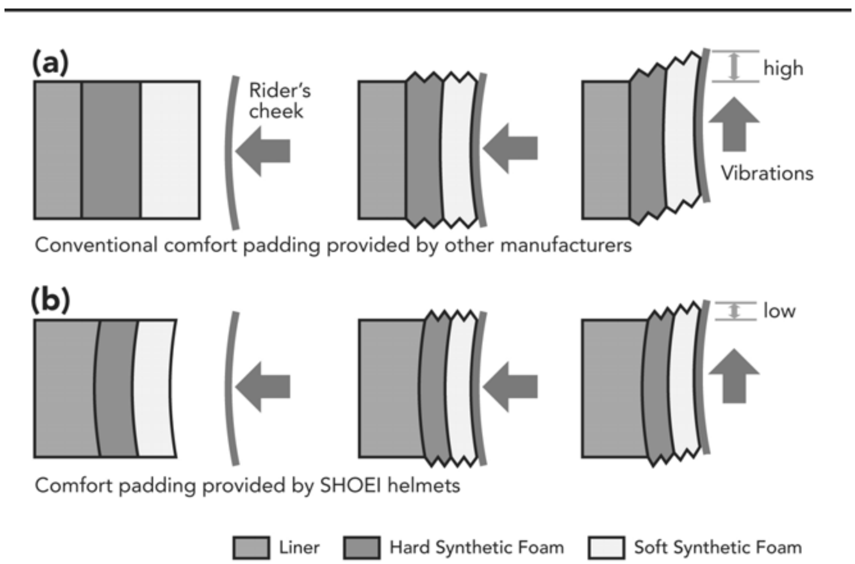
__3.1.2 Our Approach__
Our QFD is put on the last page of this report.

3.2 Couple Customer Demands with Engineering Ideas

From our QFD chart, we know that there is some customers' demand that is traditionally hard to quantify in the aspect of engineering. Here, we try to develop model or methodology to fit those sometimes "ambiguous" demands into our product development process.

__3.2.1 Comfort/fit__
To help engineers visualize what "comfort" means in a customer's mind. We suggest start from those aspects as follows:

1. No Vibrations
The reduction of vibrations, which can lead to rider fatigue or can impair visibility, plays an important role during the development of helmet design. While the comfort padding of a helmet normally only serves to ensure a secure fit, a properly designed one can provide two major advantages. The development work performed at SHOEI (quoted from SHOEI's website) suggests the creation of a three-dimensional liner shape. In conjunction with surprisingly thin, cheek-shaped comfort padding, the liner guarantees a perfect fit that prevents any helmet vibrations even at high speeds. The idea at SHOEI (quoted from SHOEI's website) is shown in the following figure.



2. No Pressure
If the comfort padding exerts pressure on specific points of the rider's head, the rider will develop a headache after a couple of hours' riding, which will in turn impair the rider's concentration and increase the risk of accident. A balanced distribution of the comfort padding also prevents a feeling of heaviness after longer periods of use. This implies a liner must always be designed suit the helmet's later actual conditions of use and that comfort padding must be head-shaped, that is various parts of comfort padding may be needed to design a "complete"

comfort padding.

3. Helmet Weight and Aerodynamics

Coupled with low weight, an aerodynamic shape also increases the wearing comfort of a helmet. Next to the actual weight of the helmet, the rider will also feel the pressure of the aerodynamic load during a ride. The inertia moment, which is especially noticeable during an accident, further increases neck strain. Reducing the moment of inertia thus lessens the pressure exerted on the neck muscles, on which the entire weight of the helmet rests, and can contribute to increasing the rider's concentration. Lowering the weight of the helmet thus plays a central role in the development work, from investigating basic structures like the outer shell and liner right up to component production. An aerodynamic helmet shape, which is optimized for each model with the help of various windtunnel tests, ensures low wind resistance during a ride and thus prevents the rider from developing muscle fatigue.

4. Ventilation

The excellent ventilation system of not only prevents the visor from steaming up, but also ensures a pleasant climate within the helmet. This spares the rider unnecessary stress due to overheating and thus avoids any loss of concentration.

5. Visor

Among other things, the visor must ensure clear visibility without optical distortion, be scratch- and water-proof and guarantee protection against UV rays. Apart from fulfilling these requirements and under consideration of the actual conditions of use, developing a special system that enables a quick visor change in the event of a sudden turn in the weather is highly demanded on the market.

6. Noise

On the one hand, excessive noise within the helmet constitutes a stress factor for the rider that can reduce concentration. On the other, it may drown out important external noises like engine sounds or warnings issued by other motorists that the rider should always be able to hear in the interest of road safety. The actual level of noise inside the helmet is dependent on various factors. While increasing the degree of wearing comfort by optimizing the comfort padding, aerodynamics, ventilation system and visor, we should always continually aim to minimize the level of noise inside the helmet.

3.2.2 Style

With respect of style, pattern design and painting play very important parts. While pattern design is quite an artistic touch which most people consider lacking in an engineer’s mind, painting actually is all about material science and techniques.

3.3 Couple Manufacturing Issues with Cost

Accurately forecasting the cost of future projects is vital to the survival of any business. The key to a successful and accurate estimation is to compile and analyze data on all the factors that can influence costs — such as materials, labor, location, and special machinery requirements, including computer hardware and software.

Fig. 7 shows a general manufacturing procedure that is generally utilized in the industry. Starting from here, we will address manufacturing issues of each part so that engineers can start thinking about how design will affect the cost, and hence couple the financial aspect with the engineering decisions.

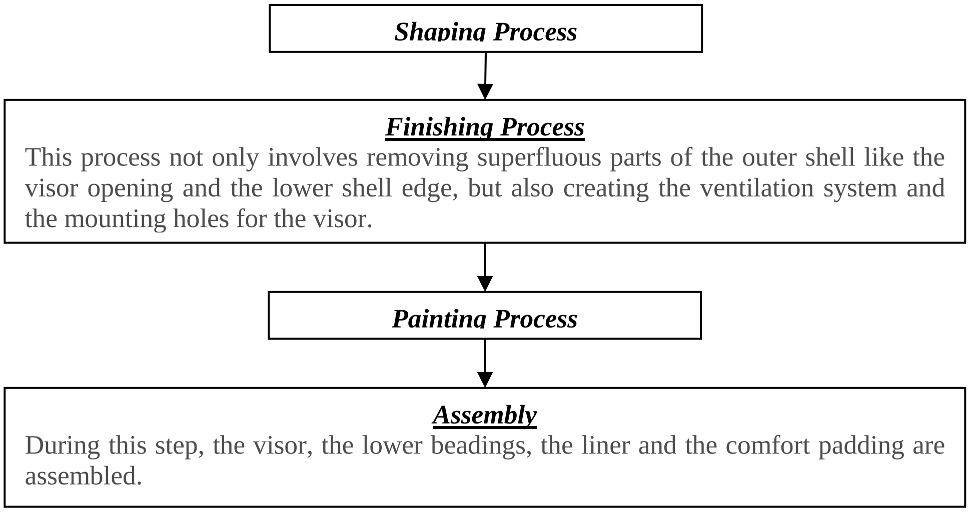


Fig. 7. The manufacturing processes

3.3.1 Shell Manufacturing

There are two different material types used for helmet shells. The shell types are the thermoplastics shells and the composite shells. Fig. 8 shows the current manufacturing techniques.

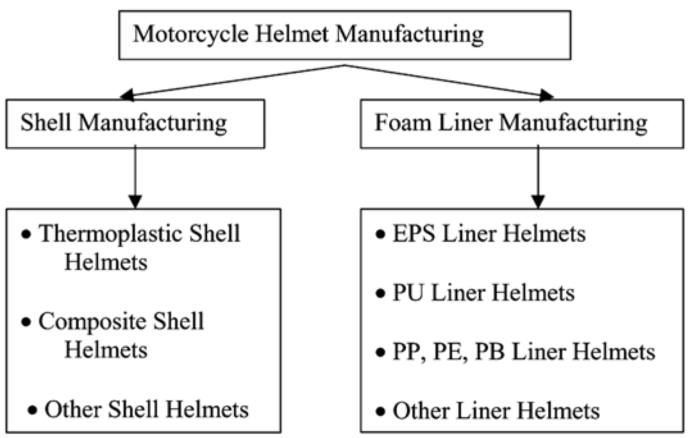


Fig.8. Categorizing of helmet manufacturing methods

Thermoplastic shells

The injection molding is the main process for these types [4]. The most popular shell materials are the ABS due to its better impact performance and less degradation problems [5]. However it suffers from brittleness such as photo oxidation due to long exposure to the environment [5].
The advantages and disadvantages of this technique are summarized in Table 2.

Table 2: The advantages and disadvantages of thermoplastic shells

Advantages	***Disadvantages***
➢ As a rule these shells are lighter than composite	➢ To exhibit sufficient impact strength, such as

shells ➢ The advantage of low cost due to using the machinery. ➢ The labor and the finishing operations are minimized. ➢ This method produces a shell of lightweight and even shell thickness. ➢ The accuracy of the helmet dimensions is excellent which, in most cases, requires no additional finishing steps such as trimming, machining or grinding	composite shells these shells should have a large thickness with a corresponding increase on the weight and the PC shells are difficult to process ➢ PC material is vulnerable to organic solvents or lacquers. ➢ Relatively poor shock absorbing capacity

Composite shell helmets

Special purpose helmets, such as that for racing motorcycles, are made of Kevlar composites, which have better performance, but are more expensive.

A positive type mold and negative type mold are used. First releasing agent and a cover layer of resin, which contains the basic color and forms the outer thinnest layer of helmet, is sprayed. Small strips of precut glass fiber mats impregnated with high viscous polyester resin and hardner are applied to the still moist covering layer. Up to a maximum number applied to the negative type mold and pressed into the mold by means of special tools, so as to be free of any bubbles. [4]. Fig. 9 illustrates the making of composite shells.

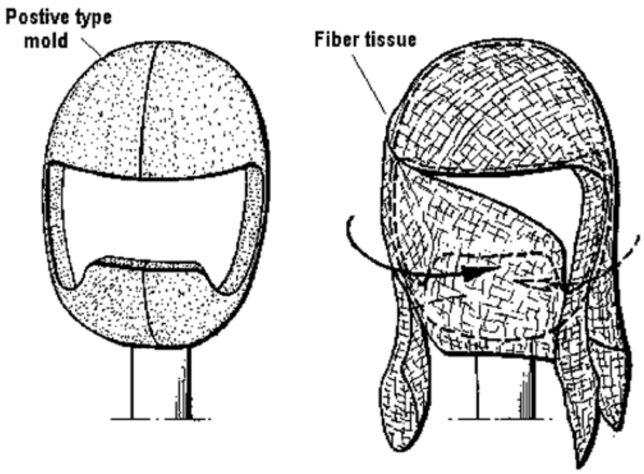


Fig.9 Composite shell making [3]

Advantages and disadvantages of composite shells are summarized in Table 3.

Table 3: The advantages and disadvantages of composite shells

Advantages	***Disadvantages***
➢ Lower capital cost in terms of machines and processes	➢ Labor intensive particularly the first procedure. Therefore if labor wages are high or not available locally this will add to the cost of the helmet ➢ Less accuracy than thermoplastic shell helmets due to the manual application of the glass fiber mattes or tissues Shells produced by this method require further finishing operation such as chipping, and grinding

3.3.2 Foam liner manufacturing

The performance of the helmet will depend largely on the type of foam used in the helmet as different foam types behave differently during impact. The use of any of the foams depends upon various factors, and the manufacturing aspect is one of them.

Helmet manufacturing can be categorized according to the foam type and are as follows:

- EPS linear
- PU linear
- PP, PE, Pb linear
- PVDC or integral skin liner

Each of the above helmet types has different manufacturing methods and differs from one the other to a certain extent. Here, EPS, our choice of design will be examined in details.

Expanded polystyrene (EPS) foam liner

EPS foam currently dominates the market [8]. The reason for this is its excellent performance and lightweight characteristics. The manufacturing cost is low for large production quantities. Fig. 10 shows the EPS foam expansion system that is typically used in the industry.

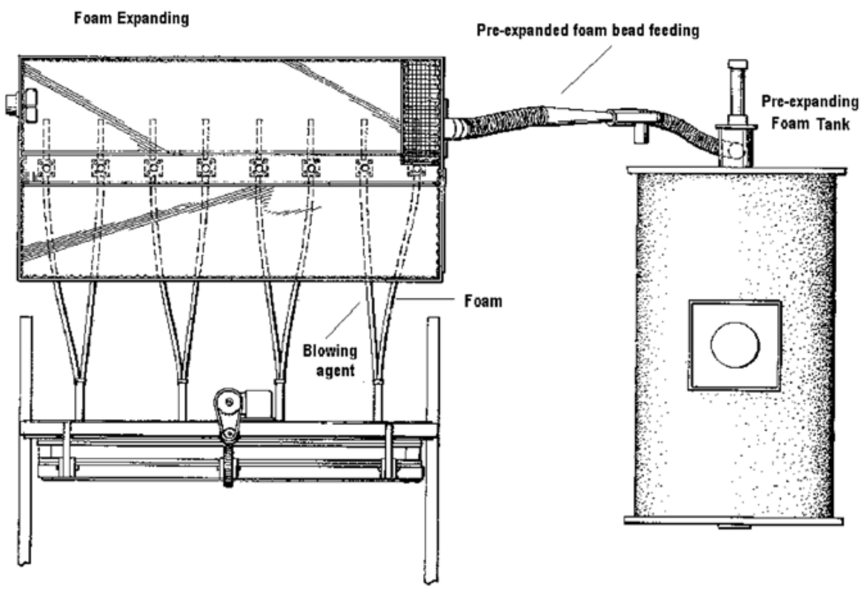


Fig. 10. EPS foam expansion system [7]

EPS helmets consist of plastic cells that have been bonded together in the shape of a helmet during the molding process. Helmets made of EPS are rigid, inelastic, and have very little flexibility.

EPS helmets are generally made by the injection molding process. A typical mold for an EPS helmet liner has a core and cavity and the gap between them defines the shape of the helmet. The core is generally hemispherical in shape and configured to roughly match the shape of human head.

An additional problem encountered in the manufacturing of EPS helmets is configuring the helmet with holes in it to accommodate a helmet retention system or air vents.
A methods that is used for forming holes in EPS helmets is to cut the holes after molding process with a hot knife or wire. The principal disadvantage to this procedure is that it can be extremely messy due to the method EPS accumulating on the knife and around the workstation where the cutting is performed.

Another attempt made to efficiently mold holes into EPS helmets is to employ "sliding" core in which there are movable projection in the core, which correspond in size to the holes to be formed in the helmet. When molding the helmet the projections are inserted into the void between the core and cavity before the polystyrene beads are introduced into the mold. After the part cools, the projections are retracted into the core before the core and the cavity are separated [6].

3.4 Cost Estimation

From previous study in the both design and manufacturing considerations arose in the real world application, we know can estimate the cost as follows.

3.4.1 Research & Development (R&D) Cost

Category	Process	Profession Required	Annual Wage	Engineers Needed	Total Working Hours
Design	Industrial Design	Industrial Engineer	$49,985	1	Unknown
	Computer-Aided Design	CAD Drafter	$34,449	1	Unknown
Analysis	Engineering Model Setup	Mechanical Engineer	$49,336	1	Unknown
	Finite Element Analysis				

Model:

$$Cost^{(R\&D)} = \sum_{n=1}^{3} \frac{W_n^{(R\&D)}}{\left(D \cdot H\right)} \cdot N_n^{(R\&D)} \cdot T_n^{(R\&D)}$$

Parameters Specification:

$W_n^{(R\&D)}$: Annual wage of the corresponding profession

$N_n^{(R\&D)}$: Number of engineer needed for the specified task

$T_n^{(R\&D)}$: Time taken per engineer to finish the assigned task

D : Annual working days per engineer

H : Daily working hours per engineer

3.4.2 Material/Part Cost

Material/Part	Type	Bulk/Unit Cost	Quantity Used
Glass reinforced plastic (GRP)	Raw	Unknown	w_{GRP}
Expanded Polystyrene(EPS)	Raw	Unknown	w_{EPS}
Visor	Semi-finished	$ 5 Per Unit	1 Unit
Comfort Padding	Semi-finished	$ 1 Per Set	1 Set

Model:

$$Cost^{(Mat)} = \sum_{n=1}^{4} C_n^{(Mat)} \cdot Q_n^{(Mat)}$$

Parameters Specification:

$C_n^{(Mat)}$: Bulk/unit cost for materials/parts

$Q_n^{(Mat)}$: Quantity consumed for manufacturing

Design Variable

w_{GRP} : Total GRP consumed

w_{EPS} : Total EPS consumed

3.4.3 Production Cost

Category	Process	Cost Type	Unit Labor/Operational Cost	Labor/Operational Time
Shaping	Baking	Operational	Unknown	15 mins
Finishing	1. Cut with Water Jets and Laser Beams	Operational	Unknown	15 mins
	2. Inspection	Labor	$20.00 Per Hour	10 mins
Painting	1. Base Coat	Labor	$20.00 Per Hour	20 mins
	2. Polishing	Labor	$20.00 Per Hour	20 mins
	3. Optical Shell Examination	Labor	$20.00 Per Hour	10 mins
	4. Painting	Labor	$20.00 Per Hour	120 mins
	5. Quality Control	Labor	$20.00 Per Hour	15 mins
	6. Markings	Labor	$20.00 Per Hour	10 mins
	7. Transferring Graphics	Labor	$20.00 Per Hour	30 mins
	8. Clear Varnish	Labor	$20.00 Per Hour	60 mins
	9. Final Inspection	Labor	$20.00 Per Hour	15 mins
Assembly	1. Visor,	Labor	$20.00 Per Hour	5 mins
	2. Lower Beadings,	Labor	$20.00 Per Hour	5 mins
	3. Liner	Labor	$20.00 Per Hour	5 mins
	4. Comfort Padding	Labor	$20.00 Per Hour	5 mins

Model:

$$Cost^{(production)} = \sum_{n=1}^{2} C_n^{(OP)} \cdot T_n^{(production)} + \sum_{n=3}^{16} C_n^{(Labor)} \cdot T_n^{(production)}$$

Parameters Specification:

$C_n^{(OP)}$: Operational cost at the corresponding manufacturing process

$C_n^{(Labor)}$: Labor cost at the corresponding manufacturing process

$T_n^{(production)}$: Time taken to finish the corresponding task

3.4.4 Quality Control

Test	Type	Sampling Rate	Cost Per Unit
Impact Absorption	Operational	30 %	Unknown
Dynamic Retention	Operational	30 %	Unknown
Roll-off Test	Operational	30 %	Unknown
Wind Tunnel	Operational	10 %	Unknown
Test Ride	Labor	10 %	Unknown

Model:

$$Cost^{(QC)} = \sum_{n=1}^{5} C_n^{(QC)} \cdot S_n^{(QC)}$$

Parameters Specification:

$C_n^{(QC)}$: Cost per unit at the corresponding test

$S_n^{(QC)}$: Sampling rate for each different test

Total cost is then given by

$$\Omega = \sum_{n=1}^{3} \frac{W_n^{(R\&D)}}{(D \cdot H)} \cdot N_n^{(R\&D)} \cdot T_n^{(R\&D)} + \sum_{n=1}^{4} C_n^{(Mat)} \cdot Q_n^{(Mat)} + \sum_{n=1}^{2} C_n^{(OP)} \cdot T_n^{(production)}$$
$$+ \sum_{n=3}^{16} C_n^{(Labor)} \cdot T_n^{(production)} + \sum_{n=1}^{5} C_n^{(QC)} \cdot S_n^{(QC)}$$

3.4.5 Assumption and Simplification

From the tables above, we clearly see that many parameters are arbitrary. Hence, an assumption is made as all unknown cost is reflected in a fixed cost 150 dollars. Also, we assume that the material cost for foam material (EPS) is included in this fixed cost, since, comparing to the cost of shell material (GPR), its cost is relatively small.

We then make a further assumption regarding the bulk/unit price for shell material (GPR) is $0.05\left(\frac{dollar}{mg}\right)$

Then, the cost model is simplified into

$$\Omega = 150 + 0.05 \cdot z_1$$

z_1: Weight of shell material (GPR) (Approximately equals to the weight of the helmet)

3.5 Demand Models

3.5.1 The Demand Curve

The relationship between price and the amount of a product people want to buy is what economists call the demand curve. This relationship is inverse or indirect because as price gets higher, people want less of a particular product. This inverse relationship is almost always found in studies of particular products, and its very widespread occurrence has given it a special name: the law of demand.

Here is a list of the variables that affect a consumer's decision.

- The price of the product
- Consumer income
- The price of substitute goods
- The price of complementary goods such as beer or lemonade
- Consumer tastes and advertising
- Consumer expectations about future prices

3.5.2 Survey Establishment

A survey is used to collect data of consumers' preference to buy a motorcycle helmet. There are 36 questions in the survey and each question includes 5 character choices, price, weight, expect ride speed, appearance and ability of ventilation. One of the samples is shown in Fig. 1.

Your Choice	Price	Weight	Designed to ride at	Painting of Shell	Ability of ventilation
1	$ 250	650g (1.43 lb.)	90 mph	Single color	Good
2	$ 250	300g (0.66 lb.)	50 mph	Colorful look	Good
3	$ 400	650g (1.43 lb.)	70 mph	Colorful look	Good
None of above					

Fig. 1 Helmet consumer preference survey question sample

The survey is design in 5 main parts to analyze consumers' abilities of purchasing a new helmet, protection requirements, exterior affection and comfort as shown in Table 1. Based on the present market prices, the helmets are set to be 3 levels, $100, $250 and $400. Consumers might choose the cheapest one because of the helmet-wear-law or may want to spend more money to get better protection and comfort. Helmets weights are separated to 3 choices, 300g (0.66lb), 650g (1.43lb), and 1000g (2.20lb). Though lighter helmets would let the motorcyclists feel more comfortable, reduce of foam and shell thickness might reduce the protection abilities of helmets. Otherwise, using specific light material, like GRP for shell, will increase the cost substantially. Riding speed choice, 50mph, 70mph and 90mph are based on motorcyclists' riding habits. High speed riders might consider helmets with better protections are necessary and probably concentrate on protecting functions when purchasing helmets. Exterior painting is one of the important factors that affect the prices of helmets, especially when some consumers request specific design. Last, choices of the ventilation ability depend on the helmet wearing time and environment. Better ventilation, of course, will increase manufacture cost.

Table 1 Levels of design characteristics

		Level 1	Level 2	Level 3
Characteristic 1	Price	$100	$250	$400
Characteristic 2	Weight	300g (0.66 lb.)	650g (1.43 lb.)	1000g (2.20 lb.)
Characteristic 3	Ride speed	50mph	70mph	90mph
Characteristic 4	Painting of Shell	Single color	Colorful look	-----
Characteristic 5	Ability of ventilation	Good	Bad	-----

3.5.2 Discrete Choice Analysis

The Multinomial Logit Model is used to analyze the consumer preference of helmet selection. From Table 1, define binary variables Z_{ijk} and coefficient β_{kl} such that

$Z_{jkl} = 1$ if product j has characteristic k at level l. (1)

$Z_{jkl} = 0$ otherwise (2)

Then, assume the functional form in terms of Z_{ijk} that

$$v_j = \sum_{k=1}^{k} \sum_{l=1}^{L_k} \beta_{kl} Z_{jkl} \tag{3}$$

The log-likelihood is defined as:

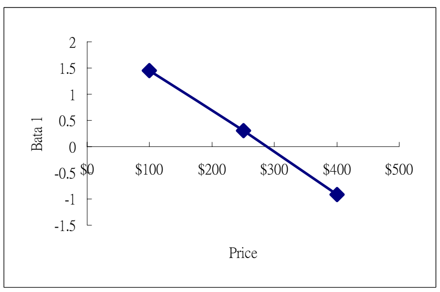
$$\sum_{n=1}^{N}\left\{\sum_{j\in J_n}\left[q_{nj}\ln\frac{\exp(v_j)}{\sum_{j'\in J}\exp(v_{j'})}\right]\right\}=\sum_{n=1}^{N}\left\{\sum_{j\in J_n}q_{nj}\ln\left[\frac{\exp(\sum_k\sum_l\beta_{kl}Z_{jkl})}{\sum_{j'\in J_n}\exp(\sum_k\sum_l\beta_{kl}Z_{j'kl})}\right]\right\} \tag{4}$$

where n is the number of questions and q_{nj} are the data from the survey results.

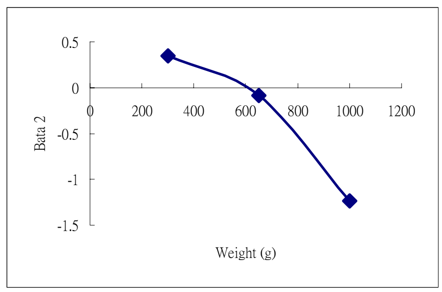
Excel solver is used to solve for value β_{kl} that maximize the log likelihood of the model. The solving result β_{kl} is shown in Table 2 and Fig. 2-6.

Table 2 Solving result for β_{kl}

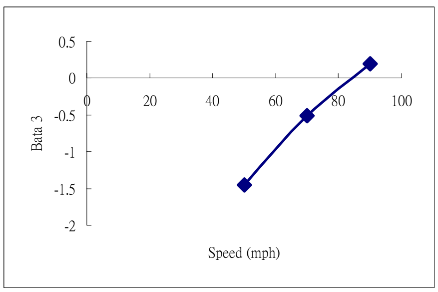
β_{kl}	Level 1	Level 2	Level 3
Characteristic 1	1.446	0.299	-0.916
Characteristic 2	0.346	-0.082	-1.234
Characteristic 3	-1.449	-0.514	0.192
Characteristic 4	0.040	0.289	---
Characteristic 5	0.961	-0.632	---



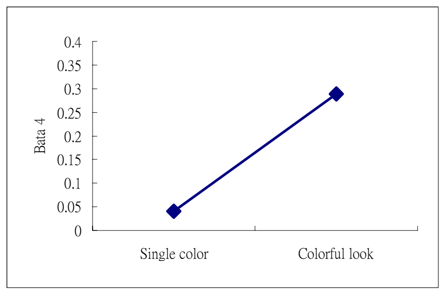
(a)



(b)



(c)



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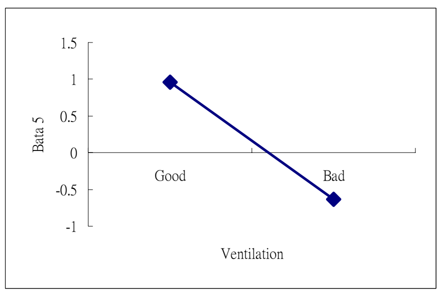


(e)

Fig. 2 Graphics of β_{kl} and each characteristic

As shown in fig. 2, lower price and weight, higher impact speed capability, colorful look and good ventilation are consumers' preference when they purchase motorcycle helmets. The results are under our expectations that we can say these survey conclusions can be used in further helmet design factors. Otherwise, it can be seen from the graphics that consumers' selection preference of price and speed capability shows linear relationship. However, from the graphic of bata2 and weight, the slope between 650g and 1000g is much larger than the slope between 200g and 650g. It is obvious that heavy helmet design is hard to be accepted by the market.

From fig. 2, each graphic is fit by function Ψ_k that interpolated beta values can be calculated for any intermediate value and the utility v can be calculated from the sum of β values.

$$v = \sum_{k=1}^{K} \beta_k \qquad (5)$$

where

$$\beta_1 = \Psi_1(p) = -0.0079p + 2.2447 \qquad (6)$$

$$\beta_2 = \Psi_2(Z_1) = -3\times 10^{-6} z_1^{\ 2} + 0.0016 z_1 + 0.1375 \qquad (7)$$

$$\beta_3 = \Psi_3(Z_2) = -3\times 10^{-4} z_2^{\ 2} + 0.0813 z_2 - 4.7953 \qquad (8)$$

$$\beta_4 = \Psi_4(Z_3) = 0.04, 0.289 \text{ (single color, colorful look)} \qquad (9)$$

$$\beta_5 = \Psi_5(Z_4) = 0.961, -0.632 \text{ (good ventilation, bad ventilation)} \qquad (10)$$

The probability of an individual choosing product j from the set of J can be written as a function of characteristics z_j and price p as

$$\Pr(j/J) = \frac{\exp\left[\Psi_1(p_j) + \sum_{k=2}^{K} \Psi_k(z_j)_{k-1}\right]}{\sum_{j'\in J} \exp\left[\Psi_1(p_{j'}) + \sum_{k=2}^{K} \Psi_k(z_{j'})_{k-1}\right]} \qquad (11)$$

If there is only one final product design that consumers can only choose to buy or not to buy, equation (11) can be reduced to:

$$\Pr(A) = \frac{\exp\left[\Psi_1(p) + \sum_{k=2}^{K} \Psi_k(z)_{k-1}\right]}{1 + \exp\left[\Psi_1(p) + \sum_{k=2}^{K} \Psi_k(z)_{k-1}\right]} \qquad (12)$$

Given a motorcycle helmet market size S, the demand for this specific design product with price p and design characteristics z_k, k=2, 3…., K, can be described as:

$$Q_m = S\,\frac{\exp\left[\Psi_1(p) + \sum_{k=2}^{K} \Psi_k(z)_{k-1}\right]}{1 + \exp\left[\Psi_1(p) + \sum_{k=2}^{K} \Psi_k(z)_{k-1}\right]} \qquad (13)$$

According to the study before, there are about 1 million helmets sold in US each year, so we can assume that $S = 1,000,000$. The other design characteristics are set with 1,000g weight, available for 50mph ride impact, single color and bad ventilation. The demand of helmet sold price can be calculated from equation (13) and the demand curve is shown in Fig. 3. Fig. 4-7 show the demand curves of different helmet characteristics design. It can be seen for Fig. 6 that consumers might not care about the exterior look when they buy a helmet. However, From Fig. 7, better design of ventilation would be more popular in the market.

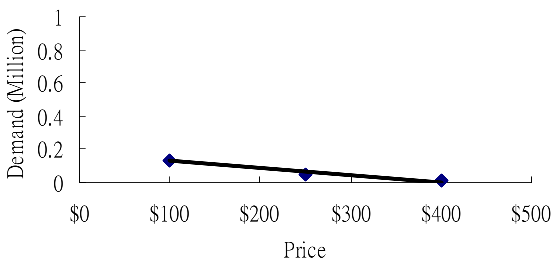


Fig. 3 Demand curve of helmets sold in US

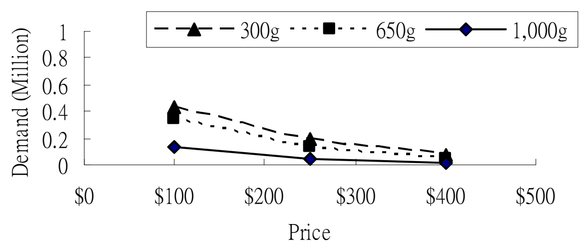


Fig. 4 Demand curves of different helmet weight

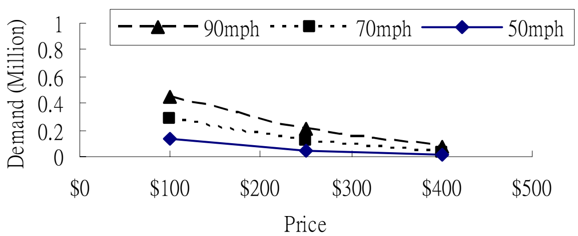


Fig. 5 Demand curves of different speed requirement

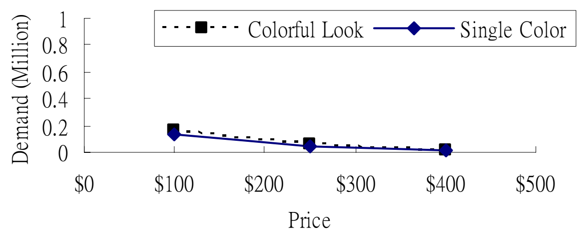


Fig. 6 Demand curves of different helmet exterior look

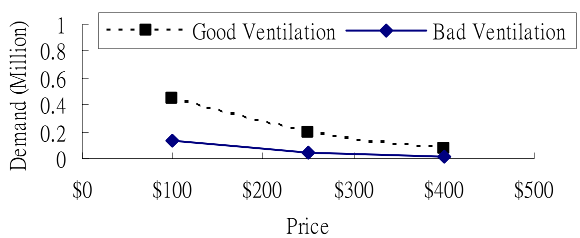


Fig. 7 Demand curves of helmet ventilation design

3.5.3 Estimation of Demand

From equation (13) we can get the demand Q_m is a function of price p and characteristics z_k. The function can be simplified as:

$$Q_m = Q_m(p, z) \tag{14}$$

From Taylor series expansion, we can describe demand function in equation (14) with specific price p_0 and characteristics z_0 as:

$$Q_m(p, \underset{\sim}{z}) = Q_m\left(p_0, z_0\right) + \left(\frac{\partial Q_m}{\partial p}\right)_0 \Delta p + \sum_{k=2}^{K}\left(\frac{\partial Q_m}{\partial z_k}\right)_0 \Delta z_k$$
$$= \left[Q_m(p_0, z_0) - \left(\frac{\partial Q_m}{\partial p}\right)_0 p_0 - \sum_{k=2}^{K}\left(\frac{\partial Q_m}{\partial z_k}\right)_0 z_{k_0}\right] + \left(\frac{\partial Q_m}{\partial p}\right)_0 p + \sum_{k=2}^{K}\left(\frac{\partial Q_m}{\partial z_k}\right)_0 z_k \qquad (15)$$

A motorcycle helmet of $300 with 500g weight, safe protection in 80mph ride, single color and good ventilation is chosen. From this product design composition, the demand function can be described as:

$$Q_m = 2.273 - 0.001029p - 0.00018z_2 + 0.0169158z_3 \quad \text{(Million)} \qquad (16)$$

3.6 Profit Model

The profile model is given by

$$\Phi = (P - \Omega)\cdot q$$
$$= \left[P - \left(150 + 0.05\cdot z_1\right)\right]\cdot q$$

where

P : Price

Ω : Cost

z_1 : Weight of shell material (GPR) (Approximately equals to the weight of the helmet)

q : Market Demand

Previously, we have

$$q = 2.273 - 0.001029p - 0.00018z_1 + 0.0169158z_2$$

Hence, we have the profile coupled with engineering variables given by

$$\Phi = (P - \Omega)\cdot q$$
$$= \left[P - \left(150 + 0.05\cdot z_1\right)\right]\cdot\left(2.273 - 0.001029p - 0.00018z_1 + 0.0169158z_2\right)$$

3.7 Solution for Optimization

3.7.1 Problem Setup

The setup of the optimization problem is given by

$$\max \Phi(P, z_1, z_2)$$
$$s.t.$$
$$0 < z_1 < 1000$$

where P : Price

z_1 : Weight of the helmet

z_2 : Maximum safety riding speed

$$\frac{\partial \Phi}{\partial P} = \text{-0.27921-0.002058P-0.00012855z}_1 \text{ +0.0169158z}_2 = 0$$

$$\frac{\partial \Phi}{\partial z_1} = \text{0.048678 -0.00012855P+0.000018z}_1\text{-0.00084579z}_2 = 0$$

$$\frac{\partial \Phi}{\partial z_2} = \text{-2.53737+0.0169158P-0.00084579z}_1 = 0$$

Solving for the 3 equations above yields the following two relations:

$P = 22.9942 + 3.65431 z_2$

$z_1 = -2540.12 + 73.0862 z_2$

3.7.2 Graphical Representation of the Solution

The solution for maximum profit is given by 2 equations

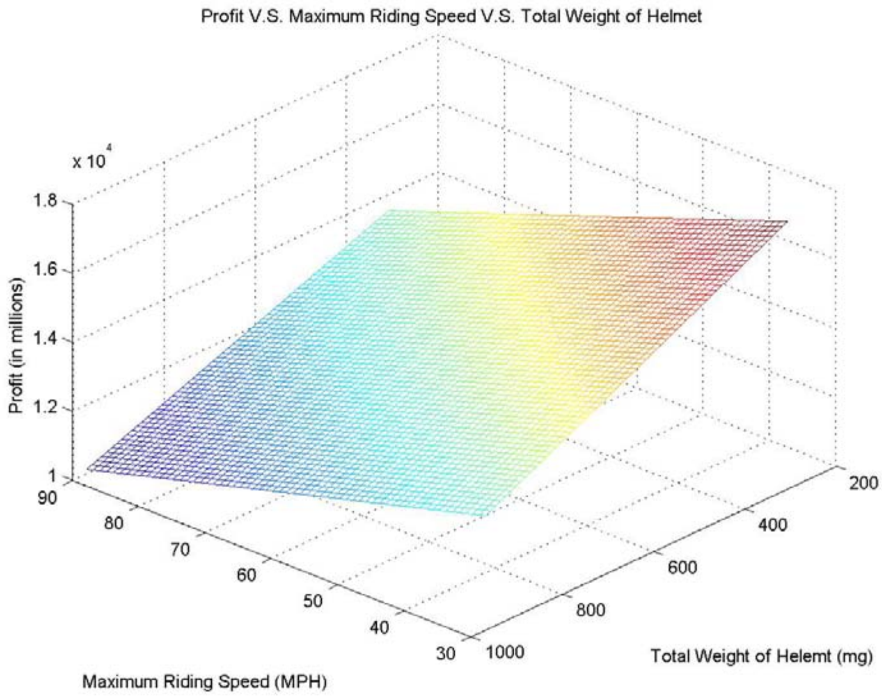
$P = 22.9942 + 3.65431 z_2$

$z_1 = -2540.12 + 73.0862 z_2$ with the constrain $0 < z_1 < 1000$

where P : Price

z_1 : Weight of the helmet

z_2 : Maximum safety riding speed



4. Production Family

4.1 Specification of 3 Products

From the survey of consumers' preference of choosing helmets, we can find that weight and protection are two of the most important facts when consumers buy helmets. However, different people would have different requirements because of different purpose of wearing helmets. Fast riders might purchase helmets with better protection design function, but long-distance riders might need light helmets to get better comfort. In this study, we would like to develop helmet design families to establish three different helmets for different requirements in the market. Equation (1) ~ (10) show the engineering viewpoint of helmet design boundaries. Assume one of the three different helmets is focused on low weight, another is focused on the protection and the other is set between those two characteristics. Based on the engineering design boundaries, each of the three products will be given further constrains to match our design goal.

$$\min G = f(q_f, t_f) \tag{1}$$

$$\min M = f(q_f, t_f, t_s) \tag{2}$$

subject to

$$\begin{aligned} M &= q_f V_f(t_f) + q_s V_s(t_s) \\ &= 126.6296 t_f^{\,3} q_f + 25338.05 t_s^{\,3} q_s \end{aligned} \tag{3}$$

$$G = -211.136 t_f - 3.2673 q_f + 3.53264 v + 226.9584 \tag{4}$$

$$0kg \le M \le 1kg \tag{5}$$

$$0g \le G \le 300g \tag{6}$$

$$50kg/m^3 \le q_f \le 68kg/m^3 \tag{7}$$

$$650kg/m^3 \le q_s \le 750kg/m^3 \tag{8}$$

$$2.5mm \le t_s \le 2.8mm \tag{9}$$

$$0mph \le v \tag{10}$$

Product A is designed for the motorcyclists who need higher protection and might not care the weight of helmet. The design objective and constrain are set as shown in equation (11).

$$\begin{aligned} &\min \quad f_A = 3M_A + 7G_A \\ &0g \le G_A \le 250g \end{aligned} \tag{11}$$

Product B is designed for the long-distance riders, i.e. the commuters, who need helmets with light weight and might not require great protection for high speed impact. The design objective and design constrain are shown in equations (12).

$$\begin{aligned} &\min \quad f_B = 7M_B + 3G_B \\ &0g \le M_B \le 500g \end{aligned} \tag{12}$$

The design characteristics of Product C are set between product A and B that for people who will consider both the weight and protection when the purchase helmets. The design objective and constrains are shown in equations (13).

$$\begin{aligned} &\min \quad f_C = 5M_C + 5G_C \\ &500g \le M_C \le 750g \\ &250mph \le G_C \le 275g \end{aligned} \tag{13}$$

We can solve the three optimization models above and get the solutions as listed in table 1. The limit of the optimal design of product A, B and C will be in the Pareto set region as shown in Fig. 1.

Table 1 Solutions of different helmet design objective.

Products	M (kg)	q_f (kg/m^3)	q_s (kg/m^3)	t_f (m)	t_s (m)	G (g)
A	1	60	700	0.046	0.0025	233.24
B	0.5	50	650	0.034	0.0025	268.43
C	0.75	55	675	0.041	0.0025	250.54

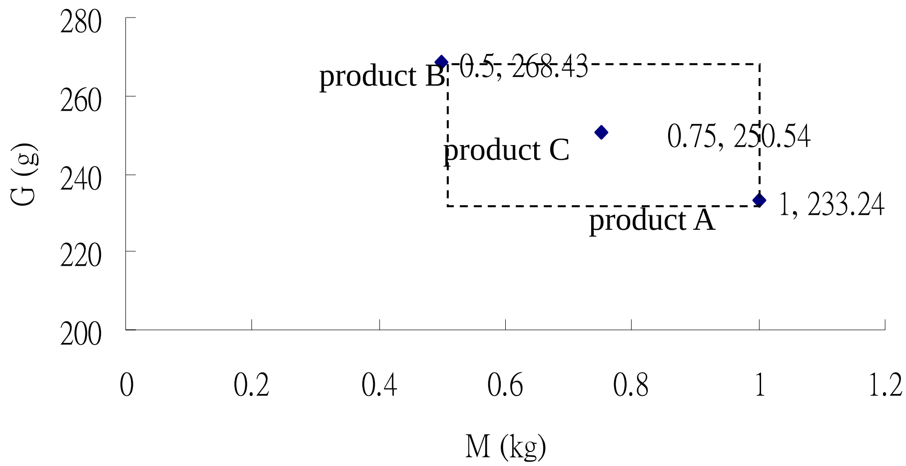


Fig. 1 Design Pareto set of helmet with different objective

4.2 Optimization of sharing foam thickness

Even product A, B and C have different design optimization results, in order to increase our profit, some components might be shared to reduce the manufacture cost. On the other way, because of sharing the components, each product might not reach its design object. From Table 1, it can be seen that helmet shell thickness is naturally shared for product A and B. This might because the shell thickness is very sensitive for the helmet weight. When the function f for each product is minimized, the helmet shell choice will go to the lower bound.

Assume helmet foam thickness, 0.036m, 0.039m, 0.041m and 0.043m, are shared for product A and B. The optimum solutions for product A and B with the same foam thickness are shown in Fig. 2. As can be see, the reduction of product A foam thickness will cause the reduce of mass and the increase of G value.

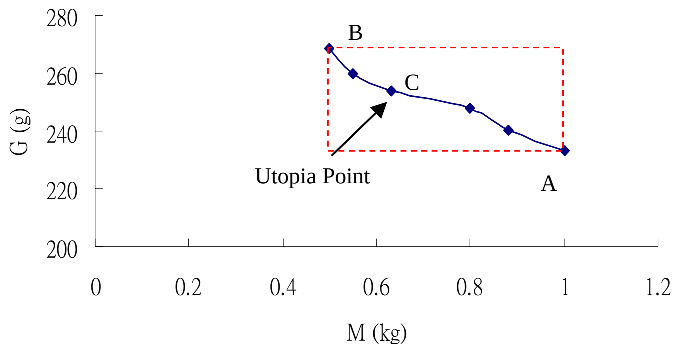


Fig. 2 Optimum design results of product A and B with same foam thickness

It can be seen in Fig. 2 that in this design Pareto curve, point C, with foam thickness 0.039m, is the closest to the utopia point. The components for products A and B in this optimum design solution are shown in Table 2. As can be seen, in order to reduce the value of head impact acceleration G, foam and shell density of product A is higher than product B. Therefore, the manufacture cost for product B would be higher than product C. Assume product A cost $300 and product cost $200, and product is designed for riding in speed 60mph that product is for 40mph. The demand for each product in this specific design component can be calculated from the demand function Q_m. Comparing to the original design without sharing foam thickness, product A can sell 0.466 million per year and product can sell 0.514 million per year. It is obviously that product A will be sold 8.0% more but product B will be sold 13.4% less. The demand increase of product A comes from the reduce of total mass. On the other word, the weight increase of product B makes fewer consumers want to buy it.

Table 2 Demand change of sharing foam thickness

Product	q_f (kg/m^3)	q_s (kg/m^3)	t_f (m)	t_s (m)	Q_m (million)	Q_m before sharing	Change %
A	60	700	0.039	0.0025	0.5043	0.466	+8.0%
B	50	650	0.039	0.0025	0.445	0.514	-13.4%

4.3 Optimization of sharing foam density

As the same method as discussed above, foam material density, 52 kg/m^3, 54 kg/m^3, 56 kg/m^3 and 58 kg/m^3, are chosen to be shared for product A and B. The optimum solutions are shown in Fig. 3. As can be seen, G reduce rate for product B is higher than G increase rate for product A. Otherwise, point C, with density 52 kg/m^3, is closest to the utopia point in the Pareto curve. Therefore, 52 kg/m^3 foam is chosen to be shared for product A and B to reach the design objective.

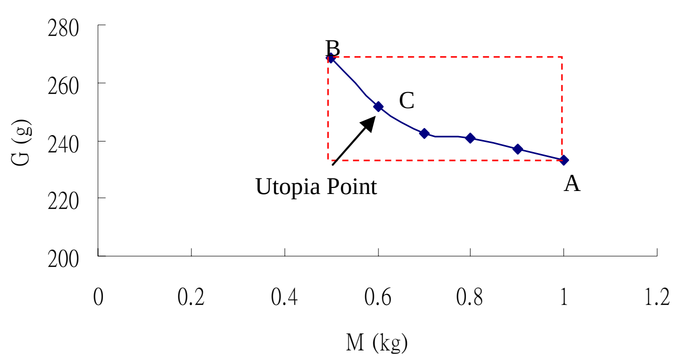


Fig. 3 Optimum design results of product A and B with same foam density

The design components of product A and B with sharing foam density and their demand change are shown in Table 3. From the slope change in Fig. 3 and the demand change in Table 3 we can see that for product A, the mass M decrease rate is faster than head impact acceleration change rate G. From the demand function, the reduce of mass will increase the demand value.

Table 3 Demand change of sharing foam density

Product	q_f (kg/m³)	q_s (kg/m³)	t_f (m)	t_s (m)	Q_m (million)	Q_m before sharing	Change %
A	52	680	0.02	0.0025	0.483	0.466	+3.65%
B	52	650	0.039	0.0025	0.502	0.514	-2.33%

From the product family optimization design, as we discussed above, product A and B might have different design components because of different design objectives. Each design objective might share the same design characteristics naturally, like the shell thickness in our helmet design. The demand might be increased or decreased by the change of component. It is hard to know the decrease of demand would reduce the profit because sharing components would reduce the manufacture cost. Manufacture cost and profit model should be involved to decide the final product family optimization design.

5. Conclusion

In the way we tackle challenges arose in the design processes of a helmet throughout the semester, we find out one very interesting thing. In an engineer's point of view, we may believe that a "good" specification will generate much more profit comparing with a "bad" specification. So, we, as engineers, always try to make our designs high performance. But, what decides "good" or "bad" specifications? One safer way to say is the voice of potential customers.

But, once we introduce business aspects into our design considerations, we can easily find out that what we believe as an engineer can be proven wrong in many cases. Different consumers may have different demands. High specification doesn't guarantee higher sale or profit.

So, maybe saying that business and engineering is an irreconcilable conflict is only stating the obvious. Does this mean that the design of something is always full of paradox? If we think really hard and further about the problem, we may find that by building a product family, we not only satisfy the business objective (which is gaining the highest profit via a lowest end product in many cases) but the engineering objective (which is propose the most advanced design and technology in most cases)

This report is itself a complete set of how we address our idea to achieve our statement above. Starting from engineering and then followed by business, we see the conflict between engineering and business. And we introduce 3 different products targeting 3 different groups of consumers which as a result, can gain high profit even one of the design is the highest end product. By a careful design, we understand that a win-win situation is possible.

Who says that you have to sacrifice something to get your job done? Well, at least not in our case.

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APPENDIX I: BUSINESS PLAN

1. Business opportunity

1.1 Business Objective

(HC^2 Manufacturing) will sell motorcycle helmets to the common commuters and amateurs and professional racers. These helmets will be 3 different models targeting different customer groups.

1.2 Production Description

(HC^2 Manufacturing) will assist its customers in selecting the best parts for their application at a price that meets or exceeds their expectations. In the event of a problem, we will be there to assist and counsel the customer to a speedy solution.

Even though our target market includes from common commuters and amateurs, our product mix will be sufficient to fill most of the needs of even the most hard-core racer. With leisure time at a premium, our reputation for having needed items in-stock will save our customers both time and money. We will be open Monday through Saturday with hours yet to be determined.

Our experience has shown that most customers’ preference is for low prices. We believe we can offer products that indeed are lower in price without sacrificing the performance and safety concerns that our customers will demand. (HC^2 Manufacturing) will provide precisely the level of service that today's entry-level racer requires.

1.3 Market Analysis

1.3.1 Market Segmentation

While there are many items from various vendors available, (HC^2 Manufacturing) has approached the market as a specialty manufacturer -- a provider of high quality helmets to its customers.

Our target customers are divided into 3 segments. The first type is the commuter type, those who ride a motorcycle to shuttle to and fro between their home and office. They will typically ride at a safe speed, and, for them, the most important factor when purchasing a helmet is the price.
The second type is the amateur type, those who ride a motorcycle as a form of recreation and a means of traveling. They will typically ride for a long distance and emphasize the handling near (sometimes even exceeding) the speed limit. For them, price and performance are equally important.

The last type is the professional racer type. Our target customer in this segment will have a wide range of racing and automotive skills, but our most important target customers are relatively unsophisticated at racing. We will be able to serve this customer well not only by offering them helmets at an affordable price, but also by giving them advice that ensures they get the task done correctly, therefore improving their on-track performance. For them, performance is the key factor.

1.3.2 Market Needs

For our target markets, the most important needs are service, price, and availability, in that order. One of the key points of our strategy is to focus on target segments that know and understand these needs and are willing for us to fulfill those needs.

1.4 Capital and personnel resources

1.4.1 Capital and personnel resources summary

We are a small company owned and operated by Chia-Yuan Chang, Chih-Hsiang Ho, and San-Yi Chang. We will need about one million to sustain through first four months to reach the peak sales season. (HC^2 Manufacturing) expects to raise $0.7 million in loans along with $0.3 million in private investment for start-up costs for the first three years.

San-Yi Chang – President

San-Yi will be the main salesperson. He will also be responsible for shipping and receiving, inventory management, and the marketing and promotion of products. Tim will assist with record keeping and cost containment.

Chia-Yuan Chang – Chief Engineer

Chia-Yuan will be in charge of the development of all products here in (HC^2 Manufacturing). He will develop computer models for finite-element analysis and analytical engineering models to optimize the initial designs. He will also be the supervisor of all fellow engineers.

Chih-Hsiang Ho – Manufacturing Analyst

Chih-Hsiang will be our manufacturing analyst to plan and optimize our manufacturing processes here in (HC^2 Manufacturing). He will work directly with Chia-Yuan Chang to ensure that our product specification is compatible with our manufacturing processes. He will also be the supervisor of all fellow technicians.

The initial management team depends on the founders themselves, with little back-up. We plan on hiring additional personnel as the need for them arises, and as we have the ability to pay them.

As for the working force in our production line, we anticipate 10 technicians will be required for a steady production at the very beginning.

1.4.2 Management Team Gaps

We depend on professionals, particularly our CPA, for some key management help. We have retained a local CPA to help us with financial and business management questions since we don't have a strong background in those areas. Also, we are short on experience concerning human resource issues; however, we plan on utilizing our network of business associates to advise us when the need arises.

1.4.3 Personnel Plan

The cornerstone of the personnel plan is to maximize productivity and minimize the labor burden on the company's operating expenses. As we grow, we expect to see steady increases in our personnel to match the increases in sales.

Personnel Plan			
	2004	2005	2006
San-Yi Chang	$50,000	$55,000	$60,000
Chia-Yuan Chang	$50,000	$55,000	$60,000
Chih-Hsiang Ho	$50,000	$55,000	$60,000
Engineer	$0	$0	$50,000
Technician	$30,000 x 15	$30,000 x 15	$30,000 x 15
Total People	18	18	19
Total Payroll	$600,000	$615,000	$680,000

2. Financial Data

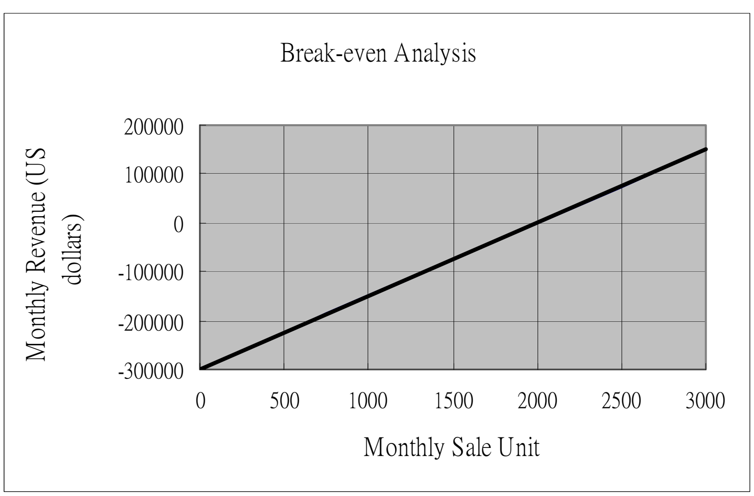
2.1 Capital equipment and supply list:

Building (Rent)
Machines and Cars (Rent)
Advertisement and Sponsor
Payroll
Material
Utilities and Others

2.2 Break-even Analysis:

For our first year break-even analysis, we assume we will produce 3,000 units per month and the cost per unit will be $100. Our total cost will be $300,000 per month, which includes payroll, rent, utilities, material, and an estimation of other running costs. The unit price will be $150.

We need to sell 2,000 per month to break even, according to our assumptions.



2.3 Pro-forma income and cost projections:

Key assumptions for (HC^2 Manufacturing) are:

- We do not sell products on credit.
- We assume the continued popularity of motorcyclists in America.
- Monthly sales are the largest indicator for this business. There are some seasonal variations, with the months April through September being the highest sales months.
- We assume access to capital and financing sufficient to maintain our financial plan as shown in the tables.

2004	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual Demand
Monthly Demand	1000	1000	2000	4000	5000	5500	5000	4000	3500	2500	1500	1000	36000

According to the previous analysis, the helmet demand in America is one million per year, we decide to have a large budget on advertisement and sponsor, it is about 1.8 million per year. Expect to take advantage of ad power to boost our sales at the very beginning. Hopefully, we may achieve 3.6%, 5%, 7% market share in 2004, 2005, and 2006, respectively.

General Assumptions	2004	2005	2006
Current Interest Rate	10%	10%	10%
Long-term Interest Rate	10%	10%	10%
Tax Rate	25%	25%	25%
Other	0%	0%	0%
Payroll Expense	600000	615000	680000

Pro Forma Profit and Loss	2004	2005	2006
Sales	5400000	7500000	10500000
Production Payroll	0	0	0
Expenses:			
Payroll	600000	615000	680000
Rent (Building)	240000	240000	240000
Rant (Machines and Cars)	360000	360000	360000
Ad and Sponsor Fee	1800000	1800000	1800000
Material	480000	650000	900000
Utilities and Others	120000	150000	180000
Insurance	10000	10000	10000
Payroll Tax	90000	92250	102000
Other	0	0	0
Total Operating Expenses	3700000	3917250	4272000
Profit Before Interest and Taxes	1700000	3582750	6228000
Interest Expense	0	0	0
Taxes Incurred	425000	895687.5	1557000
Net Profit	1275000	2687062.5	4671000

3. Supporting Documents

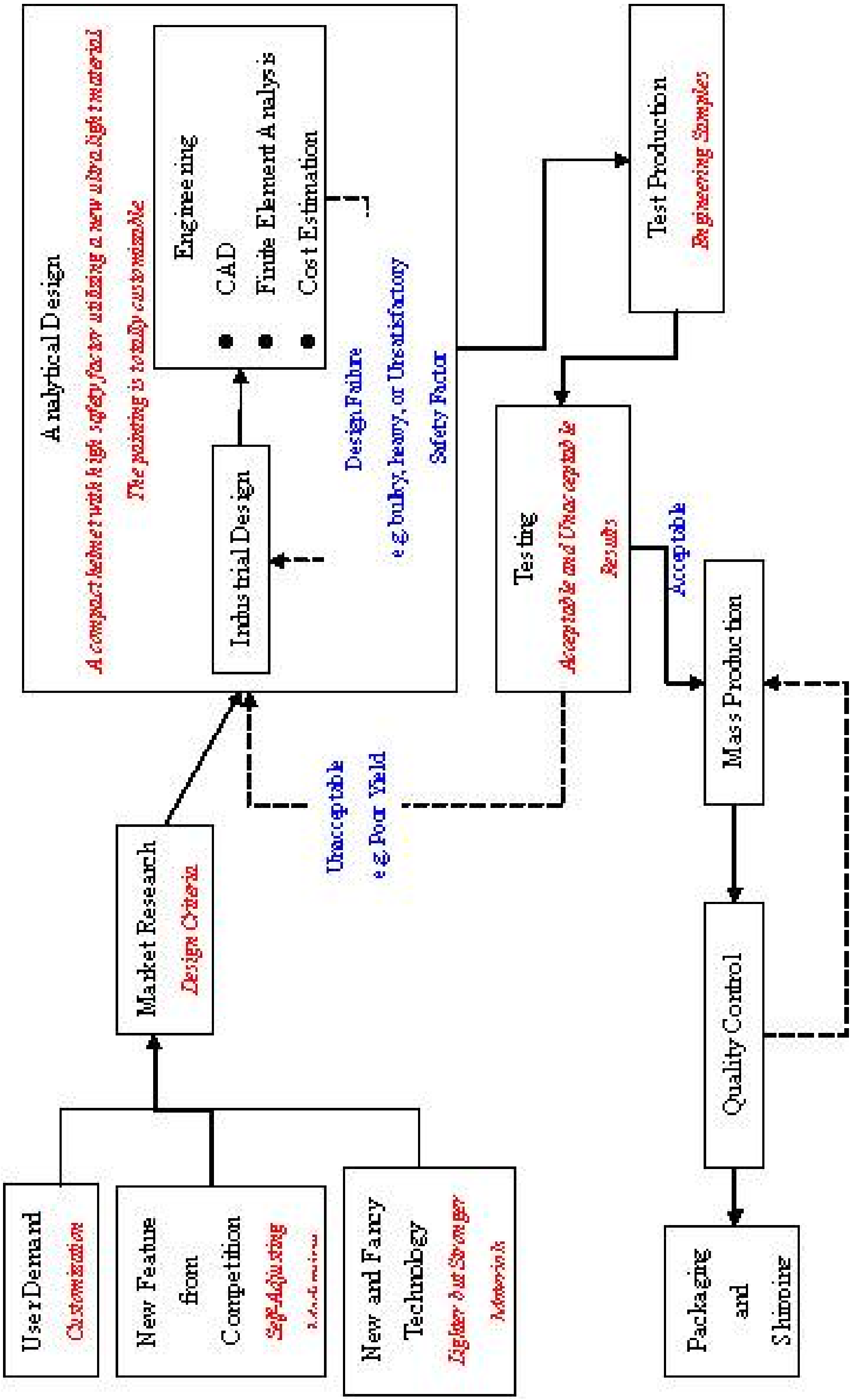
3.1 Existing Patents

No patents, which may cause legal problems, are found regarding both design and manufacturing processes.

3.2 Technical Analysis and Benchmarking

Please refer to the section 2 of our report a complete engineering is developed for analysis of any design.

APPENDIX II: Product Design Process



APPENDIX III: QFD Chart

Group	Engineering Consideration / Customer Requirement	Foam Material			Shell Material			Ventilation			Strap		Paint Material			Assembly				
Group		Stiffness	Density	Heat Conductivity	Stiffness	Density	Heat Conductivity	Top Opening	Side Opening	Flow Channel Design	Strap Material	Lock Mechanism	Recipe	Reflectivity	Finishing	Sealant	Joint Tolerance	Manufacturing Precision	Accessory Material	Mechanism
Comfort/Fit	Light		O			OO														
	Allowing Ventilation			OO			OO	OO	O	O										
	Comfortable Strap										O	X								
	Soft Foam	O	X																	
Style	Unique Pattern Design														X					
	Variety of Colors												O							
	First Class Paint												O	X	O					
	DIY Friendly															X	X	X		O
Safety	Safer When Sliding	OO	O		OO	O														
	Safer From Impact	OO	O		OO	O														
	Shatter-free Face Shield																		O	
Maintenance	Easy to Change Face Shield																X	X		O
	Easy to Replace Parts																X	X		O
	After-market Compatible																O	O		O
	All-weather Durability															O	X	X		O