ME5611

SUSTAINABLE PRODUCT DESIGN AND MANUFACTURING

FINAL REPORT (2021/22)

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CHAPTER 1

ABSTRACT

Electric Screwdriver cum drill or Cordless screwdriver cum drill (is a portable electric device that makes screwing, unscrewing, and light duty drilling jobs effortless). It is a very popular product among household and local workshop consumers. It becomes important for a responsible manufacturer to produce a mass consumed product in a more sustainable and environmentally friendly manner. This project/study aims to analyse a cordless screwdriver cum drill manufactured by a local manufacturer. The approaches taken involve disassembling the product, material classification, identifying manufacturing methods and performing design for assembly and disassembly, if necessary, also proposing material and manufacturing method changes. The ECO Indicator-99 points of the product is computed to determine the environmental load during production, use, transporting & packaging and disposal phases. A remanufacturing concept which can reduce up to 53.7% BOM cost with less than USD1000 one time investment and environmental and compliance benefits is proposed. During the study, the product gets totally disassembled to access the ability for remanufacturing and recycling. An ECO Indicator 99 Analysis is also performed, which results in 1361 points, to evaluate the environmental impact of this product. A further engineering effort is put into proposing the design changes with design for remanufacturing and design for recycling considerations. The design change suggestions including change shell material from ABS to PP, changing soldering to plug terminal and gluing the chuck clamp tip instead of press fit. A remanufacturing process workflow with those design changes is designed. Design for assembly (DFA) is also carried out using the Boothroyd Dewhurst (BD) DFA approach, and the index is improved. After the cost analysis from the open information in the market, we conclude the overall bill of material cost saving is around USD5.9 per product.

CHAPETR 2

BACKGROUND INFORMATION

2.1 Life Cycle Assessment

The term "life cycle assessment" refers to a technique for evaluating a product's environmental implications from cradle to grave, which includes raw material production, materials processing, manufacturing, distribution, use, and disposal. This diagram depicts the various steps of a product's manufacturing process. The life cycle assessment (LCA) approach follows the international organization of standards (ISO) 14040 and has a set framework. The purpose of LCA is to assure supply chain sustainability; upstream and downstream manufacturers must demonstrate that their products meet the relevant sustainability requirements. It is a vital aspect of environmental management from the standpoint of stakeholders, not only for product creation but also for building a sustainable manufacturing strategic policy.

The different stages of LCA are

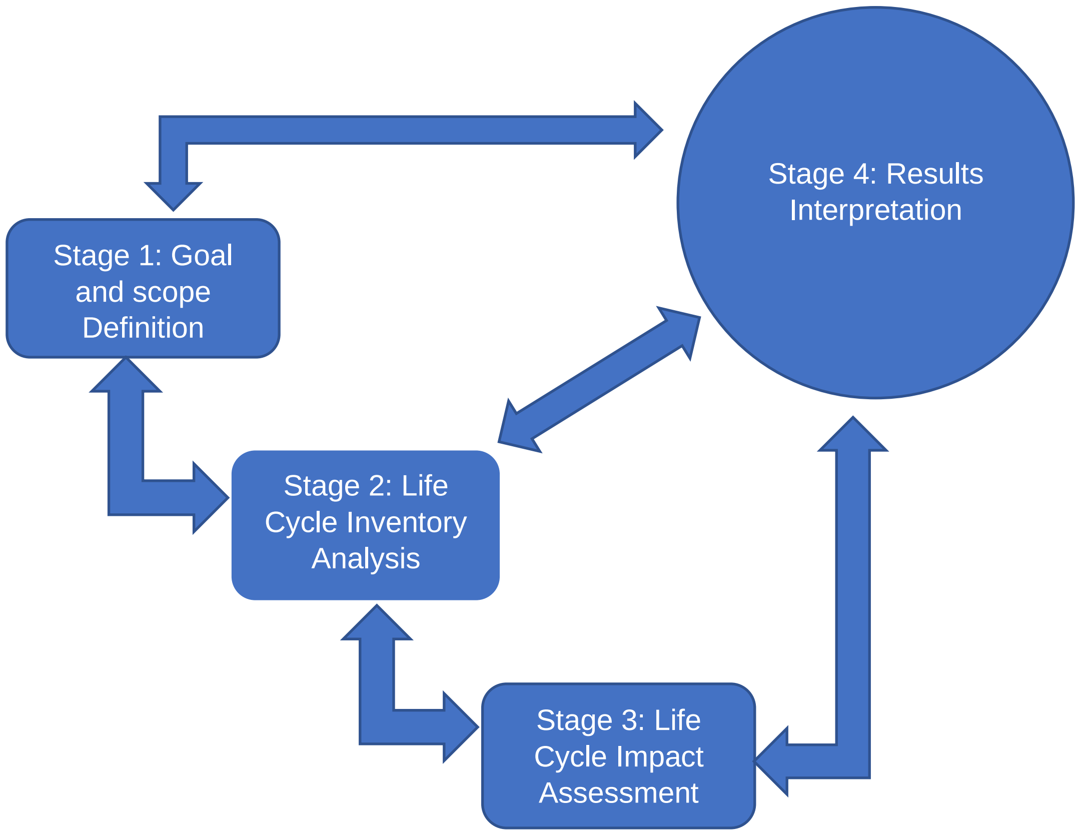

Fig.1 Structure of LCA

Goal and Scope Definition: Defining the need or significance of choosing the product for the study and identifying the possible opportunities in it.

Life Cycle Inventory Analysis: Identifying the materials used to make the product. Determining the manufacturing methods and energy flows and its interaction with environment involved in making of the product.

Life Cycle Impact Assessment: Computing the load on environment by the materials and processes involved in manufacturing, use and disposal phases of the product. Generally calculated in terms of indicator points and classified on basis of phases involved.

Results Interpretation: The process of interpreting and inferring from the results obtained from previous stages and proposing new ideas and methodologies towards sustainable development of the product.

2.2 WEEE Directive

The WEEE Directive[22] is a European Union (EU) initiative to encourage and set targets for the collection, recovery, and recycling of waste electrical and electronic equipment across Europe, as well as to reduce the amount of waste electrical and electronic equipment destined for landfill, because the amount of waste electrical and electronic equipment generated each year in the EU is rapidly increasing. E-waste has become one of the fastest growing wastes as a result of technological advancements and the introduction of new sorts of equipment. The EU's WEEE regulations are intended to solve environmental and other challenges that have arisen as a result of the growing quantity of discarded electronics in the EU. WEEE refers to a wide range of items that have reached the end of their useful lives, such as computers, refrigerators, and cell phones. This type of waste is made up of a complex mix of materials, some of which are potentially harmful. If discarded devices are not properly managed, they can cause serious environmental and health issues. Furthermore, modern gadgets include rare and costly minerals and materials that can be recycled and repurposed if trash is properly controlled. Various sorts of items are divided into distinct categories by the directive, which totals ten categories. Finally, the initiative's principal purpose might be stated as follows:

• Contribute to the circular economy by improving sustainable production and consumption, increasing resource efficiency, and improving resource efficiency.

2.3 ECO Indicator 99

Eco-Indicator 99[24] is a tool for assessing life cycle impact. Eco-Indicator 99 is a tool that helps designers assess a product's environmental impact by producing eco-indicator ratings for the materials and processes involved. The resulting milli-point scores give an indication of the product's impact areas, and possible modifications can be recommended to lower the indicator value. The Eco-Indicator is divided into three parts:

• Raw material production, processing, and manufacturing

• Product transportation, energy consumption, and consumables, if applicable.

• Disposal

Eco-indicator 99 is a pragmatic eco design method as well as a science-based effect assessment method for LCA. It provides a method for calculating numerous environmental impacts and displaying the final result as a single score.

2.4 Cordless Screwdriver/Drill (Electric Screwdriver/Drill)

Cordless screwdriver/drill[23] are portable electric hand tools used to drive screws or perform drilling operations. Compared to their manual counterparts, it saves time and effort on tasks which involve installing lots of screws, such as constructing flat-pack furniture, disassembling furniture etc. It is a popular product in the market due to its various advantages like increased productivity, efficiency, convenient ergonomics and cost effectiveness etc. over the conventional manual screwdrivers.

Currently in the market there are various kinds and styles of cordless screwdriver/drill available for light duty and considerably heavy duty works. The power of the electric screwdriver/drill depends on the voltage rating on the product. Different types are given as follows:

Straight – Usually screwdrivers with a straight handle and have a similar resemblance to manual ones.

Pistol – This type comes in as electric screw drivers/drills, usually have a pistol like handle structure which makes it is ergonomically easier to hold.

Variable - This combines the features of both straight and pistol type by which the holding mechanism can be changed between the two with a pivot.

Impact screwdrivers – These are generally used for driving large and rusty screws and are known to be powerful

Drill Driver – These are the ones which usually have both screwdriver and drill options which can fit both driver and drill bits mainly used for light to medium-heavy duty works

Although there are different kinds according to purpose, generally it can be divided to two types according to its ergonomics or holding mechanism, that is straight and pistol type:

Straight type

Pistol type

Fig.2 Different types of Cordless Screwdriver/drill

CHAPTER 3

INTRODUCTION

3.1 Goal and Scope Definition:

The global power tools market was worth USD 32.3 billion in 2019, and it is predicted to increase at a CAGR of 4.2 percent from 2020 to 2027. Power tools are tools that are actuated by a power source rather than manual labour. They're employed in a variety of settings, including production and assembly lines, maintenance and repair, packing, and do-it-yourself projects. Power tools are in high demand across a variety of industries due to their ease of use and efficiency, as well as their reduced time and labor requirements and portability. Over the next seven years, demand for power tools is expected to rise due to increased adoption in the automotive and construction industries. Fastening jobs abound on automotive production and assembly lines. Power tools can help you save time and boost efficiency by minimizing the time spent on these repetitious operations. As a result, power tools are increasingly being used by car manufacturers as well as automotive repair and maintenance service providers. Similarly, the construction industry's increased usage of drills, sanders, wrenches, and other tools is increasing demand for these products. Because of their ease of use and mobility, power tools are becoming more popular in domestic applications. The growing popularity of Do-It-Yourself (DIY) projects has led in an increase in demand from consumers. Companies are developing goods with additional safety features to cater to the needs of customers who are not qualified professionals. In addition to technological advancements, the market is being driven forward by the increasing popularity of cordless tools that enable simple mobility and do not require an external power source.

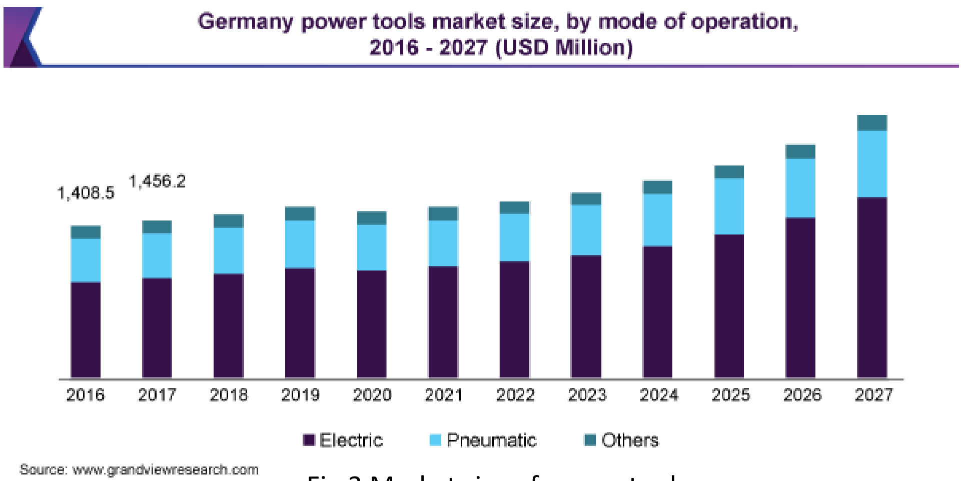

Fig.3 Market size of power tools

Electric screwdrivers are most commonly used by people in production line of a manufacturing company to streamlining the process, household, fabrication works and various other applications. So, it signifies the need for mass producing such a popular product in the market. But this aways leads to a concern which revolves around the responsible OEM to consider the environmental effects of having a mass producing a bigger product than the conventional one. As now a days initiatives like WEEE has made it mandatory to set targets for collection, recovery and recycling of waste electrical and electronic equipment. According to the directive electric screwdrivers/drill falls under category 6[26] (Electrical and Electronic tools). So, it becomes inevitable to design and manufacture the product by confirming to environmental regulations as more and more demand increases in the future.

Fig.4 YSA 12V Cordless Screwdriver/drill

PRODUCT DETAILS

Cordless Screwdriver/drill (Product) chosen for this study

YSA 12V Cordless Drill/Screwdriver

1.5Ah 12V Battery

Max Toque – 19 Nm

The aim of current project is to study the product (YSA 12V Cordless Screwdriver/drill) and to resolve the above-mentioned issue of proposing a method to produce the product in a greener way than it is currently done which will involve the analysis of the product on how it is designed, manufactured and disposed. To disassemble the product to differentiate its parts and identify the materials used in it. Overall, an attempt to improve the product lifecycle performance by indulging in material changes, end of life strategy, energy consumption optimization, cost analysis, carbon footprint analysis etc. are carried out.

3.2 Methodology

- The Product is disassembled into different components and sub parts
- The materials and manufacturing processes are identified and tabulated with weights of corresponding parts measured.
- ECO-99 Indicator points for the product is estimated with help of ECO-99 manual to interpret the environmental impact of the product at different phases like production, use, disposal etc.
- Material changes are proposed for reduced environmental impact.
- Design for Assembly/Disassembly and Remanufacturing is proposed
- Carbon Footprint analysis of the current and of the revamped product is analysed
- ECO-99 of the proposed design is also estimated
- Cost analysis and BOM estimation is performed for the proposed design.

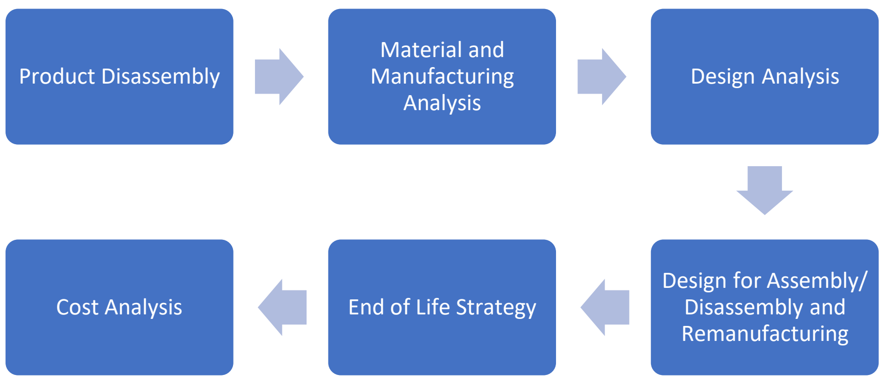

Fig.5 Project Flow Chart

CHAPTER 4
ANALYSIS AND DISCUSSIONS

4.1 Product Disassembly and Inventory Analysis:

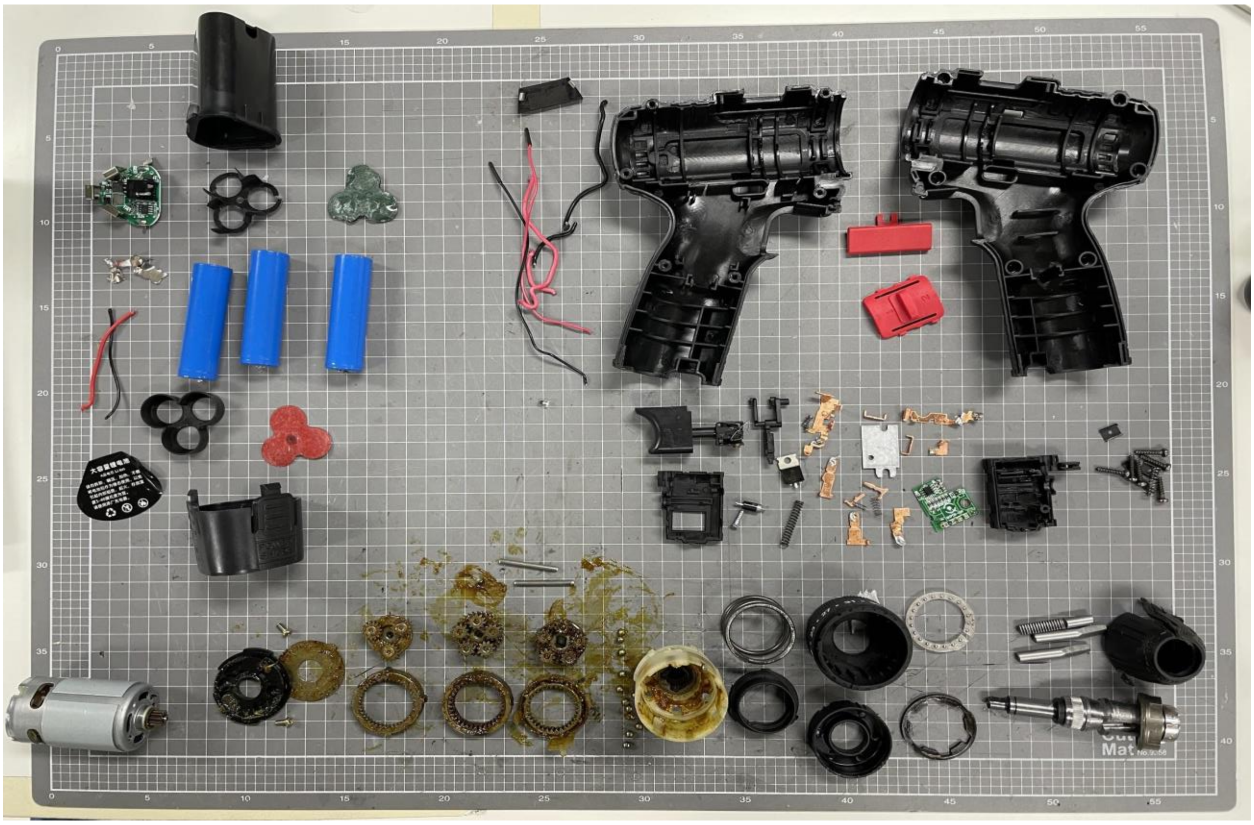

Fig 6. Disassembled Product

Table 1 gives a summary of the raw materials and manufacturing processes involved in making of the product. (Full list of components available in Appendix)

Table 1 Inventory Summary [See Table 4 Appendix]

Raw Materials	ABS Plastic Nylon Plastic Steel Aluminium Copper Brass

Manufacturing Processes involved	Injection Moulding Forging Casting Extrusion Sheet Metal Production Spring Winding Machining (Turning, Milling, Drilling) PCB Fabrication

The overall weight of the cordless drill is observed to be 1 Kg. Most of the product weight is contributed by ABS plastic and Steel. Rest all other materials are present in relatively smaller amounts.

An in-depth disassembly was carried out with the motive that the disassembled component can be recycled for other use cases. For most of the components, it had to be disassembled till it was made of the same material, but the DC motor and Li-ion battery is kept as it is since both of them are standard industry parts and can be easily used for other products. Also, the PCB parts are kept as it is since it will require professional equipment for taking out the surface mount component effectively and do not have access to it. The detailed list of components and parts are given in Appendix [Table 4]

4.2 Disassembly Process and Analysis:

1. The disassembly process to disassemble the product into major disassembled sub-parts as in Figure 6. show is very easy and well designed. They are using the identical type of screws and all the screws can be easily taken out by the easily available screwdrivers from one side. And there's no additional adhesive here. However, the electrical components are connected using soldering of wires, which will leave residue after disassembly.
2. The disassembly of one of the subassemblies, the Trigger Unit as Fig. 10 shows. The general disassembly process is relatively more complex but still feasible with normal tools and not much effort. However, the way the sheet

metal copper connector that connects to the external components with the soldering causes major problems when tried to remove it from the plastic component, a soldering station is needed to remove most of the solder before taking it out.

3. The Battery Unit is also a pretty good design for disassembly as Fig. 11 shows. The notable good design is that there are no screws here, all assembled by plastic snap-fit and adhesive which is very easy to remove. However, the way they attach the brass connector to the battery unit is a permanent method we are not able to remove it from the battery with general tools. But even with the small brass piece attached to the battery unit, it does not cause a major problem to use it for other applications.
4. The Drive Chain as in Fig. 12 consist of a brush DC motor, a 3 stages planet gearbox that offers 2-speed options and a clamp which connects to the drill bit or screw driver bit. The whole drive chain is totally not designed for disassembly. Extreme difficulty was encountered while disassembling it with a professional mechanical workshop and use professional tools including vice, all sizes of pliers, special retaining ring plier, hammers and more than one hour of time, but still at the end of day failed to disassemble the core shaft of it since there’s one screw which is way too hard to remove, it can be assumed that its using some strong thread locker to make a permanent join against high torque and vibration. Also, there is full of grease inside the gearbox, and disassemble it dirties the whole workstation, also it makes a need for a clearing process before recycling the material which can cause water pollution.

4.3 Product Life Cycle and ECO-99 Indicator Analysis (Impact Assessment) :

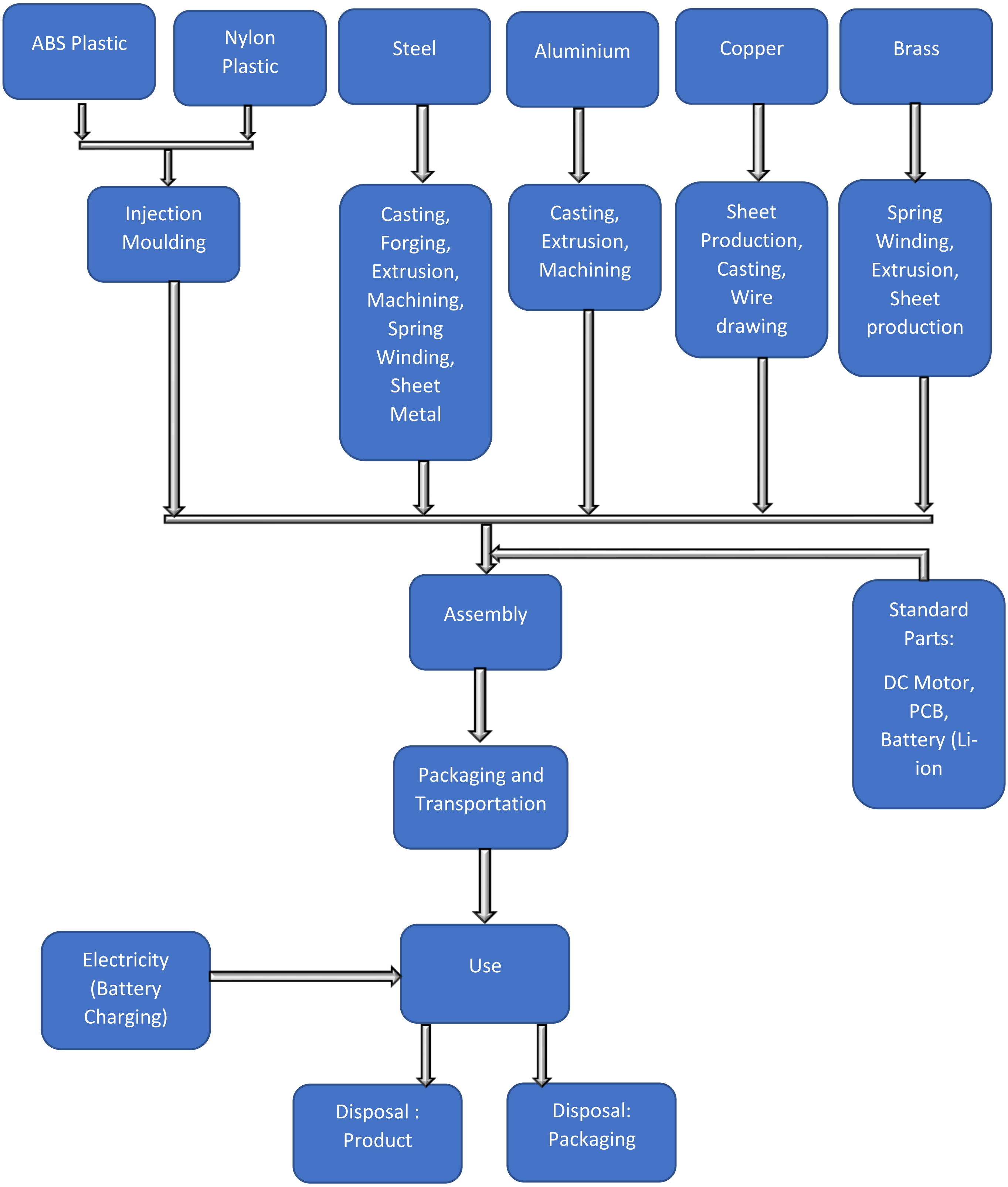

Fig.7 Product Life Cycle & ECO99 Indicator Flow

Various assumptions have to be considered while performing the Eco99 Indicator assessment. The assumptions made here are as follows:

1. The energy consumption for processing metals is acquired from a report on similar analysis done on engine cylinder and vehicle manufacturing [2][3]
2. Certain parts of the product are considered to be standard (PCB, Battery) and the energy consumption and consequently the indicator points are calculated based on information acquired from various research reports and articles. [4][6]
3. For calculation at transportation and packaging phase it is assumed that for packaging a polyethene of 5g and packaging carton (cardboard) of 300g is per item is assumed. Also, for transportation a total of 2000 items are transported along oceanic freight and truck (16t capacity) is assumed.
4. For use phase, the overall lifetime of the product is considered to be 3 years in which it consumes 0.018kWh electricity. Assumed to be used by household works for 0.5 hours a week. Time required for full charging is 2.5 hours and works for 3 hours on full charge, so likewise charging is done once in 6 weeks. The battery has 500 charge cycles. The product is assumed to be disposed after 3 years of use.

Table 2 – Summary of ECO99 Analysis (SEE Table 5 in Appendix)

Phases	**Indicator (mPt)**
Production & Processing	840
Transporting and Packaging	91
Use	433
Disposal	-2.3
Total (All Phases)	~ 1361

Table 2 shows the summary of Eco-Indicator 99 points tabulations. It can be seen from the values that the production & processing phase and use phase has the largest impact on the environment, however the use phase is based on extreme assumption that the product is used on a daily basis. So, there are possibilities that the use phase might have lesser impact than production phase.

4.4 Carbon Footprint Analysis

Below table shows approximate carbon footprint of the materials used per product.

Table 3 – Carbon footprint of material production (See Table 6 Appendix)

Material	Carbon Footprint (Kg CO2 Equivalent)
ABS	0.72
Steel	0.92
Aluminium	0.0076
Copper	0.05
Nylon Plastic	0.004

From the above values of carbon emissions released for production of the material per Kg used in the cordless screwdriver/drill, it can be observed that a total of 1.7 Kg of CO2 equivalent is released for making the product considering only the materials in a intend to propose material changes and subsequent reduction in carbon footprint. Therefore, during mass production, the carbon emission will be multiplied by the number of products manufactured.

4.5 Design Modification for Sustainability

The major problem with the current product design is addressed below and a suitable design for disassembly is proposed.

4.5.1 Electric Component Connection:

We noticed that the electronic components inside the products are all connected by wires with soldering. Which includes the connection between the trigger unit and indicator LED, the trigger unit to the DC brush motor in the drive chain as well as the trigger unit to the battery contactor. Joining the wires with soldering method has the advantage of higher product reliability during the use and manufacturing process and is relatively cheaper in cost. However, the solder also introduces additional costs and negative environmental impact. First of all, the soldering requires a soldering station in the assembly line, it needs to heat up the soldering iron at high temperatures which consume more electricity. On top of this, the workers need special training, and soldering also introduces quality control risk since the soldering technique is tricky to master. From the environmental perspective, some of the solders contain lead for easy melting, which will have significant botanical health hazards if it is not disposed to the environment properly. However usually for this kind of tool people do not dispose of it with care. On the other side, when considering recycling and remanufacturing, soldering is also not friendly as the method to join in between the major components. Because completely removing the solder from the material is very difficult and needs heating tools. Due to the above reasons, we suggest removing the soldering method and replacing it with a plug crimping terminal which is elaborated further in the following discussions.

4.5.2 Drive Chain Lifetime mismatch with battery and fashion

The Drive Chain consists of a brush DC motor, a 3 stages planet gearbox that offers 2-speed options and a chuck clamp which connects to the drill bit or screw driver bit. The whole drive chain is built with solid metals for harsh working conditions with high torque and high shock. In the meantime, this material choice makes the drive chain's lifetime unnecessarily long. The product is easily disposed with a relatively short use time. As the product is selling only for SGD23.5 [7], for the general user, it considers a cheap consumable tool. However, in the meantime, the real-life span of this product is not really dependent on the drive chain. Because of the portable and high-power output requirement, the product has to use a Li-ion battery. However, the Li-ion battery's expected life span is only 2-3 years [8]. When the battery dysfunction after 2-3 years, with a new-fashioned power drill selling at a similar price, it's very easy for the general user to dispose of the product and buy a new one instead of searching for a battery replacement with is relatively much harder to find. However, the drive chain lifetime is a lot longer. In most of the general households which purchase this cheap power drill, we estimate the product will only use once a month, every time not more than 10 minutes operating time, hence in the 3 years less than 9 hours. The drive chain's expected lifetime, however, which mainly depends on the geared DC motor, has an expected lifetime above 1000 hours [9], which is two orders of magnitude higher than the Li-ion battery. Hence for almost all of the products that get disposed off, the drive chain is considered completely new. Hence, we suggest remanufacturing the product by keeping the drive chain and just changing the new-fashioned shell and fresh battery. More details will be elaborated inside the following discussions.

4.5.3 Shell Material

The current product is using ABS as the shell structure. It has good mechanical properties of high strength and good impact resistance which is good for the product. However, when reviewed from a sustainable perspective, the carbon footprint of ABS is significantly higher than other competitors [10]. Hence from the environmental point of view, PP as the candidate which has significantly lesser CO2 emissions [10] and similar mechanical properties can be a good replacement for ABS in this case. Further analysis is carried out in the following discussions.

4.6 Design for Sustainability Suggestion:

Recommendations on design for disassembly and remanufacturing

4.6.1 Plug Crimping Terminal

As discussed in the "Electric Component Connection" section above, our team suggest a plug camping terminal [11] to replace the soldering. As the drawing (in the appendix) of the plug crimping terminal shows, the terminal connects to the electric wires by only crimping, hence there's no electrical power needed, no complicated training needed. Also, the crimping plier is a lot cheaper than the soldering iron. The plug camping terminal can be selected off the shelf to match exactly the size of the flat metal contacting piece on the motor, switch unit as well as battery contactor. This change does not need to request a change in the supply chain of all those components which can save a significant amount of cost. To join the plug crimping terminal to the contacting plate of the component just takes the plier to plug it in, does not take special tools or any special training. From remanufacturing perspective, introducing the plug crimping terminal significantly reduce the disassembly time, because to disassemble the component which connects with the wire, the operator just needs a plier to take out the connector without harming the original component or leaving any residues compared to soldering method, which needs the soldering station and solder sucker, with skilled workers. From a recycling perspective, the crimping on the wire is reversible, hence the plug crimping terminal can get totally removed from the wire without any residue. And the crimping terminal can very easily break down into components made from a single material, which makes it possible for recycling the plug crimping terminal and the motor or other component connected to it.

4.6.2 Remanufacturing Design for Drive Chain

4.6.2.1 Quick Detachable Shaft (failed)

The first idea our team worked on in the remanufacturing conceptual design for the drive chain is to design a quick detachable shaft. The idea is to make the chuck clamp, gearbox and motor can get quickly detached from each other. So that during the remanufacturing process, there's an option to change the motor, gearbox and chuck clamp according to the new design. For example, the new design requires the gearbox to have a bit lower gear ratio but the chuck clamp and motor can remain the same. Through this quick detach shaft mechanism, the gearbox can quickly get disposed and then replaced with the new one instead of disposing of the whole drive chain. The design gets inspired by a shaft connector used for a DIY mini-CNC machine [12]. The design uses easily accessible 304 stainless steel with a shaft diameter of 10mm. The shaft is connected to the connector with a set screw to a flat keyway. However, when we conduct the FEA for the maximum torque condition which is 19 Nm according to the maximum torque the website suggests [7] the FEA result shows the local stress is more than 10x of the 304 steel's yield strength, this strength requirement is more than any steel can take. Hence this design is not applicable. On top of this, the consideration of this idea will require the supply chain to customize the shaft. Also, this design will increase the overall length of the final product, hence the injection mould, packaging box, storage and shipping arrangement all need to upgrade for this design change. Hence, we conclude this idea is not feasible.

4.6.2.2 Glue Joint for Chuck Clamp Tip Assembly

To further optimize the remanufacturing process of the produce, the difficulties in the disassembly of the covers for the chuck clamp get addressed by this design improvement suggestion.

When conducting the remanufacturing, the cover for the chuck clamp needs to be replaced, because the disposed of product, the chuck clamp plastic cover has a high chance to get scratched during the harsh environment like the chips of drilling. On top of that, the remanufactured part will come with a new-fashioned shell design which will also change the shell outline of the cover of the chuck clamp. In the current product's design, all the shell of the chuck clamp is actually only constrained by the tip of the chuck clamp, which is pressed to fit onto the chuck clamp and is extremely difficult to remove with normal professional mechanical tools. However, once it gets removed, the operator can easily take out all rest of the components of the chuck clamp shell. Also, the re-assemble of the new chuck clamp shell is very easy. Hence to further optimize the remanufacturing process, an easily removable chuck clamp tip will be a critical feature to streamline the overall process. However, the chuck clamp tip is working in a harsh environment with a constraint load. The chuck clamp tip is working in a harsh environment because it is right next to the drill bit, when the power drill is working, there will be significant vibration accrued at it. On top of that, if the power drill drops on the floor, the chuck clamp tip will be the first component to hit with a significant shock. But in the meantime, the spring force from the torque limiter is constantly acting on the chuck clamp tip. If the chuck clamp tip fails, the whole shell of the chuck clamp will fall out and the product will dysfunction. Hence the reliability of the chuck clamp tip is critical. To full fill the high-reliability requirement of the chuck clamp tip, the press-fit is always the best way to go as the original design. However, with the remanufacturing consideration, press-fit takes too much effort to rework. The screw thread is not a good option here, because it does not have good resistance to the shock and vibration although it is easy to rework. The only common option is to join the chuck clamp tip with adhesives. Comparing all adhesives, epoxy is a good option since it has excellent bounding force, and durability under vibration and shock, which had been widely used for applications with critical loading in harsh environments with vibration and shock such as aerospace and automotive. To remove the epoxy, just need to heat it up more than the glass transition point, the epoxy will become soft and able to remove[13]. Here are two epoxy recommendations. One is PERMABOND® ET500 [14], it's fast setting and easy to apply, perfect for remanufacturing process. Also, the glass translation point is not super high, a heating jig can be designed to heat up and remove it. There's another interesting epoxy ElectRelease M4 [15], it can get easily removed with 10V DC electricity but in the meantime, it was designed for the air force for aerospace applications with the excellent mechanical property. By using this epoxy, the rework jig can get very much simplified and consume lesser power of heating.

4.6.3 Change Material to Polypropylene (PP)

As mentioned in the previous chapter, the current ABS material is not environmentally friendly compared to PP. Our team reach out to professional mould makers and get feedback on the cost and material property of ABS and PP which is recommended for power drill application, which is presented in the appendix. The major concern in the material change referring to the material properties is that the PP has less strength than ABS. However, if the PP can also survive the conventional application, considering the positive environmental impact, still worth the change. Hence an FEA simulation of the worst-case loading is conducted. We assume the worse loading will be the product drop from 3 meters height, free fall and crash on the floor. The impact force was calculated to be 214.6N considering the product weight 0f 0.73kg [16]. The FEA result shows the safety factor in this scenario is more than 2.8, hence we suggest it is safe to change the material to PP for this product. Another note we learned from the mould maker is that the sinking rate of ABS and PP is about 300% different, hence to change the material, a cost of a new mould has to be invested. If not, the product size will have unacceptable deviations from the original design, causing other components cannot install correctly. Hence commercial speaking, if there’s no government fund or hard compliance requirement, this material change might not make a profit from the financial perspective, unless it happens with change of the shell design because of fashion reason.

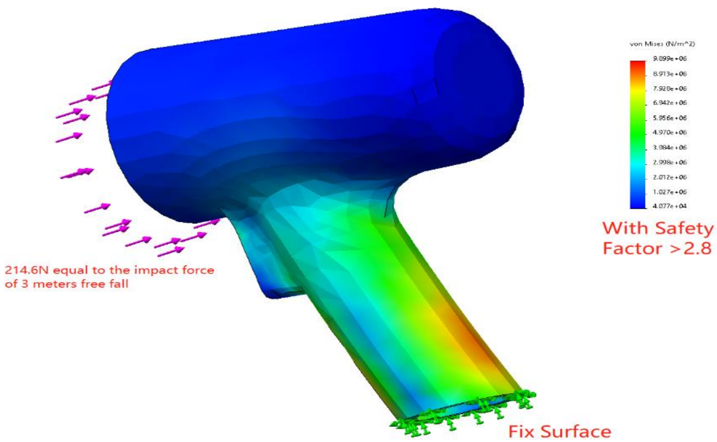

Fig.8 FEA Simulation of Simplified Shell model with PP Material

4.7 New Design Evaluation

4.7.1 Remanufacturing Workflow

After implement the design changes proposed on above chapter, the remanufacturing workflow shall be as following:

STEP 1 Incoming Quantity Check

To identify the received recycled product is the correct model for remanufacturing. Remove the produce which show the potential damage to the drive chain. Remove the battery.

STEP 2 Disassembly

STEP 2.1 Remove the 4 of M3 Self Threading screw, and open the shell

STEP 2.2 Take out the Drive Chain, and Trigger Unit Assembly. Disconnect the electrical wires easily with the plug crimp terminal

STEP 2.3 Take out the plastic parts on the Drive Chain and Trigger Unit Assembly.

STEP 2.4 Use special jig to remove the Chuck Clamp Tip (heating or 10V DC, depends on which epoxy chosen) and remove the shells for chuck clamp

STEP 3 Testing and Recycle

STEP 3.1 Recycle the shell and other shell related accessories as ABS material. For the rest of parts dispose it or send to other recycling partners.

STEP 3.2 Test the Trigger Unit, Drive Chain, if the parts are still functional, use for remanufacturing. If not, dispose it or send to other recycling partners.

STEP 3.3 Test the electric wire and battery connector, if they are still in good condition and still functional, use for remanufacturing. If not, dispose it or send to other recycling partners.

STEP 4 Reassembly

STEP 4.1 Install the new shell for the chuck clamp, glue the chuck clamp tip

STEP 4.2 Connect the Drive Chain and Trigger Unit Assembly with electric wires easily with plug crimp terminal.

STEP 4.3 Conduct product functional test. Trigger the Drive Chain with external power supply by Trigger Unit, Test the output speed and torque at the chuck clamp of Drive Chain

STEP 4.4 Assemble the new shell with other accessories.

STEP 5 Out-going quality check

STEP 6 Packaging

4.7.2 Cost Evaluation

Throughout the market research for the cost from Alibaba for each component, assuming 40% discount for large volume of the list price, our team make a Bill of Material with cost for USD12.7 which is about half of the selling price on the website. For this low end hight volume product, we see 100% additional price to the BOM cost this price is reasonable. The BOM see appendix. Based on above assumption, we found out that after implementing above design changes, we have USD5.9 and 53.7% BOM cost reduction. By considering the remanufacturing process, the only special investment is only the epoxy glue removing station in the production line, which estimated not cost more than USD200 of one-time cost. Rest of the assembly step and cost is almost the same as the original one, which we assume to be as the same. But since there’s change of procedure, we take the overall one-time investment for set up the remanufacturing no more than USD1000. Hence the conclusion is to invest no more than USD1000 to set up the remanufacturing line we can save USD5.9 per product produced.

4.7.3 Estimated reduced environmental impact after proposed design changes

The environmental impact after incorporating the proposed design changes is estimated based on ECO-99 Indicator and carbon footprint analysis.

- After changing the ABS plastic of the mentioned parts to Polypropylene (PP) a reduction of 20.3 mPt in production phase and 45.86 mPt in disposal phase by recycling of PP is obtained.
- The remanufacturing concept proposed on the drivetrain and spindle part brings about reduction of total of 304 mPt.
- The Carbon Footprint is reduced by 35.55% when the material is changed from ABS to PP for the specific parts.
- The remanufacturing concept brings about reduction of 52.17% in Carbon footprint of steel.
- Altogether the newly proposed design gives a total reduction of 370.16 mPt which is the reduced impact from 1361 mPt to 990.84 mPt.

4.7.4 Design for Assembly Evaluation

Design for assembly (DFA) based on Boothroyd Dewhurst (BD) DFA approach is also conducted. We establish the manufacturing flow for the original assembly process which bases current product design and conduct the BD DFA evaluation. Then based on the design improvement we explain above, we establish another assembly process and also evaluate with the BD DFA approach. The result shows that with the design recommendations, the production time of each new product, BD DFA Index improve to 41.29% from 29.73%, total time of 56.6 s was reduced.

We also conduct the BD DFA evaluation for the remanufacturing process, the total time for the whole remanufacturing cycle is only 353 seconds and 152 seconds longer than the original process, only about $0.6 more costly than the original process for fabricating a new part, which is way lesser than the $5.9 BOM cost saving.

4.7.5 Business Considerations for Remanufacturing

Considering that to make the whole business case works, the biggest challenge to how to take back the disposed product from the customer. We suggest should work on this issue on both the logistic partner side and the customer side. We suggest we can have a deal with a large logistic group such as DHL, use the environment improvement as the main selling point to get a delivery fee of less than USD3 to get back each product to the factory. If that is feasible, we can attach a return shipping coupon to each of our product packages. Also, we can improve the design of the product packaging box in a way that it will be able to accept by the logistic partner as the shipping packaging, hence will save customers trouble to ship it back. On the customer side, we can consider making a poster to address the shipping back as a cool and good thing to do, there’s a very successful case for instant coffee [21], and this can be a good marketing campaign. However, a gift voucher to reward the shipping back is not recommended. Because the overall saving is only USD5.6, it is pretty hard to convince people to take the trouble to ship back by USD 5 and it also reduces the profit for the company.

CHAPTER 5

CONCLUSION

This substantial design study focus on a power drill. The study examines the disassembly and material selection of the product. Evaluate the environmental impact base on ECO99. Engineering work had been conducted for a design change for recycling and remanufacturing to reduce significantly the environmental impact and also earn more profits for the business that produces the power drill.

The proposed design's ECO Indicator 99 points were decreased by 370.16 mPt, a reduction of 27.2 %. The Carbon Footprint of the proposed design is found to be reduced by 43.26%. We calculated that after applying the above design improvements, we will save USD5.9 and 53.7 percent on our BOM costs. The results reveal that following the design recommendations, the production time of each new product improved to 41.29 percent from 29.73 percent, resulting in a total time reduction of 56.6 seconds.

Through this study, We learned that substantial design does not always mean higher cost, an all-rounded business solution with a more eco-friendly product is feasible with proper engineering design with the knowledge we learn from the ME5611 module.

CHAPTER 6

APPENDIX

TABLE OF LIST OF COMPONENTS

COTS=Commercial Off the Shelf

Table 4

Component	Qty	Weight (g)	Material	Manufacturing Process
Product (Without battery)	1	734.9	-	Assembly in Factory
Battery Unit	1	136.9	-	Assembly in Factory
Charging Unit	1	46.9	-	Assembly in Factory
M2.5x13 Button Head Philips screw	6	4.1	Stainless Steel	COTS
Clip	2	0.3	Galvanized Steel	Sheet Metal
Casing (Left)	1	66.9	ABS	Injection Moulding
Casing(right	1	63.5	ABS	Injection Moulding
Speed Switch	1	3.4	ABS	Injection Moulding
Spring (Speed switch)	1	0.1	Spring Steel	Spring Winding
Direction Switch	1	2.9	ABS	Injection Moulding
Control Unit(FA2-16/1WEK)	1		-	Assembly in Factory
Heat Sink	1	1.8	Aluminium Alloy	Casting
M2x11.3 Countersunk Philip screw	1	0.1	Aluminium	COTS
Si based thermopaste (to increase thermal conductivity)	-	0.1	Silicon based	COTS
Grease	-	1	-	COTS
Circuit Board components	5	6.2	Copper (Sheet metal)	PCB fabrication and soldering
Circuit Board components	4	0.7	Copper (Casted)	PCB fabrication and soldering
Brass Spring	1	0.1	Brass	Sheet Metal
Semiconductor Chip (HGT60N06 SMP72)	1	1.9	-	COTS
Diode (IN504 P)	1	0.5	-	COTS
Springs	5	0.6	Spring Steel	Spring Winding
Direction Switch Handle	1	1.3	ABS	Injection Moulding

Control Unit Casing Cover	1	3.2	ABS	Injection Moulding
Control Unit Casing Base	1	6.8	ABS	Injection Moulding
Trigger	1	5.3	ABS	Injection Moulding
PCB	1	1.5	ABS	PCB fabrication and soldering
Solder (Lead Free)		2	-	COTS
Connection Terminal (Base	1	2.5	ABS	Injection Moulding
Connection Terminal points	2	0.2	Brass (Silver)	Sheet Metal
Wires	6	4.1	Copper with rubber/plastic insulation	COTS
LED	1	0.1	-	COTS
Gear System Components		133.5	Steel	Gear Machining
Gear system Casing	1	19.9	Nylon	Injection Moulding
Gear box component	2	7.9	ABS	Injection Moulding
Torque Control Spring	1	12.2	Spring Steel	Spring Winding
DC Motor	1	214.4	-	COTS
Spindle Head	3	41.9	ABS	Injection Moulding
Spindle Head (Shaft + holder)	5	123.4	Steel	CNC Machining
Ball Bearing Ring	1	1.1	Nylon	Injection Moulding
Battery Casing	4	25.3	ABS	Injection Moulding
Cardboard Paper Insulate terminal	2	0.1	Carboard Paper	Dia Cutting
Insulation & Shock resistant for battery	1	0.1	High Density PE foam	Dia Cutting
Battery cells	3	102.5	Li-ion	COTS
Battery Circuit Components	3	7.6	PCB	PCB fabrication and soldering
Wires (Battery)	2	0.6	Copper with rubber/plastic insulation	COTS
Bit	1	13.6	Tool Steel	Casting

Images of Disassembly

Fig.9 Housing Unit

Figure.10 Trigger/Switch

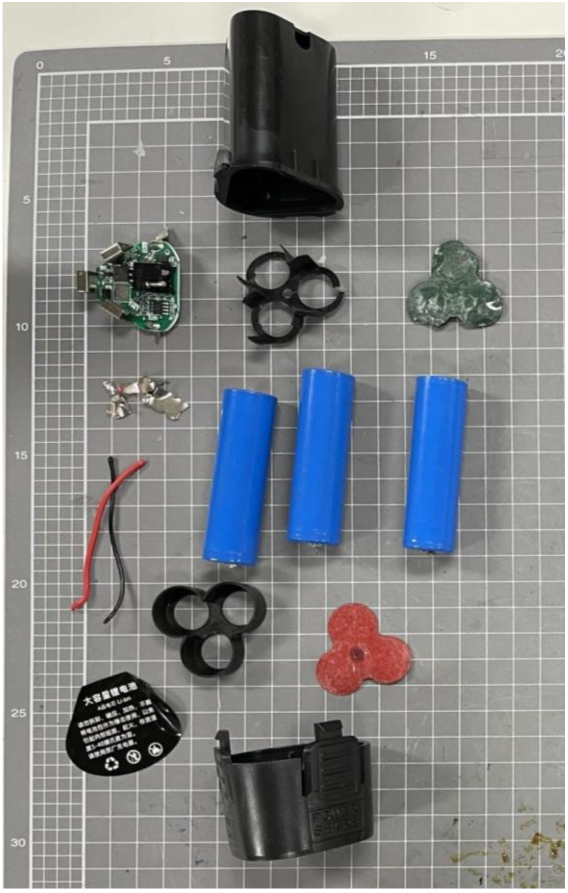

Figure.11 Battery Unit

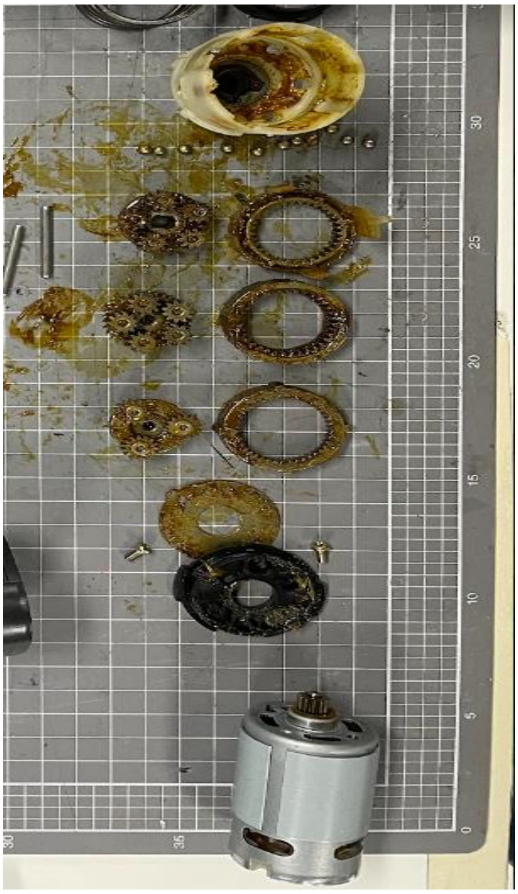

Figure.12 Drivetrain & Gear

Figure.13 Spindle Head

ECO99 TABLE

Table 5 – Eco-99 Calculation

	Production					
Material	Part Description	Weight (Kg)	Total Weight(Kg)	Indicator (I)	Result (Kg x I)	
ABS	Casing	0.1304				
	Speed & Direction switch	0.0076				
	Control Unit casing + base	0.01				
	Trigger	0.0053	0.2309			
	Connection terminal base	0.0025		400	92.36	
	Gear box component	0.0079				
	Spindle head cover	0.0419				
	Battery Casing	0.0253				

Nylon Plastic	Gear system casing	0.0199	0.021	350	7.35	
	Ball bearing ring	0.0011				
Steel	Button head Philips screw	0.0041	0.4978			
	Clip	0.0003				
	Springs	0.0129		910	453	
	Gears	0.1335				
	Spindle head	0.1234				
	Tool Bit	0.0136				
	DC Motor	0.21				
Aluminium	Heat Sink	0.0018	0.0019	780	1.482	
	Counter sunk philip screw	0.0001				
Copper	PCB (Sheet metal)	0.012	0.0214			
	Casted Copper	0.0007		1400	29.96	
	Wires	0.0087				
Brass	Spring	0.0001	0.0003	2300	0.69	
	PCB (Sheet metal)	0.0002				
				Total	584.842	
	PROCESSING					
Material	Part	Amount	Manufacturing Process	Energy Consumption (MJ)	Indicator	Result
ABS	Casing					
	Speed & Direction switch					
	Control Unit casing + base					
	Trigger	0.2309	Injection Moulding	-	21	4.8489
	Connection terminal base					
	Gear box component					

	Spindle head cover					
	Battery Casing					
Nylon Plastic	Gear system casing	0.021	Injection Moulding	-	21	0.441
	Ball bearing ring					
Steel	Button head Philips screw	0.0041	Extrusion + Machining	0.2665	4.2, 800	1.12
	Clip	0.0003	Galvanized + Sheet production + Bending	-	30 & 0.00008	0.0106
	Springs	0.0129	Extrusion + Spring winding	0.8385	4.2	3.52
	Gears	0.1335	Casting + Machining	8.6775	4.2 & 800	36.46
	Spindle head	0.1234	Forging + Machining	8.021	4.2 & 800	33.7
	Tool Bit	0.0136	Forging + Machining	0.884	4.2 & 800	3.71
	DC Motor	0.21	Casting	13.65	4.2	57.33
Aluminium	Heat Sink	0.0018	Casting	0.416	4.2	1.75
	Counter sunk philip screw	0.0001	Extrusion + Machining	0.011	4.2	0.0462
Copper	PCB (Sheet metal)	0.012	Sheet Production + Bending	-	30 & 0.00047	0.36
	Casted Copper	0.0007	Casting	0.005	4.2	0.021
	Wires	0.0047	Wire drawing	0.1175	4.2	0.5
Brass	Spring	0.0001	Extrusion + Spring winding	0.0065	4.2	0.0273
	PCB (Sheet metal)	0.0002	Sheet Production	-	30 & 0.00047	0.007
	PCB (2 Nos. 4cm x 4cm)	0.015	PCB Fabrication	4 kWh	22	88
Li-ion	Battery (1.5Ah x 12V)			1.035	22	22.77
					Total	254.622

	Packaging					
	Material		Indicator	Result		
	Polyethene (PE)	0.005	2.1	0.0105		
	Packaging Carton	0.3	69	20.7		
	Truck 16t	2000	34	68		
	Oceanic Freight	2000	1.1	2.2		
			Total	90.9105		
	Use					
	A = 1.5Ah V = 12V		Indicator	Result (mPt)		
	P = 18W					
	Use in a week	0.5 hrs				
	Electricity used for 3 years for charging	11.7 kWh	37	433		
			Total	433		
	Disposal					
	Material	Amount	Indicator	Result		
	ABS - Municipal waste	0.2309	2	0.4618		
	Steel - Municipal waste	0.4978	-5.9	-2.93702		
	Aluminium - Municipal waste	0.0019	-23	-0.0437		
	Nylon - Municipal waste	0.021	3.1	0.0651		
	PE - Municipal waste	0.005	-1.1	-0.0055		
	Cardboard - Municipal waste	0.3	0.64	0.192		
			Total	-2.26732		
			Total Indicator points	1361.10718		

CARBON FOOTPRINT VALUES

Below table shows Carbon equivalent emissions of different materials used in this product

Table 6 (Ref : Google)

Material	Carbon Equivalent (Kg) / Kg material
ABS	3.1
PP	1.95
Steel	1.85
Aluminium	4
Copper	2.4
Nylon Plastic	0.201

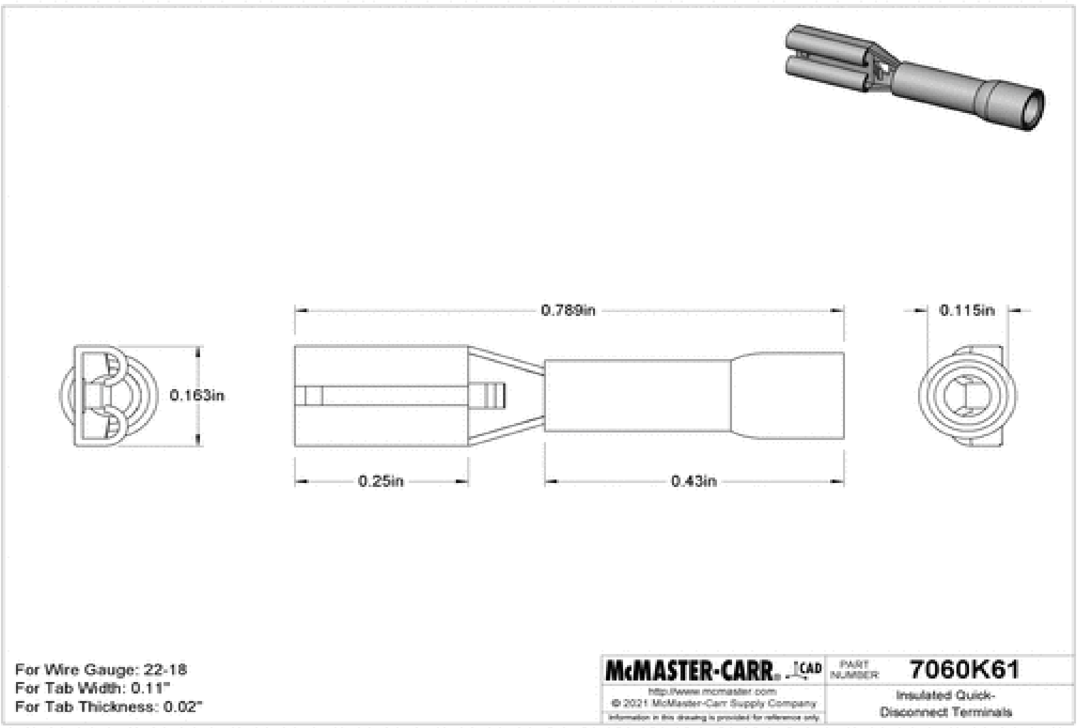

Figure.14 Plug Crimping Terminal Drawing [11]

Figure.15 Mini CNC Machine Shaft Connector [12]

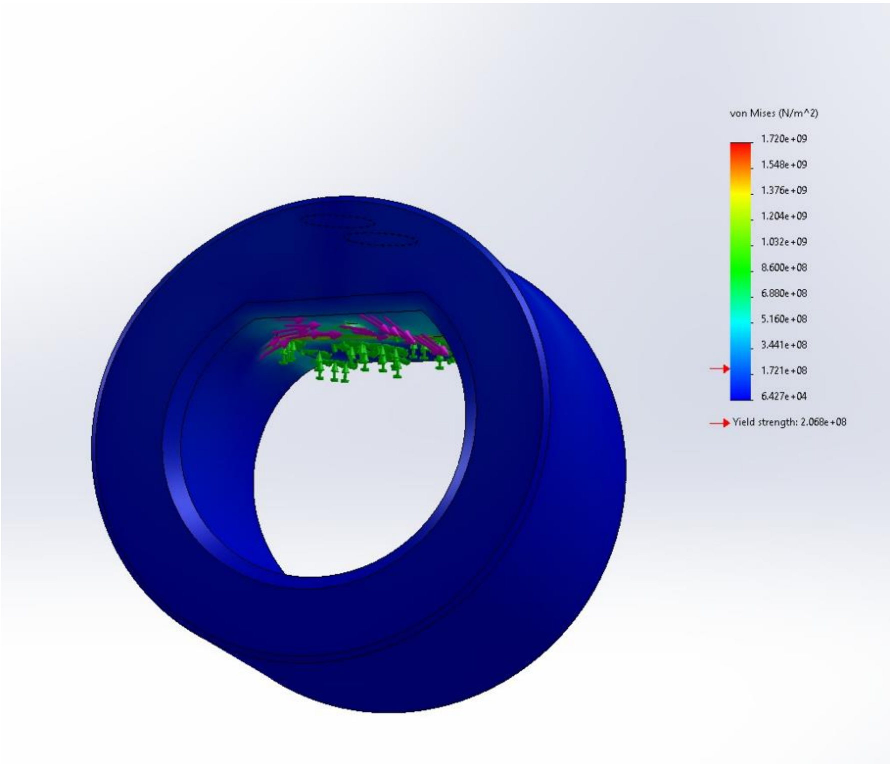

Figure.16 Shaft Connector FEA Result

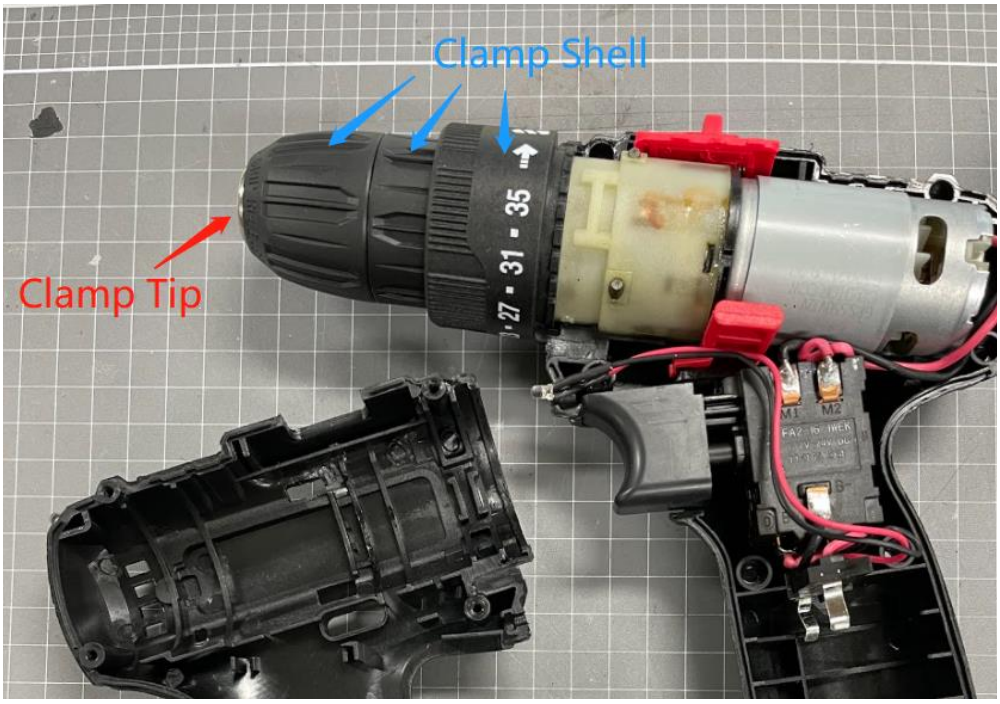

Figure.17 Clamp Tip and Clamp Shell

Table 7 – Material Comparison ABS Vs PP

Item	ABS	PP K-1108
Cost	USD25/kg	USD28/kg
Tensile Strength	62 MPa	35.3 MPa
Izod Notched Impact Strength	540 J/m	30 J/m
Flexural Strength	90 MPa	1471 MPa
Specific Gravity	1.2 g/cm3	0.9 g/cm3
Shrinkage Ratio	1.5%	0.5%
ECO99	400 per kg	330 per kg
ECO99 Mark	80 per product	64.5 per product
CO2 emission	3.1 per kg	1.95 per kg

Table 8 – Remanufacturing BOM cost estimation

ITEM	Cost - Before (USD)	Cost - After (USD)	Remarks
Motor & Gear Box	4.2	Recycled	[18] with 40% discount for large volume
Trigger Unit	0.6	Recycled	[17] with 40% discount for large volume
Chunk Clamp	2.6	Recycled	[19] with 40% discount for large volume
Battery	2.44	2.44	[20] with 40% discount for large volume
Shell & Accessaris	2.5	3	Increase for use PP
Wires	0.3	1.3	Increase for use Plug Crimp Terminal
Fasterners	0.1	0.1	
Total	12.74	6.84	Remanufacturing Cost Reduction 53.69%

Table 9 - Original Assembly Process BD DFA Evaluation

1	2	3	4	5	6	7	8	9	
Part Name	**Number of times the operation is carried out consecutively**	**2-digit manual handeling code**	**Manual handling time per part**	**2-digit manual insertion code**	**Manual insertion time per part**	**Operation time (Seconds)**	**Operation Cost (cent)**	**Figures for estimation of theretical minimum parts**	**Remanfacturing Step**
Drive Chain	1	02	1.18	NA, test in the testing jig	10	11.18	4.472	1	Test the Trigger Unit, Drive Chain
Trigger Unit	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	Test the Trigger Unit, Drive Chain
Chunk Crimp Plastic Shells	3	00	1.18	00	1.5	8.04	3.216	3	Install theshell for the chuck clamp
Chunk Crimp Tip	5	40	3.6	37	9	63	25.2	1	Install theshell for the chuck clamp

Electric Wire	5	40	3.6	95	8	58	23.2	5	Connect the Drive Chain and Trigger Unit Assembly with electric wires easily with the plug crimp terminal.
Assembled Parts	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	Conduct product functional test.
Half shell	2	02	1.18	00	1.5	5.36	2.144	2	Assemble the new shell with other accessories.
M3 Screws	4	00	1.13	83	6	28.52	11.408	4	Assemble the new shell with other accessories.
Assembled Product	1	02	1.18	NA, visual check	3	4.18	1.672	1	Out-going quality check
Assembled Product	1	02	1.18	NA. Packing	10	11.18	4.472	1	Packaging
						TM	**CM**	**NM**	
						201.82	80.728	20	
							Design Index	**29.73%**	

Table 10 - Improved Design Assembly Process BD DFA Evaluation

1	2	3	4	5	6	7	8	9	
Part Name	**Number of times the operation is carried out consecutively**	**2-digit manual handeling code**	**Manual handling time per part**	**2-digit manual insertion code**	**Manual insertion time per part**	**Operation time (Seconds)**	**Operation Cost (cent)**	**Figures for estimation of theretical minimum parts**	**Remanfacturing Step**
Drive Chain	1	02	1.18	NA, test in the testing jig	10	11.18	4.472	1	Test the Trigger Unit, Drive Chain

Trigger Unit	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	Test the Trigger Unit, Drive Chain
Chunck Crimp Plastic Shells	3	00	1.18	00	1.5	8.04	3.216	3	Install the shell for the chuck clamp
Chunck Crimp Tip	5	40	3.6	98	9	63	25.2	1	Install the shell for the chuck clamp
Electric Wire with plug terminal	5	40	3.6	95	0	1.5	0.6	5	Connect the Drive Chain and Trigger Unit Assembly with electric wires easily with the plug crimp terminal.
Assembled Parts	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	Conduct product functional test.
Half shell	2	02	1.18	00	1.5	5.36	2.144	2	Assemble the new shell with other accessories.
M3 Screws	4	00	1.13	83	6	28.52	11.408	4	Assemble the new shell with other accessories.
Assembled Product	1	02	1.18	NA, visual check	3	4.18	1.672	1	Out-going quality check
Assembled Product	1	02	1.18	NA. Packing	10	11.18	4.472	1	Packaging
						TM	**CM**	**NM**	
						145.32	58.128	20	
							Design Index	**41.29%**	

Table 11 - Remanufacturing Assembly Process BD DFA Evaluation

1	2	3	4	5	6	7	8	9	
Part Name	**Number of times the operation is carried out consecutively**	**2-digit manual handeling code**	**Manual handling time per part**	**2-digit manual insertion code**	**Manual insertion time per part**	**Operation time (Seconds)**	**Operation Cost (cent)**	**Figures for estimation of theretical minimum parts**	**Remanfacturing Step**
Returned product	1	02	1.88	NA, visual check	3	4.88	1.952	1	STEP 1 Incoming Quality Check
M3 Screws	4	00	1.13	83	6	28.52	11.408	4	STEP 2.1 Remove the 4 of the M3 Self Threading screw and open the shell
Half shell	1	02	1.18	00	1.5	2.68	1.072	1	STEP 2.1 Remove the 4 of the M3 Self Threading screw and open the shell
Drive Chain	1	02	1.18	00	1.5	2.68	1.072	1	STEP 2.2 Take out the Drive Chain, and Trigger Unit Assembly. Disconnect the electrical wires easily with the plug crimp terminal
Trigger Unit	1	00	1.18	00	1.5	2.68	1.072	1	STEP 2.2 Take out the Drive Chain, and Trigger Unit Assembly. Disconnect the electrical wires easily with the plug crimp terminal

Electric Wire with Plug Terminal	5	40	3.6	00	1.5	25.5	10.2	5	STEP 2.2 Take out the Drive Chain, and Trigger Unit Assembly. Disconnect the electrical wires easily with the plug crimp terminal
Chunck Crimp Plastic Shells	3	00	1.18	00	1.5	8.04	3.216	3	STEP 2.3 Take out the plastic parts on the Drive Chain and Trigger Unit Assembly.
Trigger	1	00	1.18	00	1.5	2.68	1.072	1	STEP 2.3 Take out the plastic parts on the Drive Chain and Trigger Unit Assembly.
Chunck Crimp Tip	5	40	3.6	98	9	63	25.2	1	STEP 2.4 Use a special jig to remove the Chuck Clamp Tip (heating or 10V DC, depending on which epoxy is chosen) and remove the shells for the chuck clamp
Drive Chain	1	02	1.18	NA, test in the testing jig	10	11.18	4.472	1	STEP 3.2 Test the Trigger Unit, Drive Chain, if the parts are still functional, used for remanufacturing. If not, dispose them or send them to other

									recycling partners.
Trigger Unit	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	STEP 3.2 Test the Trigger Unit, Drive Chain, if the parts are still functional, used for remanufacturing. If not, dispose them or send them to other recycling partners.
Electric Wire with Plug Terminal	5	40	3.6	NA, test in the testing jig	2	28	11.2	5	STEP 3.3 Test the electric wire and battery connector, if they are still in good condition and still functional, used them for remanufacturing. If not, dispose them or send them to other recycling partners.
Chunck Crimp Plastic Shells	3	00	1.18	00	1.5	8.04	3.216	3	STEP 4.1 Install the new shell for the chuck clamp, glue the chuck clamp tip

Chunck Crimp Tip	5	40	3.6	99	12	78	31.2	1	STEP 4.1 Install the new shell for the chuck clamp, glue the chuck clamp tip
Electric Wire with Plug Terminal	5	40	3.6	00	1.5	25.5	10.2	5	STEP 4.2 Connect the Drive Chain and Trigger Unit Assembly with electric wires easily with the plug crimp terminal.
Assembled Parts	1	02	1.18	NA, test in the testing jig	5	6.18	2.472	1	STEP 4.3 Conduct product functional test.
Half shell	2	02	1.18	00	1.5	5.36	2.144	2	STEP 4.4 Assemble the new shell with other accessories.
M3 Screws	4	00	1.13	83	6	28.52	11.408	4	STEP 4.4 Assemble the new shell with other accessories.
Assembled Product	1	02	1.18	NA, visual check	3	4.18	1.672	1	STEP 5 Out-going quality check
Assembled Product	1	02	1.18	NA. Packing	10	11.18	4.472	1	STEP 6 Packaging
						TM	**CM**	**NM**	
						352.98	141.192	43	
							Design Index	**36.55%**	

CHAPTER 7

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