Optimization of the package of air purifiers

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Abstract

This article presents the development of an optimization of the package for a certain air purifier. The new design was more environmentally friendly, cheaper to produce, saves storage space and simplifies the repacking processes. The concept was generated in the concept generation phase, and selected among other concepts with the help of Pugh Matrix. After an iterative development process of cushioning design, drop simulation and drop tests, the proposed concept was verified by drop simulations in ANSYS, drop tests following the ISTA 3A standard, and a brief Life Cycle Assessment. Future work was also proposed based on the findings in the project.

The theoretical background of the design, the various methods which were used in the development process and the development process itself were presented and discussed in this article. A method of rapid cushioning development was also concluded. The method was suitable for developing a cushioning system made of pre-compressed corrugated paper board based on an existing cushioning system. The method was designed to achieve a rapid iterative development for a new cushioning design with pre-compressed corrugated paper board based on an existing cushioning design.

Key words: package design, cushioning design, pre-compressed corrugated paper board
In this chapter, acknowledgement of help and assistance during the project is presented.

This project has been proceeded under the supervision of Anders Berglund from KTH Royal Institute of Technology, and Joakim Nygren from Blueair AB. A lot of help was offered by both of the supervisors. Johannes Blackne from Blueair AB also offered assistance during the whole project as the contact person.

Johan Skantorps, together with Elin Engberg, Jacob Gunnefur, Casper Törneman, Hadding Delin, and other co-workers at Blueair AB have offered guidance, insights and assistance during the project.

Tao from Dingxin Technology, Shenzhen offered help in the design of the original cushioning system, and the analysis of the air purifier.

Yi Yang
Stockholm, March, 2015
The notations and abbreviations in this article are presented here in this chapter.

**Notations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$h$</td>
<td>Drop height (m)</td>
</tr>
<tr>
<td>$g$</td>
<td>Standard earth gravitational acceleration (m/s²)</td>
</tr>
<tr>
<td>$t$</td>
<td>Time (s)</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>$H_c$</td>
<td>Collection energy (MJ/kg)</td>
</tr>
<tr>
<td>$H_{ps}$</td>
<td>Primary sorting energy (MJ/kg)</td>
</tr>
<tr>
<td>$H_{ss}$</td>
<td>Secondary sorting energy (MJ/kg)</td>
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**Abbreviations**

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>BOM</td>
<td>Bill of Materials</td>
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<tr>
<td>EPE</td>
<td>Expanded Polyethylene</td>
</tr>
<tr>
<td>EPS</td>
<td>Expanded Polystyrene</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>ISTA</td>
<td>International Safe Transit Association</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>MD</td>
<td>Machine Direction</td>
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<td>CNC</td>
<td>Computer Numerical Control</td>
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1 INTRODUCTION

In this chapter, the background and the purpose of the project are presented. The limitations of the project is also presented and discussed. The methods used in this project are also briefly presented in this chapter.

1.1 Background

The air purification industry has witnessed a rapid growth since the air quality crisis outbreak in China in the year of 2011. The rising awareness of air quality issues and respiratory health triggered a sharp increase in air purifier sales, and also raised the public concern of environmental problems.

Since the volume of production is growing very rapidly, the cost and the environmental impact of the package starts to draw people’s attention. Although the material and production cost of the package is only a minor proportion of the overall Bill of Material (BOM) cost of air purifiers, the total cost and environmental impact is large due to the large and growing volume. Especially the environmental impact of the package is even more important, because in most cases, the package has a much shorter life time comparing with the air purifier itself, and goes to disposal shortly after the unboxing of the air purifier. With the consideration of the total production and material cost of the packaging, as well as the environmental impact of the packaging material, an optimization is needed to achieve lower cost and better environmental efficiency.

Air purifiers are normally built with metal and plastic parts. There is one or more fans driven by one or more motors built in which are normally the most fragile parts. The general size of air purifiers are around 300mm-700mm on each dimension, and the general weight of air purifiers are normally around 7kg-15kg. The similarity in size and weight result in similar packaging designs. The similarity in the packaging design means that the optimization to one packaging design can be easily modified to fit most of the other air purifiers, even other home appliances with similar size and weight. Therefore, a method to optimize existing packages can be developed by summarizing the optimization process of one existing package.

The air purifier used in this project is a Blueair 400 series air purifier. The air purifier is constructed with sheet metal, contains electronic components, and weights 12 kg. The size of the air purifier is 590mm*500mm*275mm. It has one built-in fan, which is considered as the most fragile component. Figure 1 is a picture of Blueair 403 air purifier which is the basic model of Blueair 400 series. All Blueair 400 series has the same structure, same shape, and almost the same weight. The differences among different models are the control unit and sensor unit. Therefore, the Blueair 403 air purifier is the model around which the new package will be developed.

The most commonly used packages of air purifiers are brown or white boxes made of corrugated paper board, with cushioning material made of either Expanded Polyethylene (EPE), or Expanded Polystyrene (EPS). Brown boxes or white boxes are chosen based on their strength and the printability of the corrugated paper board, which is decided by the core of the corrugated paper board called fluting, or the covering surface of the corrugated paper board called liner. EPE or EPS are commonly used as cushioning material due to their relatively good cushioning performance, and their light weight. EPE and EPS also have good processability. They can be easily molded into complex shapes with a low cost.
Theoretically, EPE has a smaller environmental impact comparing to EPS. EPE will biodegrade in natural environment. But on the other hand, EPS is not biodegradable. (Zheng & Yanful, 2005) Therefore, EPE has a lower environmental impact if the material is treated properly after use. But EPE has a much higher price comparing to EPS which has a similar cushioning performance, but a higher environmental impact.

In China, which is one of Blueair’s largest market, EPE and EPS are both treated as foam, and goes to incineration or landfill with other wastes. They are not sorted or treated separately. Therefore, even EPE has a lower environmental impact in theory, it may still has major impact on the environment since the end of life scenario is not ideal. Waste sorting and treatment policies and situations are different in different countries or regions in the world. Due to the different end of life scenario, using EPE does not necessarily reduce the environmental impact in reality.

Beyond the cost issue and environment concerns, the company also has problems in production line, logistics, and after-sale services. The problems include that the cushioning material is taking up too much storage space before inserted into the package, that the whole package size does not fit the size of European standard pallet, and that the customers does not re-pack the package properly when they return the product, which result in a high damage rate among returned units. Such problems can be solved or eased by the optimization of the current package of the air purifier.

The company has a line of air purifiers that have a consistent shape. Optimization of the package can easily be applied to other air purifiers in the same product line. So summarizing a method to potentially optimize the packages of all air purifiers is very beneficial.

Since the company is in purification industry, which is closely related to environmental issues, it is important and beneficial for the company to project an image of caring for the environment. Together with the consideration of production and material cost, a project to optimize the package of air purifier 403 is carried out.

1.2 Purpose

The purpose of the project is to optimize the packaging of Blueair 400 series air purifiers. The optimization is only functional optimization. Since there is already an existing package for the
product, the optimization should make only least possible changes to reduce the shifting cost from the old package to the new one in terms of manufacturing, assembly line, and logistics.

The artwork design needs to remain the same so that the artwork of the package still matches the style of the product line. This restricts the choice of the outer box because the printing technology to be used on different corrugated paper board is different due to the different printability of the material. The current package has an outer box made of brown corrugated paper board, which is single color printed, and an inner box made of white corrugated paper board which is three color printed. The inner box is designed in an artistic way for store displays and other similar purposes. The outer box is designed to provide protection for the inner box from scratches and marks. These two boxes will not be redesigned.

The optimization of the package is internally defined as an opportunity project instead of a product development project. This means the project is focused on the pre-study phase. The deliverables of the project is one approved concept. The concept is the best concept of all the generated concepts and this concept will be approved by drop tests.

1.3 Delimitations

There are five limitations that define the project. They are related to the scale of the project and aspects to take into consideration for the project.

The optimization of the package will be limited to functional design, therefore, the artwork design will not be changed at all. The focus of the functional design is cushioning design since cushioning is the core function of the package.

The environmental impact of the optimized packaging should be lower than the environmental impact of the existing packaging. The estimation of the environmental impact should be done by a Life Cycle Assessment (LCA) which will take the whole life time of the package into consideration. Besides the actual reduction in the environmental impact, the optimized package should project an image to the customers that the packaging is more environmentally friendly. The perception by the customer is also a very important perspective for this project since it adds value to the brand.

The total size of the package will not be changed because changing package size will lead to changes of the artwork which is beyond the scale of this project. Changed size of the package will also lead to changes in logistics, which will result in a high shifting cost. Clearing out the storage of the old package before the new package is introduced will also cause additional cost. Therefore, the size of the inner space of the package is 340mm*600mm*670mm.

The design of the air purifier will not be changed because there is already a functional and verified package for the air purifier which has already passed the related standards. This means that the air purifier itself is already optimized for packaging design sufficiently for the current packaging. The new package should not require more optimization which will greatly increase the shifting cost.

There are many standards for packages, such as the Chinese national recommended standard GB/T 4857, the International Organization for Standardization (ISO) standard ISO 2248:1985, the ASTM International standard ASTM D5276, and the International Safe Transit Association (ISTA) standard ISTA 3A. The ISTA standard is chosen to be the standard that the company’s logistics supplier uses. All the packages used for Blueair products need to be verified by the ISTA standards.

The cost for production of the optimized packaging should not be higher than the existing packaging. But the cost of the optimized packaging is not a prioritised goal since the project is focused on the early phases such as concept development. Changes can be made to the selected concept in order to reduce the production cost in later phases. Also in early phases, the production
cost can only be roughly estimated according to experience. Therefore, the production cost of the optimized packaging does not need to be strictly lower than the production cost of the existing packaging. The result is acceptable as long as the production cost is not remarkably increased.

### 1.4 Methods

There are 5 methods used in this project. They are methods for packaging design, product development, and LCA. All the methods used in this project will be briefly introduced in this chapter, and will be discussed in details in Chapter 2 “Frame of Reference”.

Six step method is a method first developed by Dale Root in the year of 1988. (Root, 2014) The method was developed for a complete cushioning design. The method was designed to optimize the packaging design so that the total system of the packaging and the product itself had a performance that fitted the environment. The optimized packaging would ensure that the product was not under-protected or over-protected. Therefore, the result of the six step method is a balance of sufficient cushioning performance and minimal cost. The six steps are: 1) define the environment; 2) product fragility assessment; 3) product improvement feedback; 4) package material performance evaluation; 5) package design; 6) test the product/package system. In this project, the six step method was adjusted with consideration of the actual practice.

Finite Element Method (FEM) is a numerical technique to find approximate solutions. In engineering applications, FEM is widely used to simulate an actual situations with digital models for different purposes. In packaging design, FEM is used for drop simulations. (Yang, Zhao, & Ji, 2012) Drop simulations can provide predictions of drop test results. Drop simulations before actual drop tests can be used for verification of a packaging design since the drop tests are normally destructive, and thus expensive. Drop simulations are also time saving since there will not be any tangible models or prototypes manufactured. Due to the relatively low cost and low time consumption, drop simulations also allow rapid iterations in the develop process, since incremental changes can be made easily with a low cost. In this project, drop simulations are used before actual drop tests to verify proposed concepts before prototypes are made for drop tests. The FEM simulations are done with the software ANSYS 15.0. The module used in ANSYS is Autodyn, which is an Explicit Dynamics simulation module of ANSYS.

Drop test is a testing method for packaging design. The purpose of this test is to verify the cushioning design of the product/package system. There are several different standards regarding the test as previously mentioned. In this project, the ISTA standard is used for the verification, because the logistic supplier of the company uses the ISTA for testing the product/package system. (FedEx, 2011) The proposed concept of this project is required to pass the ISTA standard drop test for approval.

The environmental impact will be estimated with the help of LCA. But collecting the actual data related to the production and transportation is beyond the scope of this project. The comparison of the existing packaging and the optimized packaging in terms of the environmental impact will be based on a primary LCA study with CES EduPack 2013 developed by Granta Design. The data from the actual practice is not available for this project, therefore the result generated from CES EduPack 2013 will be compared with results of other studies with similar subjects. Adjustments will be made for results that can represent the reality in a more accurate manner. By comparing the result of LCA for both the existing package and the proposed concept, the improvement in reduction of environmental impact can be estimated.

Pugh Matrix is a decision matrix method invented by Stuart Pugh. This method is a simple way of effectively compare alternative concepts. It helps with reducing product ideas and narrow those down to relatively few that will be additional analysed and refined. The method is normally used in product development projects as a method for concept selection. In this project, the Pugh Matrix is used for selecting one concept in the early stage to continue the development with. With the
Pugh Matrix, different aspects of the generated concepts can be taken into consideration for making the decision of concept selection.
In this chapter, the theoretical background of the methods used in this project is presented and discussed. Theory about corrugated paper board is also presented here. Some relative studies have been done by various researchers in this field, they are also presented in this chapter.

### 2.1 Six step method

Six step method is a systematic approach of cushioning design for packages. Since the outer box of the air purifier in this project shall not be changed in order to maintain a low shifting cost, the major part of the project is cushioning design. Therefore the six step method is a sufficient method to structure the project.

The six step method is developed as a complete methodology for cushioning design. The goal of using this method is to achieve optimum product/packaging system. In order to achieve an optimum product/packaging system, the hazards of distribution environment (e.g. design drop height), product design, its fragility and improvement, and characteristics of cushioning material all need to be considered. (Sek & Kirkpatrick, 2001) If the product is under-protected, even though the cost for the packaging is low, the product will suffer a higher risk of being damaged during transportation. The overall cost including the damage cost is thus higher than the overall cost of an optimum product/package system. To the contrary, if the product is over protected, though the risk of being damaged during the transportation is minimized, but the packaging cost is higher than necessary which will make the overall cost of the product/package system too high.

![Economics of package design](Sek & Kirkpatrick, 2001)

Figure 2 is a demonstration of the trade-off between the package cost and the damage cost. In order to achieve the least overall cost, the six step method is developed. The six steps are:

1. Step one, define the environment: the environment refers to the shipping environment of the product/package system. By defining the environment, the developer decides the typical drops the product will encounter during the transportation. A design drop height is
determined in this step. The design drop height is the maximum drop height that the product can be safely dropped.

2. Step two, product fragility assessment: the fragility of the product is normally defined as a maximum acceleration that the product can survive. It is very hard to determine the fragility of a certain product unless destructive tests are done. Therefore, it is common to use experiences to estimate the fragility of the product instead of measuring in tests. Such estimations are normally conservative but sufficient when testing and accurate measuring is not available. (Department of defense, 1997)

3. Step three, product improvement feedback: after understanding the product in step two, it is possible to find out design flaws that cause higher risks of being damaged for the critical element. In this step, it is recommended that the developer gives feedback to improve the product in terms of protecting the critical element. The improvement can increase the performance of the product/package system and thus reduce the required packaging cost.

4. Step four, package material performance evaluation: data of relevant cushioning material is crucial in this step. The characteristic of the cushioning material is normally described by a set of cushioning curves.

5. Step five, package design: in this step, a package is designed based on the data collected from the previous steps. The goal is to find an optimum combination of thickness of cushioning material and cushion bearing area to minimize the total volume of the cushioning material. The combination needs to be sufficient for the product/package system to survive the environment defined in step one.

6. Step six, test the product/package system: in this step, the proposed product/package system is tested following one of the standards. If the product/package system passes the test, the concept will thus be approved.

Damage to the product occurs when the acceleration of the product during the impact exceeds the fragility of the product. (Sek & Rouillard, 2005)

Since the six step method is a complete methodology to develop an optimum product/package system from scratch and the presented project is an optimization of an existing package to which limitations apply, the six step method is modified to fit the goal of this project.

2.2 Finite Element Method

Finite Element Method (FEM) is widely used in various engineering field. In packaging design, FEM is usually used for simulation of drop tests. Simulations are used for studying the characteristics of cushioning materials such as the study carried out by Chen Li et al on the characteristics of pre-compressed multilayered corrugated paper board. (Li, Xiao, Li, & You, 2009) Simulation is also used for improving the product’s shock resistance by finding out the most fragile and most impacted part of the product, such as the study by Min-Chun Pan and Po-Chun Chen on shock resistance improvements of TFT-LCD monitors. (Pan & Chen, 2007) FEM simulations can also be used to help in development of the product/package system, such as the work by Jie Yang regarding drop simulation and cushioning package analysis of 19-inch LCD monitor (Yang, Zhao, & Ji, 2012), and the work by Mills and Masso-Moreu regarding using FEM to simulate the drop test performed on a polyethylene foam package (Mills & Masso-Moreu, 2005).

Different software can be used for FEM simulations. ANSYS is a commonly used FEM software for different purposes. In order to simulate a drop test, the explicit dynamic module of ANSYS is used for the simulation. The module is called Autodyn, which is a dedicated explicit dynamic module.
In order to simulate the drop test with ANSYS, CAD models need to be built first. But FEM simulations on detailed models require very high computational capacity and consume very long time. According to the study of K. H. Low on simulations of electronics regarding cushioning effect, a simulation on a Hi-Fi speaker with a termination time of 100ms takes up to 40 hours to finish the calculation, or a hard drive with a termination time of 4ms takes up to 4 hours of calculation. (Low, 2003) The calculation time is too long for this project and for many other studies. In most cases, for simulations of drop tests, the detailed model will not provide more information than a simplified model, therefore, simplification of the CAD model is commonly needed in drop simulations.

According to the ISTA standard, the drop test of for packaging is to drop the product/package system from a certain height onto a defined rigid surface. Different heights apply for different weights and shapes of the product/package system. (International Safe Transit Association, 2008) For example, in ISTA 3A standard, for a package that weights between 1-34kg, the drop height is 46cm. For free fall, the falling height and falling time are correlated as:

\[ h = \frac{1}{2} gt^2 \]  

(1)

in which \( h \) stands for the falling height, \( g \) stands for gravitational acceleration, and \( t \) stands for the falling time. If \( g \) is assumed to be 9.8 m/s\(^2\), since \( h \) is set to be 0.46 m, the falling time is then calculated as approximately 306 ms. The calculation time for the simulation in ANSYS is positively correlated to the simulated duration. Therefore, simulating the free fall phase of the drop test is very time consuming, and the result of the free fall phase is an ultimate speed before the impact. The ultimate speed can be easily calculated as:

\[ v = \sqrt{2gh} \]  

(2)

in which \( v \) stands for the ultimate velocity, \( g \) stands for gravitational acceleration, and \( h \) stands for the falling height. As in the previous example, \( g \) is assumed as 9.8 m/s\(^2\), and \( h \) is set to be 0.46 m. The ultimate velocity is thus 3.00 m/s. Therefore, a drop from 0.46 m is equivalent to a crash with 3.00 m/s velocity. This simplification will reduce the termination time by 306 ms which will greatly reduce the calculation time required by the simulation.

From the simulation, peak acceleration of the crash is obtained. Also, the stress on the product/package system is also demonstrated to find out the focal point of stress. Both results will help to verify the package before actual drop tests and to find out potential improvements.

2.3 Drop Test

Drop test is a major procedure to approve the packaging design according to various standards. In this project, the ISTA standard is chosen mainly because this standard is the standard that the logistics supplier FedEx comply with. The drop test is a series of drops in a defined sequence, in order to test the product/package system in all possible dropping positions.

The ISTA 3A standard is suitable for product/package systems that weigh less than 70 kg or 150 lbs. The packages are then categorized into four different categories: standard package, small package, flat package, and elongated package. For each category, different test procedures apply.

Small package refers to the packages that are smaller than 13000 cm\(^2\) in volume, have the longest dimension of 350 mm or less, and weigh 4.5 kg or less. Flat package refers to the packages that have the shortest dimension of 200 mm or less, have the second shortest dimension 4 times or more larger than the shortest dimension, and are larger than 13000 cm\(^2\) in volume. Elongated package refers to the packages that have the longest dimension of 900 mm or greater, and the other two dimensions are each 20 percent or less that of the longest dimension. All the other packages
that cannot be categorized as small, flat or elongated package are categorized as standard package. (International Safe Transit Association, 2008)

After the categorization of the package, the package needs to be labeled on all six surfaces. The labeling method is demonstrated in Figure 3:

![Figure 3 Labeling the package surfaces (International Safe Transit Association, 2008)](image)

As shown in Figure 3 the surfaces are labeled as Number 1 to 6. The edges are labeled by the number of the two surfaces that meet at the edge. For example in Figure 3, Surface 2 and Surface 3 meet at the Edge 2-3. The corners are labeled by the number of the three surfaces that meet at the corner. For example in Figure 3, Surface 2, Surface 3, and Surface 5 meet at Corner 2-3-5.

The surface for the product/package system to be dropped on should be either steel with the thickness of 1 mm or greater, or rigid ground. And for different weights of the product/package system, different drop heights apply. As for ISTA 3A standard, the drop heights and double drop heights are shown in Table 1.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Drop height</th>
<th>Double drop height</th>
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<tr>
<td>1-34 kg</td>
<td>460 mm</td>
<td>970 mm</td>
</tr>
<tr>
<td>35-45 kg</td>
<td>380 mm</td>
<td>810 mm</td>
</tr>
<tr>
<td>46-70 kg</td>
<td>310 mm</td>
<td>660 mm</td>
</tr>
</tbody>
</table>

After labeling and determining the drop height, product/package system is dropped onto the rigid surface from the defined drop height. The sequence of the drops in ISTA 3A is defined in the standard as follows: Edge 3-4, Edge 3-6, Edge 4-6, Corner 3-4-6, Corner 2-3-5, Edge 2-3, Edge 1-2, Surface 3 double height, Surface 3, Edge 3-4, Edge 3-6, Edge 1-5, Corner 3-4-6, Corner 1-2-6, Corner 1-4-5, Surface 5 double height. (International Safe Transit Association, 2008)

When the drops are done, the product is inspected for damages or structural failures. If the product is not damaged at all, the package will thus be approved by ISTA 3A standard.

### 2.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method for evaluation of the environmental impact of a certain product. LCA is a systematic approach to reveal major areas of environmental impacts and concerns. LCA studies the processes of the product from the cradle to grave in a holistic manner. The assessment is based on the data collected on the inputs and outputs of the processes. The environmental impacts are calculated and quantified based with a defined and scientific method. The results of the previous step are then classified and most importantly, the important areas are highlighted in order to improve the environmental performance. (Tan & Khoo, 2005)
One way to do the LCA study is to carry out the study by collecting all the data and establishing the model of the entire process based on a specific product. Such LCA study involves a lot of work load in data collection, and setting up the model. According to ISO 14040 series, there are four phases in an LCA study, which are:

1. **Goal definition**: forming the basis and scope of the subject or the product of interest. (International Organization for Standardization, 2006)
2. **Inventory analysis**: collecting and analyzing data of the inputs and outputs of the process. (International Organization for Standardization, 1998)
3. **Impact assessment**: translating resources and energy consumption and emissions into environmental effects. (International Organization for Standardization, 2000)
4. **Interpretation**: concluding the LCA results and finding out the potential improvement areas. (International Organization for Standardization, 2000)

The benefit of collecting the data and setting up the model of the processes is that the collected data is very specific to the subject or product of interest. Comparing with the studies with more general data, the results of such LCA studies are more accurate. Therefore, the potential improvement areas found in such studies are more realistic and specific since the processes are investigated directly. But such LCA study consumes a lot of time and human resources. In this project, such LCA study is beyond the scope of the project. Also, the main goal of the LCA in this project is to compare the environmental impact between the existing packaging and the proposed concept. So the accuracy of the result is not very important as long as the results are comparable. But results of similar studies with this method are good reference values for verifying and adjusting the results by other methods.

The other way to do a quick LCA study is to rely on LCA software. For example, CES EduPack 2013 provides a simple solution for product designers to quickly evaluate the environmental impact of their product, and to provide guidance on how to reduce it. The tool built in to CES EduPack for conducting LCA study is called Eco Audit Tool. With this tool, two well-understood environmental stressor are calculated and presented, which are energy usage and CO₂ footprint. The product life time is divided into five phases: material, manufacture, transport, use, and end-of-life. By summarizing the value of the two stressors, the most dominant phase or phases are identified, and improvement suggestions are made accordingly. (Granta Design Limited, 2013)

In this software, the whole product life cycle is split into three sections as: 1) material, manufacture, and end of life; 2) transport; and 3) use. Since the product in this project is the package, the use phase of the product is the same as transport, which does not consume any electricity or energy other than the transportation. Therefore, there are only two sections to be considered in this project, one is related to the physical object of the package, and the other is related to the transportation of the package. In order to proceed with the physical object section of the LCA study, the material, the recycled contents in the material, the total mass of the package, the primary and secondary process in manufacturing, and end of life scenario need to be defined. And for the transport section of the LCA study, the distance and the means of transportation need to be defined. It is also possible to define multiple means of transportation to calculate for the total transportation of the whole life cycle of the product.

Material can be selected from the database in CES EduPack 2013. For a product, the material is defined part by part, and for each part, the mass and recycled content are defined. The recycled content is defined by percentage of recycled material, in which 0 means using virgin material and 100 means all material is recycled material. The manufacturing processes are selected also from the database. Different manufacturing processes are applicable to different material. The end-of-life scenario is selected among seven options which are landfill, combust (for energy recovery), downcycle, recycle, re-manufacture, reuse, and none.
For the transport section, different means of transportation are available to be selected from. The result of the transport section is not dependent on the material of each part of the product. The factors that affect the energy consumption and the CO₂ footprint are the total mass and the transported distance. For each means of transportation, a coefficient of the energy consumption and a coefficient of the CO₂ footprint are available in Table 2:

<table>
<thead>
<tr>
<th>Transportation Method</th>
<th>Transport Energy (MJ/ton/km)</th>
<th>CO₂ Footprint (kg/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea freight</td>
<td>0.16</td>
<td>0.071</td>
</tr>
<tr>
<td>River/canal freight</td>
<td>0.27</td>
<td>0.071</td>
</tr>
<tr>
<td>Rail freight</td>
<td>0.31</td>
<td>0.071</td>
</tr>
<tr>
<td>32 ton truck</td>
<td>0.46</td>
<td>0.071</td>
</tr>
<tr>
<td>14 ton truck</td>
<td>0.85</td>
<td>0.071</td>
</tr>
<tr>
<td>Light goods vehicle</td>
<td>1.4</td>
<td>0.071</td>
</tr>
<tr>
<td>Air freight – long haul</td>
<td>8.3</td>
<td>0.067</td>
</tr>
<tr>
<td>Air freight – short haul</td>
<td>15</td>
<td>0.067</td>
</tr>
<tr>
<td>Helicopter – Eurocopter AS 350</td>
<td>50</td>
<td>0.067</td>
</tr>
</tbody>
</table>

The end-of-life section of the LCA study is divided into two parts, the disposal calculations, and the end-of-life potential calculations. The disposal calculations include the cost of collecting the disposed products, and separating and sorting material from the products (Granta Design Limited, 2013). The end-of-life calculations include the benefits of saving energy and reducing CO₂ emission by using recovered material or components. For the disposal calculations, the energy consumption is calculated by a fixed coefficient for different end-of-life options, as shown in Table 3. The CO₂ footprint is calculated according to the energy consumption with a coefficient of 0.07kg/MJ. For the end-of-life potential calculations, for each end-of-life option, different equations apply, and the data used in the calculations is in accordance with the specific material.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Combustion</td>
<td>0.2</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Downcycle</td>
<td>0.2</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Recycle</td>
<td>0.2</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Re-engineering</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reuse</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>None</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A report is generated as the result of the LCA study. The energy consumption and CO₂ footprint are shown in figures. Breakdown for each phase is also included in the report. The most critical phase is thus identified, and recommended improvements for potential reduction in energy consumption and CO₂ footprint are suggested. In one report, different products can also be presented in the same figure for comparison.

The LCA study uses physical properties such as material, production related data; and eco-properties such as transport, and environment related data from various sources. The physical properties of the material are measured directly with measurement equipment following certain standards, but the eco-properties of the material cannot be measured directly, and the international standard ISO 14040 does not provide the procedures in a clearly defined and easily applicable manner. Therefore the standard deviation of the result of LCA study in CES EduPack is ±10%. To be significantly different, the values of eco-properties must differ by at least 20%. Otherwise other factors such as the recycle content of the material, the durability of the product, and the ability to
recycle it at the end of life have much more significant influence on the environmental performance of the product.

Since the software based LCA study has a relatively low accuracy, and only focuses on two environmental stressors, energy consumption and CO₂ footprint, the result from CES EduPack needs to be evaluated and adjusted by comparing with similar studies regarding similar material.

### 2.5 Pugh Matrix

Pugh matrix is a decision making method developed by Stuart Pugh. The method is a simple way to compare different alternative concepts. It is one of the most popular methods among developing engineers for concept selection phase. Pugh matrix is designed to help with understanding the relationship between different issues within a project and to clarify each perspective on the issue (Cervone, 2009). It also assist the project driver to understand the issue with a fully developed perspective. (Jonassen, 2012)

Pugh matrix was chosen to be the method for concept selection because it enabled the developer to examine the concepts in various different independent aspects. In this project, the requirements of the project covered different areas including engineering, production, logistics, and marketing. Therefore Pugh matrix was decided to be the most suitable method to be the concept selection method in this project.

The essence of the method is to grade the different concepts in accordance to a pre-defined criteria. The criteria are perspectives to evaluate the concepts with weights of importance for each perspective. Ratings are given for each concept and perspective respectively, and the ratings are added up to a grade for each concept. The final result is to combine, improve or select one or several concepts that have the highest grade to continue with in the following phases in the project.

The basic steps of Pugh matrix is summarized as follows:

- Prepare the matrix and enter the concepts and criteria;
- Weight the criteria importance;
- Evaluate and rate the concepts;
- Rank the concepts;
- Decide what to do next: combine, improve or select a concept;
- Reflect on the result.

There are also critiques of Pugh matrix. Mullur claims that the Pugh matrix is based on “inadequate mathematical construct” which leads to low rating non-dominating concepts. The low grade will thus cause the elimination of these concepts which might include some more desirable or optimal concepts that are not selected to be further developed. (Anoop A. Mullur, 2003) In order to avoid such result, the reflection on the result is very crucial.

### 2.6 Pre-compressed Corrugated Paper Board

Corrugated paper board is drawing more attention as cushioning material due to its relatively low price and low environmental impact as a recyclable and easy to recycle material. But comparing with other common cushioning material, study on the cushioning properties of corrugated paper board is limited.

Corrugated paper board is a type of material with a corrugated structure made of paper. It is considered to hold a high stiffness and high resistance to buckling in relation to its light weight. The corrugated structure consist of two faces sheets which are called liners; and the wave-shaped
pipes of paper, which are called fluting. For the convenience of discussion, three directions of the corrugated paper board are marked as: 1) the machine direction (MD), which is parallel to the direction of the machine processing in the production of corrugated paper board; 2) the cross direction, which is parallel to the fluting; 3) the Z direction, which is parallel to the thickness direction of corrugated paper boards. Based on the number of layers of the flutings, corrugated paper boards can be normally divided into three categories: single-wall, double-wall, and triple-wall corrugated paper board. (Nordstrand, 2003) The directions and different categories of corrugated paper boards are shown in Figure 4.

![Figure 4](image)

Figure 4. Different corrugated paper boards categories and the three directions (Nordstrand, 2003)

Corrugated paper boards can also be categorized by the fluting shapes. Depending on the shape of the section of the fluting, corrugated paper boards can be categorized into U-shaped, V-shaped, and UV-shaped corrugated paper board. Since the UV-shaped corrugated paper board has a better cushioning performance, it is the most commonly used type of corrugated paper board for packaging purposes. (Wang, 2009) The section view of the different fluting shapes are shown in Figure 5.

![Figure 5](image)

Figure 5 (a) U-shaped corrugated paper board, (b) V-shaped corrugated paper board, (c) UV-shaped corrugated paper board (Wang, 2009)

Corrugated paper board is a relatively complex material since it has an internal structure. FEM studies are conducted on corrugated paper board to understand the properties of the material. But since the internal structure has details that are quite small in size, which will limit the minimum mesh size in the FEM study. This will result in a large number of cells in the study that will consume too much computational power which will lead to too long calculation time.
In Figure 6 a structural FEM approach is demonstrated. Such models are sufficient for analyzing the properties of the material, but when FEM is used for a model as complex as a prototype of a cushioning system, but required calculation time is very long. Therefore, homogenized models are developed to greatly reduce the calculation time. The homogenization is based on the analysis of a unit cell of the liner-fluting structure, and simplified cells having similar properties are used instead of the detailed structural model. The results of the structural FEM and the homogenized FEM are in accordance to the experimental results from the actual measurements. (Hernández-Pérez, Hägglund, Carlsson, & Avilés, 2014)

Comparing corrugated paper board with polymeric cushioning material, the fluting forms a semi-closed structure filled with air. The air trapped in the fluting contributes to the cushioning properties of corrugated paper board pads. But the study found that the influence of the trapped air is much more pronounced when the corrugated paper board is subject to a high compression ratio in the impact. The study was conducted by comparing the measurement of the stress-strain curves during impacts on corrugated paper board pads with the ends taped or un-taped to determine the influence of the air trapped in the fluting. The study also found that the virgin corrugated paper board has a high initial stiffness which is not so suitable for the purpose of cushioning. (Li, Xiao, Li, & You, 2009) The study also established a numerical model of the cushioning property of corrugated paper board.

Other than the peak acceleration during impact, the energy absorption capability is also a very important factor of cushioning material. Studies regarding the energy absorption capability of corrugated paper board were carried out. A theoretical model was established to describe the energy absorption of corrugated paper board. The theoretical model was found consistent with the experimental measurement. Figure 7 is a demonstration of the comparison between the experimental diagram and the theoretical diagram. In the diagram, the first steady increase happens in the liner-elastic phase. The rapid increase happens during the sub-buckling phase, when the compression resistance is almost constant but the energy absorbed increases rapidly. Later in the densification phase, the corrugated paper board loses its capability of absorbing energy. The study concluded that the energy absorption per unit volume of corrugated paper board is related to the corrugated structure, the basis material, and the manufacturing process. (Wang, 2010)
Wang also conducted another study regarding the energy absorption per unit volume in relation to the relative density of corrugated paper board. The finding was that the energy absorption per unit volume of corrugated paper board is roughly in direct proportion to the relative density of corrugated paper board. (Wang, 2010) The finding is shown in Figure 8:

As shown in Figure 8, the energy absorption per unit volume increases with the relative density of corrugated paper board. By increasing the relative density of corrugated paper board, the required volume of corrugated board to absorb the same amount of impact energy is reduced proportionally. This means, in order to absorb a certain amount of energy during impact, it will require the same amount of corrugated paper board in weight.

If the fluting of corrugated paper board compressed, it cannot be restored to virgin state. Therefore, the compressed corrugated paper board has a different state. The corrugated paper board in the compressed state is defined as pre-compressed corrugated paper board by the researchers. The pre-compressed corrugated paper board demonstrate very different cushioning property. (Sek & Rouillard, 2005) The difference is shown in Figure 9.
The virgin corrugated paper board mainly demonstrated plastic deformation after the initial compression. The pre-compressed corrugated paper board mainly demonstrated elastic deformation throughout the whole process. Pre-compressed corrugated paper board showed similar stress-strain curve as the traditional polymeric cushioning material. (Sek & Rouillard, 2005)
As shown in Figure 10, pre-compressed corrugated paper board showed potential of being used for cushioning material since the material has similar cushioning properties comparing with other common cushioning material such as EPS and EPE. (Sek & Rouillard, 2005) In another research, it was confirmed that pre-compressed corrugated paper board had compression resistance capability for repetitive impacts. The change of the cushioning properties were found to be minor comparing the degeneration effect on other cushioning materials, especially when the pre-compression rate is high, which means the corrugated paper board was compressed to a smaller thickness. (Garcia-Romeu-Martinez, Sek, & Cloquell-Ballester, 2009) In order to use pre-compressed paper board as cushioning material, it is important to use the cushioning curve of the material.

Cushioning curves are curves showing the relation between static stress and the peak acceleration during the impact. For different material type, material thickness, or different drop height, a different cushioning curve is generated. In order to obtain the cushioning curves of pre-compressed corrugated paper board of different type, thickness, and different drop heights of the impact, theoretical approach was done besides the actual measurement in tests. Models were built to simulate the cushioning curves of certain thickness of certain pre-compressed corrugated paper board in an impact of a certain drop height using the data obtained from static and quasi-dynamic compression tests. The simulated cushioning curve appeared to be very accurate comparing with the data from the actual tests, as shown in Figure 11.

With this method, it is possible to generate a family of cushioning curves for pre-compressed corrugated paper board. These cushioning curves were generated and documented in a handbook developed by researchers. (Sek & Kirkpatrick, 2001)

In order to use the curves for packaging development, it is important to understand the curves. For example in Figure 12, three cushioning curves are shown for comparison.
These three curves are measured with the same pre-compressed corrugated paper board with different drop heights. It can be seen that the shape of the curves are similar to each other, and also the simulated cushioning curves in Figure 11. Each curve has one and only one minimum value point in the middle. The reason for this similar shape is that when the static stress is too small, the cushioning is hardly compressed to absorb enough energy during impact; when the static stress is too large, the cushioning is over compressed, exceeding the limit of energy absorption of the cushioning; and when the static stress is within a proper range, the cushioning is properly compressed to absorb much energy during impact, which leads to a minimum value of the peak acceleration. (Guo, Xu, Fu, & Zhang, 2010)

The comparison in Figure 12 indicated that with the same material and thickness, the curve moves up and left when the drop height is increased, which means a lower optimum static stress and a higher minimum peak acceleration. The same trend is shown in Figure 13.
Comparing between Figure 12 and Figure 13, it can be seen that if the drop height and material are the same, as the thickness increases, the curve moves down and right, which means with thicker cushioning material, the minimum peak acceleration will be reduced and the optimum static stress is larger. The study also found out that more layers of pre-compressed corrugated paper board will greatly reduce the vibration transmissibility, which is also one of the cushioning properties, and part of the packaging tests. (Guo, Xu, Fu, & Zhang, 2010)

There are concerns of the durability of the cushioning systems using pre-compressed corrugated paper boards. A study was done regarding the creep characteristics of pre-compressed corrugated paper boards. Based on the data obtained from tests, curves of creep strain in relation to time were generated by fitting the test data. The curves are shown in Figure 14.

According to Figure 14 the cushioning system suffered a 0.05-0.1 creep strain as the time passed by. But the strain was stabilized after approximately 40-60 hours on a constant level, which meant the thickness of the pre-compressed corrugated paper board stayed the same after this time. (Shehab, 2011) Therefore, this creeping problem can be solved by treating the material before using them as cushioning system.

During the visit to the corrugate paper board supplier factory, it was found out that there was not any pre-compressing machines available in the production line. This raised a problem of massive production. But the supplier company used a mold cutting machine for the shapes of the corrugated paper board. According to the study on the performance of corrugated paper board boxes, the stiffness was reduced after machining procedures, due to the compression of the corrugated paper board. The thickness is measured to be only 87.5% of the virgin corrugated paper board. (Biancolini, Brutti, & Porziani, 2010) But in this study, the machining was done by a Computer Numerical Control (CNC) machine which compressed the corrugated paper board less than a mold cutting machine. Therefore, the corrugated paper board processed by the mold cutter can be considered as pre-compressed corrugated paper board.
Similar studies were made for honeycomb paper boards, too. But honeycomb paper boards did not show acceptable cushioning performance in repetitive impacts as the pre-compressed corrugated paper boards. (Guo & Zhang, 2004)

In order to demonstrate the possibility of cushioning systems with pre-compressed corrugated paper board, a cushioning system was developed for an air conditioning unit that weights 32kg. Comparison was done between the performance of the original EPS cushioning system and the new pre-compressed corrugated paper board cushioning system, as shown in Figure 15. The curve marked as EPS is the acceleration of the compressor in the air conditioning unit, which is the most fragile component, during the first impact with the original EPS cushioning system. The curve marked as CF is the acceleration of the compressor during the first impact with the new pre-compressed corrugated paper board cushioning system. The new cushioning system showed better performance. (Sek & Kirkpatrick, 2001)

As shown in Figure 16, during the second and third impact, the acceleration of the compressor with the new cushioning system increased to almost the same as the original EPS cushioning system. (Sek & Kirkpatrick, 2001)

As shown in Figure 17, the curve marked as EPS is the vibration transmissibility in relation to vibration frequency curve with the original EPS cushioning system. The curve marked as CF is the vibration transmissibility in relation to vibration frequency curve with the new pre-compressed corrugated paper board cushioning system. The curve marked as unprotected is the vibration transmissibility in relation to vibration frequency of the air conditioning unit itself without any cushioning system. It can be seen that the new pre-compressed corrugated paper board cushioning system has a lower vibration transmissibility than the original EPS cushioning system, which will protect the product better from the vibration in transportation. (Sek & Kirkpatrick, 2001)
Figure 15 Comparison of the acceleration during the first impact (Sek & Kirkpatrick, 2001)

Figure 16 Comparison of the acceleration during the second and third impact (Sek & Kirkpatrick, 2001)

Figure 17 Vibration transmissibility of the cushioning systems (Sek & Kirkpatrick, 2001)


In this chapter the working process is described. The process starts with concept generation. After the concept generation, the concepts are selected. Then the concept goes through FEM, prototyping, drop tests, and improvement iteration. The outcome is an approved concept.

### 3.1 Concept generation

The concept generation was done by a brainstorming session after browsing through different cushioning systems for inspirations. There were nine concepts generated in this phase. They are described and explained in the following paragraphs.

The first concept was Material Reduction, which was to reduce the amount of same material used for the cushioning system. During the interview with the original designer of the current cushioning system, a problem was found that the design of the cushioning system was optimized based only on test iterations. This left the possibility of reducing the cost and environmental impact just by reducing the material but still remaining sufficient cushioning performance. It was also possible for this concept to be combined with future optimization of the product itself to achieve a better product/package system as suggested by the six-step method. Since the material and the manufacturing process were not changed in this concept, the material cost and the environmental impact would be reduced proportionally. But this concept would not save the storage space or improve the repack experience.

The second concept was Air Bag, which was to replace the original cushioning pads with air bags. Researches were done regarding the cushioning property of air bags. Figure 18 shows the cushioning curve of a type of proposed air bag cushioning system.

![Cushioning curve for an air bag cushioning system (Sasaki, Saito, & Abe, 1999)](image)

In Figure 18 the three curves are the cushioning curves of three different thickness of the air bags in millimeter. It can be seen from the diagram that air bags demonstrate similar cushioning...
properties as the traditional cushioning. With this proposed air bag solution, the peak acceleration was measured to be higher than the peak acceleration of traditional cushioning systems with EPE or EPS. But it showed a clear trend of peak acceleration reduction when the thickness of the air bag was increased. The cost and the environmental impact of such cushioning system was estimated to be lower than the traditional cushioning systems, given the material consumption was significantly reduced. The air bags were only filled with air before they were packed into the packages, therefore the storage space for the unprepared air bags was very low comparing to the traditional cushioning systems. But since the air bag has a more flexible shape, the repacking process was thus more complex than the original cushioning system. Also, as shown in Figure 18, the peak acceleration was reduced by thicker air bags. This will result in even more space required for the cushioning system, which will lead to an even larger overall packaging size which will cause even more problem for fitting the packages onto one European standard pallet. New suppliers were required and a major change in the assembly line will have to be made for this change, which means the shifting cost was relatively high.

The third concept was Air Bag + CPB, which was a combination of air bags and corrugated paper boards. This concept was developed based on the Air Bag concept to improve the cushioning performance. Since the main drawback in terms of performance of the air bag concept were too much flexibility, and lack of capability to resist large impact. By using corrugated paper board inserts, the shape of the air bags will be fixed by a frame made of the corrugated paper board. And according to research, virgin corrugated paper board pad inserts can be used for reducing the peak acceleration during severe impacts for a limited number of times. (Sek & Rouillard, 2005) But the shifting cost will be even higher with the increased complexity of the cushioning system. Also this concept will not help with reducing the overall packaging size. The environmental impact of the package will also be increased comparing to the air bag concept, since more material was added to the combination, and the manufacturing complexity increase introduced by this change.

The fourth concept was CPB, which was to use corrugated paper board pads solely as the cushioning. This concept was based on the research on the cushioning properties of pre-compressed corrugated paper board. The concept was to replace all the polymeric cushioning pads with multi-layer pre-compressed corrugated paper board. In order to maintain the same cushioning performance, more material in weight was required. This will increase the environmental impact during the transportation phase of the life cycle. But the overall environmental impact needs to be examined with LCA. The material price of corrugated paper board was much cheaper than the polymeric material especially EPE. Since the corrugated paper board pads were folded, the cushioning pads were kept flat until before inserting to the packages. The storage space for unprepared cushioning material was reduced. The repacking experience was potentially optimized since the shape of the cushioning system was re-designed and the repacking experience was taken into consideration. The size of the cushioning pads was optimized by using pre-compressed corrugated paper board with different densities. As discussed in Chapter 2, in order to absorb the same amount of energy, the volume can be reduced by using corrugated paper board with higher density. Since there was already a corrugated paper board supplier in place, the shifting cost will mainly be the change of the assembly line. In Figure 19 a sample of pre-compressed corrugated paper board pad is shown. Several of similar pre-compressed corrugated paper board pads were combined and glued to one top piece and one bottom piece.

The fifth concept was Function+, which was to use items that have other functions to serve as the cushioning, or at least to replace some of the cushioning with other items. The benefit of this concept was to reduce the amount of material used for cushioning. Also the life cycle of the useful part of the cushioning system was prolonged since some or all of the cushioning system will not go directly to disposal after unboxing. By prolonging the life cycle of the cushioning system, the environmental impact was reduced. The cushioning performance of the new cushioning system was not as good as traditional cushioning material, therefore, the space needed for the new cushioning system was larger. The repacking process was more complex, since the cushioning
system was made of or partially made of parts that have other functions, the cushioning system was thus disassembled after unboxing. Reassemble of the relatively complex cushioning system introduces more risk of mistakes during assemble, which will cause more potential damage for the returned products. To implement this concept, optimization of the product itself and the content of the package need to be optimized for this purpose. Therefore the shifting cost of this concept was very high. Another disadvantage of this concept was that the useful parts of the cushioning system were subject to higher risks of impact damage. And since they were part of the product, this cause an increased damage cost.

![Figure 19 A sample of pre-compressed corrugated paper board](image)

The sixth concept was CPB+EPE, which was to combine the pre-compressed corrugated paper board with the original EPE cushioning material. This concept was an alternative to the first and the forth concept with reducing material or using solely pre-compressed corrugated paper board. The EPE compensate the cushioning performance difference between pre-compressed corrugated paper board and EPE. The cost and the environmental impact of this concept was reduced for the same reason as the forth concept. The storage space problem was not solved by this concept since this concept had a relatively complex mixture of material, a sub-assembling line was required, and the sub-assembly would take approximately the same space as the current cushioning system. The repack experience was improved by reducing the number of cushioning blocks. The shifting cost for this concept was relatively high mainly because of establishing a new sub-assembling line for the cushioning blocks.

The seventh concept was Molded Paper, which was to use molded paper as cushioning material. Molded paper cushioning systems were mostly used for light weight products. The environmental impact was greatly reduced due to the small amount of material used in this concept. The molded paper cushioning pads were normally designed so that they could be stacked in a compact manner, therefore the storage space was greatly reduced. The number of cushioning blocks was also reduced in order to simplify the repacking process. It also open up the opportunity for reducing the overall packaging size to fit in the European standard pallet. In order to implement this concept, a new supplier was needed, but no additional assembly work was required. The shifting cost was moderate.

The eighth concept was Mushroom, which was a technology developed by Ecovative, and used by Dell for its personal computer packages along with other applications. The concept was to grow mushroom to the shape of cushioning pads and use those cushioning pads to form the cushioning
system. Figure 20 shows a few samples of Mushroom cushioning blocks. The cost of this concept was much higher than the current cushioning system since new technology was used. The environmental impact of this concept was claimed to be much lower than the existing polymeric cushioning systems. But this result was not presented with a peer-reviewed LCA. The repacking experience was not improved since the number of cushioning blocks was not reduced, and the material has a low resistance against tearing. The shifting cost was also very high, since this requires a new supplier. And as a new technology, there were only a few suppliers who can provide the cushioning blocks.

![Figure 20 Samples of Mushroom cushioning blocks (Ecovative, 2015)]

The ninth concept was Honeycomb, which was to use honeycomb paper board. This concept was similar as the CPB concept, but honeycomb paper board was used instead of pre-compressed corrugated paper board. Research has found out that the honeycomb paper board has a similar cushioning curve as the pre-compressed paper board. This indicates that honeycomb paper board was suitable for cushioning. (Guo & Zhang, 2004) But the behavior of honeycomb paper board in repetitive impacts was not clear. The cost and environmental impact were reduced for the same reason as the CPB concept. The storage space and repacking problems were also addressed by this concept. According to the research of Guo and Zhang, there was a possibility of reducing the volume of cushioning material, which will help to fit the packages to a European standard pallet. The shifting cost was higher than the pre-compressed corrugated paper board concept since a new material was introduced and thus a new supplier was needed.

### 3.2 Concept selection

In order to choose one concept from the nine concepts generated from the concept generation phase, Pugh Matrix was used for the concept selection phase. The first step to implement the Pugh Matrix was to establish the criteria of the grading system. In this project, the criteria were decided based on interviews with stakeholders including people who work with product development, logistics, production, and the corrugated paper board supplier of the company. There were seven criteria included in the Pugh Matrix, which were: 1) Environmental impact, 2) Cost, 3) Repack, 4) Storage, 5) Pallet fitting, 6) Shifting cost, and 7) Marketing value. Each criterion was evaluated and given a weight from 1 to 10 for the final score of each concept. The original cushioning system was used as the reference concept whose ratings under all criteria were all 0. Rating of 0 on the proposed concepts indicated that the proposed concept was of the same or almost the same level of the original concept on certain criterion. The criteria are further explained as follows:
1. Environmental impact: This criterion measured the improvement of the concept in terms of environmental impact. Since reducing the environmental impact of the packaging was the primary goal of the project, this criterion was graded to be the most important criterion with the weight of 10. Ratings of -2 or -1 indicated that the new concept was expected to have much more or slightly more environmental impact than the original concept. Ratings of 1 or 2 indicated that the new concept was expected to have much less or slightly less environmental impact than the original concept.

2. Cost: This criterion measured the production cost of the new concept in relation to the original concept. The production cost was not the most critical aspect to evaluate the concepts, since the production cost could be reduced by implementing running changes. The weight of this criterion was set to be 5. Ratings of -2 or -1 indicated that the proposed concept was expected to have a much higher or slightly higher production cost. Ratings of 1 or 2 indicated that the proposed concept was expected to have a slightly lower or much lower production cost.

3. Repack: This criterion measured the complexity of repacking process for the customers if they wanted to return the product for some reasons. It was identified as one of the major risk of damaging the product that the package was not properly repacked and was subject to potential damage on its way back to the warehouse. The weight was set to be 7, for it was a major problem, but not the focus of the project. Ratings of -2 or -1 indicated that the proposed concept was expected to be much more complex or slightly more complex to repack. Ratings of 1 or 2 indicated that the proposed concept was expected to be slightly less complex, or much less complex.

4. Storage: This criterion measured the storage space taken by the cushioning system before it would be inserted into the package. This has caused a problem in the assembly line. The weight of this criteria was set to be 8. Ratings of -2 or -1 indicated that the proposed concept was expected to take much more or slightly more storage space. Rating of 1 or 2 indicated that the proposed concept was expected to take slightly less or much less storage space comparing to the original cushioning system.

5. Pallet fitting: This criterion measured the potential of the proposed concept to reduce the package volume and thus better fit the European standard pallets. It was not one of the major problems of the original package, but a large amount of cost can be saved in logistics if the size of the whole package can fit in a European pallet. The weight of this criteria was set to be 5. Ratings of 1 or 2 indicated that there was a potential or a very clear potential of the proposed concept to reduce the volume of the cushioning system. No negative ratings were given under this criteria, since 0 indicated that the proposed concept would not solve the problem.

6. Shifting cost: This criterion measured the shifting cost of replacing the original cushioning system with the proposed concept. The shifting cost was not considered to be a major issue because it was a onetime cost and would not raise further problems. The weight of this criteria was set to be 3. Ratings of -2 or -1 indicated that the shifting cost was very high or acceptable. No positive ratings were given under this criteria since ratings of 0 indicated that the shifting cost was minor.

7. Marketing value: This criterion measured the value added to the product, and how well it could be received by the customers through marketing. It was very important to be able to sell the idea in order to cover the cost and to increase the profitability of the product. The weight of this criterion was set to be 8. Ratings of 1 or 2 indicated that the prosed concept was expected to be well received or very well received by the customers through marketing approaches. No negative rating were given under this criteria since ratings of 0 indicated that there was not much to market about the proposed concept.
After the criteria and the weight for each criterion were decided. A Pugh Matrix was generated. The proposed concepts were rated according to the -2 to -1 scale. The final score was calculated to find the best concept. The Pugh Matrix and the ratings are attached as Appendix A. CPB was found to be the best concept with a final score of 63, with Molded Paper and Honeycomb following with 49 and 48. The rest of the concepts had scores that were far less than these three concepts.

Comparing the Molded Paper concept with the CPB concept, the main disadvantage was that the concept had a high shifting cost, and also very limited marketing value since the molded paper was a very familiar cushioning material that has been around for years. It was hard to project an innovative image by implementing this change to the cushioning system. Another concern was that since the weight of air purifiers were normally very large, and with the more purification capacity increasing as new generations of purifiers were being developed, the weight of the purifiers were increasing accordingly. Molded paper was not the best material to handle heavy products. It was likely that the weight of the units will exceed the weight limit of molded paper.

Comparing the Honeycomb concept with the CPB concept, the main disadvantage was the repacking complexity, cost, and the shifting cost. Honeycomb paper board suffered from plastic deformation during impacts, which would change the shape of the cushioning pads. The change of shape would cause confusion to the users when they tried to repack. The cost issue was mostly caused by switching suppliers. Another problem of honeycomb paper board was that there was no research regarding the behavior of the material during repetitive impacts. It was unclear that if the material can maintain its cushioning properties after repetitive impacts. This increased the risk of continuing with this concept.

The concept of CPB had acceptable rating on all aspects. It could be further improved with fitting the European standard pallet. Especially when this issue would be taken into consideration in the product development. The storage space saving of this concept was not as good as the Air Bag concept, but by flattening the cushioning pads, the storage space was already optimized. Since this concept eliminated the usage of any polymeric material, and was new to the market, the change could project a strong environmental friendly and innovative image of the company.

The result of the concept selection phase was that the CPB concept was the only concept that would be further developed since it had shown major advantages against other concepts.

3.3 FEM

In order to try different designs of the CPB concept, FEM was used for simulation before actual drop tests. As explained in previous chapter, using FEM before actual drop test made the development process cheaper, and more agile.

Before the FEM study, a CAD model needed to be built and simplified. In this project, Solid Edge ST6 was used for building the CAD model. The internal structures of the air purifier were omitted. The connections among the different parts were also omitted. The model was built as a rigid body with the shape and weight of the actual air purifier. The internal structure of the purifier was very crucial for optimizing the shock resistance of the purifier itself, but it was not the goal of this FEM study which was to find out the cushioning performance of the cushioning system. Therefore, the weight and shape of the unit were the features kept as the input of the cushioning system. The simplified CAD model is shown in Figure 21:

The model was a hollow box of the shape of the purifier. Small details such as the logo, the indicator light, small round corners were omitted, too, since they would not make a large difference to the mechanical performance of the purifier. But small details like that would significantly increase the computational requirement. The four feet of the air purifier were also omitted in the first model for the first iteration of the FEM, but the omission resulted in an unexpected failure in the drop test. Therefore this detail on the model was kept. The main reason of the importance of
this specific detail was that these four feet were the lowest points of the unit, and they were located on the bottom surface which was one of the most crucial surfaces to resist shocks.

The cushioning pads were built in details so that the simulation accuracy was acceptable. The original cushioning system was built for reference simulations. The actual cushioning pad is shown in Figure 22. And the CAD model of the cushioning pad is shown in Figure 23. The material was not defined in Solid Edge, but the physical properties were defined later in ANSYS.
Other accessories were also built in Solid Edge, such as the surface that the package system dropped on, and the outer box of the package. The different parts were then assembled in Solid Edge to export a *.asm file to be imported in ANSYS. The physical properties of EPE foam and corrugated paper board were measured. Other properties such as the density of the material were also measured. The measurement was done to determine the static mechanical properties of the two materials. The Young Modulus and the Poisson's Ratio were the input to ANSYS. Since the measured properties were only the static mechanical properties instead of dynamic mechanical properties, error occurred because of the inaccuracy. In order to reduce this error, reference simulations on the original cushioning system were done. The result of the simulation on proposed concepts were compared with the simulation results of the reference simulation. Since the current cushioning system had been proved functional in practice, therefore, if the simulation on proposed concepts had a similar result as the reference simulation, the proposed concept would be considered as approved in FEM phase. Prototypes were built when the proposed concepts were approved in the FEM phase.

The drop test standard chosen for this cushioning system was ISTA 3A because in this standard, the product/package system was subject to 16 impacts which was twice as many as in other ISTA standards. It was especially suitable for this proposed cushioning system since it challenges the durability of the cushioning system in repetitive impacts. The cushioning performance in severe impacts was also challenged by two double height drops. The standard drop height in this standard was 460mm, and the double drop height was 970mm. Using Equation 2, the impact speed can be calculated as 3.00m/s for the standard drop height, and 4.36m/s for the double drop height.

For the reference drop simulation, only one drop was simulated since the result of the simulation was used as a reference for the simulations on the proposed concepts. A drop on the bottom surface from 970mm was simulated. In Figure 24, the geometry used for the reference simulation is shown. The simplified air purifier model was placed on two pieces of EPE cushioning pads which were placed on a piece of structural steel plate. A fixed support was assigned to the steel plate to serve as the solid surface for the drop. A velocity of 4.36m/s was assigned to the air purifier and the cushioning pads. A standard gravity was assigned to the whole system. The simulation was set to run for the first 0.01 second after the impact. It was not enough time for the whole system to absorb all the kinetic energy, but it was sufficient for the air purifier to reach the lowest point during the impact. Therefore, 0.01 second was sufficient to determine the most critical challenge that the cushioning system was confronted with. Since this model of the air purifier was built for the first
prototype, the importance of building the feet was not realized. It was a more simplified model used in this simulation.

Since the most important property of a cushioning system was to reduce the peak acceleration of the product protected by it. Therefore, an acceleration probe was placed at one of the lowest points on the body of the air purifier. The acceleration of this point during the first 0.01 second of the impact is shown in Figure 25. The x axis was time from the contact, and the y axis was acceleration. The peak acceleration was determined to be 50893 m/s$^2$.

The same simulation was done on the first proposed cushioning system. Figure 26 shows the geometry of the first proposed cushioning system. The design was based on the cushioning curves from studies on pre-compressed corrugated paper board. The space under the air purifier was used so that the contact area of the air purifier and the cushioning pads was enlarged. The contact area was calculated based on the optimal static pressure for the maximum cushioning performance, Figure 27 shows the result of the simulation. The peak acceleration was determined to be 45087 m/s$^2$, which was smaller than the reference peak acceleration.
After this simulation, the first proposed cushioning system was decided to be approved by FEM study and to be carried to prototyping and testing phase. Though the drop test consisted of 16 different drops, only one drop was simulated because the cushioning system was designed in the way that on each direction, there were the same amount of cushioning material between the air purifier and the ground. The peak acceleration was assumed to be the same for all direction. Therefore, for approving the proposed cushioning system, only one simulation was required.

But the first proposed cushioning system did not pass the drop test. And several problems were identified in the first drop test. The first one was that the model of the air purifier was over-simplified. Therefore, for the second iteration of FEM study, some of the details of the air purifier were restored in the model. Also it was found that since the actual air purifier was much more complex than the simplified CAD model, peak acceleration was not the only simulation result that mattered. The strengths of the structure on different locations of the air purifier were different. Therefore certain parts of the air purifier could only sustain smaller stress comparing to the rest of the air purifier. Such weak points included the grid for air inlet and outlet on the sides of the air purifier. The grid is shown in Figure 28, and the grid is marked with dashed lines. Another set of
weak points were the corners of the doors of the air purifiers which were marked with arrows in Figure 28. The doors were connected to the body with hinges, therefore, shocks from the directions of the arrows would threaten the stability of the connection and thus damage the structure. In order to protect these weak points, the energy of the shock should be absorbed by the cushioning pads and other parts of the air purifier.

A new cushioning system was proposed to solve the problems found in the first drop test. And the FEM study was also improved accordingly. Another simulation result was introduced to decide if the proposed cushioning system should be approved. Equivalent stress on the air purifier was used to find out if the shock impacted the weak points. And simulations for all the drop directions in the drop test were done and compared to the reference simulation result in order to evaluate the proposed cushioning system.

The equivalent stress simulation result in the reference simulation is shown in Figure 29. It can be seen that the most concentrated stress is found on the front surface which is marked with dashed circle in Figure 29. The maximum value was 5.3693e7 Pa. The stress concentration was not at the weak points.

The second proposed cushioning system consisted of one top cushioning piece and one bottom cushioning piece which were identical. The CAD model of the cushioning piece is shown in Figure 30. The feet and the doors of the air purifier were suspended by the cushioning pads so that no major shocks would impact these parts. Shocks to the grids on the sides of the air purifier were also avoided.
The setting of the simulations on the second proposed cushioning system was the same as the reference simulation, the geometry is shown in Figure 31 and the results are shown in Figure 32 and Figure 33.

It was shown in the bottom surface drop simulation that the peak acceleration was much lower than the reference simulation, which indicated an improvement in the cushioning performance. The stress was concentrated in the corners of the air purifier. But the direction was not aligned with the critical stress direction. And the maximum stress was still far less than the strength of steel. Six simulation were done in total. Three of them were done on surface double height drops, and the other three were done on edge drops. Though there were six different surfaces and twelve different edges on the package, only three surfaces and three edges were chosen to run drop simulations due to the symmetry of the package and the air purifier. The three surfaces were bottom surface, side surface and front surface. The edges were bottom long edge, bottom short edge, and side edge. The definition of the surfaces and edges are shown in the simulation result figures. The results of the simulations on other drop directions are attached as Appendix B (Figure 45 to Figure 54). This simulation indicated that the proposed cushioning system was sufficient to protect the
air purifier. A prototype was made after the proposed cushioning system was approved by the FEM study.

Figure 31 The geometry of the simulations on the second proposed cushioning system

Figure 32 The simulated acceleration of the sample point in the bottom surface double height drop simulation on the second proposed cushioning system
3.4 Prototyping

There were two physical prototypes built in total. The prototypes were built with corrugated paper board of used packages of the air purifiers. This ensures that the material used for the prototype was available for massive production if the new packaging was launched without switching suppliers. The corrugated paper boards were cut, folded, stacked and taped together to form cushioning pads. The cushioning pads were then glued to two pieces of corrugated paper board to form a top piece and a bottom piece of the cushioning system.

During packing, a problem was found that the air purifier was hard to be centered when it was put on the bottom cushioning piece due to the flexibility of the cushioning pads. In order to help positioning the air purifier, the top cushioning piece needed to allow access to the air purifier from the top. For this purpose, a hole was cut in the center of the top piece.

The first prototype consisted of two different cushioning pieces: the bottom cushioning piece and the top cushioning piece. The top and bottom cushioning piece of the first prototype are shown in Figure 34 and Figure 35.

Since the first prototype did not pass the drop test, a second prototype was built. The second prototype was built with the same material but an optimized design. The hole on the top cushioning piece was kept, and a same hole was also cut on the bottom cushioning piece since the bottom cushioning pad was no longer located in the center of the cushioning piece. The hole made the top and bottom cushioning piece identical, which reduced the manufacturing complexity and also the complexity of repacking. The unified cushioning piece is shown in Figure 36.

Some of the structural parts of the second prototype were reused from the first prototypes since they were not critical cushioning parts. Such as the piece of corrugated paper board that served as the base for all the cushioning pads to be glued on.
Figure 34 The top cushioning piece of the first prototype

Figure 35 The bottom cushioning piece of the first prototype
3.5 Drop tests

The first drop test was done on the first prototype. The drop test followed the testing procedures of ISTA 3A. The most critical surfaces which were the most vulnerable to impacts were marked as Surface 3 and Surface 5 so that these two surfaces would be challenged by the double height drop.

After the sequence of drops following the ISTA 3A standard, the package was unpacked and the air purifier was examined. After the first drop test on the first prototype, four damages were found on the air purifier which indicated that the prototype failed the drop test. After the second drop test on the second prototype, no damages were found on the air purifier which indicated that the second prototype was approved by the drop test.

The four damages in the first drop test are explained further as follows.

The first damage was the deformation of the beam on which the feet of the purifier were attached. This damage was made during a bottom surface drop. The bottom cushioning pad was not thick enough to prevent the feet from hitting the bottom of the package. The energy of the impact was thus absorbed by the deformation of the beam. The damage is shown in Figure 37. The shock was then transmitted to other parts of the purifier and caused further damage. In the picture, the dashed line shows the original position of the bottom beam. And the two arrows mark the gap between the original position of the beam and the position after the impact.

The second damage to the air purifier was that a rivet was broken away. This damage was a result of the shock transmitted from the feet. This failure of the rivet severely damaged the integrity of the structure of the air purifier, which made the air purifier more vulnerable to further impacts. In Figure 38, the rivet holes are shown. The two rivet holes marked with dashed circles were connected by a rivet. The upper part of the sheet metal was behind the lower part before the impact. After the failure of the rivet, the upper part slipped out and caused deformation to the inner space of the air purifier. The two arrows show the gap between the upper part and the lower part. These
two parts were supposed to be overlapping each other to form the inner space. The failure of the river destroyed the structural integrity of this part of the air purifier. The inner space inside this part was strongly influenced by any other impacts due to the flexibility of the sheet metal. This damage was the most harmful damage, and caused further damage to the air purifier.

![Image](image1.png)

**Figure 37** The deformation of the bottom beam

The third damage caused by the drop test was the deformation of the filter. The filter was made of filter media and glued to a paper board frame. It was originally protected by the sheet metal boxing of the air purifier. The filter was inside the inner space which was destroyed by the second damage. The damage to the filter was a natural consequence. The damaged filter in the drop test is shown in Figure 39. The most damaged parts of the paper frame are marked by dashed circles. The filter was inserted in the air purifier to be protected by the structure from the impacts. But during this drop test, the structure was destroyed, and the filter was twisted and squeezed.

The forth damage during the drop test was made to the covering film of the indicator light. The damage itself was not severe, but it indicated that a major deformation took place during the drop test. The damaged covering film is shown in Figure 40. The damage is marked with an arrow. The damage was made by the LED light which served as the indicator of the air purifier. The LED light was located behind the covering film. The covering film was attached to the sheet metal and the LED light was inside the sheet metal and shone through a hole in the sheet metal. This damage to the covering film indicated that during the drop test, the LED light was dislocated and poked the covering film causing the damage. The dislocation of the LED light was a result of the destruction of the overall structure. Possible damage was made to the control circus board to which the indicator light was connected.
Figure 38 The rivet holes where the rivet broke away

Figure 39 The damaged filter
A table of all the damages and failure in the first drop test is presented below for an overview of the test result. As shown in Table 4.

<table>
<thead>
<tr>
<th>No.</th>
<th>Damage area</th>
<th>Description</th>
<th>Cause of the damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feet support</td>
<td>Deformation</td>
<td>Direct impact on the feet</td>
</tr>
<tr>
<td>2</td>
<td>Rivet hole</td>
<td>Cut loose</td>
<td>Direct impact transmitted to the rivet</td>
</tr>
<tr>
<td>3</td>
<td>Filter</td>
<td>Squeezed</td>
<td>Deformation of the filter box</td>
</tr>
<tr>
<td>4</td>
<td>Indicator light</td>
<td>Cover film broken</td>
<td>Dislocation of PCB</td>
</tr>
</tbody>
</table>

Since the first prototype did not pass the drop test, a second prototype was built with modifications. A second drop test was then performed on the second prototype following the same standard and using the same setting of the test. The second prototype passed the drop test since no damage was detected in the examination after the drop test. The second prototype was thus decided to be an approved concept.

### 3.6 LCA study

The approved concept was examined by an LCA study in order to verify if this proposed concept was improved in terms of environmental friendliness. CES EduPack 2013 was used to do a primary calculation on the energy consumption and carbon dioxide footprint. Assumptions were made in order to simplify the calculations.

The assumption made to the material part was that the corrugated paper board and the EPE foam used in the actual cushioning system was the same as the material in the CES EduPack database. The manufacturing phase was simplified to very simple steps: for the corrugated paper board, the data of the primary process was included in the material data, and the secondary process was set to be cutting and trimming; for the EPE foam, the primary process was selected as polymer molding, and the secondary process was cutting and trimming. The assumption made to the
transport part was that the transport from the cushioning supplier to the packaging line of the air purifier was omitted since it was in the same city and the transport distance was neglectable comparing to the transport distance of the whole package to the customers. The transportation was assumed to be a single trip from the manufacturer to the customers by 32 ton trucks. The distance of the transport was assumed to be 1495 km by high way, which was the distance between Shenzhen, China, where the manufacturer was located, and Shanghai, China, a major city in China. And in the final result, transport only contributed a very small proportion of the total environmental impacts. Therefore, the assumptions made to the transport would not affect the accuracy of the LCA study too much. The function of this cushioning system was only to protect the air purifier during transportation from the manufacturer to the users. Therefore, no energy was consumed during the use phase. The end of life scenario of corrugated paper board was assumed to be recycled, since in China, people could sell used corrugated paper board to recyclable material buyers, and according to the supplier of the company for corrugated paper board, the fluting was made of 100% recycled paper pulp, and the liner was made of 80% recycled paper pulp. Therefore, the corrugated paper board was made of roughly over 90% of recycled material. The end of life scenario of EPE foam was assumed to be landfill, since waste sorting was not effectively implemented in China, and polymeric foams were not recycled effectively even though EPE foam was a recyclable material.

A reference study was also made with the material of EPS, since a thorough LCA study was done to compare corrugated paper board cushioning inserts with EPS cushioning inserts. (Tan & Khoo, 2005) Same assumptions were made to the EPS reference product.

The results of the LCA study are shown in Figure 41, and Figure 42. In Figure 41, the energy consumption of each phase was broken down and compared. It was obvious that the material was the dominant phase. And corrugated paper board was calculated to be the most energy consuming option. But due to the limitation of the software, the corrugated paper board had to be set as virgin material, while in actual manufacturing, over 90% of the material was recycled material. If recycled material was used for the production, the energy consumption in the material section would be significantly reduced. But in manufacturing phase, corrugated paper boards showed very obvious advantage over EPE or EPS despite the large weight difference.

And in Figure 42, similar trend was shown. Corrugated paper boards had a much higher carbon dioxide foot print value comparing with EPE or EPS in the material phase. But in the manufacturing phase, EPE and EPS had a much higher value than corrugated paper boards.
Another observation that was that the EPE and EPS cushioning had almost the same level of environmental impact according to this study. The difference was within the 10% error range of...
the software. Therefore, the study result of the comparison of EPS and corrugated paper board cushioning was used as a reference for comparing EPE and corrugated paper board.

In Tan and Khoo’s work (2005), four cushioning systems were compared. Two of them were made of EPS and two were made of corrugated paper board. The weight of the compared cushioning systems were 1.716g and 0.6072g for the EPS cushioning system, and 5.310g and 3.198g for the corrugated paper board cushioning system respectively. It was noted that 0.6072g was 11.44% of 5.310g. And the original cushioning system for the air purifier was 304g and the prototype of the approved concept was 2722g. The weight of the original EPE cushioning system was 11.17% of the weight of the proposed pre-compressed corrugated paper board cushioning system, which was almost the same proportion as in Tan and Khoo’s work. Their work examined the climate change, eco-toxicity, acidification/eutrophication, and fossil fuel. Scores were given under each section, and a final score was given based on weighed sum of the scores under each section. Recycled material was not considered in the results. The LCA study indicated that the corrugated paper board cushioning system did not demonstrate an overall advantage over the EPS cushioning, but under the fossil fuel section, EPS cushioning was much worse than the corrugated paper board cushioning. And a proposed concept using recycled material reduced the environmental impact notably. Therefore, with 90% of the material used in the proposed cushioning system of pre-compressed cushioning paper board, it was reasonable to speculate that the environmental impact of the proposed concept was lower than the original cushioning system.

Another conclusion from both the CES EduPack study and Tan and Khoo’s study was that reducing material usage in the cushioning system was the key to further reduce the environmental impact.
In this chapter, the outcome of the package development is presented. The details of the proposed concept is introduced.

As previously defined, the outcome of this development project was an approved concept of a new package of the air purifier. The concept was a new cushioning system to be used in the original outer package. The cushioning system was made of pre-compressed corrugated paper board. The CAD model of the concept is shown in Figure 30.

In order to explain the concept in a more detailed manner, a detailed CAD model was made to explain the structure of the cushioning system. The model was built with Solid Edge ST6 Sheet Metal. The cushioning system consisted of two identical pieces, for the top and the bottom. Each piece can be folded from a single piece of pre-compressed corrugated paper board. The detailed CAD model is shown in Figure 43. And the flattened view of the cushioning system is shown in Figure 44.
The detail design of the cushioning system follows four principles: 1) reducing the use of glue or any type of binder to the minimum; 2) fulfilling the manufacturing requirements; 3) reducing the waste of raw material; 4) using only one piece of pre-compressed corrugated paper board if possible.

The pre-compressed corrugated paper board needed to produce this cushioning system was one piece with the size of 4664mm by 607mm. It was possible to produce corrugated paper board of this size since the length on the machine direction of the corrugated paper board was not limited. But this size created problems for other processes. The size exceeded the limit of the mold cutting machine. And one piece of material with the length of over four meters and some flexibility was hard to handle. It was common for the supplier to divide the oversize models into smaller pieces and combine the pieces with staples or glue. Therefore, this design can be manufactured by dividing the whole piece into seven smaller pieces, which were the base in the middle, four pieces for the corner cushioning pads, and two pieces for the side cushioning pads.

When the cushioning pads were folded, no glue or tape was needed between the layers since the structure ensures that as long as the cushioning pads were properly mounted to the base of the cushioning system, the shape of the cushioning pads was fixed. By this design, the usage of glue or other bindings were greatly reduced. It benefitted the reduction of manufacturing complexity and the environmental impacts.

But it was also noted that not all parts of the cushioning system were necessary for the cushioning function. The current design was a compromise of environmental optimization and cost including shifting cost and manufacturing complexity. A more environmental friendly solution was possible, but the manufacturing complexity will be greatly increased by that change.

Besides the actual cushioning system developed for the 400 series air purifier, a method of rapid cushioning development was concluded from the development process to be used in future cushioning development for similar air purifiers. The method was suitable for developing a pre-compressed corrugated paper board cushioning system based on an existing cushioning system. The steps were:

1. FEM reference drop simulations: building simplified CAD model of the original product/package system, running FEM drop simulations on the CAD model, and understanding the original cushioning design;

2. Designing the new cushioning: using the cushioning curves of pre-compressed corrugated paper board to define the size of the theoretically optimized cushioning pads, and combining the cushioning pads into a cushioning system;

3. FEM drop simulations: building simplified CAD model of the proposed cushioning system, running FEM drop simulations on the CAD model, and compare the acceleration and equivalent stress result with the reference simulations;

4. Prototyping: building prototypes if the concept is approved by the FEM drop simulations;

5. Drop tests: performing drop tests on the prototype built in step four following an existing packaging standard, and evaluating the test result.

Step two to step three and step two to step five form two iteration loops. If the outcome of step three or step five is negative, the project is carried back to Step 2 for reviewing and improvements.
5 DISCUSSION AND CONCLUSIONS

A discussion of the approved concept in accordance to the pre-defined goals of the project is presented in this chapter. And a conclusion of the project was given.

5.1 Discussion

The purpose of this project is to optimize the packaging for air purifier. The requirements are presented and discussed in Chapter 1. The requirements include reduced environmental impact, reduced or equivalent production cost, reduced storage space, reduced re-packing complexity, and equivalent cushioning performance. All these aspects were addressed in the development process.

The result of the development was a compromise of all the limitations defined for this project. The delimitations were: lower environmental impact, lower production cost, same outer package, and same product structure. There were also problems needed to be addressed, which were storage space problem in the production line, fitting of the European standard pallet, and repacking complexity.

As presented in 3.6 “LCA study”, the proposed concept has a lower environmental impact comparing with the original cushioning system. The main source of this improvement was found to be the high proportion of recycled material used by the supplier. The study also indicated that further improvements were possible. But as mentioned in 2.6 “Pre-compressed corrugated paper board”, in order to absorb the same amount of impact energy during the drops, the same weight of cushioning material was required, therefore, for the same cushioning performance, it was not possible to reduce the weight of the cushioning material in order to reduce the environmental impact. But in the FEM study, the peak accelerations in the drop simulations were much smaller than the reference simulation on the original cushioning system. This indicated a possible over-protecting cushioning system with unnecessary cushioning material. But in this project, since either the air purifier itself or the outer box of the package could be changed, reducing cushioning material was not possible. Another aspect to look at the environmental impact.

The production cost was hard to estimate since the project was not carried into the manufacturing phase. But during the interview with the original cushioning system designer and the manager of the corrugated paper board supplier, the production cost of the proposed concept was estimated to be “around the same” as the original cushioning system. The estimation was done based on the first prototype, therefore, the production cost for the final concept was estimated to be lower. The reduction of storage space also reduced the overall production cost.

The shape and size of the outer package was left the same. And no changes were done to the air purifier itself. These limited the possibilities of further improvement of the cushioning system. Some part of the cushioning system did not have a direct contact to the air purifier, and thus did not provide cushioning to the air purifier. By changing the air purifier, the cushioning material could be used more efficiently. On the other hand, if the shape or size of the outer package could be changed in this project, the density of the pre-compressed corrugated paper board could be optimized to have a better fitting of the European standard pallet. But in order to maintain a low shifting cost, no adjustments were done on the outer package or the air purifier itself.

The storage space for the proposed cushioning system as flattened model was calculated. The original cushioning system consisted of four pieces of EPE foam with the size of 350mm by 130mm by 125mm. The total space that one set of the original cushioning system occupied if they were stacked one on another was 22750.0 cm³. The proposed cushioning system was made of 2
pieces of the base, 8 pieces of the corner cushioning, and 4 pieces of side cushioning if the parts were divided as presented in Chapter 4. When they were stacked properly, the total space that one set of the proposed cushioning system occupied was 18732.5 cm$^3$, which was 17.7% less than the original cushioning system. The net volume of the cushioning material in the original cushioning system was 17220.0 mm$^3$, which was 24.3% less than the space occupied by the original cushioning system, compared to the 17.7% of the proposed cushioning system. Therefore, even though theoretically it was still possible to reduce the storage space, the proposed cushioning system was already very space saving.

Since the size and shape of the outer package was not changed in this project, the problem of fitting European standard pallets could not be solved within this project. But the findings in this project such as that the proposed cushioning system was over-protecting according to the FEM study, and that using higher density of pre-compressed corrugated paper board would reduce the volume of required cushioning material supported the possibility of reducing the volume of cushioning material needed in the package. By reducing the volume of cushioning material, a better fitting to the European standard pallet could be achieved.

The repacking complexity was greatly reduced. The proposed cushioning system consisted two pieces of cushioning that fitted the size of the outer package. The two pieces were identical so it did not matter which piece was placed on the top or on the bottom. The complexity was reduced by reducing the number of parts. The procedures of repacking the original cushioning system were to: 1) position the first bottom cushioning block; 2) position the second bottom cushioning block; 3) put the air purifier into the box; 4) position the first top cushioning block; 5) position the second top cushioning block, and 5) close the box. Since the bottom cushioning would not be removed from the box, and the cushioning fitted inside the box to avoid needs of re-positioning, the procedures of repacking the proposed cushioning system were reduced to: 1) put the air purifier into the box; 2) position the top cushioning; 3) close the box. And if the cushioning was not inserted properly, it was not possible to seal the box. Through such design, repacking mistakes were avoided.

The proposed cushioning system achieved the goals defined for this project, and at the same time, opportunities were identified to further improve the product/package system.

5.2 Conclusions

In this project, a new cushioning system was proposed. The concept was generated in the concept generation, and selected by the Pugh Matrix, and verified by FEM studies. Improvements were made to the concept after the first prototype failed the drop test. The second prototype passed the drop test. A brief LCA study suggested that the environmental impact of the proposed cushioning system was lower than the original cushioning system due to the use of recycled material. The production cost and the storage space of the cushioning system were also reduced. Also, a method of rapid cushioning development for developing pre-compressed corrugated paper board cushioning system based on an existing cushioning system was concluded, which could be applied to other similar products.
In this chapter, some suggestions of future work are presented. These suggestions serve as inspirations of further improvements of the cushioning system of all air purifiers.

There are three aspects to consider if the product/package system needs to be further improved. They are: 1) improving the air purifier itself, 2) using pre-compressed corrugated paper board with higher density, 3) reducing the cushioning material to the minimum.

The first one is to improve the air purifier in order to work better with the cushioning system. This aspect requires changes on the air purifiers, but the outcome will be very beneficial since the product/package system can only be optimized to the fullest by changing both the product and the package for the best match. But such changes are very expensive, but it is a valuable aspect to consider in the development of future products.

The second one is to examine the outcome of using pre-compressed corrugated paper board with higher density. According to the theory, using such material will reduce the total volume of cushioning material, which will lead to the reduction of storage space for the cushioning system and the reduction of the overall package size. The latter outcome will further ease the problem of poor fitting with the European standard pallets. This improvement requires a large number of simulations and experiments. Also a re-design of the outer package including the structure and the artwork is needed.

The third one is to reduce the cushioning material in order to avoid over protection in the product/package system. FEM drop simulations indicated that the proposed cushioning system is potentially over-protecting the product. Reducing the cushioning material to the minimum will help reducing the material usage in the cushioning system production which will lead to a lower environmental impact. The production cost will also be reduced due to the reduced material cost. For similar reasons, this improvement is also helpful addressing the storage space and pallet fitting problems. Therefore, same as the second aspect, a re-design of the outer package is needed.

These three areas could be further improved for the cushioning design of 400 series air purifier or any other air purifiers, especially for the products being developed. But due to the delimitation of this project, these potential improvements were not able to be implemented in this project.


Appendix A is the Pugh Matrix used in the Concept Selection process.

Table 5 Pugh Matrix for concept selection

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Original</th>
<th>Material reduction</th>
<th>Air bag</th>
<th>Air bag +CPB</th>
<th>CPB</th>
<th>Function</th>
<th>CPB+EPE</th>
<th>Molded paper</th>
<th>Mushroom</th>
<th>Honeycomb</th>
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<tr>
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<td>-2</td>
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<td>-1</td>
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<td>1</td>
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<tr>
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</table>
Appendix B is the simulation results of the second iteration. The acceleration diagrams and stress concentration figures of drop simulations on different directions are included.

Figure 45 The simulated acceleration of the sample point in the bottom short edge drop simulation on the second proposed cushioning system.

Figure 46 Equivalent stress of the bottom short edge drop simulation on the second proposed cushioning system.
Figure 47 The simulated acceleration of the sample point in the bottom long edge drop simulation on the second proposed cushioning system

Figure 48 Equivalent stress of the bottom long edge drop simulation on the second proposed cushioning system
Figure 49 The simulated acceleration of the sample point in the side surface drop simulation on the second proposed cushioning system

Figure 50 Equivalent stress of the side surface drop simulation on the second proposed cushioning system
Figure 51 The simulated acceleration of the sample point in the side edge drop simulation on the second proposed cushioning system

Figure 52 Equivalent stress of the side edge drop simulation on the second proposed cushioning system
Figure 53 The simulated acceleration of the sample point in the front surface double height drop simulation on the second proposed cushioning system

Figure 54 Equivalent stress of the front surface double height drop simulation on the second proposed cushioning system