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**Improvement on the Design of RapMan 3.1 3D printer  
using Boothroyd Dewhurst DFMA**

by

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## LIST OF ABBREVIATIONS

|       |   |
|-------|---|
| 2D    | 2 dimensional   |
| 3D    | 3 dimensional   |
| ADDIE | Analysis-Design-Development-Implementation-Evaluation |
| AEM   | Hitachi Assembly Evaluation Method                    |
| AHP   | Analytic Hierarchy Process                            |
| AUVSI | Most Innovative Air Vehicle                           |
| CAM   | Computer-Aided Manufacturing                          |
| DFA   | Design for Assembly                                   |
| DFM   | Design of Manufacturing                               |
| DFMA  | Design for Manufacturing and Assembly                 |
| DIW   | Direct Ink Writing                                    |
| DIY   | Do It Yourself  |
| DLP   | Digital Light Processing                              |
| DMLS  | Direct Metal Laser Sintering                          |
| EBF3  | Electron beam freeform fabrication                    |
| EBM   | Electron-beam melting                                 |
| FDM   | Fused Deposition Modelling                            |
| FFF   | Fused Filament Fabrication                            |
| GNU   | General Public License                                |
| IARC  | International Aerial Robotics Competition             |
| LOM   | Laminated Object Manufacturing                        |
| PC    | Polycarbonate   |
| PC    | Polycarbonate   |

|        |                              |
|--------|------------------------------|
| PPSF   | Polyphenylsulfone            |
| PPSF   | Polyphenylsulfone            |
| QFD    | Quality Function Deployment  |
| RepRap | Replicating Rapid Prototyper |
| RP     | Rapid Prototyping            |
| SGC    | Solid Ground Curing          |
| SHS    | Selective heat sintering     |
| SLA    | Stereo lithography           |
| SLA    | Stereolithography            |
| SLM    | Selective laser melting      |
| SLS    | Selective Laser Sintering    |
| SLS    | Selective laser sintering    |
| UAS    | Unmanned Aerial Systems      |
| UAV    | Unmanned Vehicles Systems    |

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## LIST OF SYMBOLS

|                      |  |
|----------------------|--|
| $W$                  | Weight   |
| $t_{pw}$             | Effect of Weight on Handling Time  |
| $W_{t_h}$            | The aggregate time punishment because of weight  |
| $t_h$                | The essential time for taking care of a "light" part   |
| $C$                  | The impact of chamfer plan on addition operation   |
| $D$                  | The width for the gap  |
| $d$                  | The measurement for the peg  |
| $f(\text{chamfers})$ | Equivalent - 100 for no chamfer, - 220 for chamfer on gap, - 250 for chamfer on peg and 370 for chamfer on peg and gap |
| $L$                  | The length of the gap  |
| $t_i$                | Estimation of Insertion Time   |
| $\eta$               | Design efficiency  |

## Abstrak

Kajian ini fokus kepada penggunaan Reka Bentuk Untuk Pembuatan dan Pemasangan (DFMA) untuk menambahbaik pencetak RapMan 3.1 3D. Terdapat banyak kaedah DFMA seperti Kaedah Penilaian Pemasangan Hitachi (AEM), Lucas-Hull dan Boothroyd Dewhurst; walaubagaimanapun kajian ini menggunakan kaedah Boothroyd Dewhurst untuk menambahbaik RapMan 3.1. Penggunaan Boothroyd Dewhurst DFMA memberikan beberapa kelebihan seperti memberi strategi metodikal untuk menyiasat plan cadangan dari perspektif himpunan fabrikasi. Hasilnya adalah lebih banyak barang pepejal yang kurang susah yang kurang mahal untuk dikumpulkan dan dibuat. Ia dapat memberikan nilai asli hasil dari masa, kos yang diukur sebelum dan selepas proses membangun menentukan cara yang terbaik dan paling berkesan untuk membangunkan unit dan memperkuasakan teori. Walau bagaimanapun, dengan penggunaan DFMA telah terbukti bahawa reka bentuk baru yang dibangunkan lebih cekap, dan menjimatkan kos dan masa. Kelebihan ini membuatkan ia disyorkan untuk menggunakan kaedah ini dalam meningkatkan RapMan 3.1 yang merupakan satu jenis pencetak 3D Reprap. RapMan 3.1 telah diperhatikan sangat sukar untuk dipasang, kerana persamaan antara kepingannya, sama ada dengan orientasi atau simetri yang sama. Selain itu, semasa pemasangan terdapat terlalu banyak kepingan yang sukar dicapai, jadi, untuk menyelesaikan masalah tersebut, mereka bentuk semula unit supaya menjadi lebih sesuai untuk pengguna biasa dan juga mereka bentuknya dengan lebih efisien menjadikan unit lebih mudah untuk dipasang, menjimatkan masa, wang dan membuktikan prinsip keupayaan menaik taraf Reprap. RapMan 3.1 mempunyai bentuk padu yang dibina dari sudut bentuknya. Proses reka bentuk semula termasuk hanya lapan kepala sudut kerana ia termasuk kebanyakan bahagian kecil, yang sangat mudah hilang dengan tiada alat ganti, dan begitu juga dengan sebahagian besar bahagian yang sama, mengurangkan bilangan bahagian dari 15 bahagian kepada hanya satu bahagian. Pelarasan ini akan meningkatkan pencetak RapMan 3.1 3D. Reka bentuk baru yang dibangunkan akan lebih cekap, menjimatkan kos dan masa. Langkah peningkatan dalam kajian ini bermula dengan merekabentuk melalui lakaran tangan kemudian perisian Solidwork, menggunakan Jadual Kecekapan DFMA dengan membuat dua jadual salah satunya untuk bahagian asal dan yang lain adalah untuk bahagian-bahagian baru, Kemudian membuat perbandingan antara hasil kedua-dua reka bentuk untuk mengekstrak kecekapan reka bentuk, menggunakan persamaan DFMA seperti kesan berat pada persamaan masa pengendalian dan kesan persamaan reka bentuk chamfer, dan menggunakan kaedah Pugh dengan memilih satu dari tiga reka bentuk dan langkah terakhir adalah fabrikasi bahagian dengan menggunakan RapMan 3.1 pencetak 3D dan bahan ABS. Kesan dari langkah-langkah ini akan membawa kepada pengurangan jumlah pemasangan dari 429 langkah ke 349 langkah, mengurangkan bahagian dari 1502 bahagian menjadi 1182 bahagian, dan mengurangkan masa pemasangan dari 5197.24 saat hingga 3999.26 saat. Ia akan menjadikan pemasangannya lebih mudah dengan mengurangkan bilangan bahagian yang akan mengurangkan bilangan langkah. Oleh itu, banyak masa dan usaha akan diselamatkan serta menggalakkan peminat pencetak 3D (DIY) untuk mula menghasilkan lebih banyak idea kreatif mengenai beberapa cara untuk menambahbaik jenis pencetak ini. Juga pelanggan yang lebih suka (DIY) pencetak 3D akan teruja dengan versi baru RapMan 3.1 dan melihat ke hadapan kepada lebih banyak peningkatan dalam bidang ini.

## Abstract

This study focus on using Design For Manufacturing and Assembly (DFMA) to improve RapMan 3.1 3D printer. There are many methods of DFMA such as Hitachi Assembly Evaluation Method (AEM), Lucas-Hull and Boothroyd Dewhurst method; however this study uses Boothroyd Dewhurst method for improving RapMan 3.1. Using Boothroyd Dewhurst DFMA gives some advantages such as giving a methodical strategy to investigating a proposed plan from the perspective of assembly and fabricate. The outcome is less difficult to assembly which is less costly to collect and make it can give a pure resultant value of the time, cost measured before and after the developing process determining the best and the most efficient way to develop the unit and powering the theory. However, using DFMA has proved that the new developed design is more efficient, and saves cost and time. These advantages made it recommended to use this method in improving RapMan 3.1 which is one type of Reprap 3D printers. RapMan 3.1 has been noticed to be very difficult to assemble, due to the similarity between its pieces, whether it was by same orientation or symmetries. Also, during the assembly there are too many pieces which are hard to reach, so, in order to solve such a problem, redesigning the unit to be more suitable for regular user and also designing it more efficiently has made the unit easier to assemble, saving time, money and proving the principle of the Reprap upgrading ability. The RapMan 3.1 has a cubic shape constructed from the corners of the form. The process of redesigning included only the eight head corners as it includes most of the small parts, which are very easy to lose with no spare parts, as well as most of the similar parts, decreasing the number of parts from 15 parts to only one part. These adjustments will improve RapMan 3.1 3D printers. The new developed design will be more efficient, saves cost and time. Improving steps in this study starts with designing by handing sketches then solid work software, using DFMA Efficiency Table by making two tables one of them for the original parts and the other is for the new parts, Then making a comparison between the results of both of them to extract the design efficiency, using DFMA Equations such as effect of weight on handling time equation and effect of chamfer design equation, and using Pugh method by selecting one from three designs and the last step is parts fabrication by using RapMan 3.1 3D printer and ABS material. The consequences of these steps will lead to reduce the total assembly steps from 429 steps to 349 steps, reduce the parts from 1502 parts to 1182 parts, and reduce the assembly time from 5197.24 Sec to 3999.26 Sec. It will make its assembly much easier by reducing the number of parts which will reduce the number of steps consequently. Hence, a lot of time and effort will be saved as well as encouraging fans of (DIY) 3D printers to start generating more creative ideas about some ways improve these type of printers. Also for those customers who prefer (DIY) 3D printers will be excited about the new version of RapMan 3.1 and looking forward to more enhancements in this field.

## 1.1 Introduction

There are many methods of Design For Manufacturing and Assembly (DFMA). One of the fundamental methods is Hitachi Assembly Evaluation Method (AEM). This method is based on the principle of "one part - one motion". It uses two performance indicators which are the Assembly Cost Ratio and the Design Quality. It has not been practiced in general as it's a very primitive method. Lucas-Hull is also DFMA method which almost looks like the Boothroyd Dewhurst, that's because the originator of this method worked for Boothroyd Dewhurst method in its beginning. It also relies on a structured, cyclic approach which carried out analysis, assessment and synthesis repeatedly. Lucas-Hull method process consists of three fundamental stages each of those stages has its own "pass" criterion, those three stages are Functional Analysis, Handling Analysis and Fitting Analysis, respectively. The initial Lucas/Hull DFA method documented the DFA knowledge into a paper manual which has become an interactive economical computer based system having a considerable advantage compared to other systems. Information analysis in this method has witnessed a lot of improvements in the structured, steady information evaluation. The last method is Boothroyd Dewhurst DFA method. This method has been chosen for this study as it's used for redesigning purposes. In this study it is used for redesigning the current design of RapMan 3.1 3D printer.

In the field of design, projects has established a great development through time, the development main aims were to reduce cost and save time for both designers and users, Regarding this, rapid prototyping is one of the great steps in the field of designing, to make it simple, taking a 3D object and slicing it into very thin layers then start to attach all the layers in just 2D increasing the third dimension (height) and keep repeating this action until reaching to the original 3D object design. All rapid prototyping works on the same principles. Taking an existing 3D model and export to a compatible file type (de facto standard is. STL) Slicing that file type into a various identical layers using additional software Print first 2D slice increment height a certain amount then print next layer repeat until the last layer is completed.

As it has been considered as a designing revolution, thus, it's noticed the rapid increase in using it. This technology is being used by every 3D printer but in different steps as some 3D printers print the final material directly while other units combine two technologies to create a solid material, anyway, all the steps are the same, it just depends on the method as some 3D printers require additional supports added to the original 3D model in order to print correctly. Others require a layer material to be deposited before a layer can be printed. However, Reprap machines are considered the most famous machines in the Do It Yourself (DIY) 3D printers which is also known by the Lego type, as it has a low cost and it can also be manufactured by the same unit and its also can be easily upgraded in its design and control, as it has become widely used by researchers and designers even armatures, so, 3D printing through the Reprap. Facilitates outsourcing, as well as the sharing of designs among designers and users. Software programs such as Alibre and Autodesk enable the designer to design a product at home or in the office, and then send the design via e-mail to a customer. Designs can also be very easily shared in 3D printing.

Consider Nick Staro, a mechanical design engineer, RapMan 3.1 is one of the 3D printers made by Bits from Bytes corp. Which is considered one of the Reprap applications. The RapMan 3.1 unit is a very difficult to assembly as it has too many symmetric parts and more than 1200 pieces. However, in order to solve such a problem, the design for manufacturing and assembly (DFMA) method has the perfect approach as using it ease the process of picking the disposable component and the applicable to merge component in order to get a net result with less cost and time, thus, DFMA is considered as a very powerful alternative to all thru running design management methods as it provide lots of advantages.

## 1.2 Problem Statement

- i. One of the biggest problems that face the user with the RapMan 3.1 is that it takes too much time to assemble especially in the early stages of assembly (the 8 corners) at least 72 hours to assemble the whole printer, which afford the user too much time as he also could get some labor to finish the job for him which will cost extra money demolishing the fact that the unit can be provided in cheap price.
- ii. Another problem is that it has too many small important components including screw, bolts, nuts, and washers (have sizes between 7mm to 28mm) which can be easily lost which will stop the process of assembling the unit without these parts.
- iii. Regarding the component, similar parts in the unit components with similar orientation with no distinguishing code wither by numbers or color can be very confusing to the user as combined with the time issue it will be nearly impossible to be assembled by one person.

- iv. Concerning the assembly, during the assembly the user will find it too difficult to attach some of the part as it's too hard to be reached, so, it was a necessary to make these parts friendly to reach by changing the design.

### **1.3 Research Objectives**

- i. To investigate the design efficiency of the RapMan 3.1 3D printer.
- ii. To improve the design efficiency of the RapMan 3D printer by redesigns the product using Boothroyd Dewhurst DFMA approach.
- iii. To fabricate a new parts design and evaluate the performance of RapMan 3.1 3D printer.

### **1.4 Scope and Limitations of Research**

Using RapMan 3.1 as case study, as it become very clear while assembling the unit the disadvantages and the difficulties which faces the user during the process. Using Boothroyd Dewhurst methodology as the DFMA tool to define all the parts of the unit and determining the disposable parts and the parts that can be redesigned in order to ease the process of assembling the unit. In order to fabricate the new redesigned parts, it was a must to use lightweight materials so that the units remain with approximately same weight and the same strength, thus, using lightweight materials such as Nylon or Teflon as the parts in assembly was the perfect choose to start the process of redesigning.

## 1.5 Significance of Study

It will make its assembly much easier by reducing the number of parts which will reduce the number of steps consequently. Hence, a lot of time and effort will be saved as well as encouraging fans of (DIY) 3D printers to start generating more creative ideas about some ways improve these type of printers. Also for those customers who prefer (DIY) 3D printers will be excited about the new version of RapMan 3.1 and looking forward to more enhancements in this field.

## 1.6 Summary

Using the DFMA method provides the perfect approach to determine the all the disposable parts as also the parts which is going to be redesigned. Calculating the time and cost which to be saved through the design efficiency table. This idea can be an inspiration for a new innovation fields to the researchers to continue developing the other parts design. This idea proves that the open source like the one represented the featuring principles in RapMan 3.1 because it can be promoted independently without the support of any other unit.

## 2.1 Introduction

Traditionally, basic Analysis-Design-Development-Implementation-Evaluation (ADDIE) is observed to be followed in a linear fashion in most conventional design models, as shown below in the diagram in Figure 2.1. The steps are separated from one another and well-defined each one on its own. While recently, a series of prototypes are built and evaluated rapidly during the design process in what is known as Rapid Prototyping. Prototypes are incomplete version of the desired final product. These incomplete models keep running through a cycle to be refined after gathering information about each one of them in a process called formative evaluation that is aimed to revise the prototypes until it meets its objectives as shown below in the diagram in Figure 2.2 (Clark, Designer & Service, 2015).

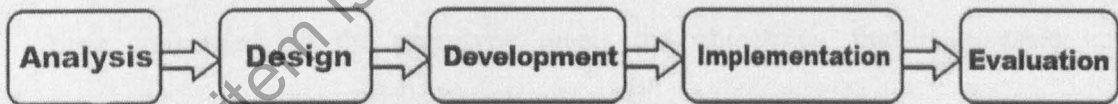


Figure 2.1: Traditional ADDIE Model (Clark et al., 2015).

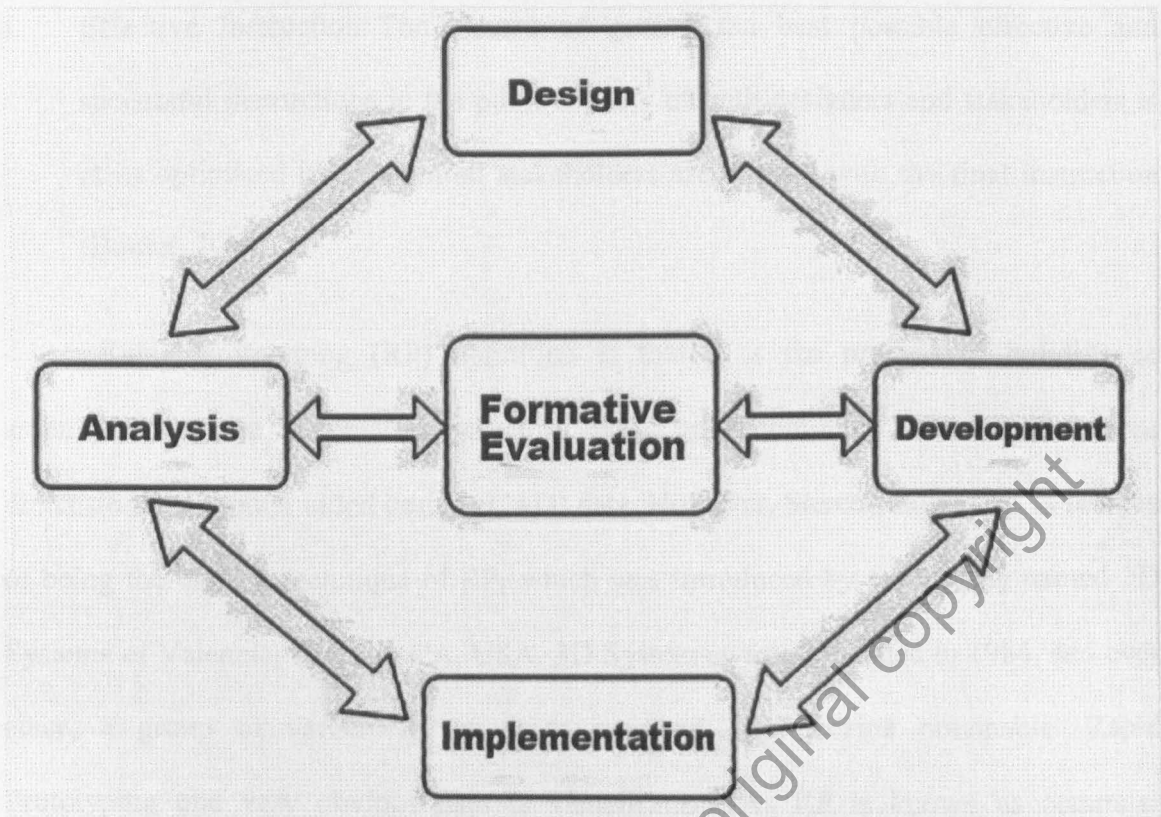


Figure 2.2: Rapid Prototyping Model (Clark et al., 2015).

Rapid prototyping aims to:

- i. **Efficiency:** Rapid prototyping aims at higher efficiency levels by cutting cost and time consumed till the prototype meets the objectives, that it assesses any suggested major changes or issues in the prototype, e.g. issues related to the instructions, during early stages. Unlike conventional design models, however, that follows a summative evaluation, which may need the designers to start all over again from and rebuild the design, increasing by that the cost and time (Boulet, 2007).
- ii. **Stakeholder and designer satisfaction:** Rapid prototyping takes into consideration every party involved in the process, from designers to financiers to stakeholders (Boulet, 2007).

- iii. Effective Instruction: The chance of getting the best possible effective and successful instructions in the point of view of both designers and stakeholders is at its optimised level when all stakeholders are content with the final instruction (Boulet, 2007).

Rapid Prototyping (RP) definition is that it is the process of building or assembling a three dimensional structure based on a computer software of a three dimensional computer aided design (CAD) data. However, Stereolithography is famous of being the earliest technique of RP, which was introduced by a company named 3D Systems of Valencia, based in CA, USA. 3D Systems was established in 1986, and ever since, a group of variant RP methods emerged and became obtainable. Rapid Prototyping one very obvious uses is visualisation. As RP is known as computer automated manufacturing, solid layered manufacturing, and free-form manufacturing. Additionally, one prominent use of RP models is testing, as when wind tunnel is to be used to test an airfoil shape. RP models useful for creating tools, as they can be the male part as a silicone rubber shapes and investment casts. Although sometimes RP piece is final one, but usually the materials used in RP are not adequate enough nor have the desired accuracy. However, producing quite complicated designs (inclusive pieces built inside other pieces) is possible when the material used in RP is appropriate due to the nature of RP. Many RP techniques are commonly available on commercial level such as: Fused Deposition Modeling (FDM), Stereolithography (SLA), Solid Ground Curing (SGC), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), and Ink Jet printing techniques, while a large number of experimental RP techniques are being developed or being used by a little number of people (Pena, 2016).

Currently 3D printers Considered as one of RP instruments, Chuck Hull created Stereo lithography; SLA for short that stands for (Resin/Laser based printing) and additionally and the STL record organize and began 3D Systems in 1986. Stratasys was established in 1989 and introduced the Fused Deposition modeling technique identified as FDM (Extruder based printing) and successfully provided 44% of the world demand in additive fabrication machines by the year 2007. Only big universities and companies could afford to use 3D printers due to the high price tag that was at least \$20000 during the 1990's. Z-Corp, Stratasys and 3D Systems were the leading producers in providing 3D printers. Home PC users and hobbyist gained better access to the world of 3D printing taking advantage of the advanced technology and user friendly 3D modeling at the beginning of the new millennium. The hobbyists were able to produce tinier and less expensive and easily accessible machines by taking signals from the larger ones made by the big companies. In 2005, RepRap was the earliest home based system machine (T.Rowe Price, 2012).

Since the late 1970s, 3D printing witnessed few types of processes; nevertheless those printers had limited number of what could be printed on them, besides their huge sizes and the amount of money they cost. On the contrary, a big amount of additive processes are highly available as shown in Table 2.1. Those additive processes vary among each other on the way they deposited the materials to make the parts, besides the materials used or could possibly be used in the process. In General, melting or softening the materials are the most common types of processes such as; FDM, SLS, Direct Metal Laser Sintering (DMLS), or Selective Laser Melting (SLM). However, SLA is one other common method that cures liquid materials by engaging a set of complicated technologies. And LOM that creates shapes by joining thin layers of the cut materials such as polymer, metal, and paper. In fact, each one of the methods has its own strength